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THE STUDY OF COMETS

Part 1

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October 28–November 1, 1974

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-393

THE STUDY OF COMETS

Part 1

The Proceedings of IAU Colloquium No. 25,
Co-Sponsored by COSPAR,
and held at Goddard Space Flight Center,
Greenbelt, Maryland, October 28–November 1, 1974

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INTRODUCTION

In 1972, the Laboratory for Extraterrestrial Physics at the Goddard Space Flight Center began a detailed study of the technical and scientific phases of a cometary mission. One outcome of that activity was the realization that much information about comets needed to be acquired in order to properly carry through a cometary mission analysis. It appeared that an international meeting with emphasis on the structure and composition of the nucleus and coma would be timely in late 1974. This would be four years after the Leningrad meeting which emphasized problems of the motion and orbital evolution of comets as well as the nature of the nucleus.

Such a meeting was proposed to the IAU and COSPAR and was approved as IAU Colloquium No. 25 with cosponsorship by COSPAR. The International Organizing Committee Consisted of B. Donn (Chairman, USA), L. Biermann (Germany), A. Delsemme (USA), O. V. Dobrovosky (USSR), B. J. Levin (USSR), B. Marsden (USA), N. F. Ness (USA, representing COSPAR), E. Roemer (USA), P. Swings (Belgium), V. Vanysek (Czechoslovakia), F. L. Whipple (USA). The discovery of Comet Kohoutek (1973f) in March 1973 with its anticipated great luminosity near perihelion in late December 1973 led to a revision of the Colloquium program. The combination of a bright comet and a number of new or improved observing techniques indicated that important new results would soon be forthcoming. This expectation together with observations of other recent bright comets, Comet Bennet (1970II) and Comet Tago-Sato-Kosaka (1969IX) led to a division of the program into two parts. The first two days were devoted to Part I: Observations of Recent Comets. Part II: Theory and Interpretation of Cometary Observation, took up the last three days. The division of the material was not, of course, as distinct as the titles of the two parts would indicate.

It was believed that the meeting would be more valuable by concentrating on reviews or selected areas and extensive discussion among the participants. Significant new results were generally presented by the investigators whereas the reviewer was requested to summarize and coordinate papers reporting on similar types of standard observations, e.g. photometric or spectroscopic measurements. We wish to acknowledge the cooperation of all authors and reviewers in making this procedure as successful as it was. All papers not published elsewhere for which manuscripts were submitted are included in the Colloquium Proceedings. For papers already published, abstracts with reference to the detailed paper, are given. In the case of a review all discussion remarks made following it are given after the review, although in a few cases the comments referred to a summarized paper subsequently presented and published here in full.

In order to expedite publication, discussion questions and comments were edited by the Local Organizing Committee. Only where a complete statement was not available or where a statement appeared to require clarification was it sent to the speaker for review. In some cases this judgement may have done a speaker an injustice for which an apology is extended. We trust the value of early publication is adequate compensation for such incidents. A few discussion remarks were omitted by the editors when the exchange became too confused even with the tape recorded material or if they were trivial comments. Some of the lengthier exchanges were considerably reduced by the editors or the speakers during their review.

The Local Organizing Committee consisted of W. Jackson (Chairman), M. A'Hearn, R. S. Harrington and M. Mumma. Phyllis Zuckerman accepted the task of arranging for guests of participants to visit various governmental, educational, medical, social service and similar agencies or services in the metropolitan Washington area in addition to visits to interesting sights.

This Colloquium was made possible by the facilities and financial support provided by the Goddard Space Flight Center - NASA, for which we are indebted to Drs. John Clark and George Pieper. The Graphic Arts Branch provided valuable assistance prior to and during the Colloquium. The publication of these Proceedings has received considerable support from the Publications Branch, particularly from Margaret Becker. Additional financial assistance was provided by the IAU, Howard University Graduate School and the University of Maryland Department of Physics and Astronomy. The initial motivation for this Colloquium came from Norman Ness who had an active role in the early stages of its formulation and gave continued support during its preparation. The Local Committee is grateful to Barbara Holland, Blanche Newton, Carl Wagonfuhrer, Sandra Morey and Martha Harding, for their efforts prior to and during the Colloquium.

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Goddard Space Flight Center
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N76-21053

PHOTOMETRY OF THE COMETARY ATMOSPHERE: A Review

V. Vanysek*

1. INTRODUCTION

Photometry and polarimetry of the cometary heads still constitute one of the most important sources of information about the physical processes in comets. For instance, most of the present estimates of molecular lifetimes are based on the observed distribution of molecules in the cometary head and the assumption of a particular kinematical behaviour of the matter in the cometary atmospheres.

The study of kinematics and dynamics of cometary heads and tails has been based upon the analysis of the forms and apparent motions of well-defined envelopes, halos, knots in tails and streams. Direct inspection of a large number of photographs (or drawings from the last century) of several bright comets demonstrates that the cometary head is generally a complicated object. The heads consist of nearly circular diffuse patterns with superposition of different features, particularly of curved streams. This is illustrated by the Atlas of the Cometary Forms compiled by Rahe, Donn and Wurm (1970).

Comets of small apparent dimensions exhibit few features which could be observed directly and could be used for the interpretation of physical processes. Therefore, for many comets the information available for comparison with theories of the mechanism and tail or head formation was obtained mostly only from the study of distribution of the surface intensity.

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*Read by J. Rahe

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It is, however, essential that the observations should refer, as far as possible, to the radiation emitted or reflected by different kinds of particles (dust, C_2, C_3, CN, CO^+, etc.). It is, therefore, evident that the interpretation of the structure of comets requires monochromatic observations.

Direct unfiltered photography is still valuable for the continuous monitoring of the rapidly changing cometary phenomena—as, for instance, of some features in the tail. It is almost useless for other information about the processes in cometary bodies. The amount of useful monochromatic observations of comets has been still lamentably poor in the past decades—in contrast to the photometry of stars and nebulae, where rapid progress has been achieved. The number of comets observed with adequate modern techniques is small and limited mostly to bright objects observed since 1956. A most dissatisfying circumstance is the fact that photographic and photoelectric observations do not usually lend themselves to the transformation of the absolute photometric scale into isophotes which can be obtained with high angular resolution only from large-scale photographs.

The best discussion of this problem is in a short review by F. D. Miller in the Appendix to "Report on Planned Programme for Comet Kohoutek 1973f" by Brandt, Rahe and Vanysek (1973).

Table 1

Narrow-Band Filters for Standard Cometary Photometry and Photography (Recommended)

Cometary Emission	λ_{max}(Å)	FW(Å)
CN	3880 4738	70 to 80 50 to 60
C_2	5170	50 to 60
CO^+ (tail)	4267	<50
Na	5893	<50

λ_{max} = wavelength of the maximum transmission
FW = full width at half maximum

Table 2

Sample of the Narrow-Band Filters Used for Photometry of CN, C_2 and Continuum*

Author	CN	C_2	Continuum
Bappu et al. (1967)	3859(163)	4720(71)	4310 4860(65) 5875(97)
Vanysek (1969)	3880(240)	4740(90)	4860(180)
Miller (1969)		5136(96)	4850(64)
Konopleva et al. (1970)		4740(190) 5225(480)	4380-4470 4750-4840 5640-5700
Borra et al. (1971)	3878(95)	5117(95)	4870(95)
Kohoutek (1974)	3892(42)	4747(58) 5180(78)	5306(73)

*Four digits are peak transmission wavelength and in parentheses the width at half maximum; both in Å.

2. PRESENT STATE OF COMETARY PHOTOMETRY

Even though the narrow-band photometry is being used more extensively, the available photometric observations of comets suitable for the study of the different compounds' distribution are still lacking, and only a few homogeneous sets of observations have been obtained. The paucity of accurate photometric observations of comets in monochromatic light is due merely to the fact that it is very difficult to reconcile the needs of cometary photometry with those of stellar photometry.

The results obtained from the wide-band photometry must be regarded as tentative only, unless it is quite evident that either continuum or emission bands were absent in the spectral region studied. There is only one exception: the photometry and photography obtained with red filter (e.g., Schott RG 1) provide data for the dust part of the coma or tail. But in other visual spectral regions the situation is more complicated. One can, for instance, hardly make some reasonable conclusion about the dimension and shape of the CN or C_2 coma because of overlapping with CO^+ features.

The acceleration of CN and C_2 molecules due to the light pressure estimated from the oscillator strength for typical bands is 0.3 to 0.5 cm sec^{-2} at 1 AU and leads to some deformation of the CN and C_2 isophotes by shifting them slightly into the tail direction. However, the kinematics of CO^+ ions required obviously larger accelerations thus the typical "onion-like" form of the isophotes obtained from measurements near the CN emission pass-bands is due to the overlap of the CN and CO^+ emission and, of course, also to the scattered light on the dust particles. This effect can easily be demonstrated in many direct photographs or even on the isophotometry charts.

The colour photography is one of the very efficient methods for a direct inspection of dust and gaseous forms in comets. Photographic colour emulsions with very low reciprocity failure are available and show promise in the study of cometary structure and morphology. An example of the possibilities was shown by Dr. J. C. Brandt by a colour photograph of Comet Bennett which showed the dust tail as yellow and the ion tail as blue. A black-and-white photograph of the comet taken at approximately the same time did not permit the two tail types to be easily distinguished.

In the visual region the UBV colour system used in routine stellar photometry is inadequate for cometary photometry. The unusual intensity distribution in cometary spectra means that the colour of the comet cannot be transformed to any conventional colour system. The U-filter covers practically only CN bands (3880 Å) while the V- and B-filters include the most prominent band sequences of C_2. The C_3 emission and most of the CO^+ lines are in the range of the B filter. Only from the U-B colour, which is more sensitive to the behaviour of cometary spectra, the relative contribution of CN to C_2 may be qualitatively estimated.

Somewhat more suitable for cometary photometric studies is the uvby system combined with the H_β narrow pass-band filter. The H_β and b filters can be used for the determination of C_2 $\Delta v = +1$ emission band and continuum flux near the H_β wavelength. The region close to 4860 Å is not strongly contaminated by molecular emission and, therefore, the H_β photometry combined with a wide-band filter seems to be the best "two-colour system" for routine photometry of faint comets. Also measurements in the near infrared—i.e., R and I—may sometimes be contaminated by molecular emission, particularly by the CN red system.

For practical purposes the colour difference D may be introduced, defined by

$$D = (U-B)_{comet} - (U-B)_s$$

where $(U-B)_{comet}$ is the colour corresponding to the comet, and $(U-B)_s$ are the colours for the Sun or stars with the continuum distribution similar to the distribution in the cometary continuum. When D = 0 no emission of CN is present. The value of D increases with molecular emission up to the maximum value which depends on the filters' transmission at 3880 Å.

A very serious problem is the fact that most parts of the available photometric data of comets have been usually obtained from observations which were made at large zenith distances. Therefore, their accuracy cannot be compared with those achieved by routine photoelectric methods, and absolute flux values are about 10% or more uncertain in contrast to the relative intensities of nearby passbands which may be precise enough when, for instance, a tilting filter technique is applied.

This method was used recently by Barbieri et al. (1974) for the determination of the continuum flux at 8560 Å and 8748 Å of Comet Kohoutek 1973f, by means of a narrow Fabry-Perot filter. The advantage of solid etalons in wavelength scanning by tilting is an extensive exploit in atmospheric studies and even weak emission can be identified. By a tilting method it can be easily demonstrated that the continuum of Comet Kohoutek was free of any molecular emission around 8750 Å. However, such observations are unique and limited to bright comets.

Valuable observations were obtained by a photoelectric spectrum scanner by O'Dell and Mayer (1968) for Comet Rudnicki (1966e), and by Gebel (1970) for Comets Ikeya-Seki (1967a), Honda (1968c) and Thomas (1968b). A similar observational method was applied by Babu and Saxena (1972) to Comet Bennett (1969i) and by Babu (1974) to Comet Kohoutek (1973f). Unfortunately, these observations had relatively low angular (and space) resolution.

From poor space resolution suffer, to some extent, also the photographic measurements which were used for studying the molecular density distribution in the cometary heads. (See Vorontsov-Velyaminov (1960), Vanýsek and Žáček (1967), Dewey and Miller (1966), Borra and Wehlau (1971, 1973).) The best material of this kind with high angular resolution (about 14"/mm) in monochromatic light has been obtained by Rahe et al. (1974).

Perhaps the most important photometric data (with regard to the photometric profiles of cometary neutral atmospheres) have been obtained by Malaise with the aid of his six-channel photometer with adjustable wavelength and passbands (Malaise, 1970); but a considerable amount of his observations were still recently being reduced. The instrument itself was recently attached to the 2-meter Ondrejov telescope, but very bad weather conditions in January 1974 permitted only one incomplete observation of Comet Kohoutek made by Malaise and the author of this report.

3. RECENT RESULTS

From preliminary reports obtained by many observers an unusually great number of photoelectric observations of comets has been obtained very recently. Both bright Comets Kohoutek 1973f and Bradfield 1974b were observed so extensively that the observations are only partly reduced and the following summary represents only a small sample of the results.

A very large and homogeneous set of photoelectric and infrared measurements before the perihelion passage of Comet Kohoutek was published by Rieke and Lee (1974). Their results are important for the interpretation of infrared radiation (particularly the 10μ "bump") of the dust in the cometary atmosphere. The data for UBVRI colours may, however, provide only rough information about the behaviour of the continuum radiation of the comet in the first half of October 1973, when the contribution of the emission bands was negligible. After October

16, the emissions of CN and C_2 bands in the spectrum of the comet were apparent and only observations in narrow pass-bands might provide exact data for the determination of albedo of the dust particles, by a comparison of the integrated surface brightness in the infrared and surface brightness of the scattered light in the visual spectral region. Therefore, the numerical expression involving albedo derived by Rieke and Lee should be considered to be only very preliminary. Their data in the UBVRI system for different diaphragms indicate that the colour index B-V of the inner part of the coma was almost the same as that of the Sun while the outer region shows a decrease of the index U-B which was probably due mainly to the CN band.

One of the sets of pre-perihelion observations in the narrow pass-bands was obtained by Babu (1974), with the spectrum scanner (Babu, 1971) measuring the intensities in the pass band about 35 Å in the range 3700 to 6400 Å. His results indicate that absolute fluxes of CN emission at 3880 Å varied approximately with r^{-2} while C_2 and C_3 bands increased with r^{-4} in the interval of heliocentric distances $r = 0.73$ to 0.52. But because the change of geocentric distance was very small and the radius of the coma measured with a fixed diaphragm was almost constant (about 4×10^4 km), a fast increase of the C_2 and C_3 intensities with decreasing r was due, partly at least, to a decrease of the length scale of the parent particles rather than to an increase in the abundances of these molecules. This effect was caused by a shrinking of the gaseous coma which, for small diaphragms, is more pronounced for C_2 emission than for CN.

This fact was confirmed by the photometric data submitted by Cowan and A'Hearn (1974) which provided the total flux in the C_2-band sequence at 4700 Å measured in a very large diaphragm 116 and 193 arcsecs corresponding to the coma diameter about 10^5 and 1.8×10^5 km in the interval from December 1 to December 7. The luminosity of the C_2 (0, 1) band remains essentially the same—about 2×10^{19} erg $\sec^{-1}$—in the time interval between December 2 and December 7 and was slightly lower than on December 1.

The results obtained by Babu for the continuum energy distribution in the head of Comet 1973f indicate some reddening of the scattered light with respect to the Sun, decreasing with phase angle ϕ (in the interval $\phi = 51°$ to $57°$) and with heliocentric distance so that the reddening disappeared on December 17.

The positive colour excess has been confirmed in several comets (Walker, 1958; Bappu and Sinvhal, 1960; Liller, 1960; Vanysek, 1960; Kharitonov and Rebristyi, 1974). Some spectrophotometric results lead to the conclusion that the colour of comets resembles the spectral distribution of G8 V stars and this reddening may be attributed to selective light scattering on small dust particles. However, the results obtained by Gebel (1970) for Comets 1968 I, 1968 V and 1968 VI show that the spectral distribution of continuum was "grey"—i.e., it coincided with the colour of the Sun.

In the case of Comet Kohoutek, measurements of the continuum spectral distribution were made at very large zenith distances where some uncontrollable influence of anomalous extinction must be expected. Therefore, it is not quite certain that the differences with respect to the solar continuum are real.

Post-perihelion photoelectric observations have been made by Kohoutek of his bright comet in the UBV system as well as in the pass bands near λ(Å) = 3880 (CN); 4267 (CO^+); 4738, 5172 (C_2); 5300 (continuum) and one centered on the sodium doublet.

This set of observations covers the range of heliocentric distances r from 0.65 to 1.0 AU. Kohoutek reported that measurements in the 4267 Å pass-band indicated a negligible intensity of CO^+ bands in diaphragms 40 and 80 arcsecs and the measured intensity virtually refers only to the continuum radiation. Emission of the sodium doublet was detected only on January 15 and 16, but at the heliocentric distances 0.7 to 1.0 AU the sodium lines (if any) were very weak. It must be noted that the intensity of NaI emission before perihelion passage was obviously also low, as follows from the above-quoted measurements made by Babu. If the results obtained by Kohoutek for 4267 Å, 5300 Å and 5890 Å are interpreted as intensities for the continuum, then solar radiation scattered on the dust particles exhibited some red excess, which is in agreement with the selective "reddening" of the cometary continuum observed in several previous comets studied photometrically and spectrophotometrically. The estimated contribution of the C_2 $\Delta v = 0$ band to the continuum in the V-colour was about 1:0.7, and about 1:1 in the B-colour where, of course, $\Delta v = +1$. The C_2 band as well as the CN band dominates in the U-colour where the band/continuum ratio was about 1.66 (for a heliocentric distance r = 1 AU).

The dust coma, according to these measurements, was more concentrated toward the nucleus than the CN and C_2 atmospheres. The "colour effect" described by Vanysek (1960, 1966)—i.e., an increase of the colour index with diameter of the diaphragm, is quite evident in B-V from Kohoutek's measurements. The absolute colour indices in the 40 and 80 arcsec diaphragms increase slightly in BV from 0.85 to 0.94. The magnitude difference Δm of the measurements in two diaphragms with the radii $\rho = 40$ and 80 arcsec indicates a deviation from the surface intensity law ρ^{-1} for a spherically symmetric coma. The deviation can be expressed by ρ^{-n} where $n < 1$, and is due to the "flatness" of the photometric profile of the inner part of the coma where visible radicals are produced from parent particles. This means, of course, that the "zone of production" for C_2 and CN was traced at least up to 4×10^4 km from the nucleus.

Kohoutek found that the comet's brightness decreased after the perihelion passage more rapidly in the inner part of the coma (with $r^{-4.6}$ to r^{-5}) than in the outer one ($r^{-3.6}$ to $r^{-4.2}$). A very rapid change in surface intensity was observed photoelectrically by Mrkos and Vanysek in Comet Bradfield 1974b. This is merely a well-known effect due to the coma expansion with increasing heliocentric distance r—i.e., a reversal of the pre-perihelion shrinking of the cometary head.

Although the results discussed here and obtained by Babu, Kohoutek and Cowan and A'Hearn represent not quite homogeneous sets of observations, the pre-perihelion and post-perihelion total luminosity of the C_2 (4734Å) Swan-band can be compared. If the available data are reduced to the heliocentric distance $r = 1$ AU and to the diameter 5.5×10^4 km then the post-perihelion luminosity decreases by a factor of about 10:

pre-perihelion $F_0 = 2 \times 10^{18}$ erg sec^{-1} (from Cowan and A'Hearn's observations);

post-perihelion $F_0 = 1.5 \times 10^{17}$ erg sec^{-1} (Kohoutek).

The post-perihelion decrease of the luminosity of CN seems to be not so sharp. The relative intensities of the CN band in December 1973 obtained by Babu are considerably lower than those of the C_2 $\Delta v = 0$ band but the post-perihelion results reported by Kohoutek indicate that the CN emission was slightly more luminous than that of the C_2 main band. Therefore, the luminosity of CN (reduced again to $r = 1$ AU and the same area) was lower after the perihelion passage only by a factor of about 2.5 to 3. A considerable diminution in luminosity occurred in the continuum, as follows from almost all available observations.

One can believe that Kohoutek 1973f was a "normal" comet and the relatively high brightness at large heliocentric distances shortly after discovery till the beginning of October 1973 may be attributed to dust clouds surrounding the central condensation (or nucleus), which diminished slowly when the comet was approaching the Sun. This means that at least this particular comet may be described as a nucleus surrounded by a swarm of dust particles from which the very small (and volatile) ones were expelled and evaporated beyond $r \geqslant 0.8$ AU. Barbieri et al. (1974) concluded from the near-infrared observations at 8560 and 8748 Å that the dust production rate decreased by a factor of 10 relatively to the gas production in the post-perihelion period.

Although the above discussed results are somewhat incomplete, it is evident that C_2 emissions are more sensitive to a change of dust content than the CN band. Unfortunately, the luminosities of bands of molecular origin are not sufficient for the determination of the production rate without knowledge about kinematics and lifetime scale of the respective compounds. However, there is strong indication that the C_2 production rate depends on the dust contents in the cometary atmosphere (and, consequently, on dust production) more than CN and perhaps other molecules.

4. POLARIMETRIC MEASUREMENTS

The available polarimetric data of Comet Kohoutek are only few and must be considered only as preliminary. Michalsky (1974) reported polarization measurements made by Avery, Stokes, Zellner, Wolstencroft and himself at three observatories in Hawaii, Arizona and Washington State. Pre- and post-perihelion observations were made with broad and narrow filters, which included or excluded emission lines and/or bands. All measurements were centered on the coma condensation with apertures ranging from 15-40 arcsecs in diameter. As for Comet Bennett 1969i, higher linear polarization was observed in the red than in the blue. Rayleigh scattering is excluded because of the colour of the comet.

The maximum of linear polarization was found by Avery on January 9—26%—in B colour, and Zellner (also 26%) on January 16 in the close area (15 arcsecs) around the central condensation.

Measurements made in adjacent spectral regions when emission was included and excluded indicate that the magnitude of the polarization is higher in emission—this unusual effect has not been reported previously. Other measurements bear out this behaviour after perihelion passage as well as before. Because the polarization of the molecular bands should be only 8 to 10% this effect must be analyzed again very carefully. All measurements showed the direction vector to be rigidly perpendicular to the scattering plane.

Michalsky noted that the light scattered from nonspherical aligned particles should show a small circularly polarized component. A search for this component led to a value of 0.02 ± 0.06% showing that no large effect is present, but observations indicated an increase of linear polarization with decreasing aperture, which may imply alignment possibly contradictory to the previous discussion.

The most important results concerning the polarization of the cometary light are those reported by Weinberg; however, these did not concern the comet's head but the tail. A multicolour photoelectric polarimeter was used at Mt. Haleakala Observatory to observe the tail of Comet Ikeya-Seki (1965 VIII) on 4 nights following perihelion on 21 October 1965. Observations were made at six continuum wavelengths and with two different filters centered at the 5577 Å emission of OI. From preliminary results only the observations at 5400 Å on 28/29 October 1965 are available. Measurements were made by scanning at 0.5 deg/sec over a 9 x 20 deg section of the sky containing the comet: in azimuth, from 105 to 114 deg (90 = east), and in elevation, from 0 (horizon) to 20 deg in steps of 1.0 deg. This method of scanning provides considerably more information in the direction normal to the axis of the tail of the comet and the intensity can be easily derived from the total brightness (radiance) of background plus comet for different zenith angles.

Of particular interest is the change in polarization between 6 and 7 deg elevation (approximately 11 deg from the nucleus). Since the background (primarily zodiacal light) and comet radiations are independent, their Stokes parameters are additive. The polarization of zodiacal light in this area is positive—i.e., the electric vector is perpendicular to the scattering plane. Only negative polarization at distances greater than 11 degrees from the nucleus can produce the observed net decrease in total polarization in the direction of the comet tail.

The comet was ideally positioned with respect to the main cone of the zodiacal light, and the separation of the comet from the smooth fall-off in total brightness is easily accomplished. The sharp change of orientation of the polarization plane (orientation of the electric vector) with the phase angle is very typical for the polydispersed optically thin cloud containing particles with very low imaginary part of the refractive index. Therefore, the polarization data obtained by Weinberg are compatible with infrared results at $\lambda = 10\mu$ where the emission-like peak (observed in spectra of Comets Bennett and Kohoutek) may be ascribed to dielectric silicate particles (Maas et al. (1970), Ney and Ney (1974), Kleinmann et al. (1971)).

Moreover, negative polarization (with respect to the orientation of the electric vector) as in the case of zodiacal light, requires the presence of dielectric or irregularly-shaped particles. The use of additional observations at several wavelengths at different times, as Weinberg suggests, may single out a rather small family of permissible solutions for the size distribution and chemical composition of the particles in the tail of the comet if the particles are spherical or have large-volume shapes.

The possibility that elongated particles are dominant in the cometary dust is supported by some earlier measurements. Clarke (1971) showed that the plane of polarization for Comet Bennett 1970 II deviated significantly from one of the two possible orthogonal positions to the scattering plane. This effect can be explained by scattering on the aligned elongated particles. Harwit and Vanysek (1971) proposed the bombardment of dust particles by solar wind protons as efficient alignment mechanism. Because the rate at which the alignment occurs depends also on the gas flow from the nucleus, the polarization near the nucleus would be more arbitrarily oriented than in the tail where the solar wind predominates.

The elongated form of the particles can be expected if the crystalline formaldehyde polymers are present in the cometary dust. Vanysek and Wickramasinghe (1975) have recently discussed the possibility that the polymers $(H_2CO)_n$ are one form of formaldehyde in the comets. The polymerization process may produce polymer chains with variable length helically wound into a stable crystal. These particles would grow as long whiskers and possess optical properties in the visual and infrared region similar to those of the silicate grains.

5. PHOTOMETRIC PROFILES AND THE LIFETIME OF PARENT MOLECULES

The photometric profiles of the coma in monochromatic light are still used for the determination (or, better, estimates) of the lifetime of the parent molecules or precursors for the observed radicals, mainly CN and C_2.

The lifetime τ is defined as a reciprocal value of dissociation probability

$$\tau^{-1} = \int \sigma_\nu F_\nu \, d_\nu$$

where σ_ν is the photodissociation cross-section and the flux at a frequency ν is defined as $F_\nu = cu_\nu/h\nu$ where u_ν is the density of solar radiation (c = light speed, $h\nu$ = photon energy).

The value of σ_ν is about 10^{-18} to 10^{-17} cm^2 for the most common compound.

Results concerning the prospective parent molecules for cometary radicals (Potter and Del Duca, 1964) show that τ derived from the known cross-section and F_ν is for most compounds estimated longer than 10^5 seconds. These results, however, were not comparable with the scale-length for parent molecules determined from the polarimetric profiles of cometary heads.

The lifetimes derived from the early measurements on comets (a summary of these results is in Vanysek's paper [1972] in Nobel Symposium No. 21) suggest $\tau_p \sim 10^4$ sec. But the lifetimes determined for some components which could be possible parent molecules are $\tau_p = 10^{5.5}$ to $10^{6.5}$ seconds (except for NH_3 as a source of NH_2, with $\tau_p \sim 10^3$ sec).

The differences between laboratory and astronomical results were so striking that the hypothesis for the production of observed neutral molecules in comets via photo-decomposition processes was almost (but prematurely) abandoned and other theories were proposed (Wurm, 1961; Opik, 1963; Herzberg, 1964; Jackson and Donn, 1968).

The decomposition of parent molecules was ascribed to the predissociation or to the chemical reaction in the innermost part of the coma, or in the nucleus, or to the presence of free radicals in nuclei.

Delsemme and Swings (1954) considered that free radicals may be embedded in ice in the form of clathrates. This idea has been modified by Delsemme who assumed that small fragments of ice of submillimeter dimensions expelled from the nucleus into the surrounding halo contain considerable amounts of clathrate hydrates formed in the cavities in the water ice lattice where different molecules, even unsaturated, can be bounded by van der Waals forces. By a destruction of the lattice by solar radiation the encaged molecules are liberated into space and ejected isotropically from the cometary head. If the molecules are free radicals, or very short-lived precursors of such radicals, the ice particles play the role of parent molecules.

However, the problem of the precursors of the observed radicals is still the problem of the methods used. The lifetime of parent molecules τ_p and of the produced radicals τ_r can be estimated, in fact, only indirectly by determining $v_p\tau_p$ and $v_r\tau_r$ (where v_p and v_r are the expansion velocities, and supposed to be constant) from the intensity distribution in the cometary head. For the interpretation of the intensity distribution only a relatively simple model (Hazer, 1957) is usually applied in which the expansion velocity has no significant distribution.

However, the radiation energy absorbed by the molecule during the dissociation processes may be higher than the dissociation energy and may lead to a significant increase of the velocity distribution of dissociated compounds. For instance, if the difference between the absorbed energy and dissociation, $\Delta h\nu$, is only one or a few eV, then the velocity distribution $\pm\Delta v$ around the mean expansion velocity $\bar{v}_p$ for particles of molecular weight 20 may increase up to some km-sec^{-1}. Then a considerable number of the produced daughter molecules flow back into the "zone of production" up to some distance toward the nucleus where the collisions with expanding parent molecules and others increase above some critical limit. Only from this rough qualitative description does it seem to be evident that the simple coma model is invalid and the actual density of daughter molecules—radicals—should be considerably higher at distances, say 5×10^3 to 10^4 km, from the nucleus.

Moreover, recent results concerning the determination of lifetimes of the parent molecules from monochromatic isophotes with high angular (and consequently also spatial) resolution indicate that the scale-length $v_p\tau_p$ should be longer than 10^4 km (Rahe and Vanysek, 1974; Delsemme and Moreau, 1973; Kumar and Southall, 1974). Rahe and Vanysek found for the scale length of CN the parent molecule of Comet Bennett 1970 II $v_p\tau_p \simeq 5 \times 10^4$ km and about the same for C_2. For the virtually "dust-free" Comet Tago-Sato-Kosaka the results are: (CN) $v_p\tau_p \sim 8 \times 10^4$; ($C_2$) $v_p\tau_p \approx 4 \times 10^4$ km.

Kumar and Southall revised the isophotes of Comet Tago-Sato-Kosaka used by Rahe and Vanysek and applied a new correction of the sky background. The new results are: (CN) $v_p\tau_p = 1.7 \times 10^4$ km; (C_2) $v_p\tau_p = 2.5 \times 10^4$ km. (All values are for heliocentric distance $r = 1$ AU.) The average value for $v_p \tau_p$ from recent results is equal to about 2 to 6×10^4 km, and if we assume the expansion velocity as derived from the radioastronomical detection of methyl cyanide $v_p = 0.4$ km sec^{-1}, then $\tau_p \sim 10^5$ sec $\sim$ 20 hours.

Most important results have very recently been obtained by Delsemme and Moreau (1973) from the spectra of Comet Bennett (1970 II) who determined the profile of the C_2 and CN bands from the distribution of brightness of the emission perpendicular to the spectrogram dispersion. It was proved that the scale-length of CN as well as of C_2 varied with r^2; the scale-length reduced to $r = 1$ AU was found to be 1.4×10^5 km for CN, and 0.9×10^5 km for C_2. The corresponding values for the parent particle scale-lengths are: (CN) $v_p \tau_p = 5 \times 10^4$ km and for $C_2 = 2 \times 10^4$ km. Delsemme and Moreau noted that the scale-length for parent particles grew with increasing heliocentric distance r somewhat less rapidly than would be expected. However, the increase in geocentric distance was almost exactly the same as the increase in $v_p \tau_p$, and the effect of the variation of space resolution on the determination of parents' scale-length in this case must be taken into account. Moreover, these results may be affected by the kinematical behaviour of CN and C_2 molecules because the measurements provide profiles across the coma along the radius vector Sun-comet only.

Even if the solid hydrates of gases (clathrates) in icy grains are the source of some observed molecules in comets, the problem of other prospective parent molecules remains substantial; and there is no reason for excluding them as possible constituents in the cometary nuclei. One of the arguments for the "clathrate" model arises from the short lifetime of parent particles exposed to the solar radiation field. However, the scale-lengths of hypothetical precursors have been derived from the photometric profiles of cometary heads by an inaccurate method. Moreover, the expansion velocities of parent particles cannot be directly described and the real value of $v_p \tau_p$ remains highly uncertain and can easily be underestimated.

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OMIT

DISCUSSION

W. Jackson: I don't know whether I heard you correctly or not, but did you say that you could not explain the free radicals by photodissociation?

J. Rahe: I think one can.

W. Jackson: Yes, because the lifetimes that you get from the photometry are of the order 10^4 to 10^5 seconds.

J. Rahe: Yes. Up to rather recently the lifetimes derived from cometary measurements seem to be rather short. Only after you had observations with high resolution, both angular and space reolutions, could you get a better determination of the lifetime of parent particles. This value increased considerably and the results of Delsemme and Moreau, Kumar and Southall, and Vanysek and myself are consistent.

W. Jackson: I see.

But the only point I was trying to make was that the lifetime measurements you are getting now are about the same as the lifetime measurements you would estimate for, say a typical parent molecule of CN.

J. Rahe: I think they are very close now. The new results obtained from high space resolution measurements are larger than follows from older observations. Low angular resolution and contamination of band measurements with the continuum background means most likely an apparent increase of the ratio ρ_τ/ρ_p.

G. Herbig: What is the reason that the polarization in the tail of comet Ikeya-Seki was negative?

I didn't understand your explanation.

J. Rahe: I think Dr. Michalsky is here later. Isn't he giving a paper?

You see, I received this paper only last night, and I didn't have any chance to check on this.

W. Jackson: Does anybody have a comment in terms of Dr. Michalsky's paper?

J. L. Weinberg: The polarization reversal refers to a crossover from positive to negative polarization, i.e., the electric vector flips by 90 degrees—

from perpendicular to the scattering plane to parallel to the scattering plane. We have preliminary results for Comet Ikeya-Seki that I have worked out versus scattering angle and we find along the axis of the tail that the polarization at 5300 Å goes from plus 22 percent to minus 45 percent with the neutral point at around 125-1/2 degrees, and it falls very sharply across the line of zero polarization. It goes, for example, from 8 percent positive to 8 percent negative in 1-1/2 degrees of the phase angle.

We also found the history of the neutral point, that is the position of the crossover changes with time at the same color and it also changes with color. That is the neutral point moves toward the head (toward smaller scattering angle) with increasing wavelengths. The observations off the axis at different colors are still being reduced.

These results strongly suggest the presence of dielectric particles. (See contributed paper by Weinberg - ed.)

D. J. Malaise: I don't understand how improved space resolution can result in getting longer formation times for the observed radicals. It seems that if the true photometric profile is worked out near the center of the coma by the space resolution, you would get an upper limit for the time of formation and that any improvement in space resolution would lead to shorter times of formation. And I remember when I measured the profile of molecules in '65 on Comet Burnham (1959k). The resolution was between 500 km and 1000 km on the comet; this is the best space resolution I know of, just because the comet passed at 0.2 AU from the earth; in this case the formation distances of CN and C_2 were in the range of 2×10^4 km.

J. Rahe: What time did you get?

D. J. Malaise: I did not get time, I got scale length. It was about 20,000 kilometers.

J. Rahe: Oh, I see.

D. J. Malaise: And I still don't understand why you say that when you increase your resolution you get longer lifetimes.

J. Rahe: The lifetime of hypothetical parent particles of the observed radicals have been estimated from the observed photometric profiles of the cometary head and expressed in the scale length, ρ ($\rho = \tau v$; τ = lifetime; v = expansion velocity) in which the particle decay takes place. The scale length, ρ_r of the observed radicals can be determined with fair accuracy directly from the surface brightness decrease near the edge of the coma. But the scale length, ρ_p for the parent particles depends on the accuracy of the ratio ρ_r / ρ_p which can be derived from a comparison of the "flatness" of the observed photometric curve in the central part of the coma with the theoretical curve calculated, e. g. using Haser's model. This method is thus rather sensitive to the space resolution: measurements made with low angular and space resolution give higher values for the ratio ρ_r / ρ_p and, consequently, relatively shorter scale lenghts ρ_p.

D. J. Malaise: Yes, that is my second point. Haser's model does not describe any data close to the nucleus, so either the model is wrong or, I think, the model is too simple. I am very doubtful whether mean times of formation of free radicals can significantly be deduced by fitting a profile on both ends (center and edge of the head). The main reason is that in most cases the profile does not fit in the intermediate part. This is, in my opinion, due to the fact that the theoretical profile used for the fitting is based on an oversimplified model of the source. In particular, the yield of the source is assumed to be constant which is hardly tenable over periods of the order of 10^5 seconds. In fact, the shape of the profile is more likely to reflect the time variations of the source yield than the lifetimes of the particles. The profiles are usually quite asymmetrical and vary from day to day. The lifetime computations always rest on the assumption that we deal with steady state situations. This may of course happen but to my knowledge it is quite exceptional.

J. Rahe: Yes, you have to improve the model, there is no question about that as was pointed out in Vanysek's paper.

W. Jackson: I don't believe that.

I don't agree, because I think that Kumar and Southall took the data that you measured, here at Goddard, the monochromatic isophotes and fitted them both at the edge and at the nucleus.

They could get a fit only when they went back and reexamined the plates to remeasure the sky background. When they took out the sky background, they got a fit over the whole curve.

But you said, I thought, you could only get a fit at the ends—you didn't get a fit in between.

D. J. Malaise: My argument is that there is selectivity in the source of molecules which depends on temperature and depends on time.

Of course you can get examples where the coma is symmetrical and you can get a fit over a range that is quite wide.

And if it is quite unsymmetrical a fit from the direction of the sun gives a very different scale length than a fit in the perpendicular direction.

J. Rahe: Well, for instance these results from Kumar and Southall for Tago-Sato-Kosaka showed rather symmetrical profiles, I suppose.

Voice: Yes.

J. Rahe: But Tago-Sato-Kosaka was a dust-free comet.

W. Jackson: So one would say that if you started out with a symmetric profile, of the radical, say, Haser's model worked pretty well.

But if you get a situation where you get asymmetry in the photometric profile, then you know that Haser's model is not going to work very well for that particular comet.

D. J. Malaise: My contention is that whenever I observe a comet, in most of the cases I get asymmetric profiles.

B. Donn: I would like to point out that you get better spectral resolution if you measure the profile along the lines the way Delsemme does with a spectrograph than you get with a filter.

On the other hand, you only get the profile in one direction and you do not know then if there is any asymmetry. This is a problem one has to take into account.

D. J. Malaise: Yes, but this is exactly what I said in 1965, you know. It was on high resolution spectra. When you are looking at long range, usually your spectra do not reach far enough unless your spectrograph is very, very fast.

A. H. Delsemme: For reasons of spectral contamination discussed in Delsemme and Moreau (1973 Astrophys. Lett. 14, 181) photographic plates exposed through properly chosen filters give poor values of the exponential scale lengths for the decay of the emitters of light. This explains why Kumar and Southall's adjustment of Haser's model remains poor, as demonstrated by their Table 1. Therefore their comparison given by Table 2 does not make sense because they put very accurate measurements of many spectra and poor

DISCUSSION (Continued)

measurements of one photograph on the same footing. Malaise has just reminded us why his early profiles also give poor values for the same scale lengths. This is because they were not extended to the outer coma, since the exposure times would have been prohibitive.

Because of the use of an image intensifier, a large fraction of the 81 spectra of Comet Bennett used by Delsemme and Moreau (1973) reached those distances in the outer coma where the decay of CN (or of C_2) is already very large, showing for instance slopes of -3 and more for the photometric gradient. This made the fitting of Haser's model extremely accurate and provided for the first time a reliable dependence on distance for the scale lengths in the outer coma, also helping a better assessment of the parent's scale lengths because they are interdependent in Haser's model.

We had also the problem of the small dissymmetry between the two photometric profiles, sunwards and anti-sunwards; this dissymmetry was rather easily discounted by using a very simple formula based on constant acceleration coming from the sun.

I wish to add a few words about the "activity" of the comets. The word "activity" conveniently hides our ignorance. This activity may come from some variation in the excitation from the sun, or from a variation in the production rates.

Sometimes we have, indeed, variations which show up as humps in the brightness profiles: They seem to be originated by time variations in the production rate of the comet. In principle, the expansion velocity of the humps could be measured by their displacements. So far, nobody has ever succeeded in identifying these humps from day to day, as Bobrovnikoff did for halos observed in Comet Halley.

For our observations of Comet Bennett, we had many days where the "activity" of the comet was not apparent, and the photometric profiles were very smooth. The observed profiles could then be accurately fitted to Haser's model with two parameters.

A serious disadvantage of Haser's model is however that the two scale lengths of the parent molecule and of the light emitter, can be switched because of the symmetry of the formula.

Everybody always accepts that the shortest of the two times is the parent's lifetime, and the longest, that of the dissociation of the light-emitter. This is probably true but has never been proved for each radical and its parent molecule. In particular I think of OH which seems to decay with a lifetime not too different from that of its probable parent: H_2O.

J. C. Brandt: I am not clear whether dissociation can explain the parent molecules. In my notes, I thought you said in your review it could not, but I thought you said in response to Dr. Jackson's question, it could.

There are a lot of arguments both ways, but since this is a crucial point, you know for the clathrate model, I would like somebody to state whether or not this is the actual situation.

Can photodissociation account for lifetimes observed for parent molecules ?

J. Rahe: It seems according to this review, that lifetimes are very similar. Assuming of course, a spatial velocity, an expansion velocity.

And then this seems to be able to be accounted for by photodissociation.

J. C. Brandt: Professor Delsemme, do you agree ?

A. H. Delsemme: Yes, I would like to add some more words in this respect.

I believe that the work which has been done in the laboratory is incomplete and therefore inconclusive.

The work of Potter and del Ducca was very important. It has been used so far repeatedly, but has never been reproduced; besides, they have never given the details of their integrations, and it is unclear whether they have neglected to include some predissociation bands of some molecules. Therefore, it has not yet been conclusively proved or disproved whether the observed lifetimes can be explained by specific parent molecules, in particular since we have the alternate hypothesis of the existence of a halo of ice grains.

W. Jackson: They didn't miss many molecules, but they did give one detail. They used for the absorption coefficient, in order to obtain the lifetime, only the absorption of the continuum.

As Professor Herzberg pointed out, (Trans. I. A. U. , 12B, 1964. p. 194) you have to include the possibility of predissociation.

DISCUSSION (Continued)

All of the large molecules, in all likelihood, will predissociate even though they may have a reasonably sharp band. If you integrate under the total band including the line structure, you end up with photodissociation lifetimes that are of the order of 10^4 or 10^5 seconds for cyanogen for example. HCN is particularly long, unfortunately. It is of the order of 9×10^4 second. Cyanogen is of the order of 1×10^4 second. And cyano-acetylene is of the order of 1×10^4 seconds.

I have recomputed them myself. And I will show those results Wednesday.

In answer to the question about which scale length you used, which one is the shortest, the parent or the radical, for C_2 and CN in all likelihood, the parent has to be the shortest.

The bond strength of CN is almost as strong as CO and N_2. There is no evidence from the spectra that CN predissociates in the region where it absorbs in the visible. So in all likelihood, those have a long lifetime.

There is a question about OH. You can get predissociation in OH in the higher rotational levels. However, these probably aren't excited, since OH has cooled rotationally before it can reabsorb.

Now on the other hand, some of the OH is produced in highly rotationally excited states from the photodissociation of H_2O. So some of those radicals may be lost through predissociation.

But that is still a small portion compared to the total amount of OH that is produced from the photodissociation of water.

So I think for most of the radicals it is a reasonable approximation that the radical has the longer lifetime as compared to the parent molecule.

The person who could probably answer that question best is Professor Herzberg, who is sitting back there, since he knows more about the spectra of radicals and molecules, than most of us. At least more than I do.

J. C. Brandt: So could I summarize the last 10 minutes by saying that photodissociation can account for the lifetime of the parent molecules, and in that sense the clathrate grains are not demanded as the source?

W. Jackson: Yes. That is true.

If you want to say that the clathrate model was needed to hold the radical, true. But that was not the reason the clathrate model was introduced.

DISCUSSION (Continued)

A. H. Delsemme: I would like to straighten out ideas about the gas hydrates (clathrates) hypothesis, because it has been sometimes distorted in the literature, and this distortion has appeared in the present discussion.

The hypothesis was introduced by Delsemme and Swings (1952) mainly to explain why all molecular emissions appear at short heliocentric distances only. The explanation is that: most of the carbon and nitrogen compounds are imprisonned in the lattice of the water clathrates, and are liberated in proportion of the vaporization of water. The hypothesis is reinforced if thermodynamic equilibrium is reached within the nucleus, because the clathrates are implied by it. Delsemme and Miller (1970) have also shown that the clathrates are the limiting case of gas absorption in water shows, and cannot really differentiate from gas absorption. Of course, in order to have clathrates, a prerequisite is to have large amounts of water. Delsemme and Rud (1973) list eight different arguments proving that water is a major constituent controlling the vaporization of several comets. This is easier to defend since the discovery of H_2O^+ in Comet Kohoutek and H_2O in Comet Bradfield. Now, an entirely different line of arguments stem from Delsemme and Wenger's (1970) laboratory experiments on clathrate ices. They have shown that the clathrate-hydrate of methane comes as a granular powder. When it vaporizes in vacuum, the vaporizing gases drag some of these grains away from the main body of snow. From their sizes and velocities, the building up of a halo of icy grains surrounding the cometary nucleus is predicted. Delsemme and Miller (1971) propose that the extended source of light emitters deduced from photometric profiles, could come from the size of the icy halo, and therefore does not give any information whatsoever on the parent molecules, that are therefore not detected through the photometric profiles. This proposal is shown to be consistent with the photometric profiles of the C_2 emission and of the continuum of Comet Burnham. The existence of the parent-molecule is not really disputed, but their scale lengths are not automatically given by the photometric profiles and the use of Haser's model. Another approach which seems to suggest the existence of the halo of ice grains comes from the work of Delsemme and Moreau on the dependence on heliocentric distance of the assumed scale length of the parent molecules of CN and C_2, which vary, not like parents should vary (inverse square law) but like the icy halo should vary (simple inverse law).

Now, there is still room for some leeway. The scale lengths of the CN and C_2 parents are not yet very accurately known, their dependence on distance still is disputable and may come from other causes. Only comet Burnham was used to check the existence of the halo of ice grains, and some numerical coincidences although difficult to justify are not to be totally excluded. Other comets (like Bennett) often are too dusty to be used for the same purpose. However, the ice grain hypothesis has also been used with success by Sekanina to explain the tail orientation of the faraway comets. To summarize, the hypothesis of the halo of ice grains has not yet been sufficiently confirmed, but seems to stand on a firm basis. The ice grains must not necessarily be made of clathrates. Gas absorption on snowflakes of water would give the same result. Pure water ice grains would also satisfy Sekanina's explanation of the tails, as well as the photometric profiles of the continuum if we have an approximate numerical coincidence of the radius of the ice grain halo and of the scale length of the C_2 parent, near 1AU.

D. J. Malaise: Yes, I would like to remind you that what we measure is scale lengths and what we are discussing is lifetimes, and both are independent variables. If the molecule doesn't move in a straight line, that is if collisions increase the time spent in the inner coma, there is not a simple relation between scale length and lifetime.

W. Jackson: Right.

It can collide many times before it gets into free flow.

D. J. Malaise: This could explain the observation that the photodissociation times do not agree with laboratory data.

W. Jackson: I disagree.

Because, what happens is, if you get enough collisions near the nucleus, you quickly go into a fluid flow. And once you have the expansion into the vacuum, the the stream lines pull everything off, and it doesn't take long before the random motion is converted into directed flow.

So it really doesn't make any difference. If you raise the pressure higher, you are not going to appreciably change the residence time of the parent molecules, even though that was what I said a long time ago.

At least that is what I thought a long time ago.

D. J. Malaise: You have hydrodynamics where the molecules are produced and you have free flow where the molecules are observed. You don't know how it goes from one to the other.

W. Jackson: Once you get the hydrodynamic flow, the stream lines are the same as the free expansion. I would say you go from hydrodynamic flow to free expansion in a very continuous fashion.

You don't go into a discontinuous situation.

DISCUSSION (Continued)

M. K. Wallis: I would agree with Dr. Jackson, that in simple hydrodynamic flow the velocity quickly reaches that of uniform radial expansion (within 100 km). Except, that if you have photodissociative heating, or some other heating process such as collisions with dust from the nucleus, the pressure can be increased enough to reduce the velocity of the gas, the hydrodynamic flow near the nucleus and you will get — it seems backward, but you will get lower velocities nearer the nucleus than you would get further out on the free molecular expansion.

So you still have to be careful. With no heating, you are right. The velocity soon gets up in the hydrodynamic flow — say within 100 km. But if you have got heating, as we all believe, then you can't stay up any longer.

W. Jackson: Well, if you have got heating, are we talking about a 10 percent change in the residence time of the parent?

The point is that when you get heating, you have got the daughter formed already because you can only get heating through the photodissociation. There is a possibility of getting heating by some other mechanism that I -

M. K. Wallis: Photodissociation, or collisions with the dust.

W. Jackson: Or, some people might argue for electrons heating up the molecules by the plasma coming in.

I don't understand that, so I am not going to get into that.

M. Dubin: Let me ask Jurgen Rahe a question that relates to this.

I thought I heard you say about comet Kohoutek that it was a normal comet. I didn't finish the question yet, because I want to know what a normal comet is.

You further indicated that the comet, in terms of its general brightness after perihelion in mid-January, late January was 10 times dimmer than at the same distance from the sun before perihelion. And that is a normal comet?

You indicated that sodium was observed later, only on a few days, for this normal comet. And then you also indicated that you thought that the early observations were a result of a swarm of dust evaporating.

And as we heard also in terms of the clathrate argument, a swarm of particles would change the nucleus model from the solid nucleus considerably, and these same particles have already been reported to probably be vaporizing to try to explain the anti-tail on the comet.

So please, would you explain what a normal comet is?

DISCUSSION (Continued)

J. Rahe: First I should like to point out that when I said normal I was just reading the paper by Dr. Vanysek. And doing justice also to the question Dr. Brandt asked I think I should perhaps later, make a Xerox copy of his statement and distribute this. But this question probably wasn't quite clear due to my German English, not a question of text.

Now the question, what a normal comet is, of course, is very difficult to answer. But the brightness development of comet Kohoutek was not so surprising if you look back now.

(Laughter.)

I don't know whether you read one article in Sky and Telescope written by Dr. Jacchia. He compared the brightness development of comet Kohoutek with many other comets, and compared with those comets, Kohoutek didn't do really that badly.

M. Dubin: But compared with many other comets it did do badly. There are a class of comets that did do better than Kohoutek. But, which is the normal group?

J. Rahe: Yes, this is very difficult to say.

M. Dubin: Now what does this do to your model here?

J. Rahe: According to what Dr. Vanysek says here, he seems to change the nuclear model of Dr. Whipple a little bit. But the thing might be easier if you comment on it, Whipple, because it is very difficult to change a nuclear model just from these observations of comet Kohoutek, I would say.

F. Whipple: I don't think I have any special comments on that point. I am not exactly sure what he did to the nuclear model and — just from mere reading of the papers, I don't believe I can comment on that.

I think that since I first visualized it, the only real change has been the introduction of the clathrates, and otherwise the whole picture is very much the same.

But then we have the chemistry which is very involved.

But I am not sure how he changed it, so I don't think I can answer the question.

DISCUSSION (Continued)

J. Rahe: He is talking about the clouds of dust particles surrounding the nucleus of the comet. And this cloud is supposed to be responsible for the large brightness of comet Kohoutek from the time of discovery, until the beginning of October.

M. Dubin: I raised that question, because I say that it has already been observed that probably the cloud of dust particles around the comet were not a simple cloud, they were vaporizing or sublimating. They are also possibly clathrates and this would change the distribution of the parent molecules in the coma region, which in turn would relate to the discussion we have had in the last few minutes.

J. Rahe: All the measurements Dr. Vanysek was referring to in his paper were made when the comet was much closer to the sun. These observations were made the beginning of January, and he is talking here about the dust cloud here until the beginning of October, October and earlier.

And what you said about this sodium observation, we were able to observe sodium emission, (observations made in Chile at the European Southern Observatory) up to about 0.7 astronomical units — but not further out.

This is very common behavior, that you observe sodium closer to the sun and not further than 0.7 or 0.8 astronomical units.

H. U. Schmidt: Dr. Dubin just said that Kohoutek behaved differently than some comets. What photometric observations do exist for a new, undisturbed comet with a small q (perihelion distance) at large distances before perihelion besides Kohoutek? It seems to me that comet Kohoutek showed just the photometric behavior which is in line with a statement by Oort in his theory 23 years ago. He stated that a genuine new comet must have a chance of being detected which is much larger than its chance to be detected at later returns. He concluded this directly from the statistics of very small values of 1/a. Since Kohoutek was much brighter before perihelion than afterwards, it followed this prediction by Oort.

DISCUSSION

M. Dubin: In reply to Dr. Schmidt's point – I was just questioning what a normal comet was, initially because of the brightness difference observed of about a factor of 10 as reported by Vanysek and Rahe.

There is, in fact, one observation that has been made and reported earlier, that showed an anomaly on Kohoutek. This was reported at the Huntsville workshop and further defined by Page, Carruthers and others, on the hydrogen emission of the comet.

They find that comet Kohoutek had possibly an explosion of hydrogen in early December, where the rate of generation of hydrogen was considerably greater in that period than even at perihelion.

Now I don't understand comets too well —

(Laughter.)

— but that is why I asked the question.

E. Ney: I am a little amazed by the factor of 10 before and after perihelion of Kohoutek, because within one astronomical unit, all the visual and infrared observations do show that it is dimmer after perihelion passage, but only by about a magnitude.

So the factor of ten if it does exist must be at more than an astronomical unit, or it could be because of the diaphragms that were used, or that the reduction wasn't exactly the same.

I only know of a factor of two to three that Kohoutek changed before and after perihelion, which was also the same amount that Ikeya-Seki changed.

J. Rahe: This observation was made by Kohoutek in a B filter with an aperture of 80 arc seconds.

E. Ney: At what distance from the sun?

Voice: It must have been about one astronomical unit, but it takes a very short time, I found that out.

D. A. Mendis: I would like to make a comment regarding the time scale and the length scale.

If you have a distributed source model rather than a simpler source model, whatever way the distributed source is brought about, either by a clathrate model, with icy grains around it, or in the form of a cluster of grains, then the time scale, or the length scale that you measure must necessarily be larger than the dissociation length scale.

It will mimic a much larger dissociation length scale. In other words, the scale length is almost completely meaningless in such a situation.

You see, because you can get the molecules out to 10^4 kilometers before they are released from the grains.

B. Donn: We have some preliminary results on this distribution of parent molecules, it seems to me, from the radio observations which have detected them. As I see these observations in the case of the water in Comet Bradfield, the evidence is that the water is concentrated toward the nucleus.

There is a problem here that it may be not just a density, but also an excitation process, and this we have to work on trying to understand.

The same thing, as I recall, is true with the methyl-cyanide, that is if you move your beam off the nucleus a short way, then the density, or at least the antenna temperature drops.

And this observation suggests that from the signal we are getting, the excited molecules are very closely concentrated to the nucleus.

Unfortunately both the water and the methyl-cyanide we observe in excited states, and therefore there is an excitation process that needs to be interpreted.

I would like to say one other thing about a somewhat different aspect of this problem, and that is that for comets at distances beyond 3 AU, almost the only features we have observed are the continuum; the emission spectrum has not been strong enough to be detected, I think with the exception of one that Dr. Dossin took of comet Humason and that was a strange beast anyway.

And so we have the problem that at large distances any comet, at 3 AU and beyond — in the case of Halley at 3 AU and the outbursts of Schwasmann-Wachman at 5 AU, all that has ever been observed is a dust continuum in which we have seen the Fraunhofer spectrum of the sun.

So it is generally characteristic at large distances that we are seeing dust, no matter what the comet is.

Now among the important pieces of observational data that are missing are intensive studies of these comets at larger distances to get data on the spectra, and on the luminosity variations at large distances so we can have more data for interpreting the sort of work, for example, the Marsden and Sekanina have been doing on these distant comets.

These are observational data that we need to get, and I was just thinking of the comet observers, could they put more emphasis on these faint distant comets—okay, you don't get as much data, but it would be very important for studying the evolution of the nucleus as it approaches the sun.

W. F. Heubner: I would like to get back to the question of: what is a normal comet?

First of all, I think we agree that the brightness of the comet drops by a factor of ten in the visual from before to after perihelion.

However, in the infrared, I think the drop is much smaller. The reason for it is that the particles which scatter the light in the infrared are the larger particles, and they happen to hang around the comet nucleus for a longer time. You are quite right when you say that you probably only see a brightness change of a factor of two in the IR. That comes from the scattered light on the solid particles, the largest solid particles.

In the visual we see molecular emission from fluorescence and the scattering from the smaller particles superimposed. Here the change in brightness from before to after perihelion can be much greater.

Secondly, I would like to comment on the brightness of the comet at very large distances: it seems to me that if one wants to have a cloud of particles around the nucleus at very large distances—and we are talking now distances of Jupiter and further out—then one needs a shell of gas, of frozen gas on the outside, which is extremely volatile. Something like CH_4 that can propel these dust particles to form a coma (unless they happen to be already in a coma, which I don't quite believe).

CO does not seem to be a likely candidate. It does have the right latent heat of vaporization, but one would then have to see a tail. But CH_4 does not leave a tail, at least not a visible one. I think it is likely that there was a shell of frozen CH_4 on the outside of the nucleus. Whether that makes it a normal comet or not, I don't know.

F. L. Whipple: For those that haven't lived with comets for so many years, I think the observations of the orbits that probably will be discussed later by Marsden and Sekanina are very important here.

The peculiarity of these comets, ones with extremely long periods and perihelion distances out between 3 and 5 AU, is that they seem to be coming in new; you don't find the returned ones. They should be coming back with much the same orbits with somewhat smaller perihelion distances, which indicates very strongly that the first time a comet comes in there is this outer layer of methane or whatever, that throws out dust and gives it this halo to make the comet bright at the distance of 3 to 5 AU.

But the comet loses it after it makes one passage, and as Marsden points out, there is a real dearth of these comets that come in with somewhat shorter orbits. There should be a lot of them returning if you look at it statistically over the eons. And you have comets with extremely long period orbits, going out to 20- 30,000 AU.

Z. Sekanina: I would just like to say that a study of the tails of the distant comets as I made about a half a year ago, suggested that there is a very strong evidence that the activity of these incoming comets of large perihelion distance, tends to decrease as the comet approaches perihelion, which is something that would be normally regarded as very un-normal.

It certainly is not valid for typical comets of a small q.

Now there is an indication that the comets are more active, up to as far as I would estimate 10 to 15 AU before perihelion, and as the comet approaches the perihelion, which in this case is on the order of between 3 and 5, the activity already starts dropping down.

The evidence is extensive from the tail.

From the orientation of these tails, you can rather confidently say at what time the tails were formed, and for all the directions that a tail would cover corresponding to ejection times near the perihelion, there are simply no tails in those directions, while there is a beautiful tail in the direction corresponding to ejection at 10 to 15 AU before perihelion.

W. Jackson: Are you saying that the orientation of the dust tail is an indication of when the activity started?

Z. Sekanina: That is right.

W. Jackson: And from a study of the orientation of the dust tail, it looks like the activity started at large astronomical distances.

Z. Sekanina: That is right and one sees the tail production decrease as the comet approaches perihelion.

Voice: This is a question to Sekania.

Do you mean today that you observe comets at 10 to 15 astronomical units?

Z. Sekanina: Not necessarily. We observe comets at, say, 4 AU and these have tails, and we observe that they are straight and you can say, under simple assumptions, from the direction that the matter was released at 10 to 15 AU.

Voice: So you deduce the activity between 10 and 15 AU from these tails that you observed orientations of.

J. T. Wasson: I would like to speak briefly to the point raised by Huebner about the possibility of methane ejecting the dust.

It is improbable that pure methane is an important cometary constituent. It is highly volatile and condenses out of a nebula having a pressure of 10^{-3} atm at temperatures of 40°K.

If comets formed within the solar system and temperatures were as high as or higher than those at present, methane would not have condensed inside 30 AU.

It is possible to condense methane far away from the sun, out in the Oort cloud, but then you run into problems of condensing out very much material at the low gas density there.

And so I think you are probably going to have to look for a volatile other than methane to eject the dust.

Secondly, I would like to ask how well you know that there is no CO^+ at 5 AU and beyond?

How accurate are the observations and what kind of limits can one give on carbon monoxide abundance?

W. F. Huebner: I think if CO were present then we would have seen it in the tail just as we saw it in Humason, and as far as the CH is concerned, I don't mean to imply that this is the only possibility.

Certainly there are other molecules which do not radiate in the visual, and are highly volatile. I just mentioned that the CH_4 might be a possibility.

But I do disagree with you about the condensation temperature. We have made calculations which indicate that CH_4 will condense out at about 100 degrees.

DISCUSSION (Continued)

Voice: Is it pure or as a clathrate?

W. F. Huebner:

It is pure, that is right. In a mixture of other gases.

W. Jackson: I would like to make a comment about whether or not you would observe CO^+ at 5 AU. Humason is probably one of the most unusual comets rather than a reasonably normal comet, because the amount of material that had to be produced to observe that amount of CO^+ out there would suggest that comet Humason was an extremely large comet.

Now a "normal comet" with a radius of the order of 5 kilometers, would not show any CO^+ or any molecular emission unless you use very sensitive techniques.

You possibly — I don't know, with image intensifiers, maybe there is a possibility of observing something way out there, but I think it would be extremely difficult.

E. Roemer: I should like to call attention to the fact that comet Sandage, 1972h, is currently observable with an asymmetric coma 25 arc sec (100,000 km) in radius at a heliocentric distance of 6.8 AU. The perihelion distance is a bit beyond 4 and the magnitude of the nuclear condensation is about 20. A photograph from the September 1974 dark run will be shown tomorrow as part of my review presentation on astrometry and luminosity.

B. Donn: I will make a brief comment here on the place of origin of comets and will discuss it in more detail in the session on comet origins. It is not necessary to assume that comets could only form within about 30 AU of the sun because the density of matter was much to low everywhere else. We know that stars tend to form in clusters and it may be that is the only way they can form. If the sun originated as a member of a cluster there was appreciable density over a volume of several parsecs. Within 50 to 100 thousand AU of sun small sub-clouds may well have had densities large enough for bodies as small as comets to accumulate in the available time. Cameron has published a scheme of interstellar comet formation in sub-clouds that separated from the collapsing cloud which formed the sun. In his theory comets could readily form in such regions. By means such as these comets may have formed in the region of the Oort cloud.

L. Biermann: In connection with this question of the relative merits of CH_4 and CO for explaining the appearance of comets at very large distances from the sun, beyond 5 AU, I would just like to make reference to a paper which I gave last year at the conference in Barcelona. I started using some figures given by Arpigny on the emission rate of CO^+, about ten years ago, and I used laboratory work on ion-molecular reactions to show that CO was likely to be produced in larger quantity than I would adduce from the CO^+, largely because a sizeable fraction of the observed CO^+ is removed, not by flowing out into the tail, anyhow in a fairly typical, ordinary comet, the typical bright comet, but by being transformed into different kinds of ions.

And so the observed intensity of the CO^+ might be misleading concerning the quantity.

Now I suppose at some later sessions we could take up this question; maybe some of us can get together and make an estimate for showing — my feeling is, what was expressed already — what you would have to expect from a typical comet, at distances beyond 5 AU would turn out to be invisible as a CO^+ tail; it would turn out to be invisible with available optical means — anyhow. For past comets you would not expect to have seen anything. For future comets, using advanced techniques, things are, of course, different.

H. U. Schmidt: I have a short question to Dr. Huebner. You spoke about a thin layer of volatile material formed at lower temperature than in the solar nebula which would be needed to produce the bright image of Kohoutek at large distance before perihelion. Would you think it is possible that this thin layer might have been formed on an old nucleus originating in the solar nebula but suffering additional accretion in interstellar space at lower temperature for a longer time?

W. F. Huebner: I think I would agree with that in general, that one can accrete highly volatile materials. I'm not quite sure where or what they would be, but it wouldn't be very much. And I think the amount would have to be significant if one really wants to account for a large dust coma around the nucleus at that distance.

(Simultaneous discussion.)

F. L. Whipple: It was part of my comment. I didn't want to enlarge on it, but —

W. F. Huebner: It's thin, but it must be big enough to bring out the dust.

F. L. Whipple: I think that Bert Donn and his group and I have been thinking about the same sort of thing, that if you do make these comets at great solar distances early in the game, you are probably in an extremely dense nebula, and there's no reason why you couldn't get a large accumulation of interstellar dust there that might amount to say a meter possibly, but certainly centimeters, which would probably be enough to do this for a one time affair as the comet comes in to perihelion at, say 4 astronomical units. I think that's the whole point. Or we might have gone through a dense cloud later on at a relatively low velocity, and collected a lot of material.

At the present time you wouldn't collect enough. If you have one hydrogen atom or a tenth per cubic centimeter you're not going to collect a significant amount, but in these dense clouds, which we might have gone through when the solar system originated, comets at great distances could have accumulated a lot. It might have been a part of the original accumulation of the nucleus.

B. G. Marsden: With regard to this question of normality of comet Kohoutek, I can think offhand of four comets, three other ones in addition to comet Kohoutek, which seem from the orbital evidence to be new, although we never know for sure. They just seem to be coming from large distances. But of course, the perturbations over several times around could throw them back so that they still appear to be coming from those distances.

Among these four comets also they all have small perihelion distances and all were observed for some time before perihelion.

In addition to comet Kohoutek they are comet Arend-Roland (1957 III), comet Cunningham (1941 I), and comet Seki-Lines (1962 III). Now, as of last October, when comet Kohoutek was now only 2 astronomical units from the sun, it was very easy to compare it with comet Arend-Roland. The comets look very similar. Comet Kohoutek seemed to be then intrinsically a magnitude brighter, and so that is why confident predictions were made that it would be a bright object in January.

It seemed very reasonable to compare these two comets, the only difference being comet Kohoutek did go rather less than one half the distance from the sun than comet Arend-Roland did.

Comet Arend-Roland behaved perfectly well, comet Kohoutek seems to have been, I would say, about 1-1/2 magnitudes fainter after perihelion than before, and I don't see any way in which that could have been predicted.

Comet Cunningham, which Dr. Jacchia mentioned in his paper in Sky and Telescope, is often labelled as the bête noir among comets that have failed. Again we had somewhat the same problem that two ephemerides were provided, in this case one going according to an r^{-6} law and one r^{-4} law, and everybody forgot about the r^{-4} law as time went by, and were still expecting comet Kohoutek to be -10 at perihelion, just as they were expecting comet Cunningham to be very bright.

Indications are, in the case of comet Cunningham, that it was very little fainter, a very little amount fainter after perihelion than before. It was badly placed for observation. There was only one observation made in Argentina.

And finally, comet Seki-Lines. This comet had the perihelion distance of 0.03 of an astronomical unit, and it seems from the orbital evidence, again, to be a new comet. This again, was a perfectly spectacular comet after perihelion, in spite of going so close to the sun; it doesn't seem to have suffered at all.

So I would deduce from these statistics that comet Kohoutek is in the 25 percent minority among normality of comets.

(Laughter.)

D. D. Meisel: I'd like to follow up what Brian said about the normality of comet Kohoutek.

Now, observations that Bortle and Morris gathered on comet Kohoutek show that before perihelion and after perihelion the heliocentric distance index was 2.5 in both cases, but that Kohoutek on the average, by the least squares solutions, dropped one full magnitude after perihelion.

Now, there are only about 15 percent of all the sample of comets that have had reasonable photometry done, which have indices around 2.5. So in that way, Kohoutek, at least photometrically in the crudest way we know, which are the comet magnitudes, was normal for this group with very low heliocentric index.

But again, it's only a sample of 15 percent, so how good's the weatherman?

M. A'Hearn: I just wanted to offer a further comment on the question of the normalcy of comet Kohoutek, in two respects. The first is, that if you look through the abstract booklet, at least one of the abstracts of papers that's not being presented (by L. Brown) indicates that Kohoutek underwent flaring; we've also heard about the flaring in hydrogen. I, too, have photoelectric data (A. J. in press) that indicates, for example, that it underwent a flare at least in the C_2 band on the first of December, lasting through the 2nd of December, and it may be that Kohoutek has undergone a large number of these flares, which would make it rather difficult to interpret any of the photometric data in terms of simple pictures of the production of the molecules.

DISCUSSION (Continued)

I also wanted to comment on the pre- and post-perihelion differences. My photometry indicates that in the C_2 Swan band ($\Delta\nu = +1$), the fluxes are the same before and after perihelion to within a factor of 2, although the visible continuum is way down. So the continuum in the optical is down a great deal, perhaps as much as a factor of 5 or 10, but the C_2 band is comparable to what it was before perihelion, provided you use diaphragms that isolate approximately the same linear area in the comet.

H. Keller: The observation of Skylab and the rocket observation of the hydrogen production rate indicate that there is a factor of about 3 in production rate in the difference; that means the production rate was about a factor of 3 higher, preperihelion than after perihelion at a typical distance of 0.5 AU. That alone can account for the 1.5 magnitude difference in visual brightness.

W. Jackson: But evidently if the production rate of hydrogen went down, the relative production rate of the parent that's responsible for the C_2 must have gone up, if the brightness is going to remain the same pre- and post-perihelion.

So that, again, indicates some variability in at least the layering of the comet.

N76-21054

PHOTOELECTRIC PHOTOMETRY OF COMET KOHOUTEK (1973f)

Lubos Kohoutek

1. Introduction

Comet Kohoutek (1973f) has been observed with the 50 cm (f/15) reflecting telescope of the European Southern Observatory, La Silla, Chile, on fourteen nights between January 16 and 30, when the heliocentric and geocentric distances of the comet were r=0.66 - 1.00 A.U. and Δ=0.81 - 0.96 A.U., respectively. The 40" and 80" diaphragms were used for the photometry of the cometary head (EMI 6256 A photomultiplier) in the UBV system and with six interference filters: CN 3884 Å, CO^+ 4267 Å, C_2 4737 Å, C_2 5172 Å, cont. 5300 Å and Na 5893 Å.

The atmospheric conditions were good but the accuracy of our observations was lower than usual due to large extinction (air mass 2.5 to 4.3) and twilight. The mean error of one measurement of log F in all but Na 5893 Å filters can be estimated at $\pm$0.02, whereas the accuracy through the Na filter was substantially lower.

2. UBV Observations

Observations in UBV system are given in Table 1 (N - number of measurements in the respective night). They are also presented in Fig.1, but reduced to the distance of Δ = 1 A.U. and corrected to standard circular area of D(40") = 2.90 x 10^4 km and D(80") = 5.80 x 10^4 km in diameter, respectively, centered on the cometary nucleus. The above areas correspond to those seen in the diaphragms of 40" and 80" and from the distance 1 A.U. For that correction the mean intensity gradients in the coma were applied as deduced from the measurements in both diaphragms.

D2

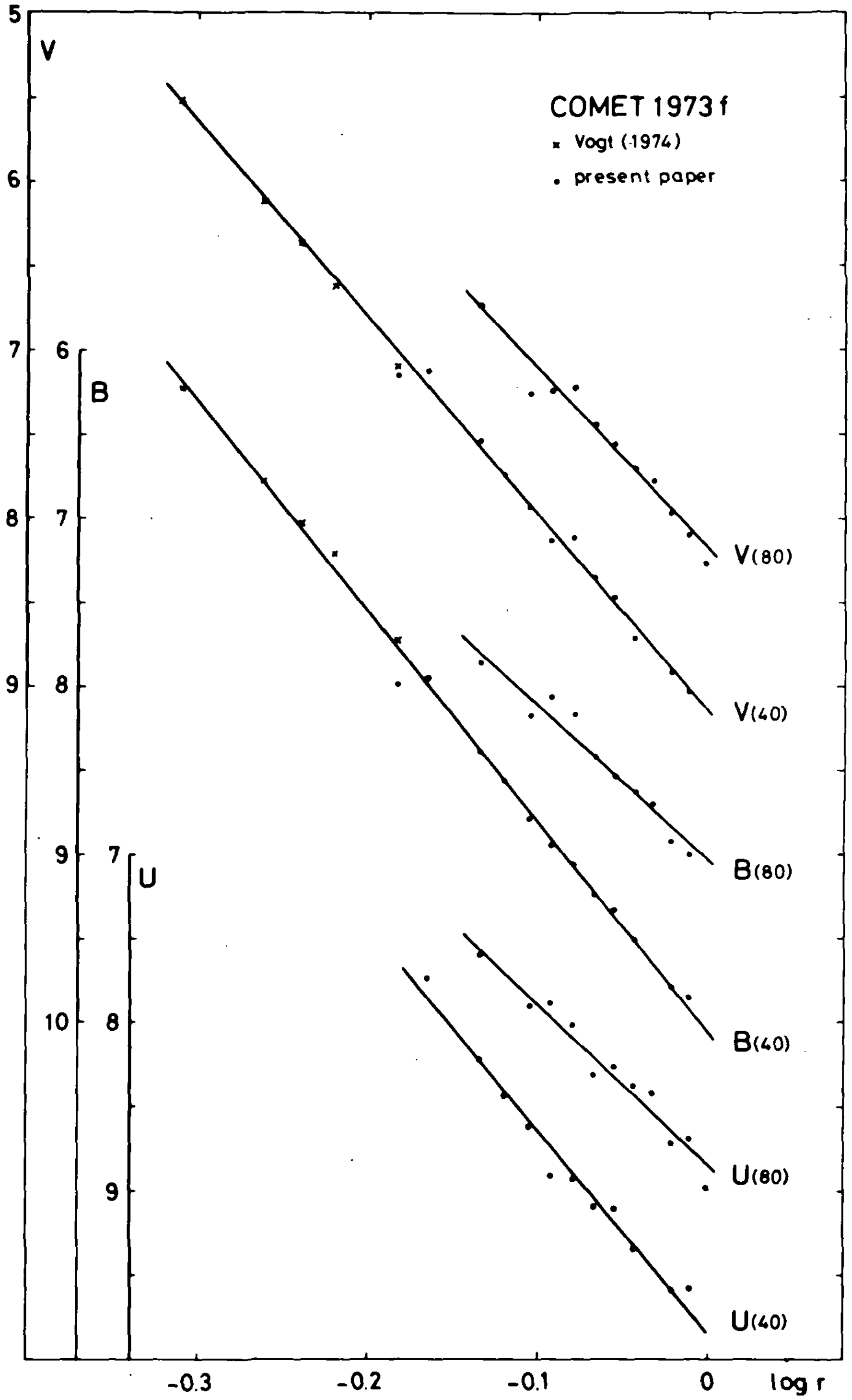

Fig. 1 The reduced brightness of Comet 1973f in UBV system [$\Delta = 1$ A.U.; standard circular area of 2.90×10^4 km (40) and 5.80×10^4 km (80) in diameter] as a function of log r.

Table 1

UBV Observations

Date (U.T.) 1974	Δ [A.U.]	r [A.U.]	Diaphragm 40"				Diaphragm 80"			
			V_{obs}	B_{obs}	U_{obs}	N	V_{obs}	B_{obs}	U_{obs}	N
Jan.16.032	0.807	0.657	6.98:	7.83:	-	1	-	-	-	
17.027	.808	.684	6.96	7.80	7.58	2	-	-	-	
19.029	.817	.735	7.38	8.24	8.06	1	6.56	7.66	7.41	2
20.023	.824	.760	7.58	8.42	8.28	1	-	-	-	
21.030	.832	.786	7.79	8.65	8.46	2	7.10	7.99	7.73	2
22.031	.842	.810	7.99	8.82	8.77	2	6.99	7.90	7.73	2
23.031	.853	.835	7.99	8.94	8.79	1	6.99	8.01	7.86	1
24.033	.865	.859	8.25	9.14	8.98	2	7.32	8.28	8.18	2
25.035	.878	.883	8.37	9.24	9.00	2	7.45	8.40	8.14	3
26.031	.893	.906	8.62	9.42	9.24	1	7.61	8.51	8.27	1
27.027	.909	.930	-	-	-		7.69	8.60	8.33	1
28.034	.926	.953	8.85	9.73	9.52	1	7.90	8.84	8.63	1
29.033	.943	.976	8.98	9.80	9.52	1	8.05	8.94	8.63	1
Jan.30.032	0.961	0.998	-	-	-		8.23	-	8.94	1

In order to increase the time interval of observation we used the photoelectric measurements which were made by Vogt (1974) at La Silla under similar conditions. The B and V magnitudes in the diaphragms of 29'' and 45'', respectively, were also corrected to standard circular area of 40'' (Δ = 1 A. U.).

The absolute magnitudes, m_o, and the photometric exponents, n, derived from the well-known formula

$$m = m_o + 2.5\, n \log r \qquad (1)$$

are given in Table 2 together with the respective interval of log r. The absolute colour indices in the 40'' and 80'' diaphragms differ from each other only slightly and within the observing errors: $(B-V)_{o,(40'')} = 0.90$, $(U-B)_{o,(40'')} = -0.20$; $(B-V)_{o,(80'')} = 0.86$, $(U-B)_{o,(80'')} = -0.19$.

The comet's brightness has been diminishing rather quickly after the perihelion passage, in fact more rapidly in the inner part of the head (n between 4.6 and 5.0) than in the outer part (n between 3.6 and 4.2). When extrapolating the best determined straight lines of V(40'') and B(40'') back to the perihelion, $V_{max}(40'') \sim -0.7$ and $B_{max}(40'') \sim -0.5$ can be obtained.

Assuming a density law $d(\rho) \sim \rho^{-2}$ (ρ is the distance from the nucleus) for the emitting molecules and dust particles in the spherically symmetrical head, an intensity law $I(\rho) \sim \rho^{-1}$ can be derived, which leads to the magnitude difference $\Delta m = m(40'') - m(80'') = 0.75$ for the diaphragms used. Our observations show $\Delta m > 0.75$ and continuously growing with time. The mean values are: $\Delta m_V = 0.904$, $\Delta m_B = 0.817$, $\Delta m_U = 0.853$. The difference between the observed and theoretical Δ m-values reflects the deviation from the ρ^{-1} law and can be expressed by $\rho^{-\mathcal{H}}$; obviously

Table 2

UBV Photometric Parameters

System	V(40")	V(80")	B(40")	B(80")	U(40")	U(80")
n	4.64 ±.08	4.22 .41	4.99 .07	3.64 .40	4.82 .32	3.79 ±.34
m_o	9.14 ±.03	8.16 .07	10.04 .03	9.02 .08	9.84 .08	8.83 ±.06
Δlog r	-0.31 to 0.0	-0.13 to 0.0	-0.31 to 0.0	-0.13 to 0.0	-0.16 to 0.0	-013 to 0.0

Table 3

Parameters of Interference Filters

Filter	CN(0-0) 3884 Å (1)	C_2(1-0) 4737 Å (1)	CO^+(2-0) 4267 Å (2)	C_2(0-0) 5172 Å (1)	Continuum 5300 Å (1)	Na 5893 Å (1)
Peak transm. wavelength [Å]	3892	4747	4265	5180	5306	5917
Peak transm. [%]	42	58	67	78	73	65
Full width at half maximum [Å]	74	52	23	54	56	59

(1) Thinfilm Products, Inc. (2) Spectrum Systems, Inc.

$$\mathcal{K} = 2 - \frac{2\,\Delta m}{5 \log(D_2/D_1)} , \qquad (2)$$

where D_2, D_1 are the respective diameters of the diaphragms. Physically it reflects (a) the production of visible radicals from parent molecules in this part of the inner coma, (b) the deviation from the regular ejection of particles from the nucleus and/or (c) the dissociation of the molecules by sunlight. This last effect can probably be neglected due to the large trajectory of molecules before dissociation compared with the size of the diaphragms used. According to (2) we have: $\mathcal{K}_V = 0.80$, $\mathcal{K}_B = 0.91$, $\mathcal{K}_U = 0.87$.

3. Observations through Interference Filters

The luminosities of the cometary head in the 40'' and 80'' diaphragms and through the interference filters (see Table 3) were measured using the comparison star η Hya, for which Hayes (1970) has published the energy distribution. We adopted the V magnitude of η Hya to be 4.289 (Blanco et al., 1968 - mean value), the V magnitude of the Sun -26.74 (Allen, 1973), and the flux from a star of zero visual magnitude outside the atmosphere to be 3.73×10^{-6} erg.cm^{-2} . s^{-1} in the V region (Allen, 1973). The observed fluxes, F_{obs}, are given in Table 4 for CN 3884 Å, C_2 4737 Å and 5172 Å, and continuum at 5300 Å.

Analogically to UBV data, the differences $\Delta m = m(40'') - m(80'')$ for molecules CN, C_2 as well as for dust in the continuum were found to be larger than expected according to the simple intensity law, and increasing with time. We found the following mean values: $\mathcal{K}_{CN} = 0.75$, $\mathcal{K}_{C_2} = 0.77$, and $\mathcal{K}_{5300} = 0.90$. The $\mathcal{K}_{5300} < 1$ can be explained by the diminishing ejection of dust particles from the nucleus. Probably both effects (a) and (b) are responsible for $\mathcal{K}_{CN, C_2} > 1$.

Table 4
Observed Fluxes of Emission Bands and Continuum
[erg. cm^2 . s^{-1}]

	log F_{obs}							
Filter	CN 3884 Å		C_2 4737 Å		C_2 5172 Å		Cont.5300 Å	
Diaphragm	40"	80"	40"	80"	40"	80"	40"	80"
Jan.16.032	-9.234		-9.802		-9.290		-10.002	
17.027	-9.209 -9.154 -9.199		-9.792 -9.668		-9.305 -9.211 -9.250		-9.967 -9.913	
19.029	-9.413	-9.048 -9.067	-9.901	-9.554 -9.600	-9.444	-9.096 -9.122	-10.115	-9.822 -9.846
21.030	-9.521 -9.519	-9.233 -9.144	-10.054 -10.042	-9.814 -9.691	-9.615 -9.602	-9.337 -9.324	-10.287 -10.277	-10.030 -9.922
22.031	-9.592 -9.613	-9.208 -9.230	-10.159 -10.135	-9.779 -9.801	-9.679 -9.696	-9.305 -9.289	-10.350 -10.357	-10.034 -9.997
23.031	-9.600	-9.190	-10.095	-9.732	-9.691	-9.307	-10.350	-10.012
24.033	-9.685 -9.705	-9.313 -9.319	-10.247 -10.243	-9.873 -9.877	-9.788 -9.802	-9.431 -9.424	-10.478 -10.421	-10.106 -10.141
25.035	-9.721 -9.732	-9.331 -9.347 -9.358	-10.298 -10.290	-9.910 -9.929 -9.929	-9.850 -9.841	-9.465 -9.479 -9.460	-10.498 -10.493	-10.134 -10.167 -10.162
26.031		-9.414		-9.994		-9.543		
27.027		-9.457		-10.006		-9.575		-10.231
28.034	-9.941	-9.532	-10.499	-10.122	-10.047	-9.668	-10.686	-10.318
29.033	-9.982	-9.585	-10.553	-10.183	-10.115	-9.727	-10.749	-10.380
Jan.30.032		-9.667		-10.264		-9.815		-10.434
F_{obs} / F_{cont}	14.8	16.4	2.33	2.44	4.45	4.67	1	1
Δm	0.944		0.927		0.925		0.822	

The energy distribution of the cometary continuum has been assumed to be of solar type. Then, the contribution of such a cometary continuum in the five interference filters could be calculated from the continuum measured in 5300 Å. The ratio of the observed total flux and the calculated continuum flux in the respective filter combination is also given in Table 4. We find that about 95 per cent of the radiation transmitted by the CN 3884 Å filter is the emission contribution and that the fraction of emissions by the C_2 4737 Å and 5172 Å filters are 58 and 78 per cent, respectively. On the other hand, the observed total flux in the CO^+ 4267 Å filter is only about 4 per cent larger than that of the continuum. Our slit spectra of January 6 to 14 show either a missing or only very faint CO^+ emission, so that the radiation transmitted by this filter should originate entirely from the cometary continuum. This fact supports strongly our assumption about the energy distribution of the cometary continuum.

Our measurements in the Na 5893 Å filter require special care. The sodium doublet was very strong on the slit spectra between January 5 and 8 (r = 0.33 to o.42 A.U.) and its brightness has diminished till January 12 (r = 0.54 A.U.) (Kohoutek, Rahe, 1974). The emission contribution in this filter was still about 75 per cent of the total observed flux on January 16 (r = 0.66 A. U.), but only about 18 per cent on January 17 (r = o.68 A.U.). After January 19 the emissions contributed only with 14 per cent assuming that the cometary continuum was of the solar type. If the natrium doublet was totally absent in r ≤ o.7 A.U., the measurements in the Na 5893 Å filter would represent a colour excess of $+0\overset{m}{.}16$ in the continuum, possibly caused by the scattering in the cometary head. Unfortunately, due to the very low quantum efficiency of the photomultiplier in that wavelength, the measuring errors were large and the above result seems to be very uncertain. For that reason our assumption that the cometary continuum is of the pure reflection type has not been changed.

The observations through the interference filters were treated in the same way as in case of UBV data. The observed fluxes were reduced to $\Delta = 1$ A.U. and corrected to standard linear area in the cometary head, D(40") and D(80"). First of all, the important ratio of the absolute brightness of the dust and of the gas coma, $k = F_{o,d} / F_{o,g}$, could be estimated. Assuming, that the effective band width in the U, B, V is 680 Å, 980 Å and 890 Å, respectively (Allen, 1973), we calculated the contribution of the cometary continuum to the total brightness in the respective colours. Putting $F_{o,cont} = F_{o,d}$ and $F_o(i) = F_{o,g} + F_{o,d}$, where $F_o(i)$ is the corrected flux energy in the i = V, B, U colour transformed from the absolute magnitude (see Table 2), we received the following results:

$k_V(40'') = 0.69$ $\qquad$ $k_V(80'') = 0.66$

$k_B(40'') = 1.06$ $\qquad$ $k_B(80'') = 0.84$

$k_U(40'') = 0.61$ $\qquad$ $k_U(80'') = 0.56$.

The dust coma is more concentrated toward the nucleus than the cometary gas. Besides, the increase of k with time in the interval between r 0.6 and 1.0 A.U. was found in all colours.

In order to know the fluxes of the emission bands, the fraction of their total radiation, that was passing through the respective filter, has to be determined. Besides, the contribution of other emissions in the filter was estimated, giving 7.3 per cent in the CN 3884 Å filter, 26 per cent in the C_2 4737 Å filter and 11 per cent in the C_2 5172 Å filter from the total emission flux. The corrected fluxes of the emission bands CN(0-0) $\Delta v = 0$, $C_2(1-0)$ $\Delta v = +1$, and $C_2(0-0)$ $\Delta v = 0$, respectively, are plotted versus log r on Figs. 2, 3 and 4 and compared with the total flux measured in the continuum 5300 Å (Fig. 5). The equivalent width of the 5300 Å filter was 46 Å.

In the first approximation there is a linear dependence of log F on log r in both 40'' and 80'' circular areas for the emission bands as well as for the continuum. The slopes, n, and the absolute brightnesses ($\Delta = r = 1$ A.U.), $\log F_o$, in the relation

$$\log F = \log F_o - n \log r \tag{1a}$$

are given in Table 5. The interval of log r was -0.18 to -0.01 in the 40'' area and -0.13 to 0.0 in the 80'' area.

For continuum at 5300 Å the following parameters were found: $n(40'') = 4.51$, $\log F_o(40'') = -10.806$; $n(80'') = 3.81$, $\log F_o(80'') = -10.424$.

The photometric exponents, n, lie for the emission bands as well as for the continuum in the same range as in case of the UBV data (see Table 2). Also $n(40'') > n(80'')$ can be stated with the exception of the $C_2(1-0)$ band probably because of larger observing errors.

4. Desorption Heats and Number of CN and C_2 Molecules

Using Levin's theory (1943) we may express the logarithm intensity of the gas constituent of the coma by

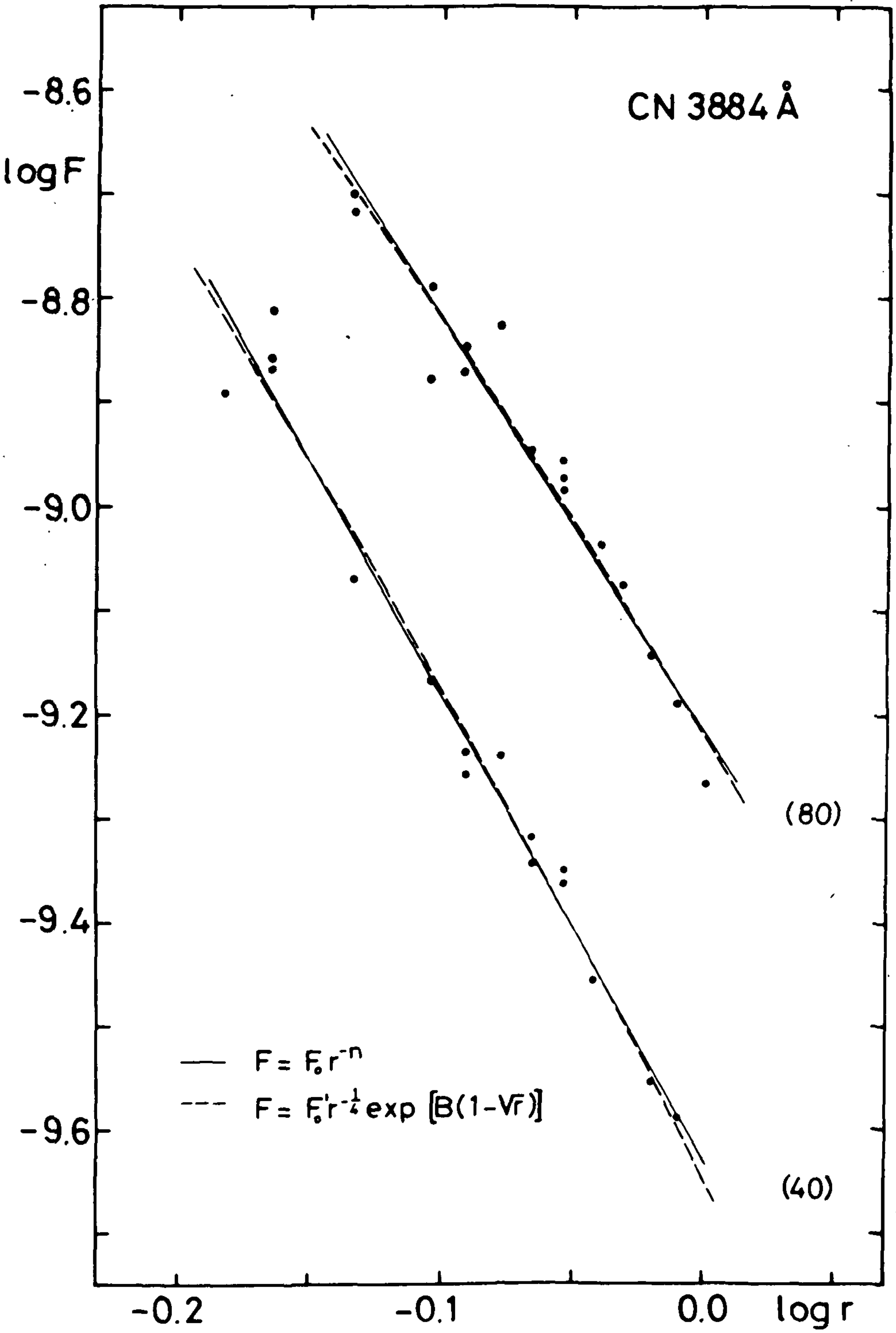

Fig. 2 The reduced flux of the CN(0-0) 3884 Å emission band as a function of heliocentric distance. See the text.

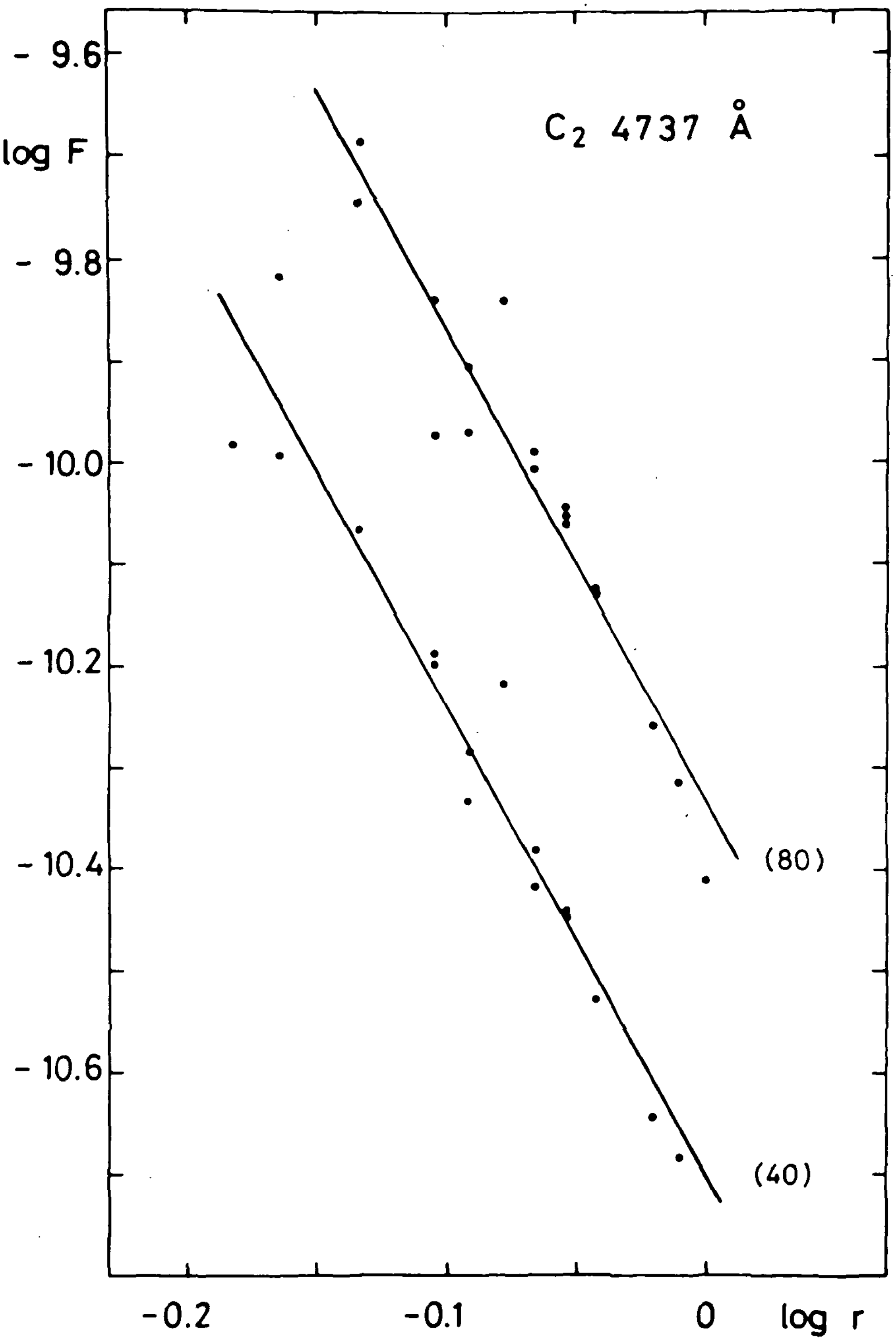

Fig. 3 The reduced flux of the C_2(1-0) 4737 Å emission band as a function of heliocentric distance. See the text.

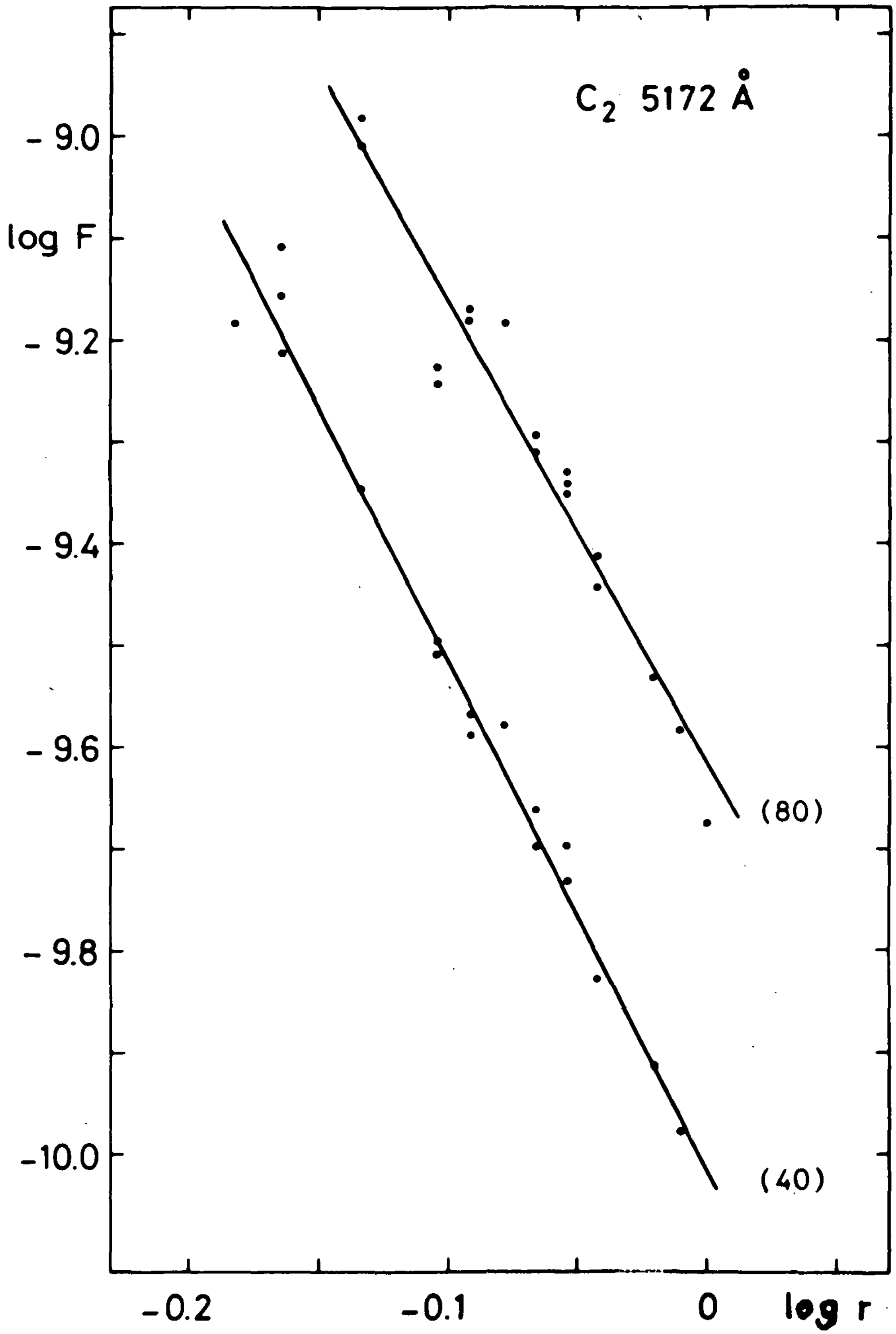

Fig. 4 The reduced flux of the C_2(0-0) 5172 Å emission band as a function of heliocentric distance. See the text.

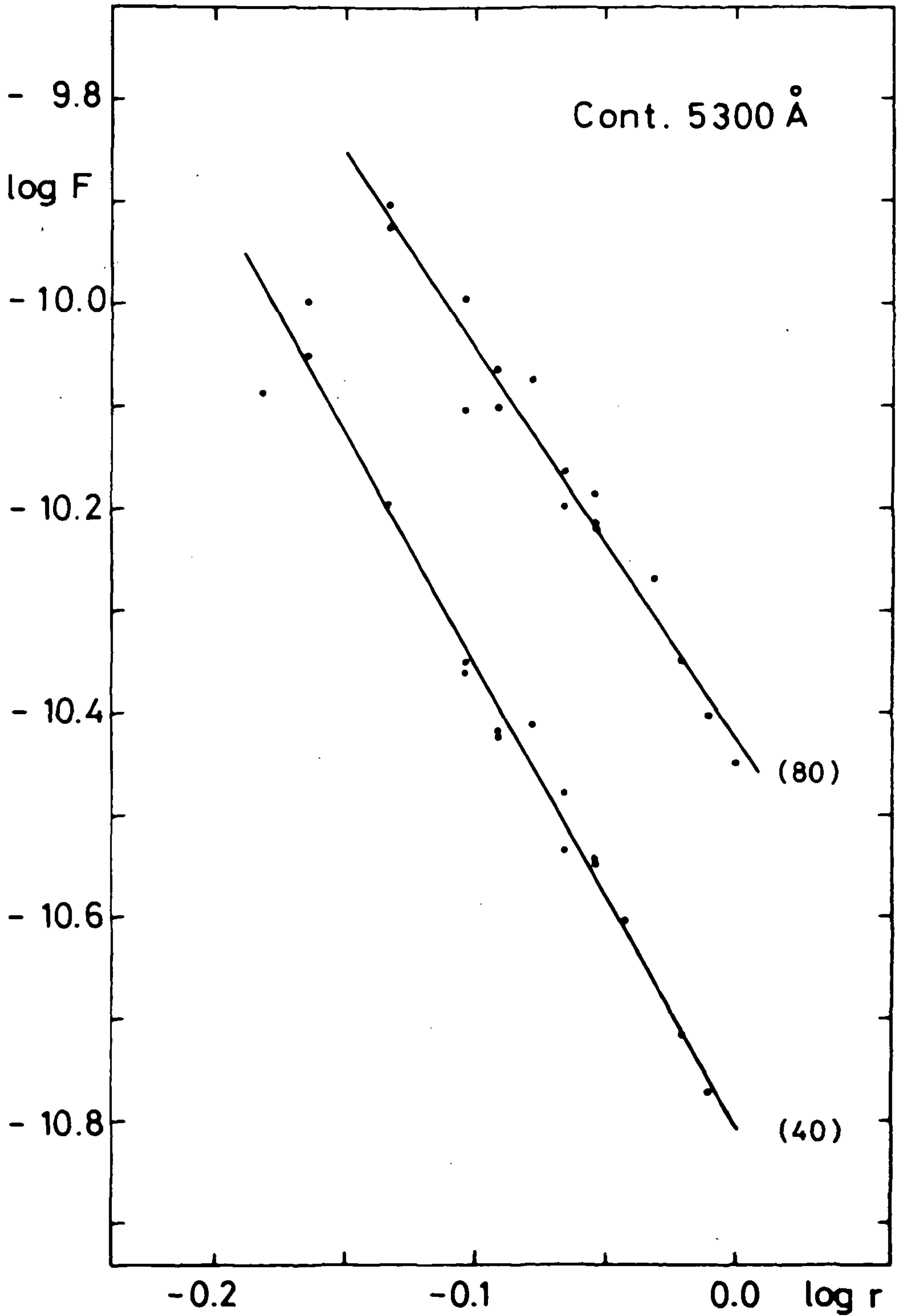

Fig. 5 The reduced flux in the continuum at 5300 Å as a function of heliocentric distance. The effective band width is 46 Å.

Table 5
Photometric Parameters of CN and C_2 Emission Bands

Band	CN(0-0), $\Delta v=0$		C_2(1-0), $\Delta v=+1$		C_2(0-0), $\Delta v=0$	
Diaphragm	40"	80"	40"	80"	40"	80"
n	4.50	3.98	4.62	4.64	5.01	4.55
log F_o [$erg.cm^{-2}.s^{-1}$]	-9.632	-9.219	-10.701	-10.330	-10.017	-9.614
B	9.51	7.88	9.79	9.53	10.67	9.33
log F'_o [$erg.cm^{-2}.s^{-1}$]	-9.650	-9.220	-10.721	-10.341	-10.037	-9.624
L [$cal.mol^{-1}$]	5670	4700	5830	5680	6360	5740
log L_o [$erg.s^{-1}$]	17.799	18.229	16.728	17.108	17.412	17.825

$$\log F = \log F'_o - \frac{\alpha}{2} \log r + B(1 - r^{\alpha}) \log e \qquad (3)$$

where $B = L/RT_o$, L - desorption or evaporation heat, R - gas constant, T_o - temperature of the nucleus at a distance of 1 A.U. The constant α in the relation $T = T_o \cdot r^{-\alpha}$ corresponds to 0.5 if the nucleus is in a thermal equilibrium state. The constants B and $\log F'_o$ for the CN and C_2 emission bands are also given in Table 5 (for $\alpha = 0.5$). Both relations, (1a) and (3) differ only very slightly from each other as shown in the example of Fig. 2. The desorption heat L [cal. mol^{-1}] was determined using $T_o = 300^o$K. The mean parent molecule desorption heats of 5200 cal. mol^{-1} and 5900 cal. mol^{-1} for the predecessor of CN and C_2, respectively, differ from each other. They are larger than the value 4500 cal.mol^{-1} which was found for CN and C_2 in Comet Rudnicki (1966e) (Mayer, O'Dell, 1968), or than the value 4800 cal. mol^{-1} for C_2 in Comet Arend-Roland (1957 III) (Liller, 1965). If we use $\alpha < 0.5$ as recommended by some authors and still $T_o = 300^o$ K, we would receive B and L even larger: e.g. 6400 cal. mol^{-1} (CN) and 7300 cal. mol^{-1} (C_2) for $\alpha = 0.4$, or 8500 cal. mol^{-1} (CN) and 9600 cal. mol^{-1} (C_2) for $\alpha = 0.3$. For that reason it seems to be more justified to accept $\alpha = 0.5$ for Comet 1973f, assuming again T_o as given above.

Following the method introduced by Wurm (1943) the number of molecules CN or C_2 in the cometary head can be calculated from the respective luminosities L:

$$N = L \frac{m_e}{\pi e^2 f p \, \rho(\nu, r)} \qquad (4)$$

where f is the oscillator strength, p is the vibrational transition probability and $\rho(\nu, r)$ is the solar radiation density at the given frequency and for the given heliocentric distance. We used the molecular constants presented in Table 6 (for f see Wentink et al., 1964; for p see Fraser et al., 1954) and $\rho(\nu, r)$ resulting from the solar spectral irradiance data listed by Robinson (1966). The absolute luminosities appearing in Table 5 were calculated from the corresponding fluxes: $L_o = 4\pi\Delta^2 F'_o = 2.812 \times 10^{27} F'_o$ · (Δ = 1 A.U.). Then, the number of molecules CN and C_2 which radiated in the cylinders extending through the comet in the line of sight and of diameters D(40") and D(80") were determined (Table 6).

The ratio $N_o(C_2\ 5165)/N_o(CN) = 1.52$ or 1.46, and $N_o(C_2\ 4737)/N_o(CN) = 0.99$ or 0.88 for the 40" and 80" diaphragms is very low and comparable with the value 0.8 obtained for Comet Burnham (1960 II) by Arpigny (1965). Also Vanýsek (1969) found for Comet Ikeya-Seki (1968 I) a rather low value of $N(C_2)/N(CN) = 3.2$. It is interesting to notice that 1960 II as well as 1973f are very probably "new" comets and that the orbital eccentricity of 1968 I was also very high (0.99915).

There exists a discrepancy between $N(C_2)$ as derived from the λ 4737 and λ 5165 bands: $N_o(C_2\ 5165)/N_o(C_2\ 4737) \simeq 1.6$. An even larger difference in $N(C_2)$ was already found for Comet Ikeya (1964f) by Kovar and Kovar (1965).

5. Conclusions

Summarizing our results based on the photoelectric observations of Comet 1973f we may conclude:

After the perihelion passage the comet's luminosity was quickly diminishing partly due to declining ejection of both gas molecules and dust particles from the nucleus. The respective photometric parameters are given in Tables 2 and 5. Measurements in two

Table 6
Number of CN and C_2 Molecules

Band	f	ɒ	$\rho(\nu,r)$	$N_o(40'')$	$N_o(80'')$
CN (0-0) 3884 Å	0.026	0.920	$1.90 \times 10^{-20} r^{-2}$	1.74×10^{30}	4.69×10^{30}
C_2 (1-0) 4737 Å	0.0030	0.237	$5.47 \times 10^{-20} r^{-2}$	1.73×10^{30}	4.14×10^{30}
C_2 (0-0) 5165 Å	0.0030	0.731	$5.58 \times 10^{-20} r^{-2}$	2.65×10^{30}	6.86×10^{30}

diaphragms, 40'' and 80'' in diameter, indicate the deviation from the intensity law ρ^{-1} for a spherically-symmetric coma and agree with the $\rho^{-\mathcal{H}}$-law; $\mathcal{H}$ decreases with increasing heliocentric distance, the mean $\mathcal{H}$ values lie between 0.75 and 0.91. The dust constituent of the coma was medium intense (k between 0.6 and 1.1), and the dust particles were probably of larger size because of the nearly pure reflecting cometary continuum. The desorption heats for CN and C_2 parent molecules were unequal (5200 and 5900 cal.mol^{-1}) and somewhat higher compared with former results. The ratio $N_o(C_2)/N_o(CN)$ was very low (0.9 to 1.5) and slightly depending on the choice of the C_2 emission band. Assuming $T_o = 300^o$ K, the constant $\alpha = 0.5$ has been accepted which corresponds to the equilibrium state of the nucleus.

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NARROW BAND PHOTOMETRY OF COMET KOHOUTEK

Larry W. Brown

I. INTRODUCTION

Photometric observations of emission line features of the coma of comet Kohoutek (1973f) were made with narrow band interference filters. The emission features observed were CN(3879 A^{o}), C_3(4057 A^{o}), and C_2(4732, 5165,5634 A^{o}). The radial dependence of the emission was investigated by employing six diaphragms set concentrically about the brightest part of the comet's head.

The photometric observations were made at the Optical Research Facility and Observatory of NASA/Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. The observatory is located 13 miles Northeast of Washington, D.C. (longitude = $5^{h}07^{m}18^{s}.22$, latitude = $+39^{o}\ 01'\ 11''.48$, altitude = 49 meters) and is operated by the Laboratory for Optical Astronomy of Goddard (GSFC).

II. INSTRUMENTATION

The photoelectric measurements were made at the Cassegrain focus of a Boller and Chivens 36-inch telescope with a digital single channel pulse-counting system. This system consisted of an uncooled ITT model FW130 photomultiplier tube whose output was connected to a Lacroy preamplifier-discriminator followed by an Atec pulse counter. The output of the counter and the timing information were digitally recorded on a magnetic tape and processed by an IBM 360-91 computer. System timing was accomplished with a Tracor model 304D rubidium frequency standard.

Table I
Filters

FILTER PARAMETER	#4	#3	#9	#8	#7	#1	#6
ELEMENT	CN	C_3	C_2	C_2	Continuum	Visual	C_2
λ (A°)	3879	4057	4732	5165	5200	5454	5634
Δλ (A°)	63	93	54	50	51	235	50
Δλ (%)	1.6	2.3	1.1	1.0	1.0	4.3	0.9
Transmission (%)	42	58	75	75	83	61	87

The narrow band interference filters were manufactured by Thin Film, Inc. Tracings of each filter were made using a Carey model 14 spectrophotometer whose intensity scale was calibrated against a set of Balzer Incomel-coated neutral density filters. The results of these tracings are presented in Table I. The number assigned each filter represents its position in the filter holder. The parameters measured were the effective wavelength (λ), full width at half the maximum intensity ($\Delta\lambda$ in A° and per cent λ), and the maximum transmission over the bandwidth.

III. OBSERVATIONS

The observations consisted of measurements with one wide and six narrow band filters. Five narrow band filters were chosen to correspond to the emission line features CN(3879 A°), C_3(4057 A°), C_2(4732, 5165, 5634 A°) of the coma. The sixth narrow band filter was chosen to provide a reference continuum (5200 A°) near the strongest C_2 emission band. The wide band filter represented an attempt to provide a bridge between the narrow band measurements and the visual magnitude of the UBVRI photometric system. In addition each filter was used with six diaphragm openings corresponding to 9,14,36,48,100 and 220 seconds of arc concentric circles about the brightest (visually) part of the comet's head.

The measurements were taken by selecting a filter,centering the brightest visual spot of the head in the smallest diaphragm, then recording a set of 30 data points of 1-second count intervals for each diaphragm from the smallest to the largest. The centering of the diaphragms was periodically checked; although, the variable drive setting of the telescope was found to compensate adequately for the motion of the comet. The data sets were averaged statistically in a computer to provide a 30 second count interval. This was done to provide some quality control over the data in an effort to compensate for the poor sky conditions near the horizon in the Washington metropolitan area. After a complete diaphragm sequence on the comet, the sequence was repeated on an area of sky. The comet measurements were then reduced by the appropriate sky measurements. Some care was taken to insure that these measurements were taken under as similiar a sky condition as those for the comet. This procedure was repeated for each of the filters. Normally the sequence followed that of the filter holder; however, when twilight interference was expected, the sequence was shifted so that those filters affected the most would be done in the darkest sky.

Whenever possible a reference star was observed both preceding and following the comet observation. The star was selected on the basis of its nearness to the comet position at the time of observation. Due to the spatially varying sky conditions, simultaneous spectral matching was not attempted in order to obtain the spatial match. The night's observing schedule was completed by similarly observing a number of other stars of different spectral type under different conditions of air mass and varying sky conditions. These stars were used to derive daily extinction corrections, to define a magnitude system corresponding to the narrow band filters used, and to check these parameters for consistency with the reference star - comet comparison.

IV. DATA REDUCTION

The raw data consists of a set of 30 data points of 1-second count intervals for each filter and diaphragm combination both on the comet and off (sky), and similarly, 60 data points both on and off the stars. These data were recorded on a 7-track magnetic tape for reduction on an IBM 360-91 computer. The initial step in the data reduction was to obtain the average 1-second pulse count and the standard deviation (σ) over the 30 or 60 second interval. Points which exceeded three times the standard deviation (3σ) were eliminated and new averages computed. If all the remaining points did not exceed the new 3σ level then the average was accepted. For those averages rejected, a visual inspection of data could in some cases eliminate bad sections of the interval and allow the recomputation of the average. The appropriate sky averages were then used to obtained the average pulse count above background for each measurement.

A least-squares-fit technique was applied to all star measurements for each particular day. This provided an approximate extinction correction for that day and a crudely defined magnitude scale. This initial fit showed that the photometric system scale was linear but that a small color correction was needed for the slope. Using the preliminary extinction corrections,all the daily measurements were combined to produce a more accurate magnitude scale. At this time obviously inconsistent star measurements were eliminated and the final daily extinction corrections and magnitude scale were computed. A total of 103 star measurements (Table II) were used in the final analysis. The daily extinction corrections and the average extinction are listed in Table III.

The magnitude scale is referenced to the UBVRI multicolor photometry system with magnitudes taken from the Arizona-Tonantzintla catalogue (Iriarte et al. 1965). The magnitudes for individual filters were found by fitting third degree polynomials to the UBVRI magnitudes (Table IV, Figure 1).

TABLE II

Reference Stars (UBVRI)

B.S.#	NAME	V	U-V	B-V	V-R	V-I	Mk SP	USED
875		$5\overset{m}{.}17$	0.13	0.08	0.11	0.18	A1 V	4
996	KAP CET	4.84	0.89	0.69	0.56	0.93	G5 V	20
1570	PI 1 ORI	4.66	0.16	0.08	0.11	0.14	A0 V	5
1983	GAM LEP	3.58	0.51	0.48	0.45	0.72	F6 V	3
2198	69 ORI	4.92	-0.71	-0.12	-0.02	-0.16	B5 V	4
2344	10 MON	5.04	-0.94	-0.18	-0.11	-0.27	B2 V	7
3492	RHO HYA	4.37	-0.10	-0.05	0.05	-0.02	A0 V	9
3759	TAU 1 HYA	4.60	0.46	0.45	0.40	0.63	F6 V	19
3970	UPS 2 HYA	4.58	-0.37	-0.09	-0.01	-0.09	B8 V	2
4119	BET SEX	5.09	-0.67	-0.13	-0.03	-0.18	B6 V	11
4468	THE CRT	4.70	-0.24	-0.08	0.03	-0.04	B9 V	6
8597	ETA AQR	4.00	-0.37	-0.09	-0.05	-0.12	B8 V	7
8969	IOT PSC	4.13	0.53	0.51	0.43	0.72	F7 V	6

TOTAL OBS. = 103

c'2

TABLE III

Extinction

Filter Day(J.D.)	#4	#3	#9	#8	#7	#1	#6
2441990.9	$0^{\mathrm{m}}.59$	0.55	0.39	0.32	0.31	0.28	0.26
2442010.0	0.56	0.52	0.38	0.33	0.33	0.31	0.30
2442016.9	0.59	0.55	0.39	0.31	0.30	0.27	0.24
2442018.0	0.62	0.59	0.46	0.38	0.38	0.33	0.29
2442021.0	0.59	0.55	0.39	0.31	0.30	0.27	0.24
2442060.5	0.59	0.55	0.39	0.31	0.30	0.27	0.24
2442061.5	0.63	0.55	0.33	0.22	0.22	0.17	0.14
2442069.5	0.69	0.61	0.34	0.20	0.19	0.13	0.09
2442075.5	0.53	0.50	0.38	0.30	0.30	0.25	0.22
2442080.6	0.78	0.73	0.56	0.47	0.47	0.43	0.41
2442094.6	0.66	0.60	0.40	0.30	0.29	0.24	0.22
2442096.6	0.61	0.54	0.31	0.19	0.18	0.12	0.08
2442099.6	0.64	0.57	0.33	0.21	0.21	0.15	0.12
Average	$0^{\mathrm{m}}.59$	$0^{\mathrm{m}}.55$	$0^{\mathrm{m}}.39$	$0^{\mathrm{m}}.31$	$0^{\mathrm{m}}.30$	$0^{\mathrm{m}}.27$	$0^{\mathrm{m}}.24$
	Range of Extinction Corrections to Data						
Minimum	$1^{\mathrm{m}}.0$	$0^{\mathrm{m}}.9$	$0^{\mathrm{m}}.8$	$0^{\mathrm{m}}.6$	$0^{\mathrm{m}}.5$	$0^{\mathrm{m}}.4$	$0^{\mathrm{m}}.4$
Maximum	3.6	3.6	1.6	1.4	1.5	2.3	1.4

TABLE IV

Reference Stars (UBVRI, 3rd Order Polynomial Fit)

Filter Star	#4	#3	#9	#8	#7	#1	#6
B.S.#875	$5^{\mathrm{m}}.28$	5.27	5.22	5.19	5.18	5.17	5.15
996	5.70	5.64	5.27	4.99	4.97	4.81	4.70
1570	4.78	4.76	4.71	4.68	4.67	4.66	4.64
1983	4.13	4.11	3.90	3.69	3.68	3.55	3.47
2198	4.50	4.68	5.01	5.05	5.05	5.04	5.03
2344	4.52	4.66	4.92	4.93	4.93	4.92	4.90
3492	4.29	4.30	4.35	4.37	4.37	4.37	4.37
3759	5.11	5.10	4.90	4.71	4.69	4.58	4.50
3970	4.35	4.42	4.56	4.58	4.58	4.58	4.58
4119	4.70	4.83	5.07	5.10	5.10	5.09	5.08
4468	4.54	4.58	4.67	4.70	4.70	4.70	4.70
8597	3.78	3.84	3.98	4.00	4.00	4.00	4.00
8969	4.71	4.70	4.47	4.25	4.23	4.10	4.02

Approximately 50% of the star measurements used to define the magnitude scale were on standard stars whose spectral characteristics (figure 2) have been measured with narrow band scanning photometers (Breger, 1971). These narrow band magnitudes (Table V) were compared to the UBVIR magnitudes. A correction factor for each filter's magnitude scale was obtained by averaging the individual difference for each standard star weighted by the number of observations of each star. The narrow band magnitude system was used then to obtain the observed magnitude of the comet. These magnitudes were found to be consistent with the direct comparisons made on the reference star measured preceeding and following the comet measurements.

TABLE V

Standard Stars (Normalized to 5480 A^{o})

Narrow Band System - Bandwidth ~50 A^{o}

Filter Star	#4	#3	#9	#8	#7	#1	#6
B.S.# 875	$0^{m}.56$	-0.14	-0.08	-0.02	-0.02	0.00	0.04
996				0.09	0.08	0.00	-0.04
1570	0.41	-0.20	-0.12	-0.06	-0.05	0.00	0.02
4119	-0.12	-0.44	-0.27	-0.12	-0.09	0.00	0.05
4468	0.22	-0.34	-0.18	-0.08	-0.07	0.00	0.03
8597	0.15	-0.31	-0.15	-0.06	-0.05	0.00	0.05
α LYR	0.45	-0.28	-0.15	-0.06	-0.05	0.00	0.04

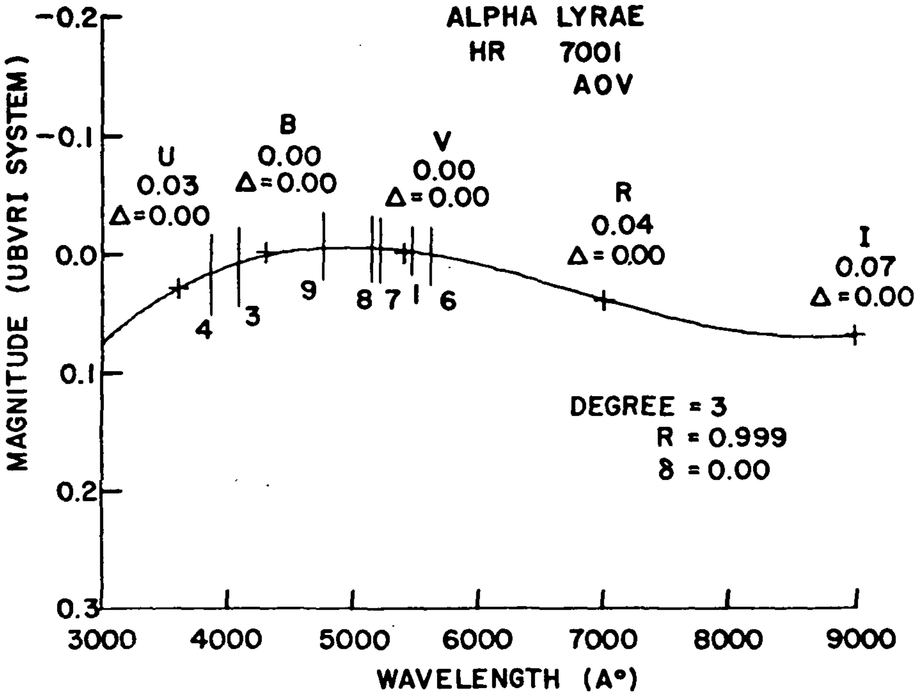

Figure 1 - Example of the determination of the star magnitude for each filter from the UBVRI system.

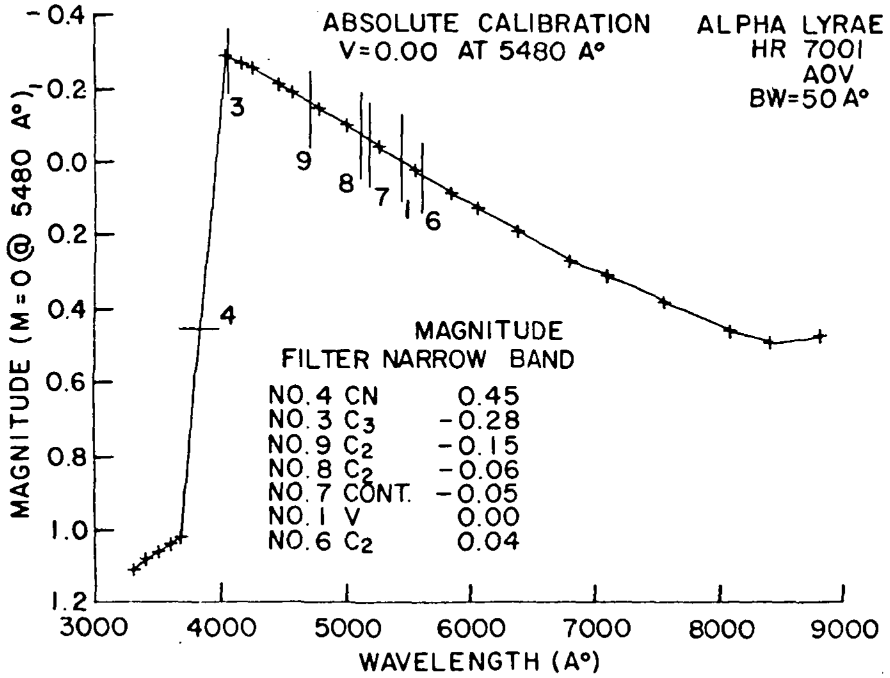

Figure 2 - Example of the determination of the narrow band magnitude scale for each filter from narrow band spectrophotometric scanner data.

V. ERRORS

The least-squares technique by which the magnitude scale was derived can be characterized by three free parameters: the zero intercept, the relative scale, and the extinction correction. These errors are listed in Table VI. For the CN molecular line (filter #4), the error is considerably higher than shown due to the filter wavelength falling on the area of the spectrum containing the Balmer jump. Additional data errors arise from converting to a narrow band magnitude system. These systems were converted to absolute flux through the measurements of Oke and Schild (1970) of the star alpha Lyrae (figure 2). The total error of the comet measurements is then the combination of all these individual errors.

TABLE VI

Data Errors (Magnitudes)

	Filter	#4*	#3	#9	#8	#7	#1	#6
Standard Stars		$\pm 0^{m}.06$	0.05	0.05	0.03	0.05	0.02	0.02
α LYR		±0.02	0.02	0.02	0.02	0.02	0.02	0.02
<ext. X>	Max.	±0.15	0.23	0.19	0.11	0.12	0.26	0.12
	Min.	±0.04	0.06	0.09	0.05	0.04	0.05	0.04
Relative Scale		±0.05	0.10	0.21	0.11	0.11	0.16	0.11
Zero Point		±0.22	0.25	0.45	0.21	0.22	0.23	0.23
Total	(Max.)	$\pm 0^{m}.28$	$\pm 0^{m}.36$	$\pm 0^{m}.53$	$\pm 0^{m}.26$	$\pm 0^{m}.28$	$\pm 0^{m}.38$	$\pm 0^{m}.28$

*Error is larger than table due to Balmer jump

VI. RESULTS

Good quality data were obtained on 13 days between November 1973 and February 1974 for all filters and most of the diaphragms. Table VII is a tabulation of these observations normalized to a distance of 1 A.U. by assuming an inverse-square distance dependence. On 1 December (2442018.0 J.D.) a small flare was observed to occur for all molecular lines and for the 5200 A^o continuum (figure 3), although the increase was small for the CN filter (figure 4). This flare was followed on 4 December (2442021.0 J.D.) by a decrease in intensity which exceeded that expected from pre-flare conditions. For the inner regions of the coma ($\leq 48''$ or $\leq 2.3 \times 10^4$ km) the 5200 A^o continuum shows an unexpectedly low intensity on 23 November (figure 5, 2442010.0 J.D.). This effect is noticeable also in figure 3 for the larger diaphragm opening of 100" (4.1×10^4 km). In the outer coma a CN flare (3879 A^o) was observed on 13 January (figure 4, 2442060.5 J.D.). Although fairly large in intensity, some uncertainty must be attached to this observation as it was made in the twilight sky overlooking Washington. On 28 January (2442075.5 J.D.) the visual filter (5454 A^o) apparently responded to an increase in intensity within its large 235 A^o bandwidth (figure 6). The reality of this increase is supported by the small increase in two nearby filters at 5165 A^o and 5200 A^o. At the same time there was also an increase for C_3 at 4057 A^o (figure 3).

TABLE VII

Magnitude (Normalized to 1 AU)

Diaphragm #1 9"

Filter Day (J.D.)	#4	#3	#9	#8	#7	#1	#6
2441990.9	-	-	-	-	-	-	-
2442010.0	9.4	-	11.7	10.4	-	-	10.0
2442016.9	8.6	12.1	11.0	9.6	11.0	11.6	9.7
2442018.0	8.6	-	10.7	9.3	10.4	11.3	9.0
2442021.0	-	-	12.1	9.6	11.4	11.9	10.1
2442060.5	8.0	11.4	10.0	8.4	11.9	10.9	9.3
2442061.5	8.1	11.5	10.6	8.9	11.3	10.8	9.8
2442069.5	9.9	12.2	12.0	10.7	12.7	13.1	10.1
2442075.5	10.0	-	13.0	11.2	-	-	11.5
2442080.6	10.8	-	-	11.8	-	-	-
2442094.6	-	-	-	-	-	-	-
2442096.6	-	-	-	-	-	-	-
2442099.6	-	-	-	-	-	-	-

Diaphragm #2 14"

Filter Day (J.D.)	#4	#3	#9	#8	#7	#1	#6
2441990.9	-	-	-	10.5	-	-	-
2442010.0	8.8	-	11.6	10.4	-	11.7	9.3
2442016.9	7.7	11.4	9.9	8.7	10.0	10.9	9.1
2442018.0	7.5	12.1	9.7	8.3	9.8	9.8	8.6
2442021.0	8.1	-	11.1	8.7	10.7	10.8	9.1
2442060.5	7.4	10.0	9.1	7.6	10.7	9.4	8.8
2442061.5	7.5	10.4	9.6	8.0	10.4	9.9	8.9
2442069.5	9.0	12.2	11.0	9.9	11.7	12.3	9.9
2442075.5	9.2	12.1	11.7	10.3	12.1	12.2	11.1
2442080.6	9.9	-	12.6	11.3	-	-	11.6
2442094.6	11.1	-	-	-	-	-	-
2442096.6	-	-	-	-	-	-	-
2442099.6	-	-	-	-	-	-	-

TABLE VII (cont.)

Diaphragm #3 36"

Filter Day (J.D.)	#4	#3	#9	#8	#7	#1	#6
2441990.9	-	10.6	11.0	9.5	-	11.1	-
2442010.0	6.5	9.6	8.6	8.0	-	8.8	7.7
2442016.9	5.8	8.8	7.7	6.6	8.3	8.3	7.3
2442018.0	5.7	8.1	6.9	5.8	7.9	7.0	6.8
2442021.0	6.1	9.2	8.3	6.4	8.1	8.1	7.0
2442060.5	5.6	8.2	6.9	5.7	8.2	7.1	6.8
2442061.5	5.6	8.2	7.1	5.8	8.2	7.6	7.1
2442069.5	7.1	9.3	8.8	7.4	9.7	9.4	8.5
2442075.5	7.4	9.8	9.4	8.1	10.3	9.7	9.1
2442080.6	8.1	10.7	10.3	9.0	11.0	11.2	9.8
2442094.6	9.2	12.1	11.7	10.4	-	-	-
2442096.6	9.2	-	12.2	10.7	-	-	-
2442099.6	10.5	-	-	11.2	-	-	-

Diaphragm #4 48"

Filter Day (J.D.)	#4	#3	#9	#8	#7	#1	#6
2441990.9	-	-	10.1	9.0	9.6	10.4	8.4
2442010.0	6.0	9.0	7.9	6.6	10.7	8.2	7.3
2442016.9	5.3	8.2	7.1	6.2	7.9	7.8	6.9
2442018.0	5.1	7.6	6.4	5.3	7.1	6.7	6.3
2442021.0	5.6	8.7	7.7	6.0	7.7	7.7	6.7
2442060.5	5.3	8.0	6.4	5.3	7.7	6.7	6.5
2442061.5	5.1	7.8	6.6	5.4	7.7	6.7	6.6
2442069.5	6.5	9.0	8.1	6.9	9.3	8.8	8.0
2442075.5	7.0	9.4	8.8	7.5	9.8	9.2	8.7
2442080.6	7.6	10.3	9.8	8.5	10.7	10.7	9.6
2442094.6	8.6	11.7	10.9	9.7	11.3	-	10.2
2442096.6	8.8	11.7	11.6	10.2	11.6	-	10.6
2442099.6	10.1	-	-	10.7	-	-	-

TABLE VII (cont.)

Diaphgram #5 100"

Filter Day (J.D.)	#4	#3	#9	#8	#7	#1	#6
2441990.9	6.8	9.5	8.8	7.7	9.0	9.6	8.2
2442010.0	4.9	7.9	6.6	5.6	8.2	6.8	6.4
2442016.9	4.3	7.6	6.0	5.0	7.2	6.5	6.0
2442018.0	4.0	7.0	5.7	4.3	6.3	5.6	5.6
2442021.0	4.6	8.1	6.7	5.2	7.0	6.5	6.0
2442060.5	4.2	7.7	5.6	4.6	6.9	6.0	5.7
2442061.5	4.2	7.3	5.6	4.4	6.9	5.8	5.8
2442069.5	5.4	8.5	6.9	5.9	8.3	7.7	7.0
2442075.5	6.0	8.6	7.9	6.4	8.8	7.5	7.7
2442080.6	6.6	9.3	8.5	7.2	9.7	9.4	8.3
2442094.6	7.5	10.5	9.6	8.3	10.4	10.8	9.1
2442096.6	7.6	10.5	10.4	8.8	10.5	11.0	9.2
2442099.6	8.5	-	-	9.2	10.9	11.7	9.8

Diaphgram #6 220"

Filter Day (J.D.)	#4	#3	#9	#8	#7	#1	#6
2441990.9	6.4	-	8.4	7.0	8.4	-	7.8
2442010.0	4.2	7.9	6.2	5.6	7.3	6.3	6.0
2442016.9	3.5	7.4	5.3	4.4	6.7	6.1	5.5
2442018.0	3.4	6.6	4.9	3.8	5.9	5.0	5.6
2442021.0	4.1	7.8	6.0	4.6	6.5	6.0	6.0
2442060.5	2.0	7.4	5.2	4.3	6.4	5.9	5.4
2442061.5	3.8	7.3	5.3	4.2	6.4	5.7	5.4
2442069.5	4.9	8.0	6.3	5.2	7.7	7.5	6.5
2442075.5	5.5	8.3	6.8	5.7	8.2	6.1	7.5
2442080.6	6.0	8.7	7.8	6.4	8.9	8.7	7.6
2442094.6	6.7	9.7	8.6	7.4	9.6	9.9	8.3
2442096.6	6.8	9.7	9.4	7.7	9.6	10.2	8.2
2442099.6	7.3	10.4	-	8.3	10.0	10.7	8.9

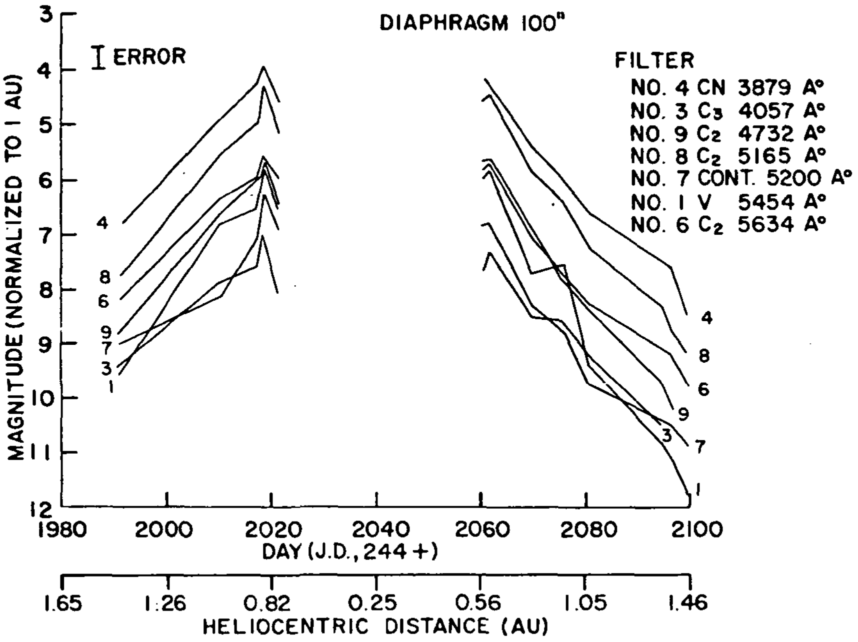

Figure 3 - Variation of comet magnitude (normalized to 1 A.U.) with heliocentric distance for each filter for the 100" diaphragm.

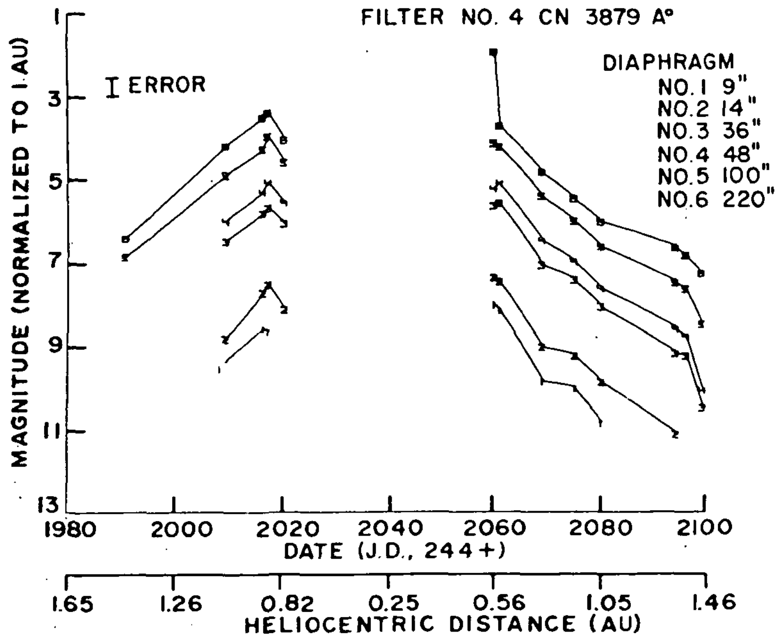

Figure 4 - Variation of comet magnitude (normalized to 1 A.U.) with heliocentric distance for the CN molecular for each diaphragm.

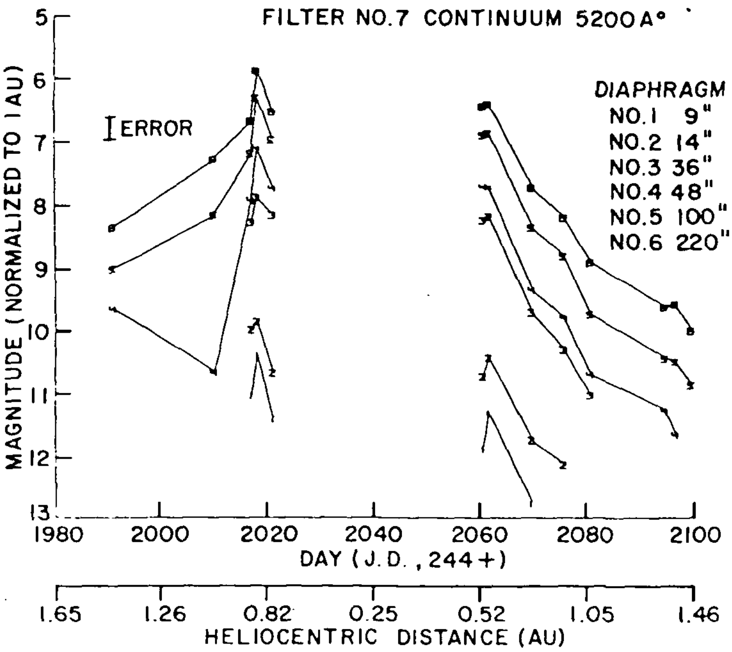

Figure 5 - Variation of comet magnitude (normalized to 1 A.U.) with heliocentric distance for the 5200 A° continuum for each diaphragm.

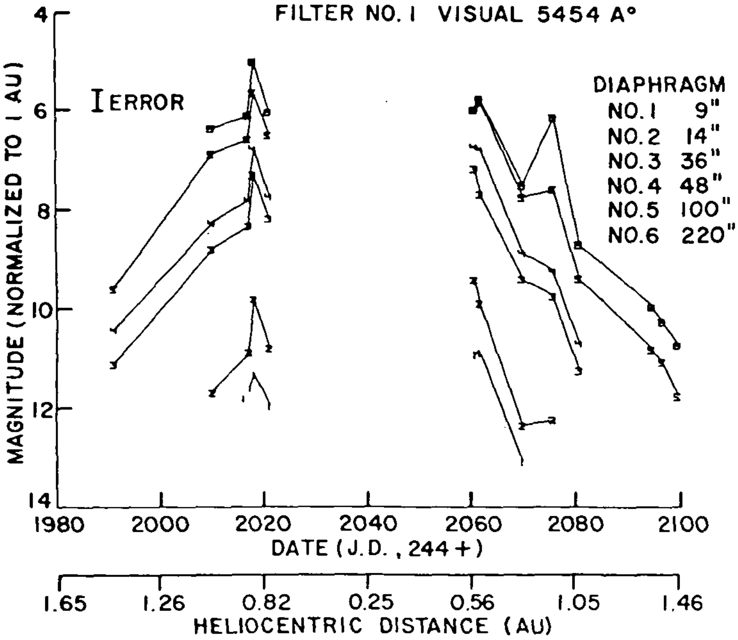

Figure 6 - Variation of comet magnitude (normalized to 1 A.U.) with heliocentric distance for the wide band visual (5454 A°) filter for each diaphragm.

The use of the six diaphragms allows a crude derivation of the radial dependence of the emission observed (assuming circular symmetry). The observed magnitude (m_i) at 1 A.U. inside a diaphragm (i) is related to the intensity, I_i (ergs $\sec^{-1}$ cm^{-2}) by

$$I_i = I_o \, 10^{-0.4 \, (m_i - m_o)} \quad , \tag{1}$$

where I_o is the intensity for a magnitude m_o. If I_o is defined as the intensity which corresponds to a magnitude of zero, then equation (1) becomes

$$I_i = I_o \, 10^{-0.4 \, m_i} \quad . \tag{2}$$

The surface brightness, S_i (ergs $\sec^{-1}$ cm^{-2} sterad^{-1}) can be related then to the intensity. In particular the surface brightness in the annulus between the radius (r_i) of the coma defined by diaphragm (i) and the radius (r_{i+1}) of diaphragm (i+1) is given by

$$S_{i+1,i} = I_o(10^{-m_{i+1}} - 10^{-m_i})/(\text{Area }(i+1) - \text{Area }(i)). \tag{3}$$

Since the magnitude scale is based on the absolute flux of Alpha Lyrae, the value of I_o(for $m = 0$) has been taken as 3.64×10^{-9} $\Delta\lambda$ (ergs $\sec^{-1}$ cm^{-2}) as given by Oke and Schild (1970). The results are summarized in Table VIII. The average radii of the different annuli from the center of the coma are given in Table IX.

TABLE VIII

Surface Brightness (ergs/sec-cm^2-sterad)

Filter #4 CN 3879 A^o

Day (J.D.)	Diaphragm Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	-	-	-	8.6x10^{-4}
2442010.0	1.53	8.4x10^{-2}	4.4x10^{-2}	7.8x10^{-2}	5.7x10^{-2}	3.5x10^{-2}	1.0x10^{-2}
2442016.9	1.38	1.8x10^{-1}	1.6x10^{-1}	1.4x10^{-1}	1.1x10^{-1}	5.8x10^{-2}	2.1x10^{-2}
2442018.0	1.36	1.8x10^{-1}	2.2x10^{-1}	1.5x10^{-1}	1.5x10^{-1}	8.1x10^{-2}	1.9x10^{-2}
2442021.0	1.31	-	-	1.1x10^{-1}	8.2x10^{-2}	4.4x10^{-2}	8.6x10^{-3}
2442060.5	0.81	3.0x10^{-1}	1.6x10^{-1}	1.7x10^{-1}	7.1x10^{-2}	6.8x10^{-2}	1.4x10^{-1}
2442061.5	0.81	2.8x10^{-1}	1.4x10^{-1}	1.7x10^{-1}	1.3x10^{-1}	6.0x10^{-2}	9.5x10^{-3}
2442069.5	0.84	5.3x10^{-2}	4.8x10^{-2}	4.2x10^{-2}	4.1x10^{-2}	2.2x10^{-2}	4.1x10^{-3}
2442075.5	0.93	4.8x10^{-2}	3.7x10^{-2}	3.2x10^{-2}	1.9x10^{-2}	1.2x10^{-2}	2.4x10^{-3}
2442080.6	1.02	2.3x10^{-2}	2.1x10^{-2}	1.7x10^{-2}	1.3x10^{-2}	7.0x10^{-2}	1.7x10^{-3}
2442094.6	1.36	-	-	6.1x10^{-3}	6.0x10^{-3}	3.2x10^{-3}	1.1x10^{-3}
2442096.6	1.41	-	-	-	3.6x10^{-3}	3.1x10^{-3}	1.0x10^{-3}
2442099.6	1.50	-	-	-	1.1x10^{-3}	1.6x10^{-3}	8.2x10^{-4}

Filter #3 C_3 4057 A^o

Day (J.D.)	Diaphragm Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	-	-	-	-
2442010.0	1.53	-	-	-	6.1x10^{-3}	3.3x10^{-3}	-
2442016.9	1.38	1.0x10^{-2}	6.6x10^{-3}	1.4x10^{-2}	1.3x10^{-2}	2.9x10^{-3}	2.8x10^{-4}
2442018.0	1.36	-	-	2.9x10^{-2}	1.9x10^{-2}	5.0x10^{-3}	1.1x10^{-3}
2442021.0	1.31	-	-	-	7.0x10^{-3}	1.8x10^{-3}	2.8x10^{-4}
2442060.5	0.81	2.0x10^{-2}	3.6x10^{-2}	2.2x10^{-2}	6.1x10^{-3}	1.5x10^{-3}	4.0x10^{-4}
2442061.5	0.81	1.8x10^{-2}	2.2x10^{-2}	2.4x10^{-2}	1.3x10^{-2}	3.3x10^{-3}	-
2442069.5	0.84	9.4x10^{-3}	-	9.3x10^{-3}	3.5x10^{-3}	1.1x10^{-3}	3.5x10^{-4}
2442075.5	0.93	-	-	5.5x10^{-3}	3.1x10^{-3}	1.4x10^{-3}	1.7x10^{-4}
2442080.6	1.02	-	-	-	1.3x10^{-3}	8.6x10^{-4}	2.1x10^{-4}
2442094.6	1.36	-	-	-	3.7x10^{-4}	3.2x10^{-4}	1.0x10^{-4}
2442096.6	1.41	-	-	-	-	3.2x10^{-4}	1.0x10^{-4}
2442099.6	1.50	-	-	-	-	-	-

Filter #9 C_2 4732 A^o

Day (J.D.)	Diaphragm Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	-	1.7x10^{-3}	9.2x10^{-4}	1.2x10^{-4}
2442010.0	1.53	8.6x10^{-3}	5.9x10^{-4}	1.0x10^{-2}	1.1x10^{-2}	7.0x10^{-3}	8.9x10^{-4}
2442016.9	1.38	1.6x10^{-2}	2.0x10^{-2}	2.2x10^{-2}	2.0x10^{-2}	1.1x10^{-2}	3.1x10^{-3}
2442018.0	1.36	2.2x10^{-2}	2.3x10^{-2}	4.9x10^{-2}	3.4x10^{-2}	1.1x10^{-2}	5.0x10^{-3}
2442021.0	1.31	6.0x10^{-3}	6.4x10^{-3}	1.4x10^{-2}	1.2x10^{-2}	5.5x10^{-3}	1.7x10^{-3}
2442060.5	0.81	4.1x10^{-2}	3.8x10^{-2}	4.6x10^{-2}	3.4x10^{-2}	1.3x10^{-2}	2.2x10^{-3}
2442061.5	0.81	2.4x10^{-2}	2.5x10^{-2}	4.0x10^{-2}	2.8x10^{-2}	1.5x10^{-2}	1.6x10^{-3}
2442069.5	0.84	6.6x10^{-3}	7.0x10^{-3}	8.0x10^{-3}	9.1x10^{-3}	5.1x10^{-3}	1.1x10^{-3}
2442075.5	0.93	2.6x10^{-3}	4.2x10^{-3}	4.7x10^{-3}	4.3x10^{-3}	1.7x10^{-3}	1.1x10^{-3}
2442080.6	1.02	-	-	2.0x10^{-3}	1.5x10^{-3}	1.2x10^{-3}	3.1x10^{-4}
2442094.6	1.36	-	-	-	7.6x10^{-4}	4.4x10^{-4}	1.9x10^{-4}
2442096.6	1.41	-	-	-	3.2x10^{-4}	2.0x10^{-4}	9.1x10^{-5}
2442099.6	1.50	-	-	-	-	-	-

Filter #8 C_2 5165 A°

Day (J.D.)	Diaphragm Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	2.7×10^{-3}	2.9×10^{-3}	2.3×10^{-3}	6.1×10^{-4}
2442010.0	1.53	2.7×10^{-2}	-	1.6×10^{-2}	5.1×10^{-2}	1.4×10^{-2}	-
2442016.9	1.38	5.5×10^{-2}	5.0×10^{-2}	5.5×10^{-2}	3.1×10^{-2}	2.7×10^{-2}	6.0×10^{-3}
2442018.0	1.36	7.3×10^{-2}	7.8×10^{-2}	1.2×10^{-1}	8.6×10^{-2}	4.6×10^{-2}	9.0×10^{-3}
2442021.0	1.31	5.5×10^{-2}	5.0×10^{-2}	6.8×10^{-2}	3.8×10^{-2}	1.8×10^{-2}	5.0×10^{-3}
2442060.5	0.81	1.7×10^{-1}	1.3×10^{-1}	1.2×10^{-1}	7.2×10^{-2}	2.8×10^{-2}	3.7×10^{-3}
2442061.5	0.81	1.1×10^{-1}	9.6×10^{-2}	1.2×10^{-1}	6.6×10^{-2}	4.2×10^{-2}	2.8×10^{-3}
2442069.5	0.84	2.0×10^{-2}	1.5×10^{-2}	2.8×10^{-2}	2.0×10^{-2}	1.1×10^{-2}	3.2×10^{-3}
2442075.5	0.93	1.3×10^{-2}	1.2×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	7.1×10^{-3}	2.0×10^{-3}
2442080.6	1.02	7.3×10^{-3}	3.0×10^{-3}	6.2×10^{-3}	4.5×10^{-3}	3.7×10^{-3}	1.2×10^{-3}
2442094.6	1.36	-	-	-	1.9×10^{-3}	1.4×10^{-3}	8.9×10^{-4}
2442096.6	1.41	-	-	-	9.4×10^{-4}	1.4×10^{-3}	3.2×10^{-4}
2442099.6	1.50	-	-	-	6.0×10^{-4}	6.3×10^{-4}	2.2×10^{-4}

Filter #6 C_2 5634 A°

Day (J.D.)	Diaphragm Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	-	-	3.6×10^{-4}	1.9×10^{-4}
2442010.0	1.53	3.8×10^{-2}	2.4×10^{-2}	1.8×10^{-2}	1.1×10^{-2}	6.3×10^{-3}	9.9×10^{-4}
2442016.9	1.38	5.0×10^{-2}	2.6×10^{-2}	2.7×10^{-2}	1.7×10^{-2}	9.0×10^{-3}	1.9×10^{-3}
2442018.0	1.36	9.6×10^{-2}	3.0×10^{-2}	4.3×10^{-2}	3.4×10^{-2}	1.1×10^{-2}	-
2442021.0	1.31	3.5×10^{-2}	3.7×10^{-2}	3.8×10^{-2}	1.6×10^{-2}	7.6×10^{-3}	-
2442060.5	0.81	7.3×10^{-2}	3.0×10^{-2}	4.5×10^{-2}	1.9×10^{-2}	1.1×10^{-2}	1.4×10^{-3}
2442061.5	0.81	4.6×10^{-2}	4.2×10^{-2}	3.3×10^{-2}	2.6×10^{-2}	1.0×10^{-2}	1.7×10^{-3}
2442069.5	0.84	3.5×10^{-2}	5.0×10^{-2}	8.1×10^{-3}	7.2×10^{-3}	3.8×10^{-3}	7.5×10^{-4}
2442075.5	0.93	9.6×10^{-3}	3.0×10^{-3}	5.4×10^{-3}	3.1×10^{-3}	2.0×10^{-3}	1.4×10^{-4}
2442080.6	1.02	-	-	2.7×10^{-3}	7.5×10^{-4}	1.3×10^{-3}	3.5×10^{-4}
2442094.6	1.36	-	-	-	-	5.9×10^{-4}	2.0×10^{-4}
2442096.6	1.41	-	-	-	-	6.1×10^{-4}	2.6×10^{-4}
2442099.6	1.50	-	-	-	-	-	1.3×10^{-4}

Filter #7 Continuum 5200 A°

Day (J.D.)	Diaphragm Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	-	-	4.4×10^{-4}	1.5×10^{-4}
2442010.0	1.53	-	-	-	-	1.9×10^{-3}	5.6×10^{-4}
2442016.9	1.38	1.6×10^{-2}	1.7×10^{-2}	1.1×10^{-2}	6.7×10^{-3}	2.6×10^{-3}	6.3×10^{-4}
2442018.0	1.36	2.7×10^{-2}	1.4×10^{-2}	1.6×10^{-2}	2.4×10^{-2}	6.5×10^{-3}	1.1×10^{-3}
2442021.0	1.31	1.1×10^{-2}	6.9×10^{-3}	1.5×10^{-2}	8.0×10^{-3}	3.1×10^{-3}	7.6×10^{-4}
2442060.5	0.81	6.8×10^{-3}	9.6×10^{-3}	1.4×10^{-2}	9.6×10^{-3}	3.7×10^{-3}	8.4×10^{-4}
2442061.5	0.81	1.2×10^{-2}	1.1×10^{-2}	1.3×10^{-2}	9.6×10^{-3}	3.7×10^{-3}	8.4×10^{-4}
2442069.5	0.84	3.2×10^{-3}	3.5×10^{-3}	3.2×10^{-3}	1.8×10^{-3}	1.2×10^{-3}	2.9×10^{-4}
2442075.5	0.93	-	-	1.8×10^{-3}	1.4×10^{-3}	7.5×10^{-4}	1.8×10^{-4}
2442080.6	1.02	-	-	-	4.0×10^{-4}	3.3×10^{-4}	1.2×10^{-4}
2442094.6	1.36	-	-	-	-	1.6×10^{-4}	6.2×10^{-5}
2442096.6	1.41	-	-	-	-	1.7×10^{-4}	6.7×10^{-5}
2442099.6	1.50	-	-	-	-	1.4×10^{-4}	4.6×10^{-5}

Filter #1 Visual 5454 A°

Day (J.D.)	Diaphragam Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	-	4.8×10^{-3}	1.4×10^{-3}	-
2442010.0	1.53	-	-	3.7×10^{-2}	3.2×10^{-2}	2.6×10^{-2}	4.2×10^{-3}
2442016.9	1.38	4.1×10^{-2}	2.6×10^{-2}	5.8×10^{-2}	4.0×10^{-2}	3.3×10^{-2}	4.2×10^{-3}
2442018.0	1.36	5.4×10^{-2}	1.1×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	6.9×10^{-2}	1.6×10^{-2}
2442021.0	1.31	3.1×10^{-2}	3.9×10^{-2}	7.0×10^{-2}	3.7×10^{-2}	3.2×10^{-2}	5.6×10^{-3}
2442060.5	0.81	7.9×10^{-2}	1.7×10^{-1}	1.7×10^{-1}	9.3×10^{-2}	3.6×10^{-2}	1.5×10^{-3}
2442061.5	0.81	8.6×10^{-2}	7.8×10^{-1}	1.1×10^{-1}	1.7×10^{-1}	5.1×10^{-2}	1.8×10^{-3}
2442069.5	0.84	1.0×10^{-2}	7.9×10^{-3}	2.1×10^{-2}	1.9×10^{-2}	1.0×10^{-2}	6.4×10^{-4}
2442075.5	0.93	-	-	1.6×10^{-2}	1.1×10^{-2}	1.5×10^{-2}	1.0×10^{-2}
2442080.6	1.02	-	-	-	2.8×10^{-3}	2.3×10^{-3}	6.0×10^{-4}
2442094.6	1.36	-	-	-	-	-	2.3×10^{-4}
2442096.6	1.41	-	-	-	-	-	1.6×10^{-4}
2442099.6	1.50	-	-	-	-	-	1.2×10^{-4}

TABLE IX.

Radius (km) at which Table VIII Surface Brightness is Calculated

Day (J.D.)	Diaphragm Δ(AU)	9"	14"	36"	48"	100"	220"
2441990.9	2.01	-	-	1.8×10^{4}	3.1×10^{4}	5.4×10^{4}	1.2×10^{5}
2442010.0	1.53	2.5×10^{3}	6.4×10^{3}	1.4×10^{4}	2.3×10^{4}	4.1×10^{4}	8.9×10^{4}
2442016.9	1.38	2.3×10^{3}	5.8×10^{3}	1.3×10^{4}	2.1×10^{4}	3.7×10^{4}	8.0×10^{4}
2442018.0	1.36	2.2×10^{3}	5.7×10^{3}	1.2×10^{4}	2.1×10^{4}	3.7×10^{4}	7.9×10^{4}
2442021.0	1.31	2.1×10^{3}	5.5×10^{3}	1.2×10^{4}	2.0×10^{4}	3.5×10^{4}	7.6×10^{4}
2442060.5	0.81	1.3×10^{3}	3.4×10^{3}	7.3×10^{3}	1.2×10^{4}	2.2×10^{4}	4.7×10^{4}
2442061.5	0.81	1.3×10^{3}	3.4×10^{3}	7.3×10^{3}	1.2×10^{4}	2.2×10^{4}	4.7×10^{4}
2442069.5	0.84	1.4×10^{3}	3.5×10^{3}	7.6×10^{3}	1.3×10^{4}	2.3×10^{4}	4.9×10^{4}
2442075.5	0.93	1.5×10^{3}	3.9×10^{3}	8.4×10^{3}	1.4×10^{4}	2.5×10^{4}	5.4×10^{4}
2442080.6	1.02	1.7×10^{3}	4.3×10^{3}	9.3×10^{3}	1.6×10^{4}	2.7×10^{4}	5.9×10^{4}
2442094.6	1.36	-	-	-	2.1×10^{4}	3.7×10^{4}	7.9×10^{4}
2442096.6	1.41	-	-	-	2.2×10^{4}	3.8×10^{4}	8.2×10^{4}
2442099.6	1.50	-	-	-	2.3×10^{4}	4.0×10^{4}	8.7×10^{4}

In summary, photometric observations of the coma of comet Kohoutek (1973f) were made at the Cassegrain focus of a 36-inch telescope. The observations consisted of one wide (visual, 5454 A^{o}) and six narrow (CN,3879 A^{o}; C_3, 4057 A^{o}; C_2, 4732 A^{o}, 5165 A^{o}, 5634 A^{o}; continuum, 5200 A^{o}) band interference filters. In addition each filter was used with six diaphragms (9,14,36,48,100,220"). Good quality data were obtained on 13 days between November 1973 and February 1974. A small flare was observed on 1 December for all filters, a CN flare on 13 January, and a visual flare on 28 January. The data have been reduced to absolute narrow band magnitudes of the comet for the 13 days. The radial dependence of the surface brightness has been derived from the set of diaphragms and future work will be directed toward using these results for modeling density distributions for the coma.

The author would like to thank C. McCracken, P. Taylor, T. Parker and C. Lowe for their valued assistance.

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PHOTOELECTRIC POLARIMETRY OF THE TAIL OF COMET IKEY-SEKI (1965 VIII)

J. L. Weinberg and D. E. Beeson

Introduction

With few exceptions, measurements of cometary brightness and polarization have been restricted to regions in or near the coma and therefore to a relatively small range of phase angles. Photoelectric techniques are required for detailed wavelength coverage, whereas large-field photographic techniques are better suited for mapping the large regions of sky spanned by a comet tail. Observations with a small field of view provide high spatial resolution but generally restrict multicolor measurements of brightness and polarization to a small region of the comet. Observations with a large field of view (diameter larger than 1 or 2 deg) provide adequate color and spatial coverage but can result in the loss of detail. A compromise is afforded by Fabry photometry, using a modest telescope of small aperture and relatively large field of view. This method (Fabry 1910, 1943) has been used successfully in photoelectric studies of the light of the night sky (Roach and Pettit 1951; St. Amand 1955; Weinberg 1964a; and others) but does not appear to have been used in the study of comets. In this paper we describe post-perihelion measurements of Comet 1965 VIII made on four nights in October-November 1965 using a Fabry photometer atop 3052m Mt. Haleakala, Hawaii, and present detailed results of observations at 5300A on October 29, 1965.

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Instrumentation and Observing Procedures

From October 1961 to May 1962 a one-color photoelectric polarimeter was used at Mt. Haleakala to measure the brightness and polarization at 5300Å of the light of the night sky (zodiacal light, starlight, airglow; Weinberg 1964a). Observations were continued until October 1964 when the instrument was modified for use in a new night-sky observatory established to provide data on the light of the night sky at line and continuum wavelengths from the visible to the near infrared. Mechanical and electronic changes were made to the polarimeter, including provision for observing at one or more wavelengths. A versatile alt-azimuth mounting and programmable control system made it possible to use automatic, manual, or mixed observing routines, with provision for varying color, scanning rate, directions and position on the sky, and shutter open/closed times. This instrument and facility was used to map brightness and polarization in the tail of Comet 1965 VIII on four nights between October 29 and November 4, 1965.

The photometer utilized a coupled rotating polaroid-half wave synchronous detector to measure the surface brightness (radiance) of the total and polarized components and the plane of polarization*. The field of view was defined by a variable-aperture diaphragm in the focal plane of a 14cm achromatic doublet. A 2.9 deg diameter field was used for observations of the comet and of the light of the night

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*Also referred to as orientation of the plane of polarization or direction of polarization or azimuth of vibration (Clarke 1974).

sky during the same period. A field lens was used to focus an image of the objective on the S-11 cathode of a DuMont 6291 photomultiplier selected for high signal-to-noise ratio. Wavelength discrimination was provided by sequential observation with narrow-band interference filters (Table 1) which were placed in the partially-collimated beam defined by the equal curvature negative and positive lenses of a Ross zero corrector (St. Amand 1955).

The measured quantities were the total brightness (B_{tot}), the polarized brightness (B_{pol}), and the plane of polarization (χ). B_{pol} was obtained by calibration with a pile-of-plates polarizer (Weinberg 1964b) and a diffuse, unpolarized standard source. This polarizer also permitted a calibration of χ and made it possible to evaluate instrumental polarization. B_{tot} and B_{pol} are equivalent to the Stokes parameters I ($= I_1 + I_2$) and Q ($= I_1 - I_2$), where I_1 and I_2 are orthogonal components of brightness having their electric vectors perpendicular and parallel, respectively, to the scattering plane. χ and Q define the Stokes parameter U ($= Q \tan 2\chi$). The degree of polarization, p, is that fraction of the total light that is polarized; i.e., B_{pol}/B_{tot}. By convention, B_{pol} and p are negative when the electric vector is parallel to the scattering plane.

Observations of the tail of Comet 1965 VIII were obtained on October 28 and 29 and November 2 and 4, 1965. At other times on these nights, and on other nights during this period, observations of the light of the night sky and of atmospheric extinction were made with the same instrument. All observations were made by scanning in azimuth over a region of sky that included the comet as seen (broadened) in the instrument system. Two methods were used to map the tail of the comet:

1. By scanning slowly (generally 0.5 deg/sec) back and forth in azimuth at a fixed altitude (elevation). This method was used for multicolor observations; e.g., a clockwise (CW) scan would be made at one color, the return (counterclockwise or CCW) scan would be made at another color, etc. until all filters were used, after which the cycle would repeat. In this way, multicolor observations were obtained both along and across the tail of the comet as the comet moved up through the chosen elevation (10 or 20 deg) in the early morning sky.

2. By step-scanning. This method was used for single color or multicolor observations; e.g., a CW scan would be made at one elevation with one color, the instrument would increase elevation by 1 deg and would scan CCW with the same filter or with another filter, etc. until the entire region of sky containing the comet was observed. This method of scanning provided more information across the tail of the comet and made it possible to map the entire tail more frequently.

TABLE 1

Interference Filter Characteristics

Color, Nominal, Å	Central Wavelength*, Å	Bandwidth at 1/2 peak Transmission*, Å
4355	4346	12.4
4760	4753	10.4
5080	5077	30.0
5300	5302	30.0
5450	5441	19.0
5577	5575.5	10.8
5577	5576.3	5.7
5750	5745	23.6

*At center of filter, 1.7°C.

The Observations

To show the relative positions and brightnesses of the comet and of the main cone of the zodiacal light, we show in Figure 1 the total night sky brightness and plane of polarization obtained on October 30, 1965 by scanning part of the morning easterly sky in azimuth at 2.5 deg/sec. The main cone of zodiacal light has a maximum brightness near the ecliptic at azimuth 95 deg and Comet 1965 VIII can be seen near azimuth 112 deg. In these regions (ecliptic elongation between 32.5 and 33.9 deg) the plane of polarization varied smoothly with the electric vector having the same direction for the zodiacal light and for the comet; i.e., perpendicular to the scattering plane. The ecliptic was inclined only 2 deg with respect to the vertical when these observations were made. The comet was ideally positioned with respect to the main cone of the zodiacal light, and the separation of the comet from the smoothly varying total brightness is readily accomplished.

Measurements at 5300Å on October 29.60 UT illustrate one method for delineating detail on the comet. Measurements were made by scanning at 0.5 deg/sec over a 9 X 20 deg section of the sky containing the comet: in azimuth, from 105 to 114 deg (90 = east), and in elevation, from 0 (horizon)* to 20 deg in steps of 1.0 deg. Figure 2 shows the total brightness of background plus comet for elevations 2 to 20 deg as seen at the base of the atmosphere. This

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*The Observatory has a depressed horizon of 1.8 deg.

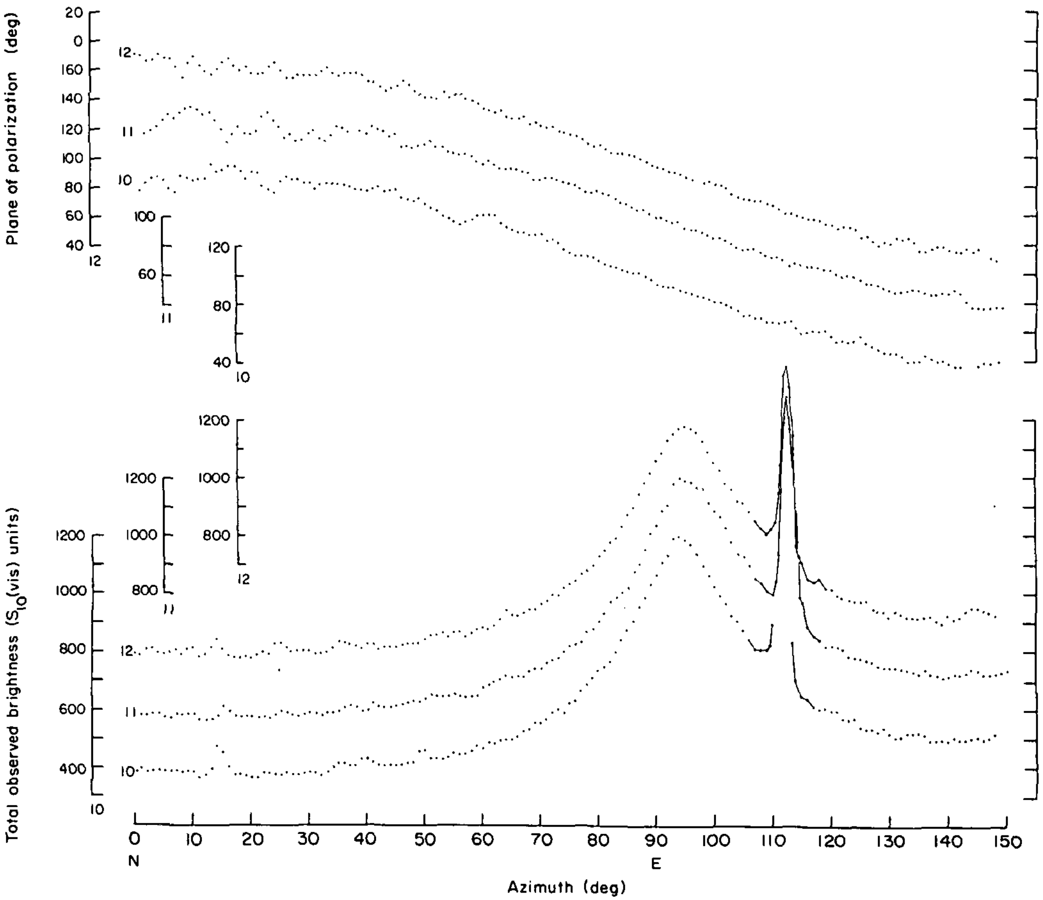

Fig. 1. Observed brightness and plane of polarization χ (azimuth of vibration of the electric vector) for the morning easterly sky, including the zodiacal light and Comet 1965 VIII; elevations 10, 11, and 12 degrees, 30 October 1965, 5300Å. Brightnesses are given in 10th magnitude (visual) stars of solar color per square degree, S_{10}(vis). χ is measured in a counterclockwise direction from the zenith.

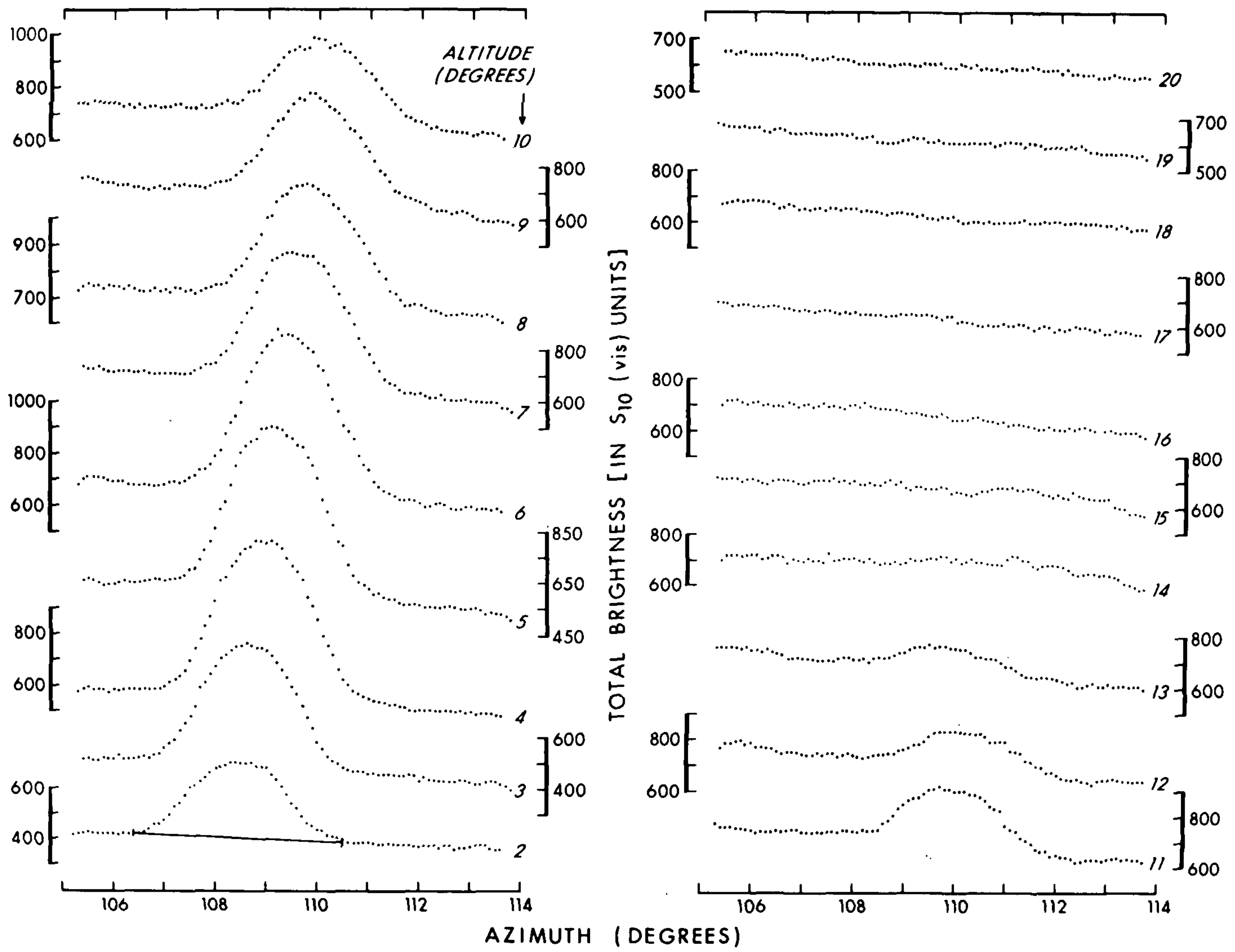

Fig. 2. Total observed brightnesses over a 9 x 18 degree section of the sky containing the comet; 5300Å, 1965 October 29.60 UT.

set of observations began at 1432 and ended at 1441 UT on October 29, with the comet nucleus 5.3 deg below the horizon at the start of the 2 deg elevation scan. A photograph of Comet 1965 VIII taken one day earlier by members of the Haleakala Station of the Smithsonian Astrophysical Observatory was modified by a translation and a rotation to illustrate (Figure 3) the relative positions of the comet and of this set of observations and to compare the photographic appearance of the comet with the way it appeared in the instrument system. The comet aspect is shown for 1435 UT, which corresponds to its position at the end of the 6 deg elevation scan. The comet, horizon (solid line), and scans (even-numbered elevations from 2 through 10) are correct as shown; star positions are not. The width of the comet tail as recorded by the polarimeter is a result of our scanning in azimuth across the tail with a 2.9 deg Fabry field of view. The field is uniform and permits resolution of detail smaller than the field size.

Figure 4 shows the brightness of the polarized component for the same times and in the same region of sky shown in Figure 2. Of particular interest is the change in polarization near 7 deg elevation (approximately 12 deg from the nucleus). Since the background (primarily zodiacal light in this region) and comet radiations are independent, their Stokes parameters are additive. The polarization of zodiacal light throughout this region is "positive"; i.e., the electric vector is perpendicular to the scattering plane. Only negative polarization at distances greater than 12 degrees from the nucleus can produce the observed net decrease in total polarization

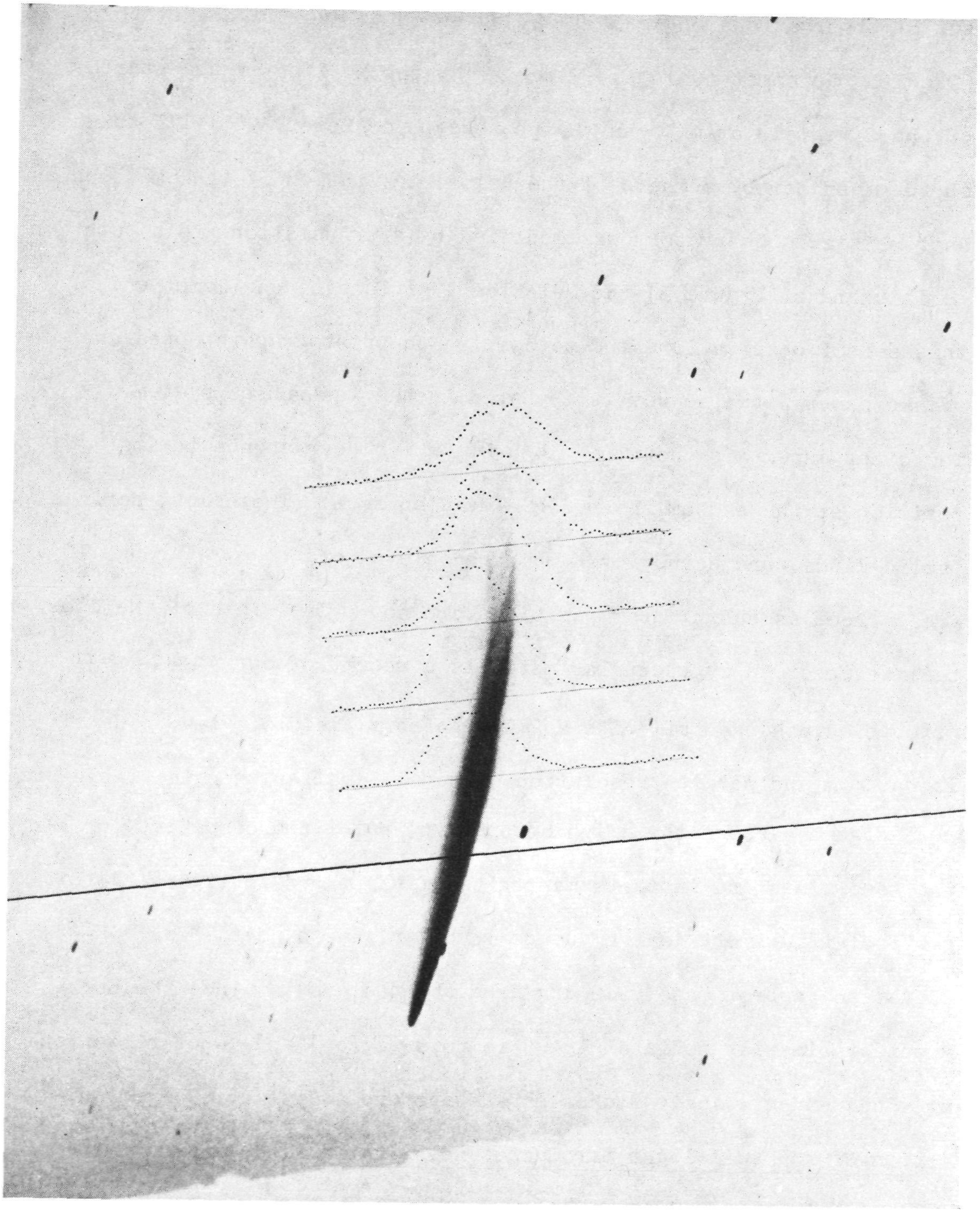

Fig. 3. Comet 1965 VIII aspect at Haleakala together with observed brightnesses for even-numbered elevations from 2 through 10 degrees; 1435 UT on 29 October 1965.

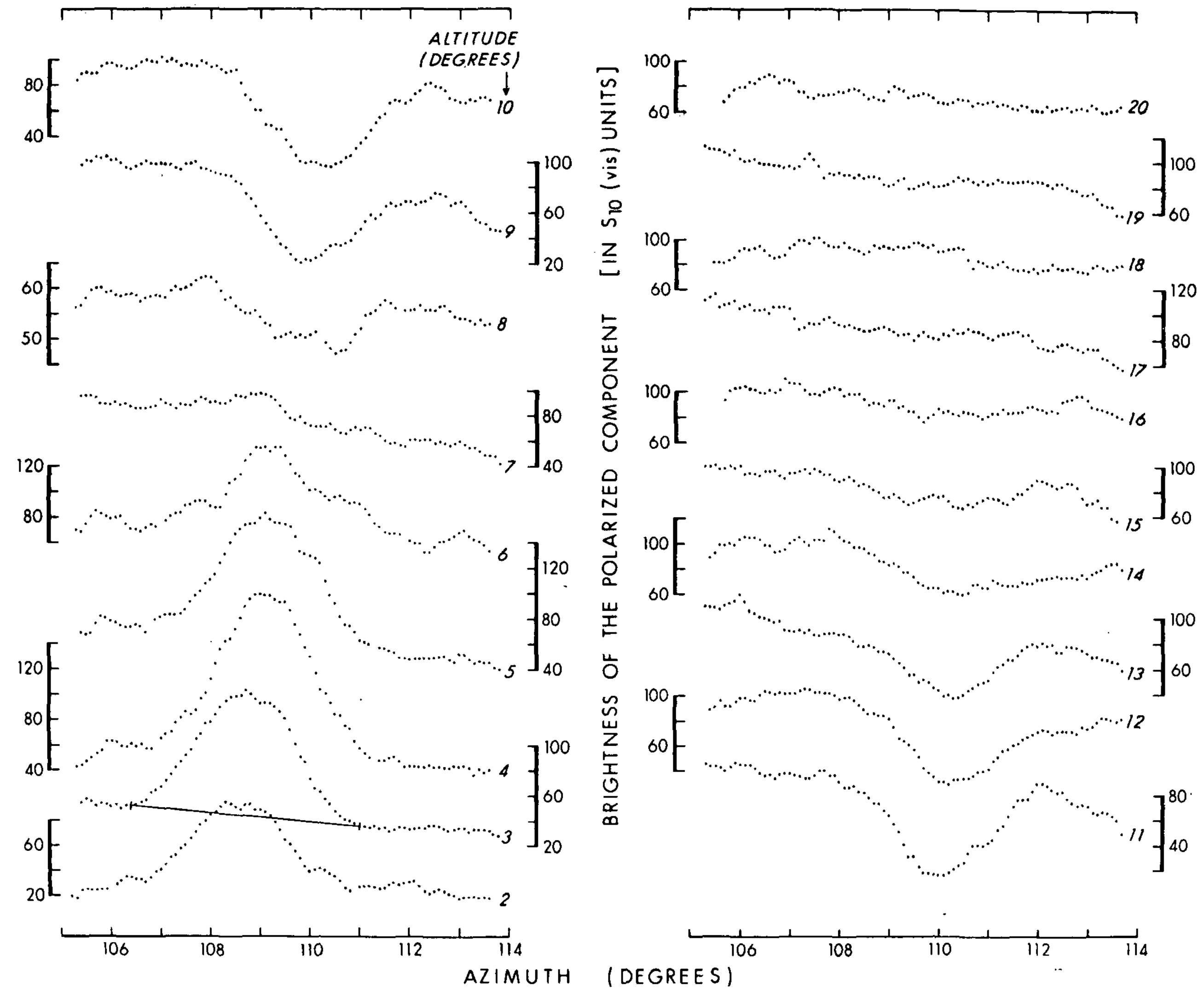

Fig. 4. Polarized brightnesses over a 9 x 18 degree section of the sky containing the comet; 5300Å, 1965 October 29.60 UT.

in the direction of the comet tail. This is further illustrated by measurements of the total plane of polarization, X (Figure 5). At elevations 2 through 6 deg, X is the same for the comet and for the zodiacal light: the electric vector is perpendicular to the scattering plane (see, also, Figure 1). At elevations 7 and 8 deg the comet polarization is very small and X is essentially that of the zodiacal light. The fluctuations in X between 9 and 11 deg are a result of the small total polarized brightness in the direction of the tail axis of the comet. There is no reversal in the total polarized brightness, meaning that the polarized brightness of the zodiacal light exceeds the absolute value of the polarized brightness of the comet throughout the region of its negative polarization. The polarized brightness of the comet is still evident at elevation 15 to 16 deg, whereas its total brightness is difficult to discern beyond 13 deg.

As noted earlier, the separation of the total brightness of the comet from the background is readily accomplished. The irregular variation of the background polarization (Figure 4) makes separation of the polarized brightness of the comet somewhat more difficult. Since the planes of polarization of the comet and of the background were either perpendicular or parallel, it was possible to separate directly the comet polarization (X and B_{pol}) from the total. The separation of the comet's brightness, B_{tot}, from the total does not depend on the planes of polarization. One method used to separate the comet radiation from the background light of the night sky is illustrated by the solid lines shown in Figure 2 (2 deg) and Figure 4

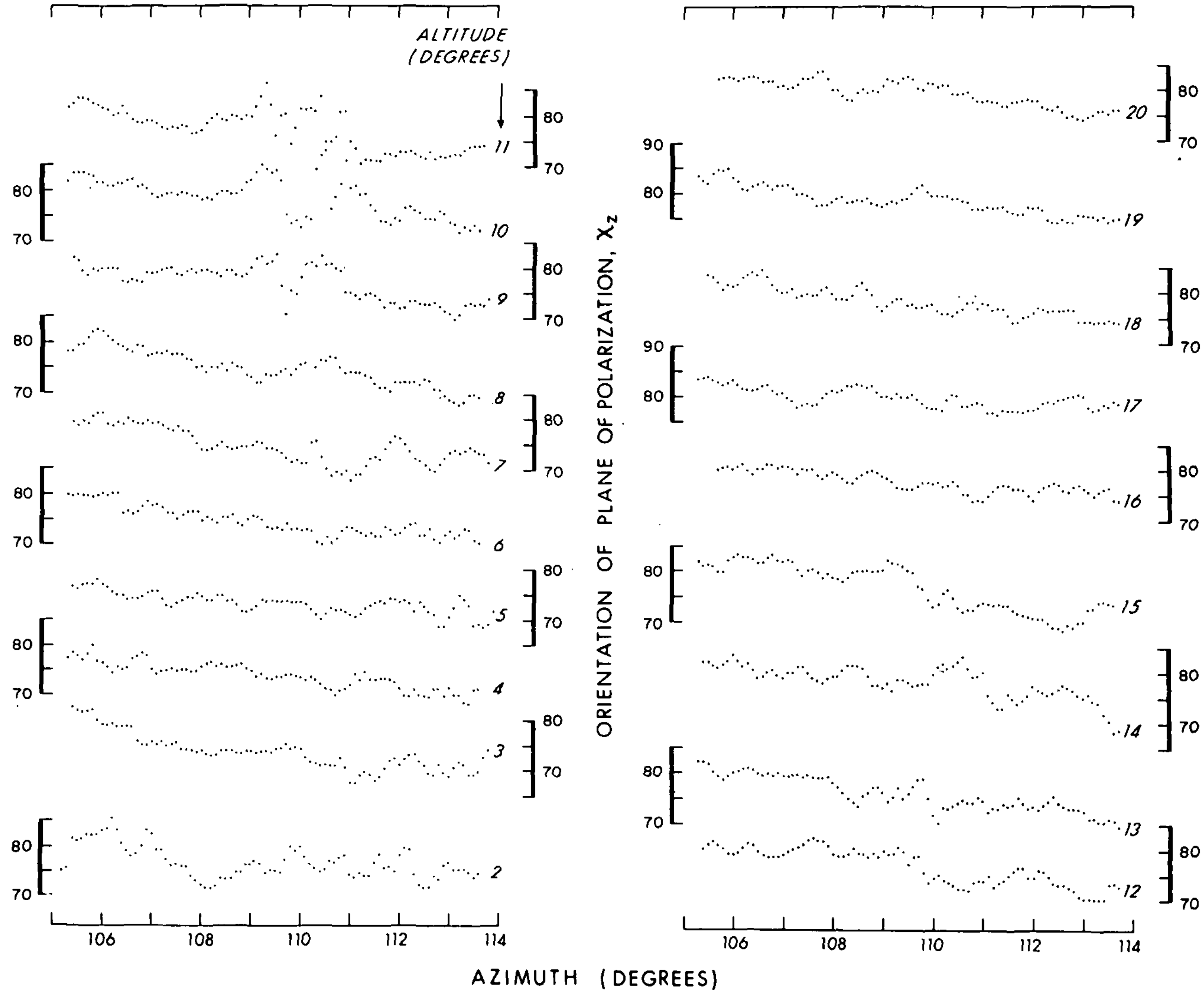

Fig. 5. Plane of polarization, nightglow plus comet; 5300Å, 1965 October 29.60 UT.

(3 deg). A similar method was used with the raw data recorded at the output of the synchronous detector. The two methods gave equivalent results. Although the total and polarized brightnesses of the comet were visible at elevation 1 deg, they were difficult to separate from the background except near the tail axis. At elevation 0 deg the comet was not visible above the background light of the night sky.

Brightnesses measured in the instrument system were converted to absolute units by reference to a C^{14}-activated phosphor source calibrated at the Fritz Peak Observatory Photometry Laboratory (Blacker and Gadsden 1967) with an estimated accuracy of ± 20% (Gadsden 1967). Conversion to the equivalent number of 10th magnitude (visual) stars of solar color per square degree, S_{10}(vis) units*, is based on Johnson's (1954) solar spectral irradiance and on an apparent solar visual magnitude of -26.73. A further comparison of calibration standards combined with the use of bright stars should improve the accuracy of the calibration to ± 8 to 10%.

Temperature effects, linearity, and instrument reproducibility were evaluated and the last was checked frequently. A measure of the precision of the observations is given by the dispersion of the measurements in regions where the observations changed only slowly over the sky: standard deviations in χ from ± 0.9 (B_{pol} between 36 and 45 S_{10}(vis)) to ± 2.0 deg (B_{pol} between 18 and 28 S_{10}(vis)),

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*1 S_{10}(vis) = 1.30×10^{-9} ergs/sec cm^2 ster Å = 4.54×10^{-16} B_{sun}, at 5300Å.

± 1.3 to ± 1.5 S_{10}(vis) for B_{pol}, and ± 1.5 S_{10}(vis) for B_{tot}. In calibrations and fixed position observations the precision is better. For the levels of total and polarized light measured here by scanning, the precision in degree of polarization, p, is typically ± .01. For fixed position observations at these same levels, the precision is typically ± .005.

Corrections for Atmospheric Extinction and Field of View

Two corrections are required to derive the intrinsic brightness, polarization, and extent of the tail of the comet:

1. Corrections for the diluted brightness observed when the comet does not fill the field of view.
2. Corrections for the effects of atmospheric extinction and scattering.

After the comet brightnesses were separated from the background, they were multiplied by the ratio of the area of the effective (equal area) field of view (2.6 deg diameter) to the area of the portion of the tail contained in the field. For instantaneous fields of view centered on the tail axis, this factor was 1.77.

In observations of the light of the night sky it is generally assumed that the effects of atmospheric extinction and of light scattered into and out of the field of view can be accounted for separately. In this study we neglect atmospheric scattering and treat the comet tail as a point source even though it appears as an extended source when scanned in the instrument system. It is assumed that the atmospheric attenuation can be characterized by the product of a coefficient (extinction), τ_λ, that is wavelength dependent and characteristic of the atmosphere as a whole and a path length (air mass), m_h, which is dependent on elevation h. Multiplying the absolute values of total brightness (B_{tot}) and polarized brightness (B_{pol}) by $e^{\tau_\lambda m_h}$ then corrects the values to "outside the atmosphere".

The atmospheric attenuation of bright stars at 5300Å was measured with the polarimeter on 6 nights between October 25 and November 1; The extinction coefficient, τ 5300, derived for the night of October 28/29, 1965 is .157 ± .003 (s.d.) per atmosphere, referred to sea level. Combining the sea level air mass of Bemporad (Bemporad 1907; Schoenberg 1929) with the reduced air mass (0.690) for Mt. Haleakala's height of 3052m above sea level gives extinction factors $e^{\tau m}$ ranging from 18.60 to 1.606 for elevations 1 to 13 deg.

At small elevations it is necessary to take account of the variation of extinction over the field of view. Figure 6 shows instantaneous fields of view centered on the tail axis for elevations 1 and 2 degrees and the large changes in air mass and extinction factor over each field of view. An effective extinction factor was derived by summing the products of $e^{\tau m}$ and area of the comet for 26 0.1 deg segments contained within the 2.6 deg diameter effective field of view. The effective extinction factor was used for elevations ≤ 6 deg. For elevations > 6 deg, the difference between the center and effective extinction factors is less than 1 per cent and the center value was used.

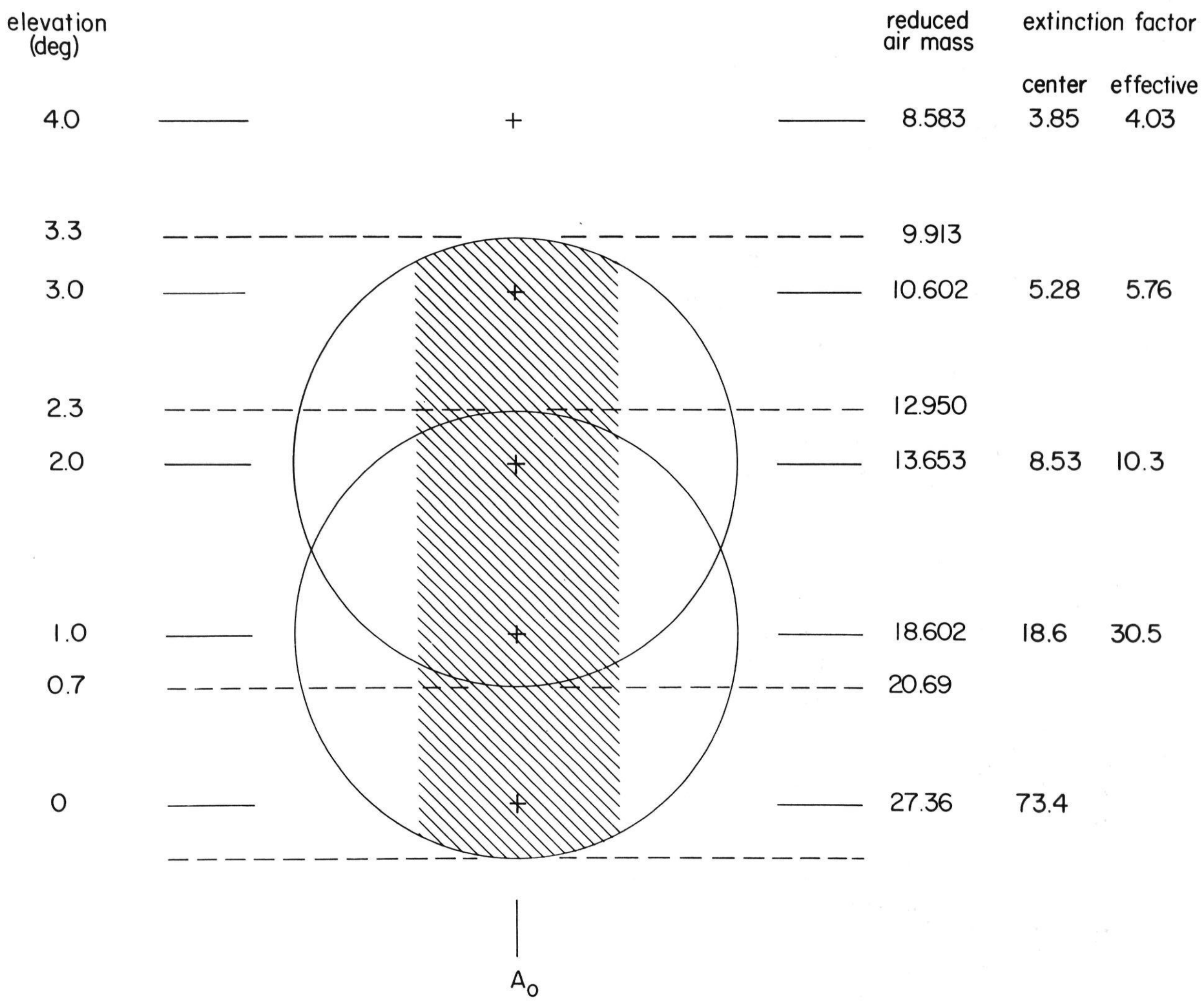

Fig. 6. Instantaneous fields of view centered on the tail axis for observations near the horizon. The cross-hatched area shows that part of the field of view containing the comet.

The data cannot be transformed at this point into brightness versus phase angle except along the tail axis where the integrated results are the same in the instrument system and in the comet system. In a subsequent analysis, fields of view off the tail axis will be used in an attempt to derive the variation of brightness and polarization over the field of view (in azimuth and elevation) and, therefore, the intrinsic brightness and polarization of the comet with phase angle throughout the tail.

Integrated Brightness and Polarization of Comet 1965 VIII

A comparison of Figures 2 and 4 shows that the rapid decrease in total brightness with elevation (distance from the nucleus) is not reflected in the rate of decrease of the polarized brightness, and the comet is visible in polarized light several degrees further than in total light. This effect is easily seen even in strip chart recordings of nightglow plus comet.

At each elevation the azimuth corresponding to the tail axis was determined from the shape of the total brightness distribution near the maximum. Phase angles were determined for epoch of date using ephemeris elements given by Cunningham (1965) and Roemer (1966). Figure 7 and Table 2 give the integrated brightness and polarization along the tail axis. The error bars in Figure 7 show the maximum effect on p_{comet} of uncertainties in separating the comet brightnesses (B_{pol}, B_{tot}) from the background; the points correspond to the most probable values for the background. The ± .01 precision in

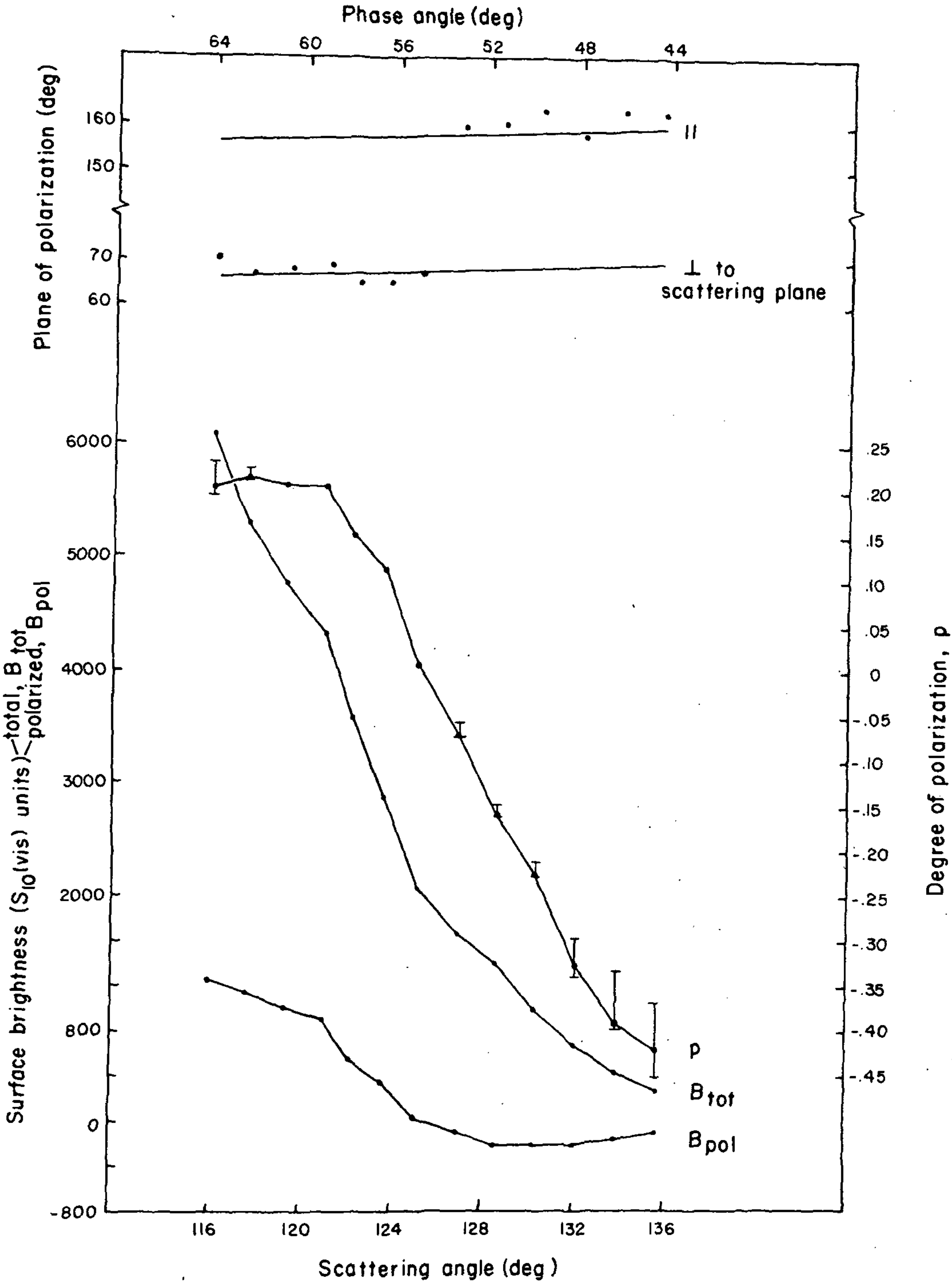

Fig. 7. Integrated brightness and polarization along the tail axis of Comet 1965 VIII; 5300Å, 1965 October 29.60 UT.

TABLE 2

Comet 1965 VIII, 1965 October 29.60 UT; Tail Axis Data, 5300Å

Elevation (deg)	Phase Angle (deg)	Total Brightness (S_{10}(vis))	Polarized Brightness (S_{10}(vis))	Degree of Polarization
1	64.0	6099	1249	.205
2	62.4	5302	1142	.215
3	60.7	4762	991	.208
4	59.0	4318	886	.205
5	57.8	3566	542	.151
6	56.4	2876	324	.113
7	54.9	2058	14	.007
8	53.1	1658	-116	-.070
9	51.4	1384	-221	-.159
10	49.7	972	-217	-.224
11	47.9	677	-221	-.328
12	46.1	415	-163	-.392
13	44.3	267	-113	-.422

p noted earlier adds .004 to .007 to the errors at elevations 2 through 10 deg and .001 to the errors at other elevations.

The electric vector was found to be perpendicular to the scattering plane for phase angles between 64.0 and 54.9 deg and parallel to the scattering plane for all smaller phase angles. This result contrasts with the photographic observations of Matyagin, et al. (1968) who found the electric vector everywhere perpendicular to the scattering plane.

The different rates of decrease of B_{pol} and of B_{tot} result in a degree of polarization beyond elevation 2 deg which changes monotonically with distance from the nucleus (with decreasing phase angle).

At each elevation the degree of polarization shows considerable structure, especially off the tail axis and in regions beyond the neutral point. After completing studies relating the comet and instrument systems in off-axis regions, we will examine the appearance of these features at other wavelengths and at 5300Å at other times and their possible correspondence with the wave-like structures seen in photographs of Comet 1965 VIII.

The different rates of change in the total and polarized brightnesses on either side of elevation 4 deg (phase angle 59.0 deg) are consistent with the distribution of brightness seen in photographs of Comet 1965 VIII.

Other results:

1. In an analysis of all data on the neutral point we found: the neutral point phase angle decreased with time* for each wavelength, the rate of decrease was less at the longer wavelengths, and the phase angle of the neutral point changed from decreasing with wavelength on October 29 to increasing with wavelength by November 2.

2. The comet was not visible in total or in polarized light with the 5.7A filter at 5577Å. A faint enhancement seen with the 10.8A filter at 5577Å can be explained by the increased amount of continuum radiation passed by the broader filter.

3. In a preliminary analysis of morning zodiacal light observations on 8 nights between 5/6 October and 3/4 November, no changes were found that could be attributed to the presence of the newly injected cometary material.

The only other published observations of Comet 1965 VIII far from the nucleus that we are aware of are those of Matyagin, et al. (1968) referred to earlier. The following results were obtained from

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*Sekanina (1975) finds that the neutral point appears to follow the motion of the peculiar wave-like structures in the tail.

their photographic observations of polarization using two instruments on 2 November 1965:

1. The polarization was found to be very high, with values of p far from the nucleus as large as .82 measured with a Meniscus Astrograph and .56 measured with a Schmidt camera.
2. The degree of polarization did not increase monotonically with distance from the nucleus, and it seemed to exhibit "waves" which were observed with both instruments.

Their data suggest that the wave front was normal to the tail axis. Although structure was observed at each elevation in the Haleakala observations, the values of p at each elevation were distinctly separated from the values at any other elevation and they increased monotonically with distance from the nucleus.

3. The electric vector was found to be everywhere perpendicular to the scattering plane "to within the errors".

Multicolor observations at Haleakala on 2 November 1965 covered the same regions of the tail observed by Matyagin and his colleagues. Polarization reversal was observed at all colors, including 4355Å which is close to the approximate effective wavelength of their photographic data.

The authors state that their observations, obtained in the same regions with different instruments and reduced by different methods, "agree well with each other". Yet even a cursory examination of the data tabulated in their paper shows large, systematic differences in the direction and in the degree of polarization obtained in the same regions of the tail with the two instruments and large differences in adjacent observations with the same instrument.

Matyagin, et al. state that the sky background density was determined by graphical interpolation. If they did not also correct for the sky background polarization, one could explain the large variations in p observed by them in the direction of the comet, especially at large distances from the nucleus, and their failure to detect negative polarization associated with the comet.

Discussion

The correspondence between the plane of polarization, χ_{comet}, and the scattering plane (standard deviation ± 2.4 deg) precludes particle alignment (Harwit and Vanýsek 1971; Clarke 1971) as a significant contributor to the polarization in the tail of Comet 1965 VIII.

As noted by a number of authors (Swings 1963; Donn, et al. 1967; Vanýsek 1970; and others), multicolor observations of brightness and polarization over a range of scattering angles are required to determine the nature of dust grains in the heads and tails of comets. A review of published model calculations that the authors were aware of and of unpublished results made available by M. S. Hanner and by B. Donn shows no model having the features of the observed degree of polarization:

1. The rapid change with phase angle.
2. The presence of a neutral point near phase angle 54.8 deg.
3. The large range in p (from +.215 to -.422).
4. The large amount of negative polarization.
5. The turnover at larger phase angles.

Model calculations of the total and polarized brightnesses of comet tails are few in number; they require as added input the numbers of particles and their spatial distribution.

At the scattering angles observed here, Mie scattering may provide information on the properties of the dust grains if they are nearly spherical. Calculations were carried out using a Mie scattering routine developed by Dave (1968) with size distributions of the form

$$n(a) = C\, a^{-k} \qquad (a_{min} \leq a \leq a_{max}),$$

where a_{min} and a_{max} are minimum and maximum radii, respectively. Table 3 lists the input values for refractive index m, size distribution k, and particle radii. No assumption was made as to the numbers of particles or their distribution with distance from the nucleus. The routine was used to calculate the total and polarized brightnesses and the degree of polarization over a range of scattering angles for each of the models using an interval of $.01\mu$ in the integration from a_{min} to a_{max}.

For almost every model listed under input in Table 3, the total brightness stayed relatively constant or increased rather than decreased with scattering angle, presumably as a result of our performing the calculations for equal numbers of particles throughout the tail. Although none of the models produced agreement with the observed features of p, they did provide information on the effects of each of the parameters on the shape, range, and position of the distribution of p with scattering angle. For example, only slightly absorbing particles produced the necessary oscillation in p

TABLE 3

Parameters for Model Calculations, 5300Å

Refractive Index, m	Size Distribution, k	Particle Radius, a Min (μ)	Max (μ)	Range of Scattering Angles, ϑ (deg)
input				
1.25-.2i	2.5	.1	.7,.8	90(01)160
1.25-.2i	3.0	.1	.6(.2)2	
1.25-.2i	3.5	.1	.7,.8	
1.27-1.37i	2(.5)4	.05,.1	.6(.2)2	110(01)140
1.33		.05	.4(.2)2	90(01)160
1.33-.05i	3.0	.1	.6(.2)2	
1.33-.1i		.1	.6(.2)2	
1.33-.2i		.1	.6(.2)2	
1.33-.5i		.1	.6(.2)2	
1.40	2(.5)4	.05	.4(.2)2	
1.45		.05	.4(.2)2	
1.45-.05i		.1	.6(.2)2	
1.45-.2i	3.0	.1	.6(.2)2	
1.50	2(.5)4	.05(.02).11,.15	.4(.2)2	
1.50		.2,.4	.6(.2)2	110(01)140
1.50		.6	1(.4)3	
1.50-.01(.01).05i		.05	.4(.2)2	90(01)160
1.50-.03i		.07,.09,.11,.15	.4(.2)2	
1.50-.05i		.1,.15	.4(.2)2	
1.50-.07i		.05,.1,.15	.6(.2)2	
1.50-.07i	4.0	.4	.6(.2)2	
1.50-.07i		.4	3(1)6	
1.50-.07i	5.0	.4	.6(.2)2	
1.50-.1i	2.5(.5)4	.1,.2	.6(.2)2	110(01)140
1.55	2(.5)4	.05	.4(.2)2	90(01)160
1.55-.05i		.1	.4(.2)2	
1.60		.05	.4(.2)2	
1.65		.05	.4(.2)2	
output				
1.255-.200i	3.00	.100	.802	
c 1.322-.082i	-67.48	.100	.600	
d 1.330-.100i	2.23	.400	.802	
e 1.397-.064i	-7.15	.084	.600	
f 1.493-.059i	-9.82	.089	.551	

(positive to negative to positive, etc. in a relatively small range of scattering angle).

An auxiliary routine was written to try to obtain fits to the observed degree of polarization versus scattering angle. Using the aforementioned calculations to suggest starting values for the real and imaginary parts of m, for k, and for a_{min} and a_{max}, a "merit" factor was computed by summing the squares of the differences between the observed and calculated p's at each scattering angle. The value of the first parameter was then changed by a small amount, the merit factor was recalculated, and the derivative of the parameter was taken with respect to the merit factor. The original value of the parameter was incremented by the product of the derivative and the merit factor, and the process was continued until the merit factor decreased. This process was repeated on each of the parameters until the merit factor approached zero.

Figure 8 contains computer plots of the observed degree of polarization (a), one of the input models (b), and several of the calculated p-distributions using the fit program (note, especially, Figures 8e and 8f). Although these models may be but a few of the possible combinations that would "fit" the observations, they illustrate several apparent properties of the particles:

1. The range of sizes is very narrow or, equivalently, the size distribution is very steep.
2. The particles have a small imaginary part of their refractive index.
3. The dominant size is of the order of the wavelength of the light.

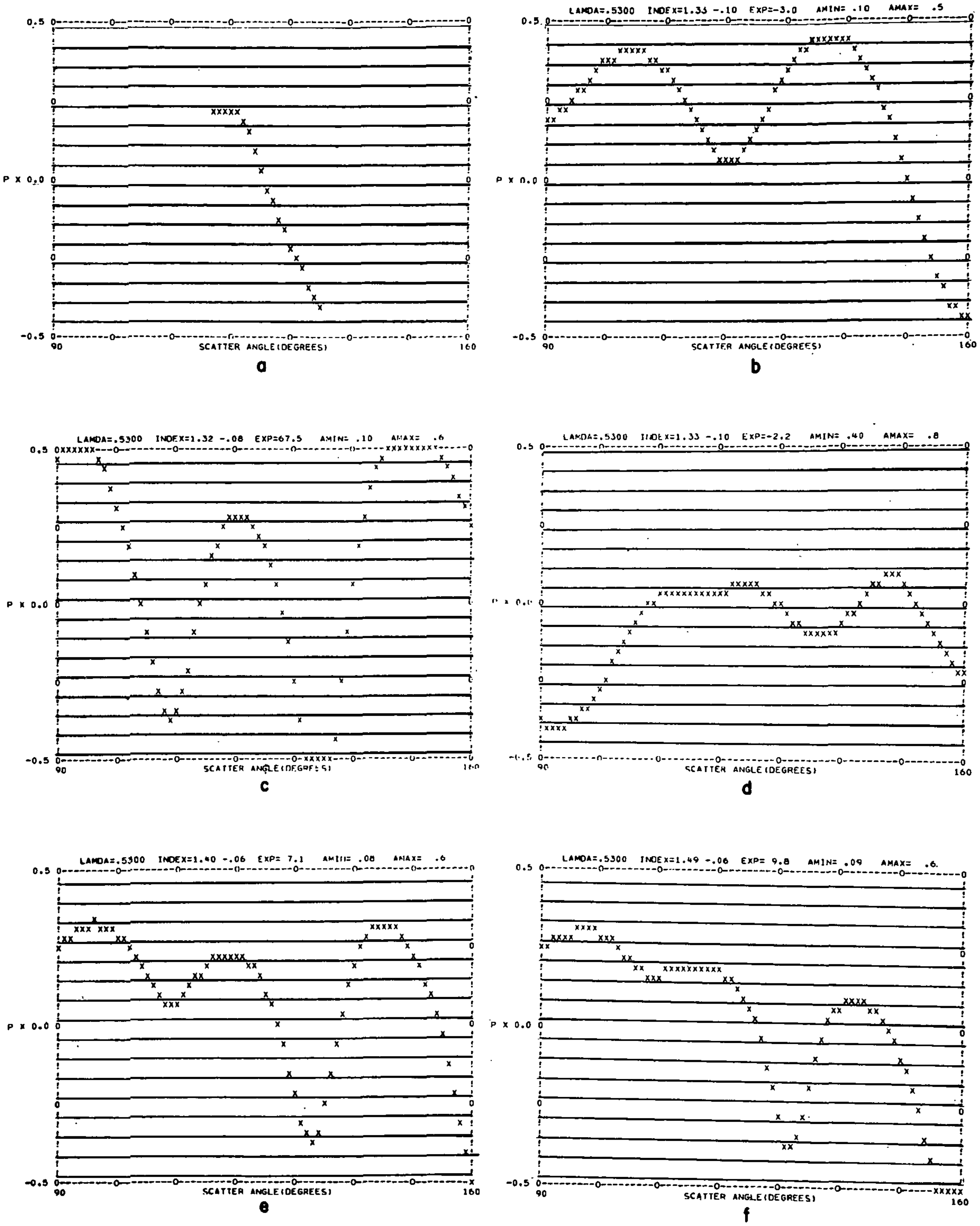

Fig. 8. Computer plots of the observed degree of polarization (a) and of the degree of polarization for selected model calculations (b-f; see, also, Table 3).

A review of our calculations and those of Greenberg (1970), Hanner (unpublished), and Donn and Powell (unpublished) shows further that the decrease that we observe in the phase angle of the neutral point with time would be expected if the particles decreased in size and/or became more absorbing.

This preliminary look suggests that analysis of the remaining data, taken at different times and at different wavelengths, will help to determine the nature of the particles and the short term changes in the averages properties of these particles in the time just after perihelion.

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OMIT

ISOPHOTOMETRY OF COMET TAGO-SATO-KOSAKA

C. K. Kumar and Rita J. Southall

ABSTRACT

Narrow-band filler photographs of comet TSK were taken in the light of C_2, CN and C_3 by Rahe McCracken and Donn, have been analysed in terms of Haser's model of the coma. The isophotes obtained from these photographs were corrected for sky background. The isophotes were circularly symmetric. Radial intensity profiles were obtained along the sunward, antisun and the two perpendicular directions. In each case, these profiles were the same within the experimental errors in intensity (±5%).

Theoretical curves based on Haser's model were computed for different combinations of the parameters β_0 and β_1 where $1/\beta_0$ is the scale length for the decay of the unobserved parent molecule and $1/\beta_1$ the corresponding quantity for the observed daughter molecule. A comparison of the theoretical and observed intensity profiles, yielded our best estimates for β_0 and β_1 for the different molecules. These are listed in Table 1. In some cases, we were able to obtain lower limits only to the ratio β_0/β_1 because the isophotes do not go out far enough, a limitation caused by the sky background. It is to be noted that the same values of the parameters were obtained from observations on different dates indicating no unusual activity in the comet in the intervening period. We believe ours is the first result ever obtained for C_3.

In Table 2, we summarize all the results for C_2 and CN in different comets. It appears that the scale lengths differ between comets, a result which cannot be attributed to different helio-centric distances alone.

Table 1
C_2 and CN Scale Lengths - Comet TSK

Observation Date UT	Molecule Wavelength Å	β_0 X 10^5 KM^{-1}	β_0/β_1	Decay Scale Length in Units of 10^4 KM (Parent)	(Daughter)
2/11.99	CN-3884	5.-6.	2.5-4.	1.67-2.	4.175-8.
2/13.026	CN-3884	5.-6.	2.5-4.	1.67-2.	4.175-8.
2/14.026	CN-3884	5.-6.	2.5-4.	1.67-2.	4.175-8.
2/12.003	C_2 -5172	4.0.	4.-6.	2.5.	10.-15.
2/12.015	C_2 -5172	4.0.	4.-6.	2.5.	10.-15.
2/13.013	C_2 -5172	4.0.	4.-6.	2.5.	10.-15.
2/14.018	C_2 -5172	4.0.	4.-6.	2.5.	10.-15.
2/12.026	C_2 -4738	4.0.	4.-6.	2.5.	10.-15.
2/12.047	C_3 -4063	12.-13.	2.	.76-.83	1.54-1.67

Table 2
Comparison of CN and C_2 Scale Lengths

Reference	Molecule Wavelength Å	Comet Helio-centric Distance A.U.	Observation Date UT	Scale Length in Units of 10^4 KM	
				Parent $1/\beta_0$	Daughter $1/\beta_1$
This Analysis	CN-3884	TSK (1.239-1.275)	2/11.99-2/14.026 1970	1.67-2	4.175-8
Borra & Wehlau (1973)	CN-3878	TSK (1.095)	2/4.0 1970	2.5	20.0
Delsemme & Moreau (1973)	CN	Bennett (1.0)	3/30-5/7 1970	5.01	14.1
This Analysis	C_2 -5172 -4738	TSK (1.239 1.275)	2/12.033-2/14.018 1970	2.5	10-15
Delsemme & Moreau (1973)	C_2	Bennett (1.0)	3/30-5/7 1970	2.0	6.31
Dewey & Miller (1966)	C_2 -5165	Seki (.935)	11/11.4 1961	4.57	8.32
O'Dell & Osterbrock (1962)	C_2 -4737	Seki (.922, .935)	11/10.4 & 11/11.4 1961	1.42	8.51
Dewey & Miller (1966)	C_2	1955e* 1955g* 1959k**		1.167	9.33

*Observations by Schmidt and van Woerden (1957)

**Observations by Miller (1961)

POLARIMETRIC OBSERVATIONS OF COMET KOHOUTEK

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ABSTRACT

Measurements of the linear polarization of the coma of Comet Kohoutek were made in the visual. Included are pre-and post-perihelion observations from three observatories. Polarization was considerably higher in the red than the blue. The emission was more highly polarized than the continuum – a circumstance not previously reported for any comet, to my knowledge. Linear polarization increased in magnitude with decreasing aperture ratio. The electric vector was rigidly perpendicular to the scattering plane for all measurements. No circular polarization was detected at the .06% level for one night's observation.

MOVIE OF COMET KOHOUTEK (1973f) AS OBSERVED NEAR MINIMUM ELONGATION BY THE HAO CORONAGRAPH ABOARD SKYLAB

E. Hildner, J. T. Gosling, R. M. MacQueen, R. H. Munro, A. I. Poland, and C. L. Ross

This paper consisted of a running commentary by Ernest Hildner on the movie as it was shown. The data from the movie has not yet been fully analyzed and will be published elsewhere. Discussion immediately followed the movie. (ed.)

DISCUSSION

Z. Sekanina: I just wonder whether there are any specific plans as to the reduction of the film. The reason that I'm asking is that I am in progress of studying the comet from ground-based data, and I will present some preliminary results from photometric study that I did on Dr. Miller's photographs. I just feel that we have a beautiful opportunity here to tie the observations from Skylab down at the time we couldn't see the comet from the ground, with the ground-based observations at the time when Skylab was working.

E. Hildner: After the first of the year, Dr. Keller is going to work very heavily with us, and I believe that's the subject on which we're going to concentrate. Perhaps you'd like to talk to that?

H. Keller: My comment on this would be that very shortly we should combine ground-based observations with Skylab observations in order to cover a larger heliocentric distance interval, because the anti-tail is clearly to be seen. I think about the 1st of January, — is that right, Ernie? About the 1st of January you can see the anti-tail on the Skylab photographs, and therefore we can go over to ground-based observations, which are beginning just about in the first of January.

I think that has to be done, to combine those.

E. Hildner: One of the interesting things is that the anti-tail is already visible in the Skylab photographs late on the 28th of December, about 10 minutes 'til midnight on the 28th. Within twelve hours of perihelion we have observations of the anti-tail.

M. Dubin: You did indicate that you have polarization data throughout the entire period, and in an earlier paper this morning, described by Jurgen Rahe and Weinberg, they find a polarization change on Ikeya-Seki which is quite substantial. What are your plans on the polarization reductions?

E. Hildner: We had very few plans until I heard that paper this morning, and now I have not formulated any since then. We'll certainly look for the polarization. So far we've concentrated, inasmuch as we've been able to do anything on the straight photometry, unpolarized photometry. I hope to get together with Dr. Weinberg and get a copy of what he said this morning.

We have rather a wide band-pass, and I have the impression that your band-pass is quite narrow, and you saw different polarizations in different colors, different wavelengths, and I'm not sure how that will reflect itself in our observations, which cover about 3400 angstroms.

DISCUSSION (Continued)

B. Donn: That could make a problem in interpreting the data, because the polarization is farily wavelength-sensitive, and in a very broad band —you're going to have a problem. You have enough problems in reducing this data, taking a size distribution of the particles into account. If you have to combine that with a large wavelength range, it certainly limits what can be done, but since this is the only data we have near perihelion, it's certainly worthwhile making an effort to see what can come out of it.

E. Hildner: Well, we certainly will look to see what the polarization does and — what the polarization is as a function of time, and as a function of phase angle and whatever. Where we go from there, I think will wait on what those measurements show us.

M. Dubin: Apparently there's a phase change on the polarization of almost 180 degrees near perihelion, for the same particles possibly, in the coma, so one could study a substantial —

Voice: Not in the coma, no.

M. Dubin: Well, it's close to the coma. It's the coma also, you observe, that has a polarization.

J. L. Weinberg: This is far out in the tail. Polarization reversal occurs at 130 degrees scattering angle, nominally, and about 11 degrees from the nucleus, so it's far out.

N76-21057

COMET DATA COLLECTIONS

H. L. Giclas

The question of the present day usefulness of the great wealth of observational material on comets buried in the archives of the older observatories is an important problem that should be evaluated soon if any action is to be taken before much of it is lost or destroyed. The beginning step has been taken with the publication of the isophotometric atlas and the Atlas of Cometary Forms which is a direct result of Recommendation No. 1 of Commission 15 of the IAU meeting at Prague in 1967. At that time a repository for cometary photographs and spectrograms was also discussed. However, in the light of observational advances and the present capability of quantitative correlation of structural changes with condensations or annomalies of the solar plasma, it is desirable to establish again that this old observational material may be useful.

Since the greatest structural changes occur nearest the sun where observations are most difficult and time limited, observations made at ground based telescopes at different longitudes contiguous in time yield the only link to the continuity of developments. Perhaps the greatest argument for collecting the earlier direct photographs and spectrograms together is the fact that the observations are unique. Though we can plan a more comprehensive observational program in the future correlating radio, OAO observations, and etc., with ground based observations, because of the unpredictable frequency of such objects, we are looking at decades of time in order to accumulate and replace this existing material. With the growing premium on building and record storage space at the older observatories, it is easy to rationalize a clean-up of old, little used, bulky data. Also with the death or retirement of older staff members, knowledge of what observational material may exist and location of the records are more and more difficult to recover. Therefore, in this matter, time is of the essence.

For example, at the Lowell Observatory there are over 2400 direct photographs and spectrograms of 170 different comets that have accumulated since the first six photographs of Comet c 1905. To enumerate a few of the earlier comets in the file of plates:

No. of Plates	Comet	
27	Giacobini	1906
59	Morehouse	1908
57 direct, 91 spectra	Comet a	1910
334	Halley's	1910
17	Mellish	1915 a
12	Wolf b	1917

Most of these plates were taken with either a 5-inch Brashear lens of 35 inches focal length or a 9-inch lens also made by Brashear of 46 inches focal length. Many of the Halley's comet photographs, when the tail was 40 to 50 degrees in length, were made with numerous different portrait lenses from 7-inch focal length to 14-inch.

With the 13-inch astrograph (fl = 66".5), I have taken over 1500 plates of comets since 1936. Of these about one-third are short exposure plates taken for position measurement, about 100 are unsuccessful attempts at recovery or checks which leaves around 1000 that may be useful to study structural detail. To enumerate the more extensive series:

No. of Plates	Comet
34	Peltier 1936 a
63	Finsler
49	Whipple 1942
59	Timmers
70	1947 n
36	Arend-Roland
81	Kohoutek

Bobrovnikoff in his paper on Halley's comet (Lick Pubs. 17, Part 2) got together 438 original plates and 271 reproductions. 227 of these plates were made by H. D. Curtis on the Crossley reflector, 60 by Ferdinand Ellerman with a 6" Brashear and 2 1/4" Tessar on Oahu, and 31 by Adams and Babcock with the 60" Mt. Wilson reflector. Add to this the 334 at Lowell and hundreds from other observatories and see how much more could be done. Other observatories have collections - Dr. Roemer, I am sure, has taken as many or more than anyone. Say that only one-half of the 300 observatories listed in the American Ephemeris would have some material that would be useful, one can begin to appreciate the magnitude of the task of just evaluating what might be available.

At Lowell we have had some experience in making world-wide collections of data in connection with the Planetary Research Center now under the direction of W. A. Baum. It had its inception from a resolution of Commission 16 at the 1961 I.A.U. meeting at Berkeley which stated, "The committee appointed by Comm. 16 on "International Collaboration for Planetary Observations" desires to facilitate international collaboration on planetary studies by the eventual establishment of at least two data centers, one in the U.S.A. and one in Europe; and meanwhile requests observatories having large collections of planetary photographs to make these available for such studies as require a full coverage in longitude" (IAU Proceedings, 1961, 245). With support from NASA over 17,355 image sequences of planets from 27 different sources scattered all over the world and dating back to the turn of the century were collected, copied and indexed. (An image sequence can be anything from four to forty single images of a planet on a photographic plate or film). Added to this older collection of data, and again with NASA support, an International Planetary Patrol was organized and operated by Lowell Observatory from July 1968 to July 1974. This added a total of 87,234 additional image sequences (1,200,000 images) of the planets from eight observing stations strategically distributed around the earth in longitude to the collection. The entire plate collection is indexed and cataloged in the computer so that retrival of data may be made from any one or more of twelve different criteria.

Just a word on the effectiveness of an organized world wide patrol. The Lowell Planetary Patrol Program has produced a photographic collection of unprecedented size, homogeneity, and continuity with time. It exceeds by five times the number of image sequences in the historical file collected from all over the world and spanning the previous 60 years which itself was the largest collection of planetary photographs in the world prior to the Patrol.

Examples of what a systematic world wide network has accomplished for the first time is observations of an entire revolution of Mars at approximately two-hour intervals, the development and regression of the great dust storm in 1971 at the time of the Mariner 9 encounter. Coverage was such that the progress could be followed on a near hourly basis. Also other interesting "ministorms" were covered in 1971 and 1973. Similar programs on the development and velocities of clouds on Jupiter were followed. Also from observations of the dark markings seen on ultraviolet photographs of Venus, a determination of the rotational period of these features was made. Applying these few examples as an analogy one can easily see the possibilities a coordinated program of world wide comet observation might give.

If it is the consensus of this group that the older existing data is useful, then an effort should be made to initiate a comprehensive survey of what material is available. From this an evaluation of the scope of the problem can be made and the next step taken.

DISCUSSION

J. C. Brandt: I would like to second almost every word that you say. When Belton and I were gathering the material for our Comet Tail Orientation Catalogue about ten years ago we encountered about every problem that you have mentioned. Perhaps one that you didn't emphasize is that most observatory directors are very cooperative but they do not know what is in their own collections. And we found many of our things by scanning log books, when Belton and I spent many, many days just reading old observing books until we found a notation that would mention a comet.

And I can add that to the extent that that catalogue has been valuable, we have been able to utilize observations to infer solar wind and comet properties so far back to 1889, and I feel that these old observations are exceptionally valuable, and — again, I can just second the remarks that you have made.

F. L. Whipple: I feel that this suggestion is extremely important, and I felt that we are in a very strange position, talking about comets, and this morning's discussion emphasized that we don't know what a normal comet is.

The fact is, that we have not proceeded to the point in comet studies of having any taxonomic study of comets. We do not have classifications of comets in any real sense. Some of the early work you mentioned there, a few years ago, was extremely valuable, and I think it would be a great contribution to the science if somebody, and about two assistants, would spend about three years going to all the observatories and studying all the spectra thoroughly, not to mention the photography, which is a bigger job.

There's a second point I'd like to make, having the floor at this time. Perhaps somebody knows the answer: whatever happened to the compilation, and I think it was a partial digest, of all of the literature on comets, that was put together by N. T. Bobrovnikov, it must have been about two decades ago? I know he had a couple of thousand pages of it, that I heard about, and I saw a microfilm of part of it, and I wonder whether that was ever put into a coherent form, and whether it is available to anyone for use, and if not, if it could be put together. Maybe NASA could make a contribution by somehow or other getting it done.

A. H. Delsemme: It happens that next week I'm going to spend two days in Columbus to make a digest of these — Bobrovnikov's papers. When I say digest I don't know yet what I'm going to do. I'm going to try to assess them to make a table of contents, to list the comets, et cetera, and to make them, by and large, available to the members of Commission 15, when they need them.

That's what I intend to do. I don't know yet whether I will succeed, really, but I intend at least not to let these precious papers get lost, you know.

DISCUSSION (Continued)

B. Donn: When Giclas proposed to describe the Lowell collection, it occurred to me that this was a good issue to raise, in a more general form, what to do with all of these enormous files, and how it might be done. We ran into the problem with the comet Atlas, with Dr. Rahe going to observatories and trying to track down some of these old plates and finding out, well, sometimes you can find them if you look through the log books; sometimes the log is there but you can't find the plate and nobody knows what's happened to them.

And it also turns out if you begin looking through some of the literature, you find that there exist, really more sequences of comet plates than one realizes. In some of these older records there are series of plates taken on successive nights, which are just the kind of thing that the people who are now getting involved in the plasma studies, the analysis of comet tails, really need to know just how do these comet tails behave and what do they look like and what are the variations?

The idea of the Atlas was to try to get us a representative picture, but you really want to have available the details, and I think what we need to come up with is — and maybe by having this discussion early we could try to come up during the course of this week with some procedures we'll follow up and get some idea how to go about this suggestion of doing something about it.

And I think maybe some of us who are interested can get together informally and see what might be done. One possibility may be to notify the chairman of Commission 15 that they should do something about, or at least support this sort of thing.

W. Jackson: I hope somebody gets some money for it.

(Laughter.)

Looks like it's a whole lot of traveling.

D. D. Meisel: Having worked under Bobrovnikov for several years I have seen those notebooks. There are five of them, and they are complete to 1943.

I was asked by Nicholas if I wanted them, and knowing the job of putting them together, I said diplomatically, "No, you'd better leave them at Ohio State," which he did. So they ought to be intact, and to my knowledge it resembles the Svetsviatskii stuff, only it's about three times as extensive, with all references cited, including the double references that usually are wrongly quoted.

DISCUSSION (Continued)

So I think that — you know — it may take you three or five years to get through it, but good luck.

(Laughter.)

B. Jambor: I'd like to ask how many of these plates, mostly the ones concerning comets and the older ones, are calibrated? To do good photometry on them you would need some kind of calibration, and then if they're not that takes quite a bit of the value out of them.

H. L. Giclas: Right.

I'm just afraid that the ones at Lowell are not calibrated. We calibrated all the planetary observations with tube sensitometers, but in the case of the comets I'm afraid this has not been done, and I agree with you it loses a great deal of the value.

R. G. Roosen: Well, it's strictly a matter of value judgments and personal opinion, having taken a lot of comet plates and scratched my head over them myself, and seeing a lot of other people scratch their heads.

Basically I think there are several points that can be made. First of all, Jack Brandt has already demonstrated how simply measuring the direction of the tail is of extreme value over the years. All that the Catalogue of Comet Tail Orientations, the Belton and Brandt catalogue, does, is measure the position angle of the tail. And he's been able to demonstrate a lot of things about the solar wind.

As has been mentioned before, the morphology of the tails isn't understood at all, and just because we don't understand this morphology very well doesn't mean that we should figure that there's no value in a picture of a lot of kinks and whirls. Tomorrow I'm going to show a particular kink that has me scratching my head, and I'm sure there's a lot more of this information on these plates.

In terms of what it would take to get this information where they would be safe, obviously many of these plates, especially the older ones, are very big, very heavy, very bulky, but Klaus Jockers took about 150 of our 4 x 5 plates from JOCR down to Sac Peak, and in one day, he made positive film copies, 70 millimeter film copies of all of these plates, and he'll show a movie which has virtually all the resolution on the original plate.

So from my way of thinking it's not a severely difficult problem. I would guess that if the National Academy, for instance, were willing to put up money for a fellowship for one or two years, that it wouldn't be too hard to get the photographic equipment together and have a single individual go around to observatories, do all this seeking and searching that's necessary, and in about two years, with the cost of his salary, a little bit of travel and a little bit of film, we really and truly could have a library on positive film copies that would be available.

Now, the thing is, that a positive film copy is also advantageous because you can get — oh, probably 300 or 400 plates on a little piece of film that you can put in a little bitty can, so you wouldn't have to have the large storage building built for your records.

W. Jackson: Curt McCracken mentioned that in addition to the professional photographs there are amateur photographs that I guess should be included in the Comet Catalogue.

Would we like to, at this particular time, suggest criteria or set up a committee to look into this problem more completely? Is that the general consensus at this point, or do we want to just drop it as we do a lot of things — and proceed, if somebody comes up with something later on?

A. H. Delsemme: Well, I think it's a very important matter that came back again and again over the years, and we have never done something really serious about it, and that's too bad.

I would like to propose that we do something. For instance, in the framework of Commission 15 it could be done. But I need, of course, advice, and —

W. Jackson: Would anybody like to volunteer —

(After much discussion a committee was appointed consisting of A. H. Delsemme (chairman IAU Commission 15), H. Giclas, J. Rahe, F. Dossin, M. Wallis, and R. Roosen.

N76-21058

REVIEW OF COMETARY SPECTRA

G. H. Herbig

Those investigators who have been active in cometary studies for a long time must by now have detected in their midst a number of interlopers from outside the solar system. As one of these newcomers from a far-off field of astronomy, who cannot possibly claim any expertise on comets, I feel compelled to account for the presence of stellar and interstellar astronomers in this arena. The reason is that some of us believe that the comets represent a sample of relatively unprocessed material from the early solar system, from which we may be able to learn something not only of the young sun and planets, but also something about the material of the parent interstellar cloud plus any fresher interstellar material that the cometary nuclei have been able to accrete over the past 4.6 billion years. The concept is hardly a new one; it probably began with Laplace, and has received increasing attention in the past decade as more information has accumulated from chemical and physical studies of condensed solar system material on the one hand, and from interstellar molecules and dust on the other. In the back of our minds, of course, there is also the thought: if the passage near the sun of a single small fragment of the condensible volatiles from the early solar nebula can result in a spectacular display such as we see in a bright comet, what is the chance that one can detect some trace of the same phenomenon in progress on a vastly greater scale around very young stars, still surrounded by very much larger quantities of similar material? Again this is not a new idea, but it is one reason for the intense interest that some stellar spectroscopists and early-stellar-evolutionists have developed in your subject.

D6

This should account for the fact that, in reviewing recent work in cometary spectroscopy and in recommending interesting tasks for the future, my point of view is less traditional and more speculative than is customary on occasions of this kind. Fortunately, Dr. Arpigny and others will appear later in this program and provide you with solid information on what can be concluded with certainty from the analysis of cometary spectra.

The recent apparition of Comet Kohoutek 1973f drew a great deal of very desirable scientific attention to this area. Although weather conditions and position in the sky were both unfavorable when the comet was at its brightest, a most impressive amount of spectroscopic material was collected. I want to call special attention to the fine work on the spectrum by Benvenuti and Wurm and by Wehinger and Wyckoff presented to this Colloquium. These contributions demonstrate how much valuable work can be done with telescopes of only moderate size (1.22 m [48-inch] at Asiago, 1.0 m [40-inch] at Wise Observatory) when used with intelligence and energy.

Both Comet Kohoutek and its contemporary, Comet Bradfield 1974b, were favorable for studies of the line spectrum of the coma because of the relatively low dust level as compared to recent very dusty comets such as Mrkos 1957d and Bennett 1969i. Nevertheless, although there are some 800 emission lines measurable on the Lick coudé spectrograms of Kohoutek between 4800 and 8600 Å., I was surprised that there is in this material so little positive information on new constituents of the coma. Most of the additions to the comprehensive list of identifications in Comet Mrkos 1957d published by Greenstein and Arpigny (1962) are weak rotational lines of CN, C_2 and NH_2.

It is worthwhile, I think, to mention briefly several molecules that were not detected in Comet Kohoutek on the Lick plates of 1974 Jan. 9, on account of their possible relevance to theoretical studies of the spectrum.

The Phillips bands of C_2 have as lower level the ground electronic state ($x^1\ \Sigma_g{}^+$) of the molecule, which lies 0.08 ev below the lower state of the Swan bands. The Phillips system has apparently not been identified in comets.* On the 34 Å/mm Lick plates of Comet Kohoutek, there are a number of rather weak emission features between 7740 and 7860 Å which coincide with rotational structure of the 3-0 band as measured by Phillips (1948) and by Ballik and Ramsay (1963). However, some laboratory NH_2 bands also occur in the same region, and are expected to be of detectable strength in the Comet. Until an analysis of this NH_2 structure becomes available, the C_2 identification remains only a possibility. The 2-0 Phillips band with head at 8751 Å falls in a less confused region, but lies off these spectrograms. A search was also made for bands of the red system of CH_2 A few coincidences were found between the list of laboratory features by Herzberg and Johns (1963) and weak unidentified cometary emissions, but there was no persuasive consistency. Certainly the red system of CH_2, if present at all, occurs in only marginal strength. The HCO molecule also is of interest in connection with cometary chemistry; the most favorable band for its detection in the optical region is probably 070 - 000 of the red system near 6780 Å. This band has been measured in the laboratory by Herzberg and Ramsay (1955); their $v_2{}'$ numbering has been changed by one unit by Johns, Priddle and Ramsay (1963). No trace of this structure was

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*I am grateful to Dr. Arpigny for calling to my attention the desirability of observations of the Phillips bands.

seen on the Lick spectrograms. The HNO molecule might also occur in comets; the strongest bands would probably be 000 - 000 and 010 - 000 which fall in the 6800 - 7500 Å region. Although a number of weak unidentified cometary emissions were measured in this range, none coincide with the structure of these HNO bands as observed in the laboratory by Dalby (1958).

The lines in Comet Kohoutek that were subsequently identified with H_2O^+ by Herzberg and Lew (1974a, 1974b) do not occur in Greenstein and Arpigny's line list for Comet Mrkos. The absolute intensity of the H_2O^+ features is greatest near the nucleus of Kohoutek, but there they are superposed upon the strong scattered solar continuum, so that they become relatively more conspicuous farther out in the coma, and especially in the tail. Wehinger and Wyckoff have measured H_2O^+ and CO^+ band intensities in the tails of both Kohoutek and Bradfield over a range of heliocentric distance (r). They find that the H_2O^+ column density in Kohoutek was five times that in Bradfield, under the same conditions. Similarly, Benvenuti notes that while H_2O^+ was strong in the tail of Kohoutek, Comet Bennett 1969i when observed with the same equipment at the same r showed no comparable H_2O^+. There thus seems to be a spread in the H_2O^+ strengths of different comets. This appeared first in the results of Miller (1962, 1964), who was the first to call attention to these unidentified features in the red, and noted that they were especially strong in Comet Ikeya 1963a. Fig. 1 shows a low-dispersion Lick spectrogram of that Comet (this plate was in fact taken at the instigation of Dr. Miller), with the principal H_2O^+ features marked. Thus these cometary lines had been known to astronomers for years, awaiting only the laboratory work by Herzberg and Lew to solve the puzzle. I return later to speculation on why comets might differ in their H_2O contents.

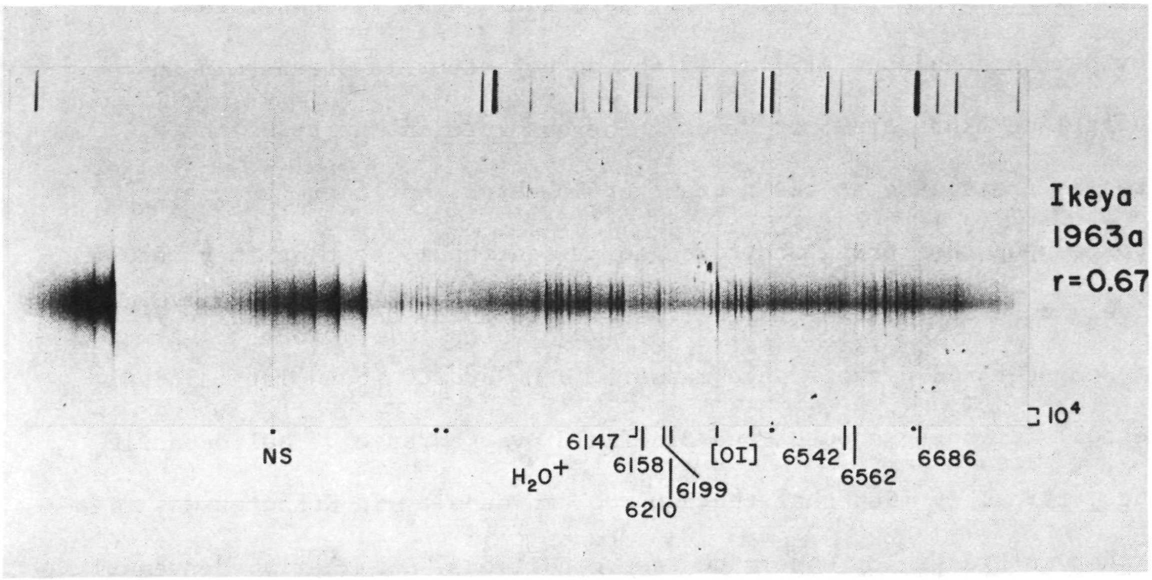

FIG. 1. The spectrum of Comet Ikeya 1963a in the region 5400-6800 Å. The spectrogram was taken by A. E. Whitford with the prime-focus spectrograph of the Lick 120-inch reflector on 1963 March 19. The original dispersion was 93 Å mm^{-1}. This plate has been described by F. D. Miller (1964). A number of features now known to be due to H_2O^+ are marked with their wavelengths. The features marked by dots along the lower edge are due to either natural or artificial airglow; that on the left marked "NS" is [O I] λ5577. The [O I] lines at λλ6300, 6363 (here marked "[O I]") originate in the coma but weak airglow emission extending the full length of the 4' slit is also present. The brackets on the right lower corner indicate the distance on the spectrogram corresponding to 10^4 km at the Comet.

H_2O^+ is therefore to be added to the list of other molecular ions observed in comets, particularly in the tails: CO^+, N_2^+, OH^+, CH^+, CO_2^+. I must mention in this connection the recent high-dispersion work by Fehrenbach and Arpigny (1973) on the structure of bands of OH^+ and CO^+ in Comet Bennett 1969i. The presence of CO_2^+ in comet tails (the strongest bands are at 3509 and 3674 Å) was established about 1948, but a detailed investigation of their structure in comets is still lacking. It seems to me that a reexamination of cometary spectra in the 3100 - 3800 Å region is overdue. For weak features we still lean heavily on the early McDonald work by Swings and his collaborators, 35 years ago. A repetition of this work at adequate dispersion will not be easy because the solar flux, which sets the intensity ceiling on fluorescent lines, is falling off rapidly in the near ultraviolet. Furthermore, the terrestrial airglow spectrum is very strong in this region, but here we do have the advantage that techniques for the subtraction of such a background are now commonplace. If close attention could be given to this region, one would not be surprised to find CN^+ (at 3185, 3063 Å) or N_2O^+ (at 3558 Å) or the near-ultraviolet bands of formaldehyde. The strongest bands of some interesting polyatomics which contain the CN radical also lie in this part of the spectrum: NCN and CNC (near 3300 Å) and HNCN (at 3440 Å). Conceivably, even the spectrum that has been attributed (Meinel 1972) to C_2^+ at 2490 Å might be detectable from outside the atmosphere.

At somewhat less difficult wavelengths, one should look carefully for NH^+ (probably the band at 4348 Å would be strongest) and H_2S^+ (an extensive electronic system like that of NH_2 and H_2O^+ lies in the blue-violet: see Duxburg, et al. 1972) and $C_4H_2^+$ (although its strongest band at 5068 Å will be confused with C_2).

The yellow, red, and near-infrared regions of the cometary spectrum are now being re-explored with respectable resolution, largely as a result of the availability of image intensifiers (with S25 and extended S20 cathodes) which offer large speed advantages over conventional photographic emulsions at the longer wavelengths. As a result, the presence of the red system of CN is now well established in Kohoutek and Bradfield. The 2-0 sequence has been well resolved, and Potter, et al. at this Colloquium report the detection of the 0-0 band near 1.1 μ, and possibly 0-1 as well. The general decrease in oscillator strengths toward the infrared, as well as the fall-off in solar flux, militates against the presence of fluorescence transitions of high intensity in the infrared, unless compensated for by high abundance. Thus one hopes that a search will be made for the electronic bands of HO_2 in the 1.4 to 2.0 μ region (Hunziker and Wendt 1974; Becker, et al. 1974) of the next bright comet. The low oscillator strength of vibration bands hinders their observation in comets, although the 5-2 band of OH at 1.08 μ was detected by Meisel, et al. in Kohoutek. Certainly strenuous efforts should be made to observe the CO fundamental and first overtone (4.7 and 2.3 μ) at the next opportunity.

Appreciation of the great amount of atomic H in comets (from Lα) led to attempts to detect Hα, and indeed a surprisingly strong emission line very near the proper wavelength (6562.82 Å) was present in both Kohoutek and Bradfield. First seen (Donn 1973) in Kohoutek, it is also discussed here in a paper by Lanzerotti, et al. Unfortunately, a fairly strong pair of lines due to H_2O^+ occur at 6562.67 and 6562.80 Å (Wehinger, et al. 1974). In Kohoutek, I had the impression that there must be some contributor other than H_2O^+ at that wavelength, because the 6562 Å line shows a stronger concentration to the nucleus than do the nearby H_2O^+ lines. But the amount of Hα contribution can be assessed only when the H_2O^+ lines are subtracted out properly. If Hα is present, presumably the n = 3 level is excited by solar Lβ which, according to Feldman, et al. (1974 and this Colloquium) may also be responsible for the emission of O I λ1304 which they observed in Kohoutek. This fluorescent cycle in O I initially populates the $3d\,^3D^\circ$ level, which then decays through emission of O I λ11287, followed by λ8446. No observations of λ11287 have been reported, but the 8446 Å region of Kohoutek is well exposed on a Lick spectrogram taken at a time when the 6562 Å feature was strong. There is no hint of emission at 8446 Å. Whether this fact can be reconciled with the intensities of Hα and O I λ1304 awaits detailed calculation.

Today there can be no doubt from modern large-scale, high-dispersion spectrograms that [O I] λλ6300, 6363 are present in cometary comae; they were very strong in Kohoutek. It will be recalled that confusion with airglow lines was a serious problem on older spectrograms. The physical mechanism responsible for the population of the upper levels of these lines leans on the question whether the green line of [O I] at 5577.35 Å also is present or not. Airglow contamination is here more serious, as is the fact that the line falls in the complex structure of the very strong 0-1 sequence of C_2 Swan bands. Its separation from these sources of confusion is a difficult matter, even at high dispersion. In Comet Kohoutek, a sharp line is indeed present at 5577 Å in the center of the coma. There is no confusion with airglow on this spectrogram. The [O I] wavelength falls in a gap in the 0-1 C_2 rotational structure, precisely between two strong blended emissions near 5576.0 and 5578.7 Å. However, a blend of three weak rotational lines of the 1-2 band essentially coincides with [O I], and until some observational or theoretical means is found to subtract their contribution, I see no way to make an estimate of the strength of the green [O I] line. Perhaps the best determination of the population of the ^1S level of O I will be by observation from above the atmosphere of the [O I] line at 2972 Å.

The region of the [N I] pair at 5197.94, 5200.41 Å is well exposed on one Lick 16 Å/mm spectrogram of Comet 1973f. Unfortunately two weak NH_2 lines occur at 5199.41, 5199.78 Å, and are seen on this plate as a faint fuzzy emission which effectively masks the [N I] positions. Nevertheless, one can be certain that if the [N I] lines are present in this Comet, they must be two orders of magnitude weaker than [O I] λ6300.

The possibility of observing the absorption spectrum of a comet has often been discussed. A campaign to observe the occultation of bright stars by Comet Kohoutek was organized through the cooperation of Dr. B. G. Marsden, but the effort was unsuccessful. This was perhaps not surprising when one considers the number of constraints: the star must be bright enough, of sufficiently early spectral type, the event must occur on a clear night at a time when the star is adequately far above the horizon at an observatory where the interested spectroscopist has access to the telescope... It might be useful to point out here what the aim and the expectation of such an experiment would be. It is quite certain that for ordinary molecules, the absorption lines will be exceedingly weak. Thus, Arpigny (1965) found that at a projected distance of 10^4 km from the nucleus, the largest value of the CH column density in the comets he studied was 5×10^{11} cm^{-2}. If all these CH molecules were in the ground rotational state, even then one would expect an equivalent width for the 4300.32 Å absorption line of CH of only 0.3 mÅ, which is undetectable by conventional methods. The best case is CN; Arpigny's largest column density is 2.5×10^{12} cm^{-2}, from which one predicts the line 3874.61 Å to have an equivalent width of about 7 mÅ. Thus one does not expect conspicuous molecular absorption lines in comets, particularly since the interference by the overlapping emission line will be serious; possibly it could be taken out by a 2-channel technique. Despite the difficulty, I think the observation would be worthwhile as a useful check. A more interesting possibility is, however, that one might in this way be able to detect in absorption some polyatomic species which do not occur in emission at all, on account of predissociation in the upper state. In addition, I have pointed out elsewhere (Herbig 1975) the curious fact that although essentially all the atoms and molecules which are found in interstellar absorption are also found in fluorescent emission in comets (the sole exception being Ti II), the diffuse interstellar bands have never been observed in comets. It would be very interesting to determine whether they can be detected in absorption against a star seen through a cometary coma.

I also would like to suggest that serious consideration be given to the direct measurement of doppler shifts due to expansion or streaming motions in comets. Atomic hydrogen expansion velocities of about 8 km s^{-1} have been inferred from the theory of Lα envelopes, but the expectation is for velocities of about 1 km s^{-1} near the nucleus for most species. Such shifts are probably in the realm of direct detection, given high spatial and spectroscopic resolution. Far out in the plasma tail, velocities in excess of 100 km s^{-1} are expected, and seem to be confirmed by the speed of motion of tail structures. Lick spectrograms of Comet Bradfield showed no detectable doppler shifts in the tail a few minutes of arc from the nucleus, but I am told that that was to be expected. The observation deserves to be repeated as far out in the tail as possible.

Let me mention two other matters that should be called to the attention of cometary spectroscopists. First, the matter of how to determine whether a newly-found comet deserves special spectroscopic attention. If another of those extraordinary, CO^+-rich objects like Comet Morehouse 1908 III or Humason 1961e should appear, certainly we should know about it as soon as possible. Such a spectrum is quite unmistakeable even at low dispersion (see Fig. 2), and the diagnosis can be performed with even a moderate-sized telescope. I would like to recommend that encouragement and support be given to anyone who is prepared to embark upon a systematic program of this type.

Second, I am very curious as to the spectra of the so-called 'giant' comets, namely those having $q = 3$ to 5 a.u. Apparently the only such objects for which spectroscopic information is available are Comet Minkowski 1951 I ($q = 2.57$) and Comet Baade 1955 VI ($q = 3.9$). Comet 1951 I had a weak CN $\lambda 3883$ on an intense solar continuum, while 1955 VI showed only a slightly-reddened continuum (Walker 1958). Surely such comets need more attention, particularly in the red. There will be an opportunity for more such observations in 1975 during the apparition of Comet Lovas 1974c, of $q = 3.01$. Unfortunately for northern observers, it will be located in the far southern sky before perihelion passage (on 1975 Aug. 22), but spectroscopic attention from either hemisphere is recommended.

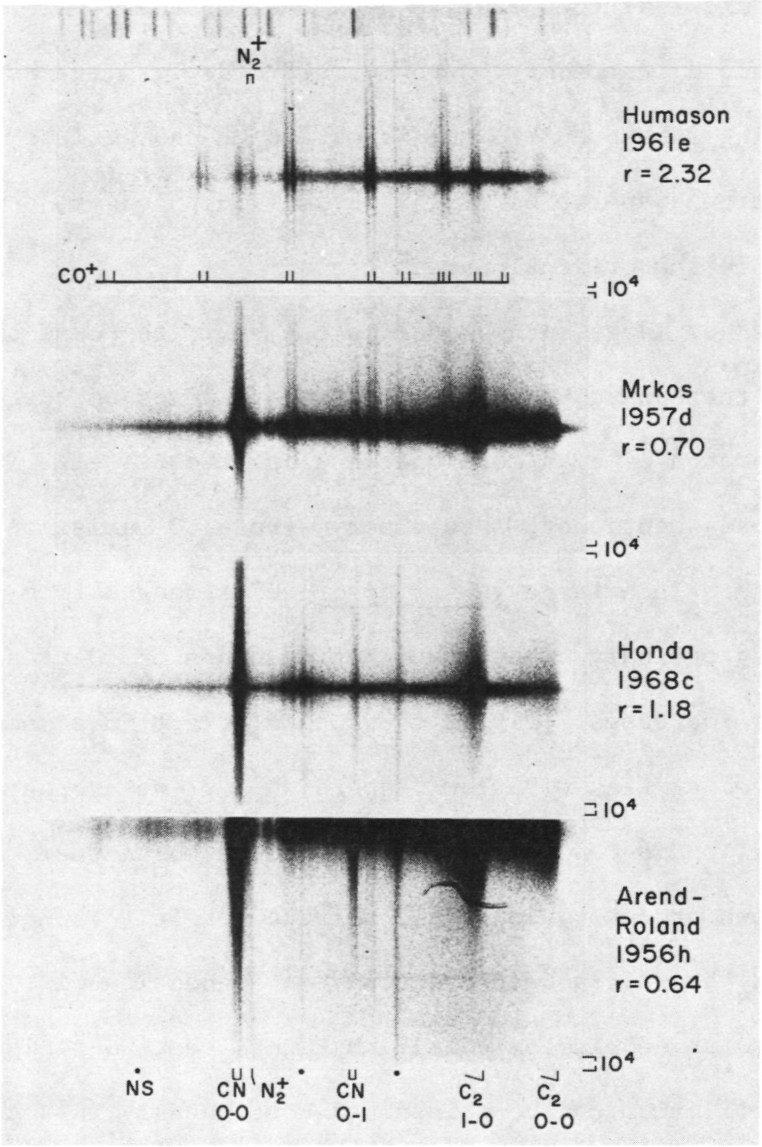

FIG. 2. A series of cometary spectra chosen to illustrate the wide range in intensity of the CO^+ emissions (marked below the spectrum of Comet Humeson, upper panel) in different comets. The features marked with dots at the lower edge of the figure are Hg lines from artificial lighting. The original negatives were taken with the Crossley reflector, at a (prismatic) dispersion of 350 Å mm^{-1} at 3950 Å. The brackets on the right side of each panel show 10^4 km at the distance of the comet.

Finally I would like to speculate upon the explanation for possible intrinsic abundance differences between comets. Here, I set aside chemical processing subsequent to the formation of the nucleus, and the effects of selective evaporation during perihelion passages, and focus on chemical effects in the original parent cloud.

Fig. 3 shows how large such anomalies can be in the case of the C_2, C_3/CN ratio; these have been commented on by Swings and Haser (1956). But the CO^+ phenomenon is even more spectacular. Comets like Morehouse and Humason, already mentioned, showed very strong CO^+ emission even in the coma. But there is a large variation of CO^+ strength from one to another even among ordinary comets, which transcends the decrease in the CO^+/CN ratio as r increases. Fig. 2 shows this effect in a sample of recent comets, as observed at Lick with low dispersion. If we are here witness to a major dispersion in CO content from one comet to another, then there exists a well-known process which could account for it. The equilibrium between CO and CH_4 has often been discussed in connection with the chemistry of the original solar nebula, originally by Urey (see Anders 1972). If thermodynamic equilibrium can be maintained continuously in a cooling gas of solar composition (i.e., hydrogen in great excess), then the progressive diversion of carbon into methane is controlled by the reaction

$$CO + 3\ H_2 \rightleftarrows CH_4 + H_2O\ , \qquad (1)$$

which at a total pressure of 10^{-6} atmosphere causes $CO > CH_4$ if the temperature is above 550°K (Anders 1972). This is the ideal situation, however; laboratory experiments under simulated solar nebula conditions, with the gases in contact with realistic catalysts (the process goes very

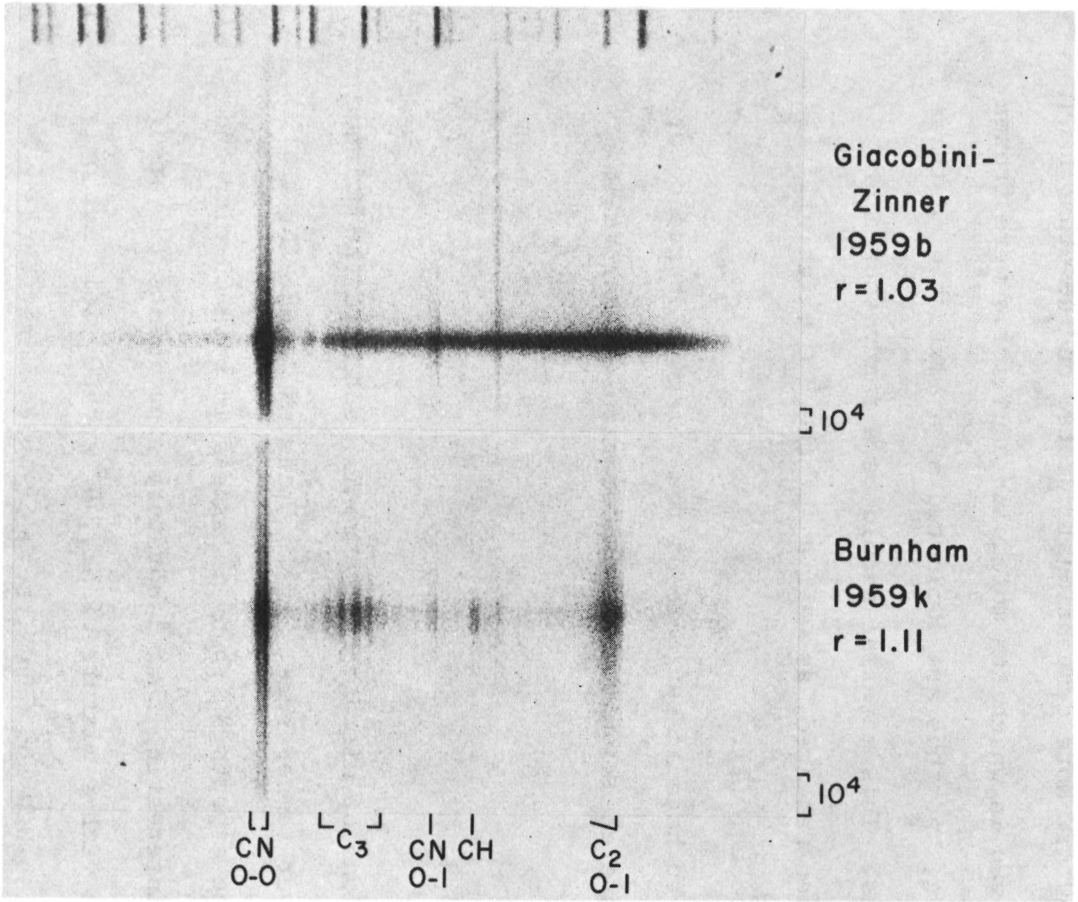

FIG. 3. An illustration of the difference in C_2, C_3 and continuum strengths between two comets having about the same CN intensity and heliocentric distance. The original spectrograms were taken with the same equipment used in Fig. 2.

slowly in the absence of a catalyst), the reaction does not run completely to methane, with its H/C ratio of 4. Rather a mixture of intermediate products with smaller H/C ratios are produced, ranging from C_2H_6 through $C_{20}H_{42}$. It is possible that the nuclei of CO-rich comets represent material that was withdrawn from the parent gas at a time when that gas was hotter than about 550°K. More conventional comets, on the other hand, may have condensed from gas in which the molecular equilibria were frozen-in at a lower temperature, and thus are dominated by a mixture of methane plus complex hydrocarbons. This material should be a ready source of volatile hydrocarbons when reheated, as well as of the H_2O which will also be abundant, according to eq. (1).

It would be useful to have an estimate of the relative abundance of N_2 and NH_3 in comets, as a check on these considerations. That is, a similar relationship

$$2\ NH_3 \rightleftarrows N_2 + 3\ H_2 \qquad (2)$$

controls the concentrations of nitrogen and ammonia, but here the balance point is struck at a lower temperature: at 10^{-6} atm, $N_2 > NH_3$ for $T > 280°K$. Therefore one expects N_2 to be in excess in both CO-rich and CO-poor comets. It is interesting that laboratory experiments (Hayatsu, et al. 1972) which begin with a mixture of NH_3, H_2 and CO yield not only N_2, NO, and $(CN)_2$ but also HCN and CH_3CN, both of which were found in Comet Kohoutek.

On these grounds, one would expect that a CO-rich comet would be correspondingly H_2O-poor. When another comet like Humason or Morehouse presents itself, it will be worthwhile to determine the H_2O^+ and OH strengths, and if possible that of Lα as well. In real life, of course one also expects to find many intermediate cases between these two extremes. In fact, if chondritic meteorites are a proper guide, one would expect that a cometary nucleus may have been assembled from materials having a variety of histories and CO/hydrocarbon contents, so that a pure sample of either extreme would be uncommon.

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DISCUSSION

F. L. Whipple: I would like to ask, in the case of comets as an aggregation of interstellar matter, what sort of reactions do you get there?

G. H. Herbig: You mean in the interstellar medium at this moment?

F. L. Whipple: Yes, like we see in clouds that are starting to form.

G. H. Herbig: The temperatures that we are concerned with here are above room temperature, 300 to 1000 Kelvin.

F. L. Whipple: I am talking about 10 degrees, 60 degrees, around there.

G. H. Herbig: I think that ordinary chemistry would go rather slowly at that.

But someone here is more informed on that subject than I. I am speaking about things that would occur in a primitive solar nebula in the presence of catalysts, and that is excrutiatingly important.

So I really can't answer your question Fred, But I think there are people here who can.

B. Donn: The regions of the interstellar medium where you observe this complex array of molecules, are at temperatures not of 10 degrees or 20 degrees, but in fact a few hundred degrees centigrade, at concentrated regions with IR sources, compact H_2 regions and such.

So we are talking about temperatures almost comparable to Herbig's.

However, an important point about all these chemical reactions is that at pressures like 10^{-6} atmospheres - where for instance you have the interstellar meduum density of up to 10^{13} - you will generally not get a thermodynamic equilibrium composition, because at these low pressures, you will not have a Boltzmann distribution of internal energy states of the molecule. They will radiate too fast for collisions to populate them.

Reactions generally take place from excited levels, not from the ground state. The rates of reaction and the processes are very dependent on having these higher states populated.

So one needs to know, in the case of a reaction you have written there, how these depend upon the excited vibrational states of the molecule, because the tendency in the experimental and theoretical results being developed now show that these results are very dependent on having excited vibrational states.

Therefore, if you don't have them, the whole process is different than what we talk about in the laboratory. We have to be very careful about using laboratory results under these conditions.

It is just a new ball game.

G. H. Herbig: Well certainly a chemist should make those comments.

But all I wanted to say is, somehow, in the early solar system, this kind of chemistry was done on a very large scale, and we can't argue with that. You pick up a carbonaceous chondrite, and that is it.

Now whether that is relevant to the comets is a matter of opinion, of course.

E. Ney: On one of your slides, George, it looked to me as if Comet Bradfield had the continuum very much less pronounced at 0.66AU than in the spectra just before it. And something drastic did happen to Bradfield in the short period there.

Did you happen to think that it was significant that the continuum was very much down in that bottom slide?

G. H. Herbig: One would have to know the exposure times, of course.

No, I haven't looked at the materials from that point.

E. Ney: Will you look at them, maybe?

C. B. Opal: With regard to detection of the 8446Å line of atomic oxygen: the oxygen coma is about 10^6 km across at 1AU, as opposed to 10^5 km for molecular constituents, so it is difficult to see the oxygen line with a high f-number, high dispersion spectrograph. The line should be detectable with a suitable instrument.

M. Dubin: Dr. Herbig, in the general pattern of the chemistry and spectroscopy on the comets and the classifications you just described, would you comment on whether the distribution of comet spectra pattern themselves into the Oort thesis, you know, of inner solar system comet formation, and then storage in the outer solar system, or more in the Cameron picture?

Would you comment in any respect, on that?

G. H. Herbig: I am not competent to discuss that subject.

DISCUSSION (Continued)

W. Jackson: In terms of the oxygen green and red line, if water is present in comets, you have to get Oxygen ^1D from the photodissociation of water, because one of the primary processes in the region below 1500 angstroms, around Lyman alpha gives H_2 plus Oxygen ^1D.

And that is one of the likely sources of Oxygen ^1D in the comet coma.

J. T. Wasson: Your explanation of the variation in CO abundance in terms of the reaction

$$CO + 3\,H_2 \rightleftharpoons CH_4 + H_2O$$

is missing one important effect—the relative volatilities of the different species. In the inner solar system (c. 5 AU) temperatures probably never fell low enough to allow CO or CH_4 to condense as pure substances. They could have condensed as clathrates, but in this case they would have been competing with each other and other substances for the guest position in the clathrate structure. Far from the sun ($\gtrsim$30 AU) CO may have been able to condense in a relatively pure form. Thus the difference in CO^+ abundance could be a measure of distance from the sun at which the comet formed.

A minor second point is that solar system abundance calculations indicate that O is about 1.5 times more abundant than C. Thus even if equilibrium conditions strongly favor the species on the left side of your reaction, about one-third of the nebular O will still be present as H_2O.

I think if the experience with meteorites means anything, (those, as you know are a complex mixture of granules, small domains having quite different histories) obviously the early solar system was a terribly complicated thing with involved time sequence of events.

I am saying that on the microscopic scale a process like CO - H_2O reaction might run, but a real comet or any real solar system body is a conglomerate of material having rather different histories. On the microscopic scale there may be enrichments or deficiencies due to local chemical effects, but the thing one actually observes in a real comet is the composite of the subsequent collection of a lot of these domains through processes of which we don't know very much.

So a comet like Humason may respond to considerations of this sort but perhaps only in a statistical sense. I don't mean that every gram of material in that object ran through this process to completion.

DISCUSSION (Continued)

You recall carbonaceous condrites are a mixture of things having obviously quite different histories. Maybe the same considerations apply in the cometary world.

F. Dossin: About the red line of oxygen, I think that the Doppler shift due to the motion of the comet relative to earth should be sufficient even at conventional Coudé dispersion to distinguish between atmospheric and cometary lines.

G. H. Herbig: Yes. The red lines, at the time these first series of plates were taken, had a cometary red shift of about 40 kilometers per seoond, that unmistakably identified them as cometary.

L. Biermann: I would like to re-emphasize that if the cometary matter formed at large distances from the sun of several tens AU or more (cf. my contribution to the Barcelona Conference 1973, Problems in Origin of Life, August/September 1974)—then the conditions were greatly different from those chosen by Anders and co-workers in these model experiments aimed at simulating the origins of meteorites. It is of course conceivable that more than one kind of cometary nucleus exists depending on the place of their formation and that the carbonaceous chondrites have a composition and place of origin between other meteorites and cometary matter.

A. H. Delsemme: In respect to the possibility of a thermal equilibrium quenched and condensed from the solar primeval nebula, mentioned by Herbig, I wish to mention the remarks I proposed on this matter at the comet Kohoutek workshop a few months ago. In particular, many clues point to a rather low redox ratio. As a matter of fact, H/O should rather be in the vicinity of 3 in the volatile fraction of the cometary stuff, than in the vicinity of the solar abundance, which is three orders of magnitude higher. This is already implied by the simultaneous presence of H_2O^+, with CO^+, $CO_2{}^+$ and $N_2{}^+$. The existence of HCN rather than NH_3, and of CO rather than CH_4, points either to the possible quenching of a rather high-temperature equilibrium, (1000 K) or rather to the absence of H which shifts the equilibria towards dehydrogenated products. Good assessments of the abundances of the major constituents of the cometary snows will bring a better answer to this interesting question.

N76-21059

SPECTROSCOPIC OBSERVATIONS OF COMET KOHOUTEK (1973f)

Lubos Kohoutek and Jurgen Rahe

1. Introduction

Between January 5 and January 15, 1974, nine coudé spectrograms of Comet Kohoutek (1973f) were obtained with the ESO 152-cm telescope in La Silla, Chile. The emulsion is Kodak IIa-O (3 plates) and Kodak 103a-F (6 plates), the dispersion is 20.2 Å/mm. The useful spectral range extends from about 3500 Å to about 5000 Å (Kodak IIa-O plates) and from about 4500 Å to about 6700 Å (Kodak 103a-F plates). The original scale was 4.55 arc sec/mm on the slit, and the full length of the slit was about 3 arc minutes. 1 mm on the plates corresponds to 66.5 arc sec, or about 3.9 - 4.4×10^4 km at the Comet projected on the plane of the sky. The slit was always centered on the image of the Comet, and except for plate No. 1436, was oriented along the radius vector. A field rotator was used which dimished the stellar light by about 30 %.

During the time of observation the heliocentric distance, r and the geocentric distance, Δ of the Comet varied from

$$r = 0.34 - 0.63 \text{ AU}$$

$$\Delta = 0.92 - 0.81 \text{ AU}.$$

The pertinent observational and cometary data are given in Table 1. All observations were severely influenced by large extinction.

D7

Table 1
Spectroscopic Observations of Comet Kohoutek (1973f)

Plate No.	Date U.T. (1974)	Emulsion (Kodak)	Quality	Exposure (min.)	α(Comet) 1950	δ(Comet) 1950	r (AU)	Δ(AU)	dΔ/dt (Km/sec)
1436	Jan. 5.025	103a-F	weak	11	$20^h\ 20^m.8$	$-15^\circ\ 51'$	0.338	0.916	-37.44
1439	Jan. 6.025	103a-F	good	30	20 32.7	-15 02	0.369	0.897	-33.54
1445	Jan. 7.031	103a-F	weak	30	20 44.6	-14 12	0.401	0.877	-29.66
1452	Jan. 8.030	103a-F	weak	37	20 56.4	-13 21	0.431	0.863	-25.89
1459	Jan. 9.033	IIa-O	weak	25	21 08.2	-12 28	0.462	0.847	-22.16
1470	Jan. 10.035	IIa-O	good	42	21 19.9	-11 34	0.491	0.837	-18.54
1478	Jan. 12.036	103a-F	weak	54	21 43.3	- 9 41	0.549	0.819	-11.45
1501	Jan. 14.040	IIa-O	good	56	22 06.3	- 7 45	0.604	0.810	- 4.69
1503	Jan. 15.040	103a-F	weak	58	22 17.6	- 6 46	0.631	0.807	- 1.45

2. Blue Region of the Spectrum

In the Kodak IIa-O plates, the violet system of CN and the C_2 Swan bands are dominating. In addition we find emission features of the C_3, CH, and CO^+ molecules. The (0-0) and the (0-1) bands of the $(B^2\Sigma - X^2\Sigma)$ system of CN are well resolved. On plate No. 1501, the (0-0) band could be traced up to R(26). The much fainter (1-1) band could not be detected. Tables 2 and 3 contain the wavelengths measured and corrected for the Doppler shift due to the geocentric radial velocity of the Comet, the visual estimates of the corresponding intensities on an arbitrary scale, and the identifications. The identifications in these and the following tables are based on Johnson (1927), Shea (1927), Phillips (1948), Hunaerts (1950), Weinard (1955), Dressler and Ramsay (1959), Dossin et al. (1961), and Greenstein and Arpigny (1962).

The $\Delta v = +1$ sequence of the C_2 Swan bands $(A^3\Pi - X^3\Pi)$ can easily be recognized. Of C_3 only three emissions could be found: λ4039.56 Å (I=1), λ4043.42 Å (2), λ4051.71 Å (4). The (0-0) bands of the $(B^2\Sigma - X^2\Pi)$ and the $(A^2\Delta - X^2\Pi)$ systems of CH are present, the latter, however, always much stronger than the first which shows essentially the $P_1(1)$ λ3892.93 emission. Table 4 lists the identified CH emissions of the (0-0) band of the $(A^2\Delta - X^2\Pi)$ system. CO^+ is present only in the best IIa-O plate (No. 1501) with

Table 2
The (0-0) Band of the $B^2\Sigma$ - $X^2\Sigma$ System of CN

Intensity	λ (Å) (observed)	Identification λ (Lab)
1	3852.32	R(26) 3852.41
0	3853.35	R(25) 3853.50
2	3855.66	R(23) 3855.63
1	3856.44	R(22) 3856.67
3	3857.65	R(21) 3857.68
3	3858.67	R(20) 3858.64
4	3859.67	R(19) 3859.67
1	3860.58	R(18) 3860.60
2	3861.52	R(17) 3861.54
6	3862.40	R(16) 3862.48
9	3863.31	R(15) 3863.40
6	3864.23	R(14) 3864.30
9	3865.08	R(13) 3865.16
6	3865.91	R(12) 3865.99
10	3866.75	R(11) 3866.82
8	3867.61	R(10) 3867.62
8	3868.36	R(9) 3868.41
11	3869.05	R(8) 3869.18
9	3869.82	R(7) 3869.92
1	3870.58	R(6) 3870.65
3	3871.25	R(5) 3871.37
6	3872.03	R(4) 3872.05
3	3872.62	R(3) 3872.74
5	3873.29	R(2) 3873.37
5	3873.98	R(1) 3874.00
0	3874.61	R(0) 3874.61
0n	3875.84	P(2) 3876.32
3	3876.70	P(3) 3876.84
2	3877.20	P(4) 3877.35
1	3877.41	P(5) 3877.84
6n	3881.05	P(13) 3880.99
6n	3882.05	P(14) 3881.30 P(15) 3881.58
6n	3882.99	Head 3883.39

Table 3
The (0-1) Band of the $B^2\Sigma - X^2\Sigma$ System of CN

Intensity	λ (Å) (observed)	Identification λ (Lab)
1	4195.97	R(13) 4195.94
1	4198.02	R(11) 4198.09
0	4206.02	R(2) 4206.19
1	4207.04	R(1) 4206.95
1	4211.85	P(6) 4211.90
3	4215.60 Head	P(17) 4215.55 P(18) 4215.68

Table 4
The (0-0) Band of the $A^2\Delta$ - $X^2\Pi$ System of CH

Intensity	λ (Å) (observed)	Identification λ (Lab)
3	4291.06	R_2cd(3) 4291.11, R_2dc(3) 4291.22
2	4292.08	R_1cd(3) 4292.05, R_1dc(3) 4292.12
5	4296.60	R_2cd(2) 4296.62, R_2dc(2) 4296.66
5	4297.95	R_1cd(2) 4297.99, R_1dc(2) 4297.99
4	4300.31	R_2cd(1) 4300.32, R_2dc(1) 4300.32
10	4303.88	R_1cd(1) 4303.95, R_1dc(1) 4303.95
9	4312.64	Q_2d(3) 4312.59, Q_2d(2)+Q_2c(2) +Q_2c(3) 4312.71
9	4314.11	Q_1c(2) 4314.21, Q_1d(2) 4314.21
2	4329.97	P_1cd(3) 4329.94, P_1dc(3) 4330.00
2	4334.01	P_2cd(4) 4333.84, P_2dc(4) 4334.00, P_1cd(4) 4334.66, P_1dc(4) 4334.78
2n	4338.74	P_2cd(5) 4338.63, P_2dc(5) 4338.85

Table 5
CO^+ Bands

(v′ - v″)	λ (Å)	System	
(1-0)	4568 - 4544	$A^2\Pi$ - $X^2\Sigma$	Comet Tail
(2-0)	4252	$A^2\Pi$ - $X^2\Sigma$	Comet Tail
(2-1)	4711 - 4683	$A^2\Pi$ - $X^2\Sigma$	Comet Tail
(0-1)	4231	$B^2\Sigma$ - $X^2\Pi$	Baldet-Johnson

Table 6
Emissions in the Visual Region of the Spectrum

Intensity	λ (Å) (observed)	Identification
8	4684.35	C_2(4-3) Head
10	4696.65	C_2(3-2) Head
5	4704.97	C_2(2-1) P_1(40), P_2(39)
8	4714.32	C_2(2-1) Head
10	4736.60	C_2(1-0) Head
3n	4941.83	C_2(0-0) R_1(72), R_2(71), R_3(70)
2	4967.46	C_2(1-1) R_3(58), R_1(60), R_2(59)
		C_2(0-0) P_3(93)
1	4970.00	C_2(0-0) R_1(66), R_2(65), R_3(64)
1	4992.37	C_2(0-0) R_3(59), R_1(61), R_2(60)
2	4996.69	C_2(0-0) R_1(60), R_2(59), R_3(58)
2	5005.42	C_2(0-0) R_3(56), R_1(58), R_2(57)
3	5009.50	C_2(0-0) R_3(55), R_1(57), R_2(56)
		C_2(1-1) R_1(49), R_2(48)
1	5013.58	C_2(0-0) R_3(54), R_1(56), R_2(55)
1	5017.53	C_2(0-0) R_1(55), R_2(54)
2	5021.88	C_2(0-0) R_1(54), R_2(53), R_3(52)
3	5033.83	C_2(0-0) R_3(49), R_1(51), R_2(50)
		C_2(1-1) R_3(40), R_1(42), R_1(41)
1	5037.69	C_2(0-0) R_3(48), R_1(50), R_2(49)
1	5052.70	C_2(0-0) R_3(44), R_1(46), R_2(45)
		C_2(1-1) R_1(36), R_2(35), R_3(34)
3	5055.95	C_2(0-0) R_1(45), R_2(44), R_3(43)
		C_2(1-1) R_3(33), R_2(34), R_1(35)
3	5063.13	C_2(0-0) R_1(43), R_2(42), R_3(41)
3	5069.95	C_2(0-0) R_3(39), R_1(41), R_2(40)
		C_2(2-2) R_1(16), R_2(15)
2	5073.38	C_2(0-0) R_1(40), R_2(39), R_3(38)
		C_2(2-2) R_1(14), R_2(13)
3	5083.00	C_2(0-0) R_1(37), R_2(36), R_3(35)
2	5086.25	C_2(0-0) R_3(34), R_1(36), R_2(35)
		C_2(1-1) R_1(23), R_2(22)
3	5089.10	C_2(0-0) R_1(35), R_2(34)
		C_2(1-1) R_1(22), R_2(21)
4	5092.24	C_2(0-0) R_1(34), R_2(33), R_3(32)
1	5095.35	C_2(0-0) R_3(31), R_1(33), R_2(32)
		C_2(1-1) R_1(19), R_2(18),
1	5097.06	C_2(2-2) Head P_3(17), P_1(18), P_1(17), P_1(19), P_2(18), P_3(18)

Table 6 (Continued)

Intensity	λ (Å) (observed)	Identification	
2	5100.84	C_2 (0-0)	$R_3(29)$, $R_2(30)$, $R_1(31)$
		C_2 (1-1)	$R_1(16)$, $R_2(15)$
3	5103.71	C_2 (0-0)	$R_1(30)$, $R_2(29)$, $R_3(28)$
		C_2 (1-1)	$P_3(42)$, $P_1(44)$, $P_2(43)$
1	5106.40	C_2 (0-0)	$R_1(29)$, $R_2(28)$, $R_3(27)$
2	5111.60	C_2 (0-0)	$R_1(27)$, $R_2(26)$, $R_3(25)$
1	5113.00	C_2 (1-1)	$P_1(38)$, $P_2(37)$, $P_3(36)$
		C_2 (0-0)	$P_1(55)$, $P_2(54)$
1	5116.75	C_2 (0-0)	$R_1(25)$, $R_2(24)$, $R_3(23)$
		C_2 (1-1)	$P_1(35)$, $P_2(34)$, $P_3(33)$
1	5120.54	C_2 (1-1)	$P_3(30)$, $P_1(32)$, $P_2(31)$
		C_2 (0-0)	$P_1(52)$, $P_2(51)$, $P_3(50)$
1	5121.30	C_2 (0-0)	$R_1(23)$, $R_2(22)$
7	5128.70	C_2 (1-1)	Head $P_1(21)$, $P_2(20)$, $P_3(19)$
2	5141.46	C_2 (0-0)	$P_3(40)$, $P_1(42)$, $P_2(41)$, $R_1(13)$
3	5144.54	C_2 (0-0)	$P_3(38)$, $P_1(40)$, $P_2(39)$
2	5146.15	C_2 (0-0)	$P_1(39)$, $P_2(38)$, $P_3(37)$
1	5147.73	C_2 (0-0)	$P_3(36)$, $P_1(38)$, $P_2(37)$
3	5149.11	C_2 (0-0)	$P_3(35)$, $P_1(37)$, $P_2(36)$, $R_1(8)$
1	5150.49	C_2 (0-0)	$P_1(36)$, $P_2(35)$, $P_3(34)$
2	5155.58	C_2 (0-0)	$P_1(32)$, $P_2(31)$, $P_3(30)$
1	5157.78	C_2 (0-0)	$P_1(30)$, $P_2(29)$, $P_3(28)$
1	5158.49	C_2 (0-0)	$P_1(29)$, $P_2(28)$, $P_3(27)$

Table 6 (Continued)

Intensity	λ (Å) (observed)	Identification	
20	5164.81	C_2 (0-0)	Head P_3(18), P_1(19), P_2(18), P_1(18), P_2(17), P_3(16)
1n	5409.09	NH_2(1,7,0)	$2_{02}-3_{12}$
4	5428.60	NH_2(0,11,0)	$2_{02}-2_{12}$, $4_{04}-4_{14}$, $3_{03}-3_{13}$, $1_{01}-1_{11}$
2	5441.12	C_2 (0-1)	P_1(81), P_2(80)
3	5442.81	NH_2(1,7,0)	$2_{21}-1_{11}$
3	5451.80	C_2 (0-1)	R_1(54), P_1(79), P_2(78)
		C_2 (1-2)	R_3(43), R_1(45), R_2(44)
3	5472.55	C_2 (3-4)	R_3(13), R_2(14), R_1(15)
		C_2 (2-3)	R_1(29), R_2(28), R_3(27)
		C_2 (0-1)	R_1(50), R_2(49), R_3(48), P_1(75), P_2(74)
1	5485.40	C_2 (1-2)	R_1(37), R_2(36), R_3(35)
2n	5492.34	C_2 (0-1)	R_3(44), R_1(46), R_2(45), P_1(71), P_2(70)
2n	5496.91	C_2 (0-1)	R_3(43), R_1(45), R_2(44), P_1(70), P_2(69)
		C_2 (1-2)	R_1(34), R_2(33),
5	5501.43	C_2 (3-4)	Head
		C_2 (2-3)	R_3(17), R_2(18)
		C_2 (0-1)	R_1(44), R_2(43), P_1(69), P_2(68)
2	5505.96	C_2 (0-1)	R_3(41), P_1(68), P_2(67), R_1(43), R_2(42)
		C_2 (2-3)	R_3(15)
2	5514.81	C_2 (0-1)	R_1(41), R_2(40), R_3(39)
		C_2 (1-2)	R_2(29), R_2(28), R_3(27)
		C_2 (2-3)	R_3(11)
3	5523.78	C_2 (0-1)	R_3(37), R_1(39), R_2(38), P_1(64), P_2(63)
2	5527.78	C_2 (0-1)	R_1(38), R_2(37), R_3(36), P_1(63), P_2(62), P_3(61)
		C_2 (1-2)	R_3(23), R_2(24), R_1(25)
3	5532.11	C_2 (0-1)	R_3(35), R_1(37), R_2(36)

Table 6 (Continued)

Intensity	λ (Å) (observed)	Identification	
3	5536.26	C_2 (0-1)	$R_3(34)$, $P_1(61)$, $P_2(60)$, $R_1(36)$, $R_2(35)$
1	5537.52	C_2 (2-3)	$P_3(20)$, $P_1(22)$, $P_2(21)$
4	5540.20	C_2 (2-3)	Head $P_3(17)$, $P_1(18)$, $P_2(17)$, $P_2(16)$, $P_3(16$ $P_3(15)$, $P_2(15)$, $P_2(14)$, $P_3(14)$, $P_2(13)$
2	5544.04	C_2 (0-1)	$R_1(34)$, $R_2(33)$, $R_3(32)$, $P_1(59)$, $P_2(58)$
2	5551.54	C_2 (0-1)	$R_2(32)$, $R_2(31)$, $R_3(30)$, $P_1(57)$, $P_2(56)$
2	5559.10	C_2 (0-1)	$R_3(28)$, $P_1(55)$, $P_2(54)$, $P_3(53)$
3	5565.68	C_2 (0-1)	$R_1(28)$, $R_2(27)$, $R_3(26)$, $P_1(53)$, $P_2(52)$
		C_2 (1-2)	$P_3(33)$, $P_1(35)$
1	5569.20	C_2 (0-1)	$R_2(26)$, $R_3(25)$, $R_1(27)$
		C_2 (1-2)	$P_3(31)$
2	5572.38	C_2 (0-1)	$R_1(26)$, $R_2(25)$
		C_2 (1-2)	$P_3(29)$, $P_1(31)$, $P_2(30)$
10	5585.02	C_2 (1-2)	Head $P_1(18)$, $P_2(17)$, $P_3(16)$, $P_1(17)$, $P_2(16)$, $P_3(15)$, $P_1(16)$, $P_2(15)$, $P_1(15)$, $P_2(14)$, $P_3(14)$, $P_1(14)$, $P_2(13)$
		C_2 (0-1)	$R_1(22)$, $R_2(21)$, $R_3(20)$, $P_1(47)$, $P_2(46)$
1n	5588.07	C_2 (0-1)	$P_1(46)$, $P_2(45)$, $P_3(44)$
1	5590.70	C_2 (0-1)	$R_3(18)$, $P_1(45)$, $P_2(44)$, $R_2(19)$
1	5593.55	C_2 (0-1)	$R_3(17)$, $P_1(44)$, $P_2(43)$, $P_3(42)$
		NH_2(0,11,0)	$5_{41}-4_{31}$
1	5595.99	C_2 (0-1)	$R_1(18)$, $R_2(17)$, $R_3(16)$, $P_1(43)$, $P_2(42)$
2	5600.72	C_2 (0-1)	$R_1(16)$, $R_2(15)$, $R_3(14)$, $P_1(41)$, $P_2(40)$
1n	5612.33	C_2 (0-1)	$P_1(36)$, $P_2(35)$, $P_3(34)$
1n	5614.27	C_2 (0-1)	$P_1(35)$, $P_2(34)$, $P_3(33)$

C. 3

Table 6 (Continued)

Intensity	λ (Å) (observed)	Identification	
6	5635.06	C_2 (0-1)	Head $P_3(14)$, $P_3(15)$, $P_1(17)$, $P_2(16)$, $P_3(16)$
2	5703.06	$NH_2(0,10,0)$	$2_{12}-2_{02}$
30	5889.92	Na I	D_2
20	5895.89	Na I	D_1
1	5939.47	$NH_2(0,10,0)$	$5_{32}-6_{42}$
6	5977.02	C_2 (3-5)	$R_2(11)$, $R_1(12)$
		$NH_2(0,9,0)$	$3_{03}-3_{13}$, $5_{05}-5_{15}$, $1_{01}-1_{11}$, $2_{02}-2_{12}$
5	5994.96	$NH_2(0,9,0)$	$1_{01}-2_{11}$
		C_2 (1-3)	$R_1(37)$, $R_2(36)$, $R_3(35)$
		C_2 (3-5)	$P_1(26)$, $P_2(25)$
3	6004.21	C_2 (3-5)	Head
		$NH_2(0,9,0)$	$4_{23}-3_{13}$
5	6020.03	$NH_2(0,9,0)$	$3_{03}-4_{13}$
		C_2 (1-3)	$R_2(31)$, $R_3(30)$
3	6033.56	C_2 (1-3)	$R_1(29)$, $R_2(28)$, $R_3(27)$
		C_2 (2-4)	$P_1(34)$, $P_2(33)$
		$NH_2(0,9,0)$	$3_{21}-3_{13}$
3n	6059.14	C_2 (2-4)	Head
1	6081.51	$NH_2(0,9,0)$	$4_{23}-4_{31}$
1	6096.71	$NH_2(0,9,0)$	$2_{21}-3_{31}$, $2_{20}-3_{30}$
2	6098.44	$NH_2(0,9,0)$	$2_{20}-3_{30}$, $2_{21}-3_{31}$
3	6121.86	C_2 (1-3)	Head
2	6190.74	C_2 (0-2)	Head

Table 6 (Continued)

Intensity	λ (Å) (observed)	Identification
1	6255.89	$NH_2(0,9,0)$ $6_{43}-6_{33}$
1	6274.28	$NH_2(0,8,0)$ $3_{12}-2_{02}$
1	6297.32	$NH_2(0,8,0)$ $2_{12}-2_{02}$
2	6298.58	$NH_2(0,8,0)$ $2_{12}-2_{02}$
10	6300.33	$NH_2(0,8,0)$ $4_{14}-4_{04}$, $6_{16}-6_{06}$ [OI]
3	6334.56	NH_2(Em)
1	6357.46	$NH_2(0,8,0)$ $3_{13}-4_{23}$
2	6360.31	$NH_2(0,8,0)$ $3_{12}-4_{22}$
2	6363.87	[OI]
1	6601.40	$NH_2(0,7,0)$ $3_{03}-2_{11}$, $4_{04}-3_{12}$, $5_{05}-4_{13}$
1	6618.07	$NH_2(0,7,0)$ $1_{01}-1_{11}$
2	6619.08	$NH_2(0,7,0)$ $5_{05}-5_{15}$, $3_{03}-3_{13}$, $2_{02}-2_{12}$
2	6640.62	$NH_2(0,7,0)$ $1_{01}-2_{11}$
2	6671.47	$NH_2(0,7,0)$ $3_{03}-4_{13}$

its emissions given in Table 5. It was too faint to be seen in any other spectrum.

3. Visual Region of the Spectrum

Table 6 contains the list of the measured emissions in the visual region of the spectrum with wavelengths λλ4684-6671 Å (Kodak 103a-F plates) together with the corresponding identifications. We find essentially the sequences $\Delta v = 0$, $\Delta v = -1$, and $\Delta v = -2$ of the C_2 Swan bands, and NH_2 emissions. Since NH_2 is more concentrated towards the nucleus than C_2, it is easier lost in the continuum than C_2. In addition to C_2 and NH_2, the NaI D_1 and D_2 lines are very strong, and forbidden [OI] can also be identified. New lines could not be detected.

4. Discussion

The sodium doublet (5889.97 Å, 5895.93 Å) was very strong at small heliocentric distances (0.3 - 0.4 AU), but later it weakened considerably. The intensity distribution along the lines is given in Figures 1 and 2. The profiles are remarkably asymmetric with respect to the nucleus; the gradient on the sunward side (S) is much steaper than on the tail side (RV). The intensity decrease of Na in the nucleocentric distance between 2 and 5×10^3 km on the sunward side and between 2 and 7×10^3 km on the tail side is approximately linear with a mean slope of -20 and -12, respectively. Towards the sun, Na extends to about 1.2×10^4 km,

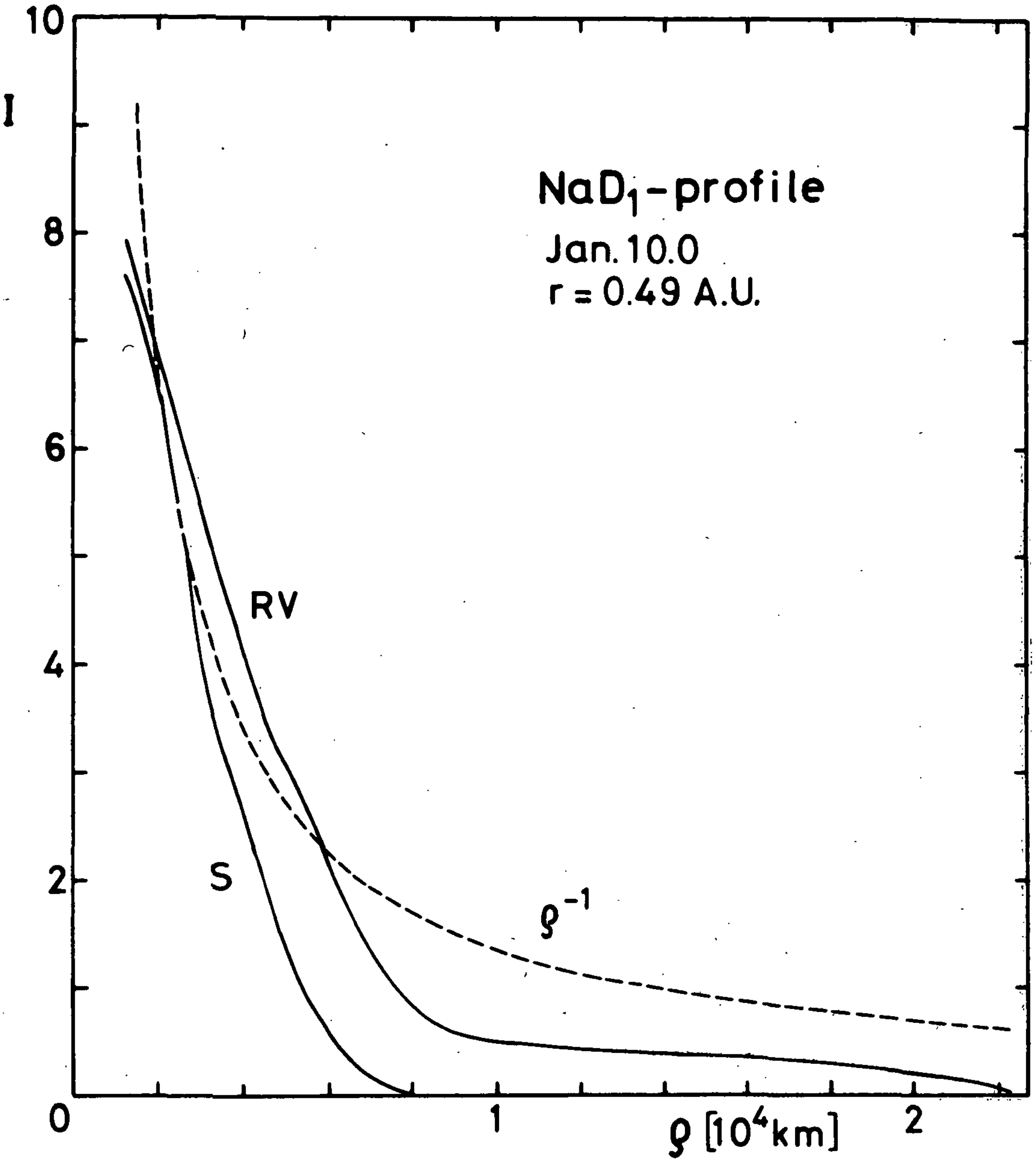

Figure 1: Na D_1-profile on January 10.035 UT, 1974, at r = 0.49 AU. The intensity (I) is given in arbitrary units as function of the distance (ρ) from the nucleus in units of 10^4 km in the direction towards the sun, (S); and in the tail direction, (RV). The dashed curve is calculated for an intensity law $I(\rho) \sim \rho^{-1}$.

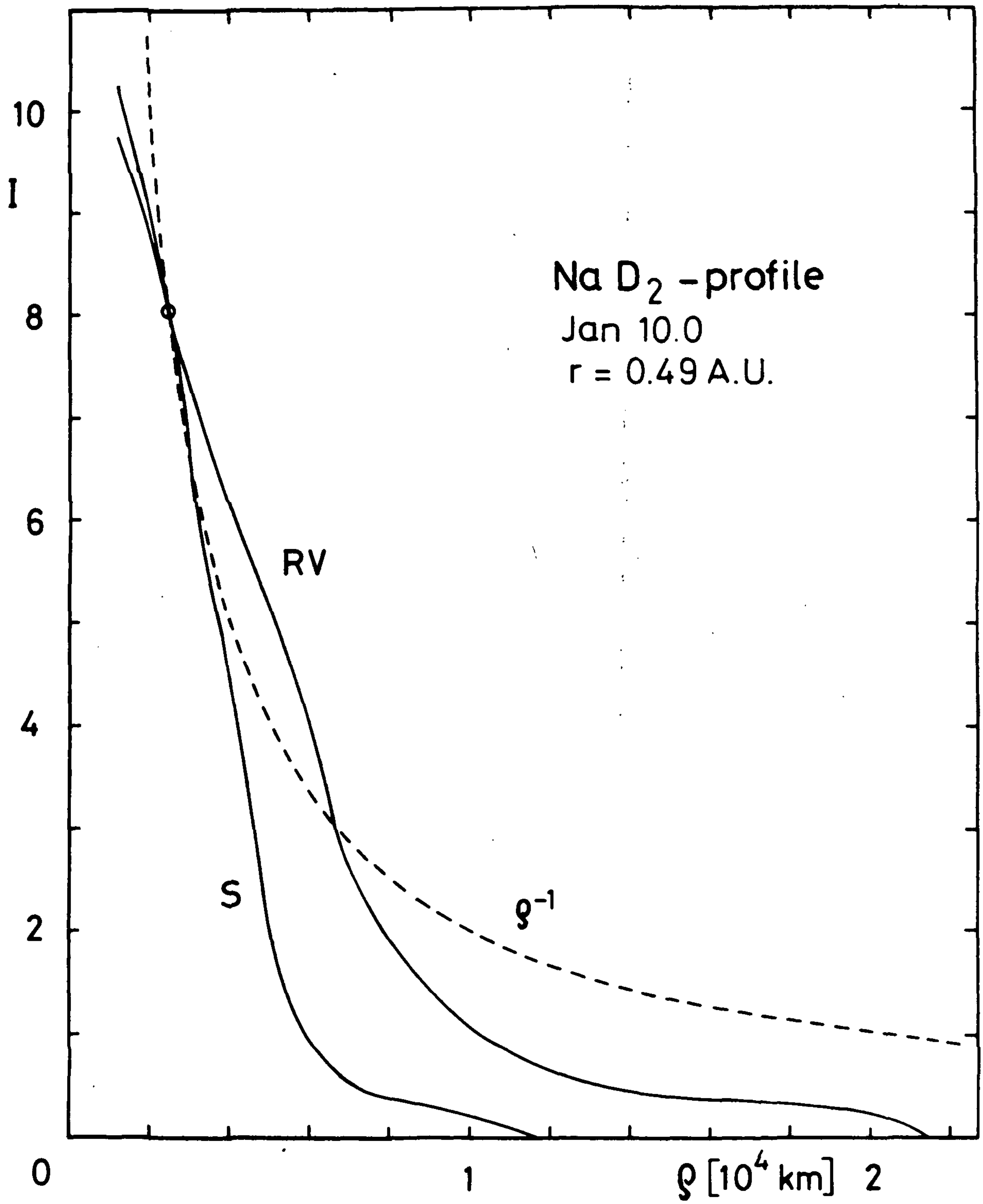

Figure 2: Na D_2-profile on January 10.035 UT, 1974, at r = 0.49 AU. For details see Fig. 1.

in the tail direction up to over 2×10^4 km. This asymmetry is caused by radiation pressure. Due to their larger f-values, the Na D-lines are more sensitive to this effect than the neutral molecular emissions ($f(CN)=3\times10^{-2}$, $f(C_2=3\times10^{-3})$ which are nearly symmetric to the nucleus as is illustrated in Fig. 3, showing the C_2 λ4737 Å-profile on January 14, 1974. The ρ^{-1} -law fits relatively well for both C_2 curves, (S) and (RV) , indicating a density law $D(\rho) \sim \rho^{-2}$ for the radiating C_2 molecules. On the other hand, the density distribution of Na atoms can be approximated neither by the simple law $D(\rho) \sim \rho^{-2}$, nor by $D(\rho) \sim \rho^{-2}\, e^{-(\rho/\rho_o)}$ (Haser, 1957; Wurm and Balazs, 1963) and should be investigated in more detail. We observe a similar behavior as for Comets Mrkos 1957 V (Greenstein and Arpigny, 1962) and Bennett 1970 II (Rahe et al., 1975).

The intensity evolution of the main emission bands during the period of observation is given in Tables 7 and 8. The intensity values refer to the intensity of the region close to the nucleus (up to about 10^4 km) and are given relative to the brightness of the violet (0-1) band of CN (Table 7) or to that of the (1-2) Swan band of C_2 (Table 8) which are both normalized to 10.0.

The C_2 (1-0) intensity increases relative to the CN (0-1) emission with increasing heliocentric distance (Table 7, r = 0.46 - 0.60 AU). The CO^+ emission, though very faint, decreases relative to CN as the Comet recedes from the sun while the CH emission clearly increases. At r = 0.46 AU the CH lines are still rather weak, but strengthen with growing r

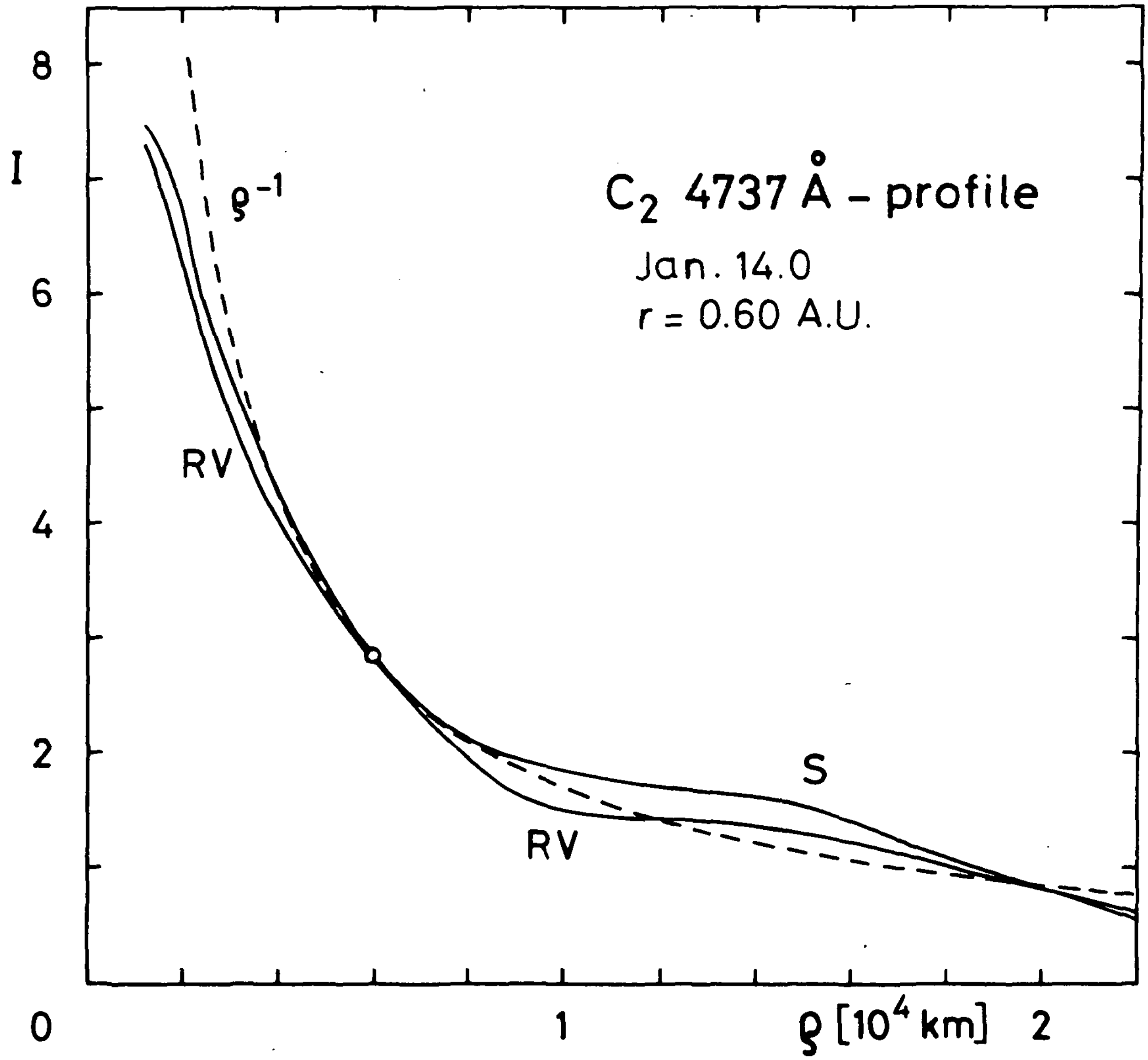

Figure 3: C_2 λ4737 Å-profile as observed on January 14.040 UT, 1974, at r = 0.60 AU. For details see Fig. 1.

Table 7
Intensity as Function of Heliocentric Distance
[relative to CN(0-1) = 10]

Plate No.	Mean air mass	r [A.U.]	C_3 4043.6	C_3 4051.6	CN(0-1) 4214.7	CO^+ 4231	CH 4296.6	CH 4298.0	CH 4303.9	CH 4312.6	CH 4314.2	C_2(1-0) 4737.2
1459	9.4	0.46	-	-	10.0	4.0:	2.7	0.8	1.8	3.6	3.2	18.2
1470	7.6	0.49	5.7	4.6:	10.0	1.7:	2.6	1.5	4.2	4.9	2.4	21.6
1501	5.1	0.60	4.3	8.4	10.0	0.5:	4.1	4.6	8.1	10.7	8.8	33.3

Table 8
Intensity as Function of Heliocentric Distance
[relative to C_2(1-2) = 10]

Plate No.	Mean air mass	r [A.U.]	C_2(1-2) 5585.0	NaI(D_2) 5889.9	NaI(D_1) 5895.9	NH_2 5976.7	[OI] 6300.4	[OI] 6363.9
1436	16 :	0.34	10.0	39.8	27.0	1.8	3.2	-
1439	10.9	0.37	10.0	overexposed		2.7	3.1	0.9
1445	12.0	0.40	10.0	12.3	5.8	-	-	-
1452	9.0	0.43	10.0	32.7	20.2	5.7	-	-
1478	5.9	0.55	10.0	4.1:	-	-	-	-

(see also Fig. 4). For the first two plates (r = 0.46 and 0.49 AU), the lines 4291 - 4300 Å of the R-branch of the CH ($A^2\Delta$ - $X^2\Pi$) system are weaker than the (0-1) band of CN, in the third spectrum (plate No.1501, r = 0.60 AU) both intensities are comparable. The brightness of the 4312 and 4314 Å emissions of the Q-branch even excels that of the CN (0-1) sequence. The strength of NH_2 also grows as compared to C_2 (1-2) (Table 8, r = 0.34 - 0.55 AU), whereas the intensity of the sodium doublet drops considerably at the same time by about one order of magnitude. It was very strong between January 5 and January 8 at r = 0.34 and r = 0.43 AU, respectively, but had nearly vanished on January 12 at r = 0.55 AU (see also Kohoutek, 1975). However, a pronounced increase in the Na brigthness occured on January 8 at r = 0.43 AU (plate No. 1452). The average intensity ratio of the two sodium D lines was $I(D_2)/I(D_1) = 1.7$ which is in agreement with the resonance fluorescence hypothesis, according to which this ratio should be $\leqq 2$. It is certainly smaller than the intensity ratio $I(D_2)/I(D_1) = 2.5$ determined by Warner (1963) from the spectrum of Comet Seki-Lines 1962 III.

The C_3 and the [OI] observations are too limited to allow any conclusion.

The spatial extension of different emissions as function of heliocentric distance can be compared in Table 9. The dimensions are determined along the spectral lines (i.e., their lengths perpendicular to the dispersion) and are clearly limited by exposure time and plate emulsion, thus giving only lower limits of the actual extension of the

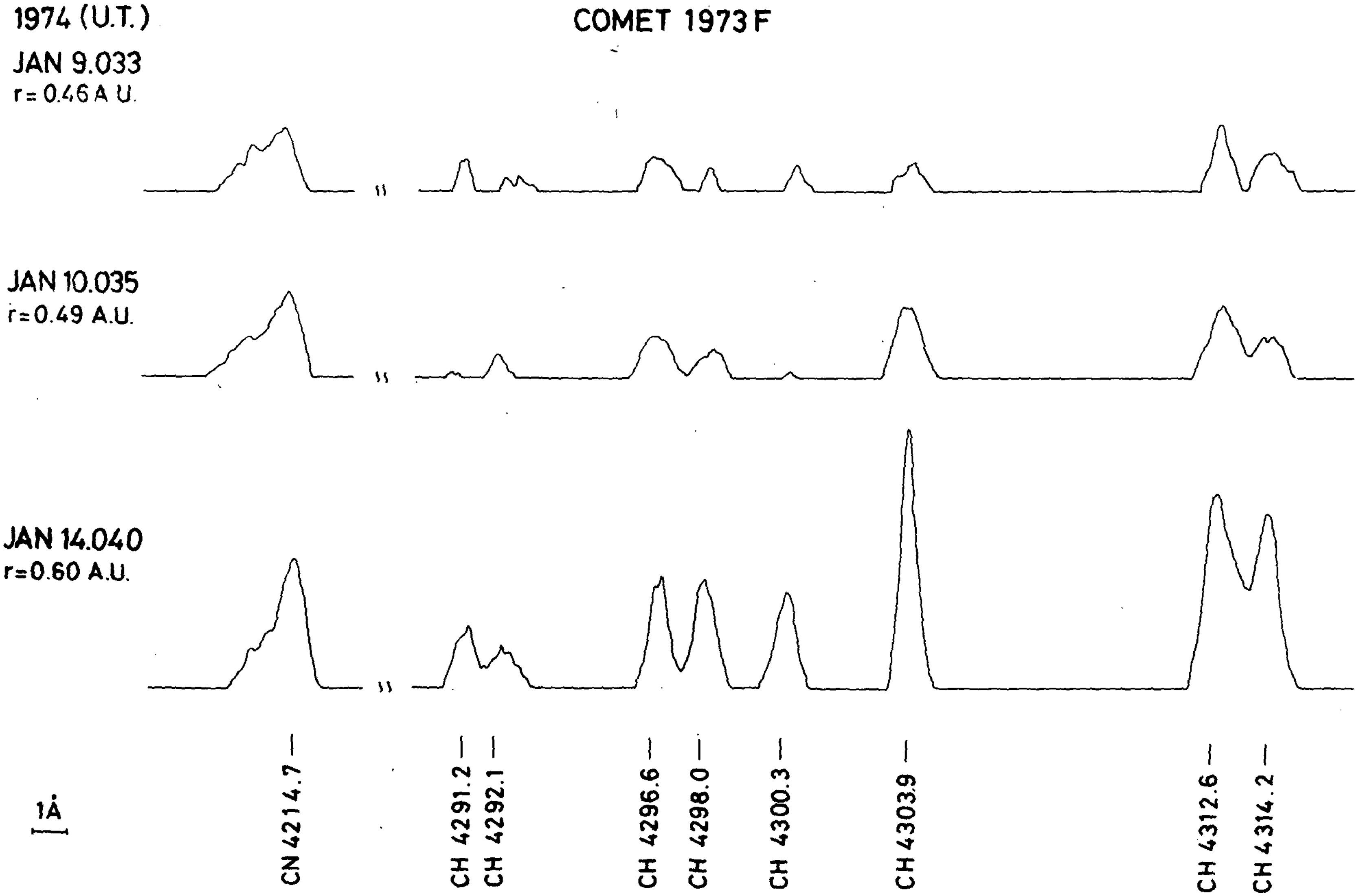

Figure 4: Variation of CH intensity.

Table 9

Extension of Different Emissions (in 10^4 km)

Plate No.	C_2 5165.2	NaI 5889.9	NH_2 5976.7	[OI] 6363.9	CN 3883.4	C_2 4737.1	C_3 4051.6	CH 4312.6
1436	1.68	1.86						
1439	3.89	2.12	0.74	1.43				
1445	2.83	1.27						
1452	2.00	0.87						
1459					2.49	2.70	0.29	0.57
1470					4.80	2.91	0.36	0.69
1501					5.86	4.49	0.23	0.66

various species. Different particles show very different extensions. CN has the greatest extension, C_3 the shortest. Arranged in order of decreasing extension in the head of the Comet we find CN, C_2, CH, C_3. Due to its faintness, the size and shape of the CO^+ emission could not be determined.

The molecular lines are superimposed on a relatively weak continuous spectrum which showed a stronger concentration toward the nucleus than the coma emissions. In Comet 1973f, the continuum (relative to the discrete emissions) was weaker than that of Comets Mrkos 1957 V (Greenstein and Arpigny, 1962) or Bennett 1970 II (Babu and Saxena, 1972) where it was rather strong and the intensity ratio of emissions to continuum small, but it was stronger than that of the "gaseous" Comets Burnham 1960 II (Dossin et al., 1961) or Ikeya 1963 I (Fehrenbach, 1963) where it was very weak and narrow or practically non-existent. This is in agreement with the photometric measurements (Kohoutek, 1975).

We wish to thank Mr. J. Prölss for his assistance with the reduction. We are grateful to the ESO directorate for providing us with observing time at the 1.52 m telescope and to the Stiftung Volkswagenwerk for a grant which supported this work.

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HIGH RESOLUTION SCAN OF COMET KOHOUTEK IN THE VICINITY OF 5015 Å, 5890 Å, AND 6563 Å *

L. J. Lanzerotti, * M. F. Robbins, N. H. Tolk, and S. H. Neff *

ABSTRACT

High resolution scans were made of the head of Comet Kohoutek (1973f) using the McMath solar telescope at Kitt Peak National Observatory. The data were taken on 1 and 4 January 1974 UT, just after the comet perihelion: A spectrum taken in the vicinity of 6563 Å on 4 January (Figure 1) with a 9.4 arc second round aperture shows evidence of H_α emission, doppler-shifted from the atmospheric solar absorption feature.

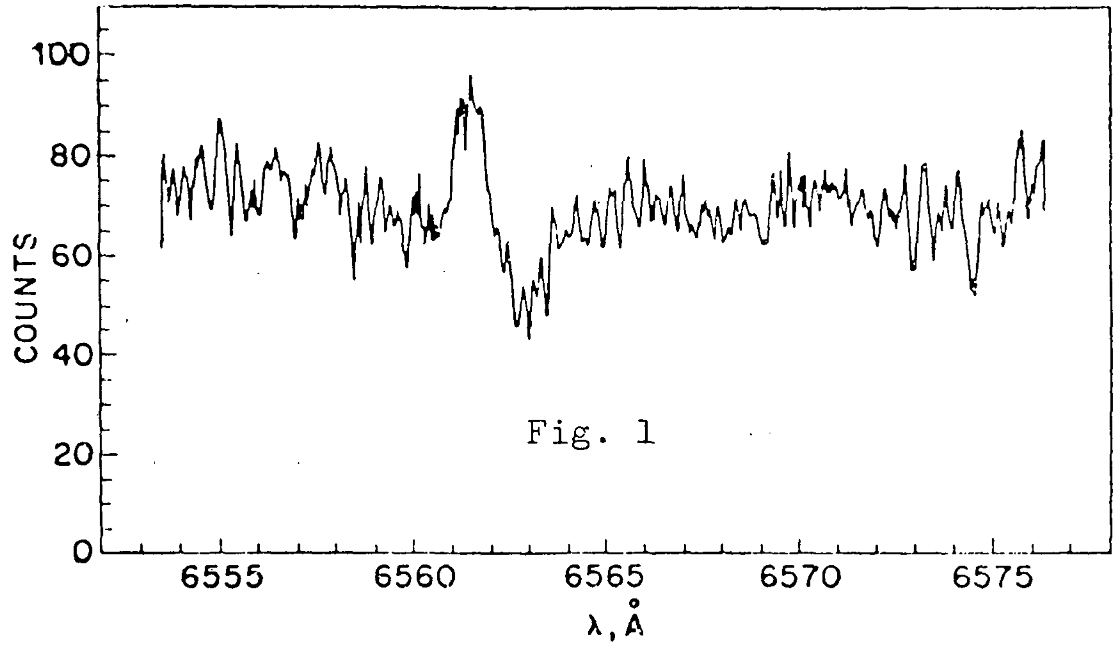

Fig. 1

The H_α emission intensity in the area observed was ~4.1 x 10^{27} photons sec^{-1}. An H_2O^+ ion line occurs at the position of H_α and at ~6574 Å (Herzberg and Lew, 1974; Wehinger et al., 1974). At 100°K, the intensity of the H_2O^+ line at ~6574 Å is about one-half the intensity at 6562.8 Å. The data of Figure 1 indicate that the emission at ~6574 Å is

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*Visiting Astronomer, Kitt Peak National Observatory

Herzberg, G., and Lew, H. (1974). Astr. and Ap., 31, 123

Wehinger, P. A., Wyckoff, S., Herbig, G. H., Herzberg, G., and Lew, H. (1974). Ap. J., 190, L43

$\lesssim 10^{27}$ photons sec^{-1}. The contribution of H_2O^+ emission is thus probably much less than one-half of the measured H_α emission in the area of the head of the comet measured. An upper limit on the He I (5015) radiation was determined to be less than two percent of the observed H_α emission. Measurements made with a 4.7 arc sec round aperture in the vicinity of 5890 Å on both nights indicated that the D2/D1 line intensities were ~0.5, indicating an optically thin emission region in the area of the head observed.

A spectrum of the NaD region taken on 1 January is shown in Figure 2. The emission intensity was ~ 1.2 x 10^{29} photons sec^{-1} in the region observed (the intensity on 4 January was ~7.9 x 10^{28} photons sec^{-1}). Assuming a resonance-fluorescence emission rate for the optically thin target, it is found that the ionized Na$^+$ production rate at Kohoutek in the region measured was ~2.2 x 10^{23} atoms/sec on 1 January and ~1.4 x 10^{23} atoms/sec on 4 January assuming a photo-ionization lifetime of ~5 x 10^4 sec for Na at 1 a.u. These data also yield sodium number densities of ~2.9 x 10^{29} and ~7.3 x 10^{28} on 1 and 4 January, respectively.

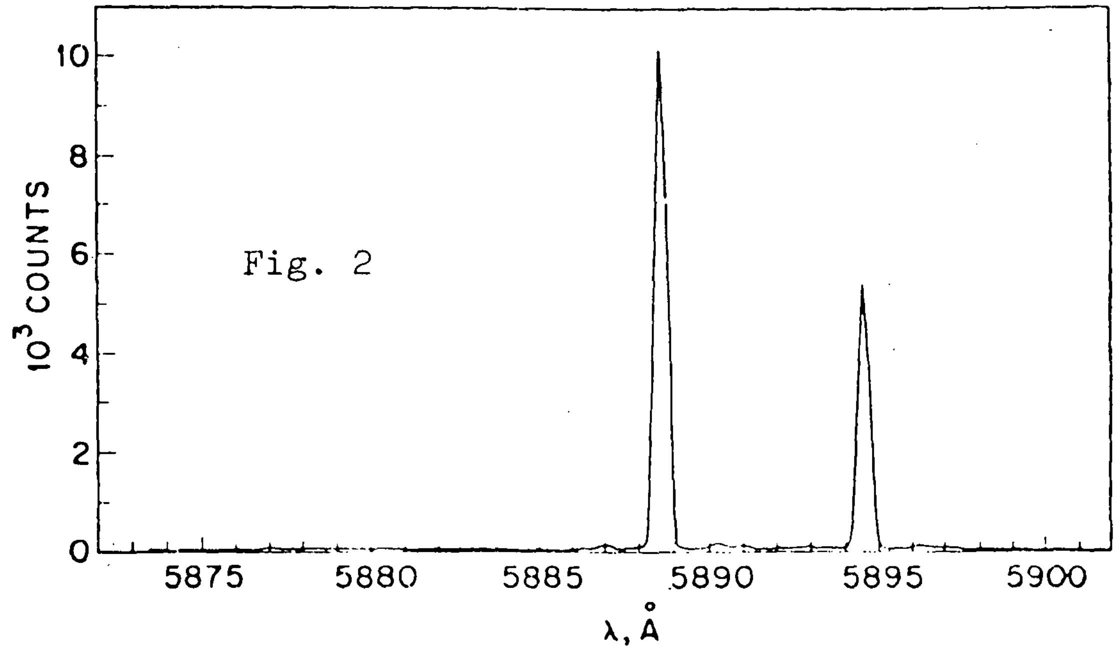
Fig. 2

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[1]* See Icarus 23, 618 (1974) for the complete text.

N76-21060

SPECTROSCOPIC OBSERVATIONS OF COMET KOHOUTEK (1973f) - II

Piero Benvenuti

Systematic spectroscopic observations of comet Kohoutek (1973f) were scheduled at the Asiago Astrophysical Observatory, starting from the end of October. The nebular spectrograph for the newtonian focus of the 122 cm reflector was selected as main instrument for this research. This spectrograph, described by Bertola (1970), is followed by a WL-30677 image tube and it is particularly designed for extended objects of low surface brightness. Two gratings were used giving a dispersion in the first order of 125 Å mm^{-1} and 240 Å mm^{-1} respectively. The scale normal to the dispersion is 127 arcsec mm^{-1} and the full length of the slit is 8 arcmin.

Weather conditions, particularly bad after the 25th of January, shortened the observational program, and the 40 available spectra cover six nights before perihelion and five nights after perihelion. The material is listed in Table I.

As already published (Herbig, 1973, Benvenuti and Wurm, 1974) the first spectra of the coma of comet Kohoutek were characterised by some fairly strong, asymmetric, unidentified emissions in the red and the near infrared spectral regions. From these very preliminary indications Herzberg and Lew (1974) proposed a tentative identification of the H_2O^+ ion. As soon as the comet approached the perihelion and further spectra became available, other H_2O^+ emissions appeared (Benvenuti, 1974, Wehinger and Wyckoff, 1974), and the tentative identification was confirmed (Wehinger et al., 1974).

D8

Table 1
Log of Observations

Date	r	Δ	Spectrum No	U.T.	Exposure	Dispersion	
Oct 30	1.55	2.15	2127	4^h 19^m	17^m	240 Å mm^{-1}	
			2128	4 33	6	240	
Oct 31	1.53	2.12	2137	3 50	10	240	
			2138	4 14	10	240	
			2139	4 29	15	240	
Nov 2	1.49	2.06	2150	4 00	20	125	
Nov 21	1.10	1.58	2166	4 12	10	125	
			2167	4 25	3	125	
			2168	4 38	10	125	
			2169	4 49	15	125	
Nov 23	1.06	1.53	2171	4 29	20	125	
			2172	4 56	20	125	
Dec 4	0.80	1.30	2195	4 55	5	240	
			2196	5 02	1	240	
			2197	5 15	5	240	
			2198	5 25	10	240	
Dec 6	0.75	1.27	2199	5 07	5	240	
			2200	5 22	5	240	+
Jan 17	0.70	0.82	2227	17 18	3	240	
			2228	17 25	10	240	
			2229	17 37	5	240	
			2230	17 46	1	240	
			2231	18 10	15	240	+
			2232	18 28	15	240	+
Jan 18	0.73	0.83	2235	17 32	10	125	
			2236	17 41	4	125	
			2237	17 52	10	125	
			2238	18 18	5	240	+
			2239	18 35	20	240	+
			2240	18 54	15	240	+
Jan 23	0.85	0.87	2266	17 27	4	125	
			2267	17 36	10	125	
			2268	17 47	3	125	
			2269	18 02	10	125	
			2270	18 18	15	125	
			2271	18 50	30	125	+
Jan 25	0.90	0.90	2277	17 54	1	240	
			2278	17 57	10	240	
			2279	18 05	10	240	
			2280	18 15	1	240	
			2281	18 31	15	240	+

(+) Tail Spectrum

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H_2O^+ emissions were measured in two high quality Asiago spectra. The resulting wavelengths, in good agreement with those published by Wehinger et al. (1974), are listed in table II, together with laboratory data. In these spectra some features remain still unidentified, even if, as for their spatial behaviour, i.e. the asymmetricity respect to the continuum, they look like ion emissions. As the H_2O^+ bands identified so far belong to the v' progression (0,v',0) - (0,0,0), it is likely that the unidentified lines come from other progressions with higher vibrational levels in the lower state. These progressions are present in the laboratory spectra but not yet completely analysed.

H_2O^+ emissions are extremely asymmetric respect to the nucleus. This is shown in Fig.2, where two microphotometric tracings of the spectrum No 2235 are reported: in case a the slit was put on the tail side, in case b on the opposite (Sun) side, symmetrically respect to the continuum. The distance between the two slit positions was 2×10^5 Km. Moreover Fig. 3 shows the profiles, normal to the dispersion, of the two more prominent lines of H_2O^+ and of the adjacent continuum (the profile of the 6122 Å NH_2 line is also reported for comparison). From these tracings an upper limit of 2.5×10^4 Km can be derived for the extension of the H_2O^+ ions towards the Sun. For several spectra the slit of the spectrograph was set normal to the radius vector in order to derive the radial distribution of H_2O^+ around the nucleus, but in that case no traces of ions emission was found over the continuum.

Table II

Cometary and Laboratory Lines of H_2O^+

Sp No 2171	Sp No 2235	Laboratory (Å)	Assignement	
-	5521.0	5521.2	10-0, π	${}^{p}P_{2,N-2}(2)$
-	5798.3	5799.7	9-0, Σ	${}^{p}Q_{1,N}(3)$
-	5915.7	5915.3	9-0, Δ	${}^{p}P_{3,N-2}(3)$
6148.3	6146.9	6147.1	8-0, π	${}^{r}R_{0,N}(0)$
6158.4	6158.1	6158.7	8-0, π	${}^{r}Q_{0,N}(2)$
6187.5	6187.3	6187.2	8-0, π	${}^{p}Q_{2,N-1}(3)$
6199.7	6199.6	6199.4	8-0, π	${}^{p}P_{2,N-2}(2)$
-	6210.6	6210.5	8-0, π	${}^{p}P_{2,N-2}(3)$
-	6222.9	6222.4	8-0, π	${}^{p}P_{2,N-2}(4)$
-	6542.6	6542.8	7-0, Σ	${}^{p}Q_{1,N}(1)$
-	6561.8	6562.7	7-0, Σ	${}^{p}P_{1,N-1}(1)$
6576.2	6576.9	6575.0	7-0, Δ	${}^{r}R_{1,N}(1)$
-	6594.2	6594.3	7-0, Δ	${}^{r}Q_{1,N}(4)$
6684.9	6686.7	6686.0	7-0, Δ	${}^{p}P_{3,N-2}(3)$
6969.9	-	6971.9	6-0, π	${}^{r}R_{0,N}(0)$
6984.4	-	6986.5	6-0, π	${}^{r}Q_{0,N}(2)$
7039.2	-	7039.3	6-0, π	${}^{p}P_{2,N-2}(2)$
7052.7	-	7054.1	6-0, π	${}^{p}P_{2,N-1}(3)$
7069.8	-	7069.9	6-0, π	${}^{p}P_{2,N-2}(4)$

Laboratory wavelengths are averages of the spin doublets.

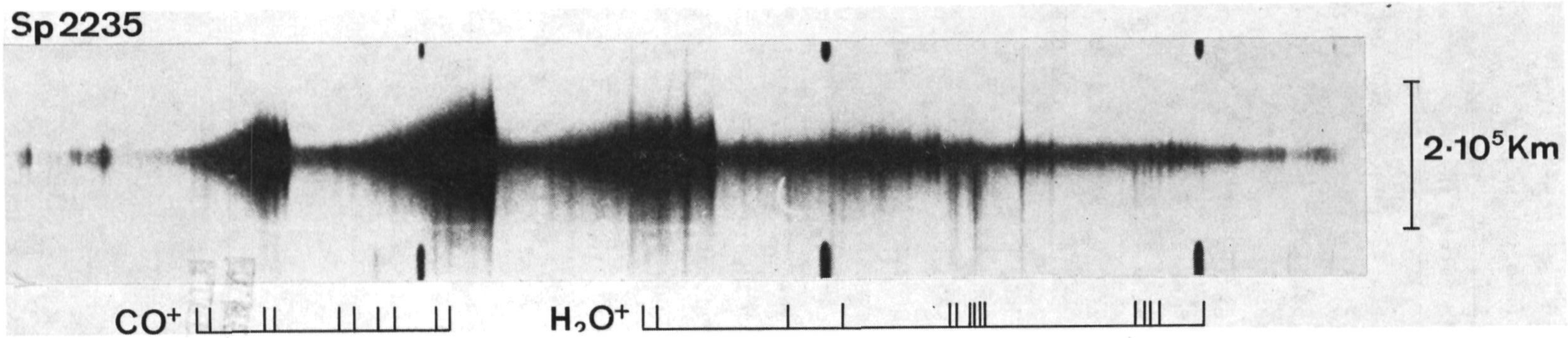

Fig. 1 - Comet Kohoutek. Spectrum No 2235, Jan 18.73 U.T.
The slit was put along the radius vector.

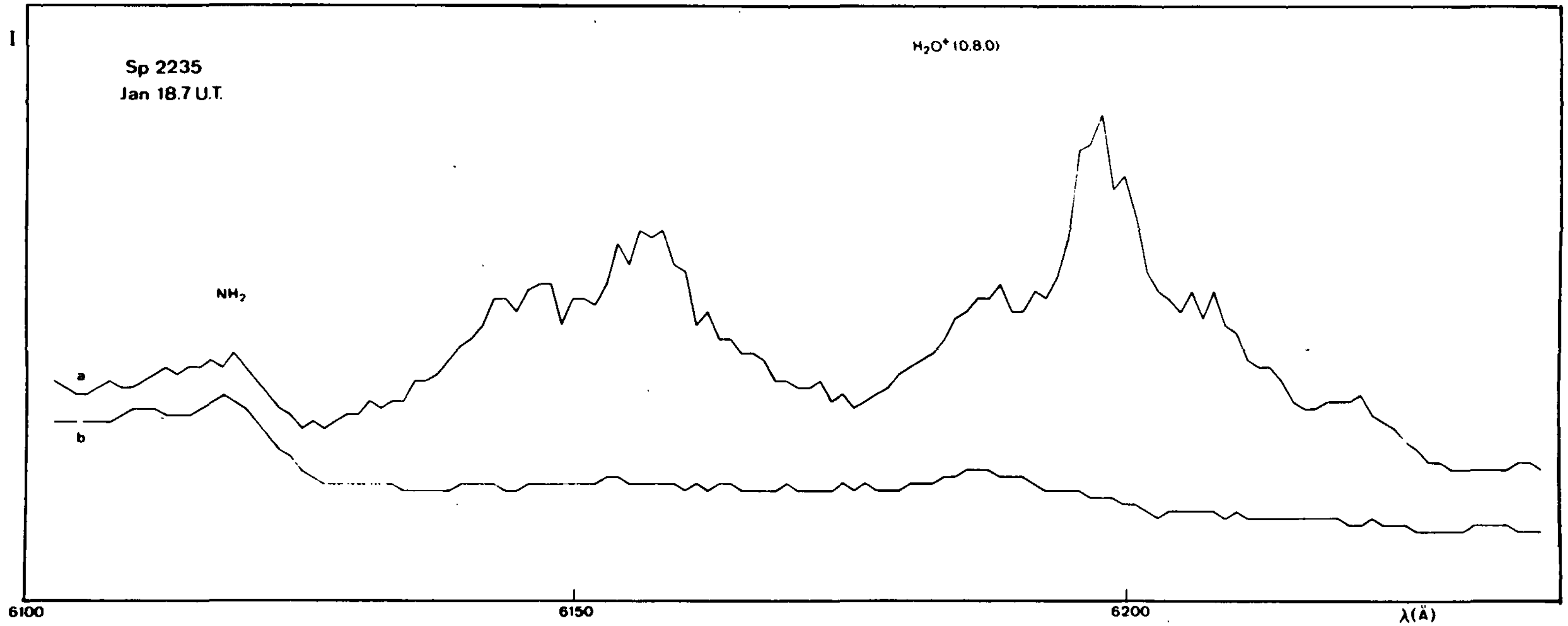

Fig. 2 - Microphotometric tracings of Spectrum No 2235 (see Fig. 1). The microphotometric slit in case a was towards the tail, in case b towards the Sun.

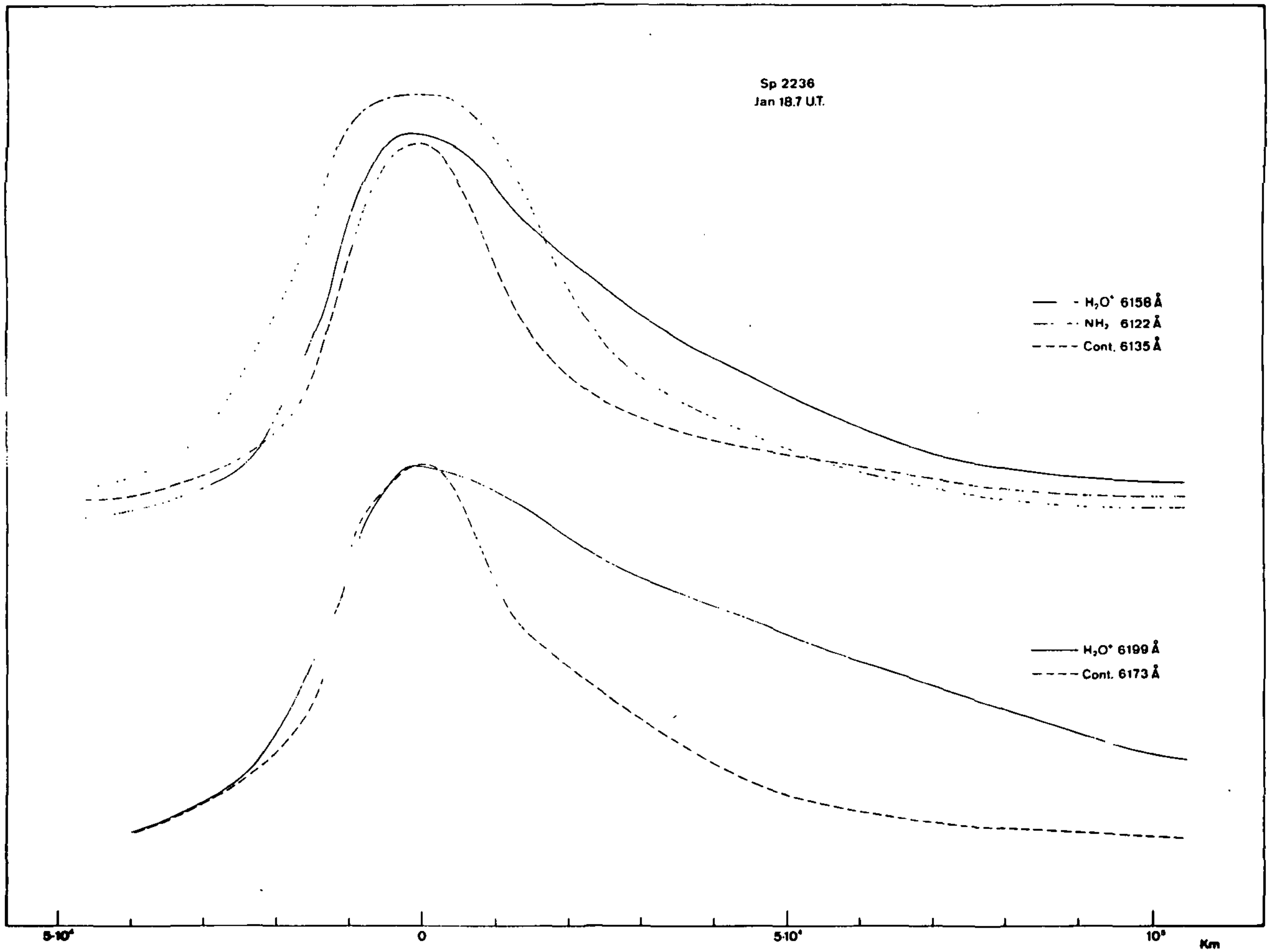

Fig. 3 - Microphotometric tracings, normal to the dispersion, of two H_2O^+ lines and of the adjacent continuum. The profile of NH_2 at 6122 Å is also reported.

H_2O^+ emissions dominate also the tail spectrum: this was roughly evident when red Schmidt plates of the Comet showed sharp filaments of the type I tail over the smooth dust tail. This was confirmed by some spectra taken in the tail at distances from the nucleus ranging from 5.5 x 10^5 Km to 1.4 x 10^6 Km (spatial resolution was achieved by offset guiding on the nucleus). Fig. 4 shows two of these spectra, and Fig. 5 reports the slit positions on a blue photograph taken at the same time with the 90/60 cm Schmidt telescope. At this heliocentric distance (r = 0.70 A.U.) also CO^+ emission was fairly strong and traces of C_2 and CN were present at about 8.2 x 10^5 Km from the nucleus. Spectrum No 2232, normal to the radius vector, shows that the more prominent tail stream of Jan 17th had very sharp edges, suggesting a bounded structure. The evolution of this feature can be followed in the plates of Jan 16th and 19th (Figs. 6,7): on the latter date it became unstable and a screwlike structure appeared. It would be very interesting to match these photographs with other plates (if available somewhere) taken at intervals of a few hours.

Besides the H_2O^+ emission, another peculiarity of Comet Kohoutek was the appearance of the [OI] forbidden lines at λλ 6300 - 6364 Å, already at heliocentric distance r = 1.55 A.U. (Comet emissions were clearly visible in short exposure spectra, although our dispersion were too low to show any Doppler shift from the night sky lines). The [OI] emissions are present in all our sample and became

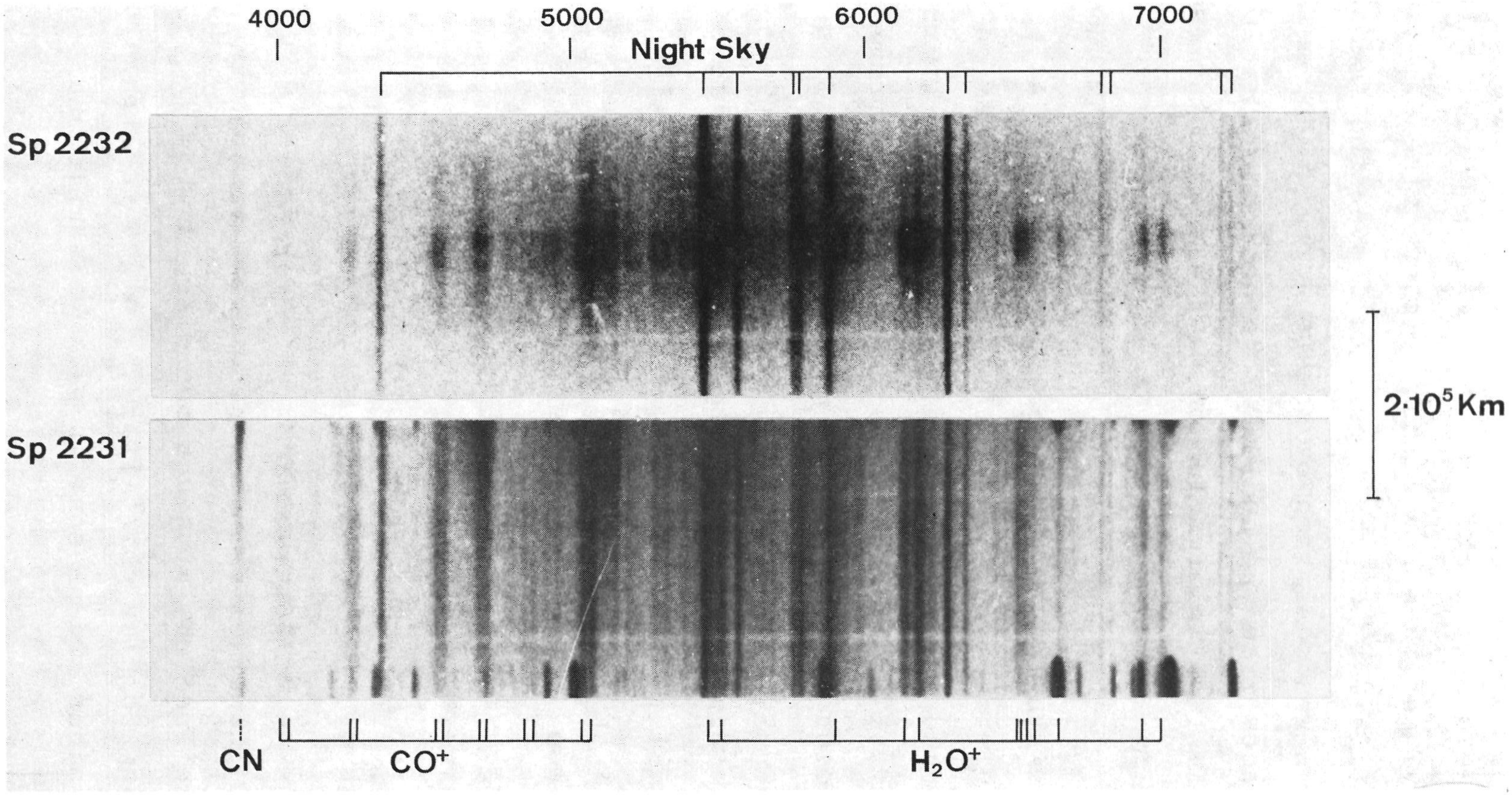

Fig. 4 - Tail spectra of Comet Kohoutek. The slit was centered at 8.2 x 10^5 Km from the nucleus, along the radius vector for Spectrum No 2231, perpendicularly to it for Spectrum No 2232.

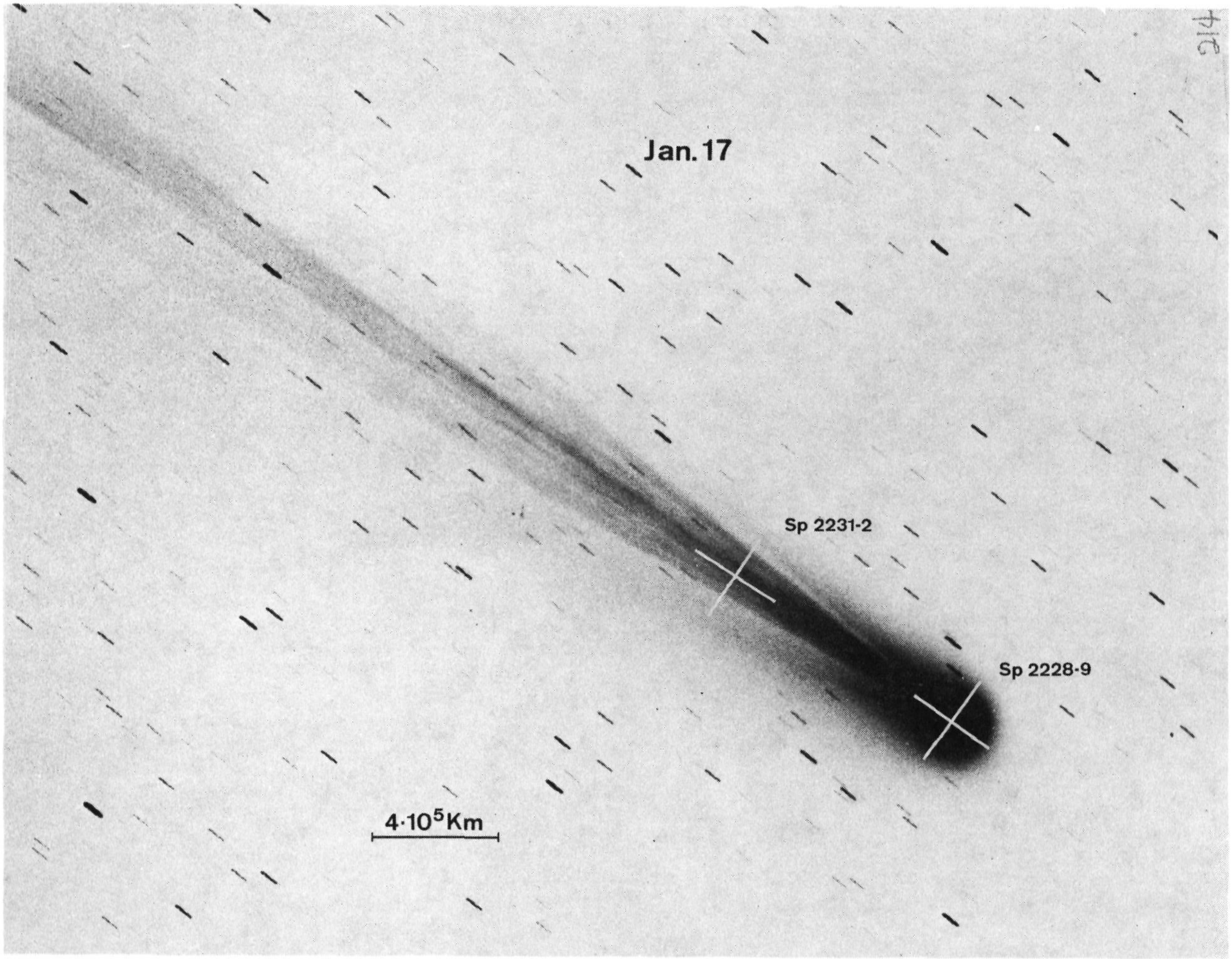

Fig. 5 - Comet Kohoutek. Asiago 90/60 cm Schmidt Telescope, Jan 17.76 U.T., 103a-O, 15^m exposure. Slit positions of Spectra Nos 2228-9 and 2231-2232 are reported.

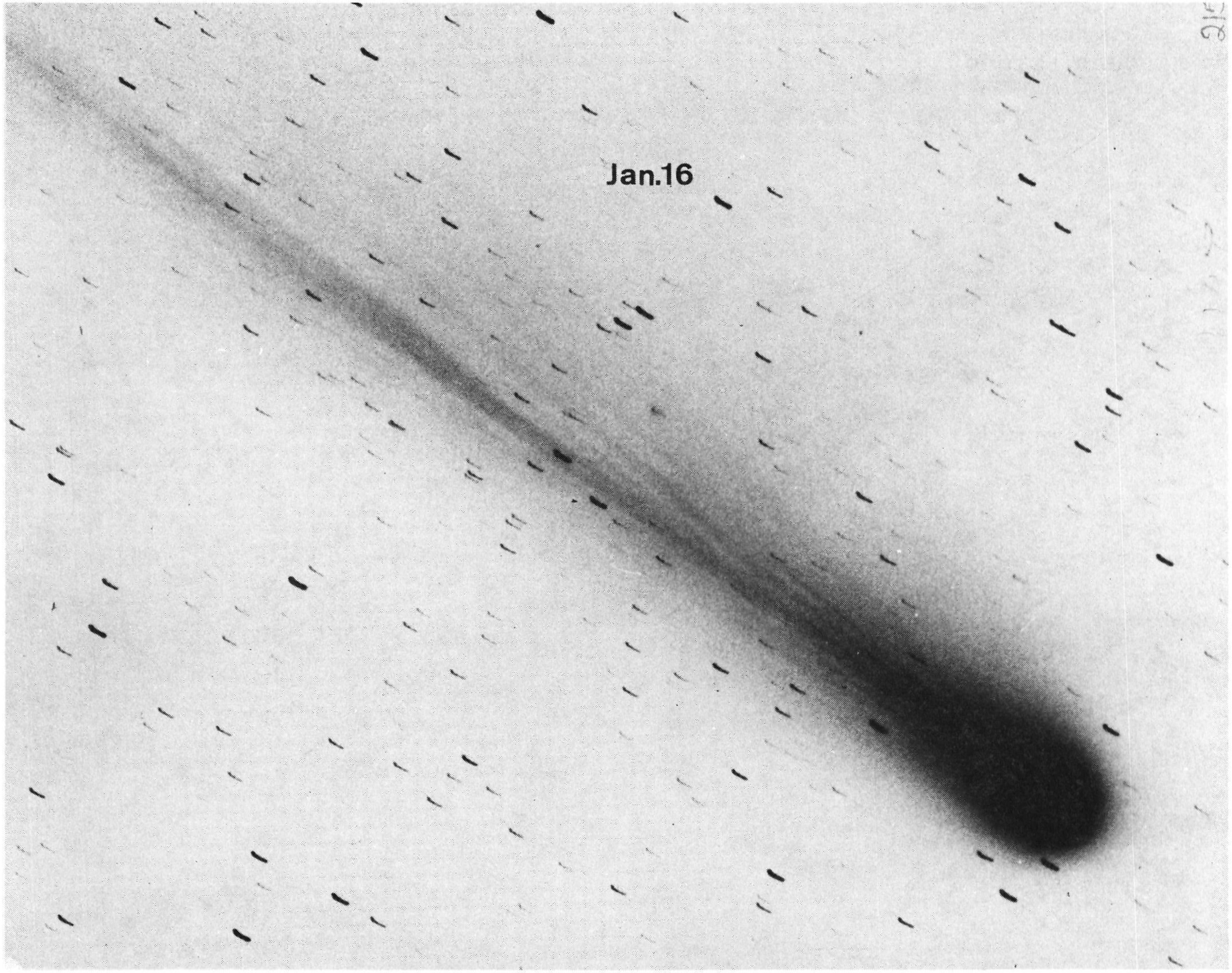

Fig. 6 - Comet Kohoutek. Jan 16.75 U.T. (data as Fig. 5)

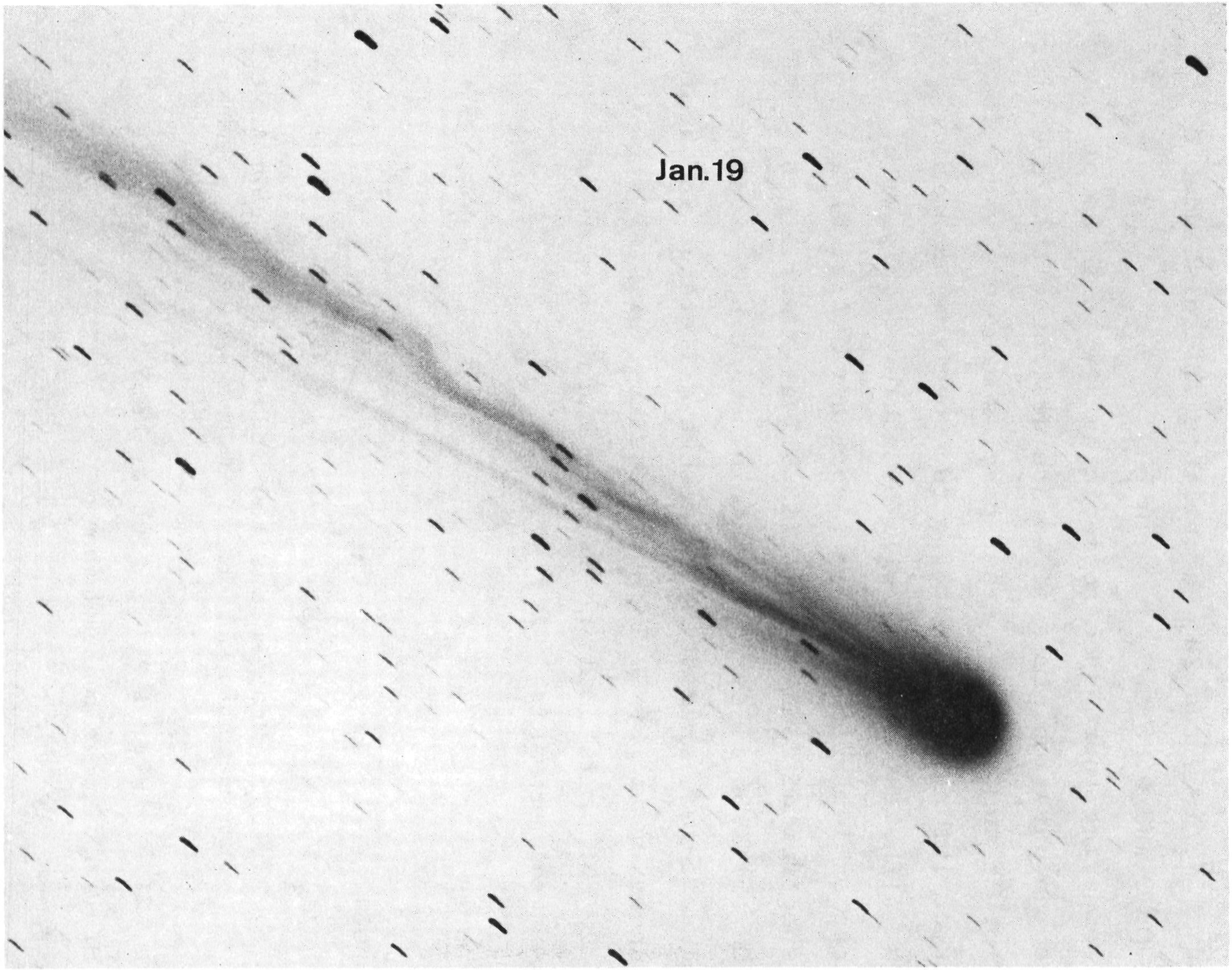

Fig. 7 - Comet Kohoutek. Jan 19.75 U.T. (data as Fig. 5)

fairly strong at r 0.80 A.U.. CO^+ was rather poor in Comet Kohoutek: its emissions are present only in the spectra of Jan 17th, 18th and 23rd at heliocentric distances of 0.70, 0.73 and 0.85 A.U., respectively.

Comparing these spectroscopic data with those of other comets the question arises if we are dealing with a peculiar comet or if the observed discrepancies are merely due to a lack of information about the red spectrum of previous comets. Although an answer will be achieved only with new data on future comets, we report here (Fig. 8) a tail spectrum of Comet Bennet (1969i) at $r = 1.1$ A.U.. The CO^+ emission is clearly visible but no H_2O^+ features can be detected, suggesting that some difference in chemical abundances or in physical conditions must exist.

The author is much indebted to Drs. Herzberg and Lew for useful communications.

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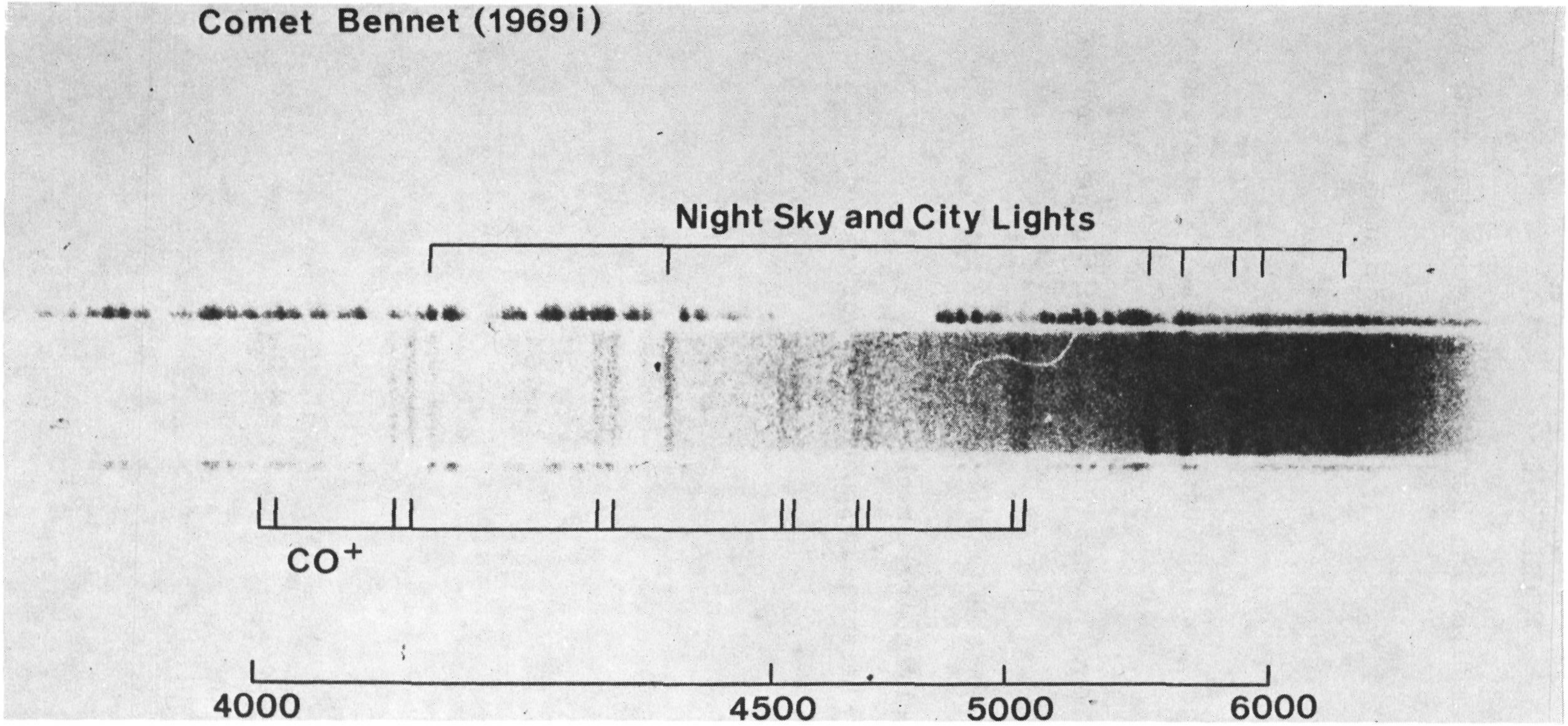

Fig. 8 - Comet Bennet (1969i). Tail spectrum, May 3.30 U.T., 1970. The slit was put normal to the tail at about 6.2×10^5 Km from the nucleus. Heliocentric distance $r = 1.1$ A.U.

DISCUSSION

G. Herzberg: I was going to ask Dr. Herbig, and perhaps Benvenuti can comment on that, too.

Dr. Herbig told us that in his spectra H_2O^+ is strongest at the head, if I understood correctly.

D. H. Herbig: Correct.

G. Herzberg: Now my question is, what about CO^+, is it also strongest at the head?

D. H. Herbig: I don't know. It wasn't in the region of the spectrum we photographed.

G. Herzberg: Would you be able to tell?

P. Benvenuti: In the region near the nucleus?

It is very difficult to say because my spectra are overexposed near the nucleus.

N76-21061

H_2O^+ IONS IN COMETS: COMET KOHOUTEK (1973f) AND COMET BRADFIELD (1974b)

Peter Wehinger and Susan Wyckoff

1. INTRODUCTION

Herzberg and Douglas (1973) first predicted that the H_2O^+ ion might be observable in comet tail spectra. Subsequently Lew and Heiber (1973) discovered the laboratory spectrum of H_2O^+. In October and November 1973, Herbig (1973), Benvenuti and Wurm (1974), and Wehinger and Wyckoff (1974) reported unidentified features in the tail spectrum of comet Kohoutek. On the basis of these observations, Herzberg and Lew (1974) made a tentative identification by pointing out coincidences with several strong low-lying lines in the H_2O^+ spectrum. Further observations were obtained in November 1973 and January 1974 at the Wise Observatory and by Herbig at the Lick Observatory. Six vibronic bands (5-0 through 10-0), including a total of approximately 50 rotational lines were identified with laboratory H_2O^+ spectrum (Wehinger et al. 1974). The predicted spin splitting of those lines with 2 to 4 Å separation was observed in the coude spectra of Herbig. In February 1974 comet Bradfield (1974b) was discovered and spectra were subsequently obtained at the Wise Observatory in March and April. Comet Bradfield displayed the same H_2O^+ bands as seen in comet Kohoutek (Wehinger and Wyckoff 1974).

2. OBSERVATIONS

The image-tube Cassegrain slit spectra (150 Å mm^{-1}, 5000 to 9000 Å and 75 Å mm^{-1}, 3500 to 5200 Å), obtained of comets Kohoutek and Bradfield, listed in Table 1, were calibrated and reduced to relative intensities using Oke's (1964) spectrophotometric standard stars, observed at the same zenith angle as each comet. The spectral energy distributions were put on an absolute scale, with a zero point in wavelength at 5556 Å, adopted from Ney's (1974) photometric observations, assuming essentially all of the light from the cometary coma entered the diaphragm of his photometer (20 arc sec square). Digital microphotometer scans of our spectra (unwidened and giving a spatial resolution of ~2000 km), were made at a distance r_n of 2×10^4 km from the nucleus in the tail with a projected slit width approximately equal to the seeing disk (~2 arc sec or ~1000 km at the distance of the comet). From several scans (at various r_n) through the tail spectra, perpendicular to the direction of dispersion, we determine monochromatic changes in the surface brightness for various neutral and ionized molecules. The intensities of C_2 and CN decreased approximately four times faster than the intensity change for the H_2O^+ features as a function of r_n (out to $r_n \sim 5 \times 10^4$ km). We estimate the uncertainty in the absolute luminosities to be a factor of 2 or 3 while the relative band intensities are accurate to ~±30 percent. The orbital parameters were taken from Yeomans (1973), Candy (1974) and Jacobs (1974). The integrated visual magnitudes of the comae were from Deutschmann (1974) and Ney (1974).

Table 1

Observational Data

Comet	UT Date	r (AU)	Δ (AU)	m_v	$\mathcal{L}(H_2O^+)$ (phot s^{-1})	g (phot s^{-1} cm^{-2})
Kohoutek	1973 Nov 30.1	0.9	1.4	5.6	20×10^{28}	0.68
(1973f)	1974 Jan 10.7	0.5	0.8	4.2	8	2.2
	1974 Jan 18.7	0.7	0.8	5.1	6	1.1
Bradfield	1974 Mar 28.7	0.6	0.7	5.8	1	1.5

The luminosity radiated in the H_2O^+ $\tilde{A}^2A_1 \rightarrow \tilde{X}^2B_1$ system was determined from measurements of the absolute energy distributions derived by Wyckoff and Wehinger (1975).

3. DISCUSSION

We have shown that the excitation mechanism for the observed H_2O^+ bands is by fluorescent scattering of the incident solar radiation (Wyckoff and Wehinger 1975). Consequently the g-factor for the H_2O^+ $\tilde{A}^2A_1 \rightarrow \tilde{X}^2B_1$ bands ($v_2' = 5$ through 15) was calculated from

$$g = \sum_{v''} \left[\frac{\pi e^2}{mc^2}\right] \lambda^2_{ov'} \cdot f_{ov'} \cdot \pi F_\odot \cdot \frac{A_{v'v''}}{\sum_{v''} A_{v'v''}} \qquad (1)$$

where g is expressed in phot sec^{-1} ion^{-1}, $\frac{\pi e^2}{mc^2} = 8.83 \times 10^{-21}$ cm^2 A, $\lambda_{ov'}$ = wavelength of the Q-branch of a given H_2O^+ band, $f_{ov'}$ is the absorption band oscillator strength computed from lifetimes for the upper vibronic levels determined by Erman and Brzozowski (1973); $\pi F_\odot$ is the integrated solar flux over the solar disk including effects of the Fraunhofer spectrum (Labs and Neckel 1968), $A_{v'v''}/\Sigma A_{v'v''}$ is the probability that the ion de-excites to the $v''_2 = 0$ level and was assumed to be 0.5 for all bands. We note that no H_2O^+ bands with $v'_2 > 10$ were detected in our spectra of comet Kohoutek. The relevant g-factors for the observational data are listed in Table 1. The g-factors for fluorescent scattering at 1 AU for H_2O^+ was 0.6 phot sec^{-1} ion^{-1}.

The production rates for H_2O^+ ions in both comets were estimated using Feldman et al. (1974),

$$Q_{H_2O^+} = \frac{\mathcal{L}}{g\tau} \tag{2}$$

where $\tau \sim 25$ hr is the lifetime for the H_2O^+ ions (assumed equal to the H_2O lifetime, Jackson 1972). The H_2O^+ production rates are listed in Table 2 for comets Kohoutek and Bradfield.

If we assume H_2O^+ is produced entirely by photoionization and that decomposition of H_2O is essentially complete at $r_n \sim 10^4$ km, then the H_2O production rate $Q_0 \sim 25\ Q_+$ (Wyckoff and Wehinger 1975). Thus from the production rates given in Table 2 we infer $Q_0 \sim 10^{25}\ s^{-1}$, which is orders of magnitude less than the production rate determined for comet Kohoutek by Feldman et al. (1974). We conclude that either the H_2O^+ or the H_2O lifetime is much smaller than the photodecomposition lifetime.

4. EFFECTS OF SOLAR ACTIVITY

Solar activity data were compiled from data kindly supplied by Thomas (1974) for the nights when observations of comet Kohoutek were obtained. The relative sunspot numbers and the solar flux at $\lambda = 10.7$ cm were used as indicators of solar activity. On one night's observation (1974 January 10.7) a flare of importance "one" was observed simultaneously in the United States while the comet was observed in Israel. However, owing to the low sensitivity of our spectral intensities to small intensity changes in the source, we did not detect any changes due to the flare. It is expected that the photoionization rate of H_2O in a comet would increase if the ultraviolet solar radiation in the Lyman continuum were enhanced by flare activity. Observations of another bright comet at the time of maximum solar activity to determine changes in band intensities of comet tail ions would be of interest.

Table 2

Observed Production Rates for H_2O^+

in Comets Kohoutek and Bradfield

Comet	r(AU)	Q_+(ion s^{-1})
Kohoutek	0.9	3.7×10^{24}
	0.5	1.5×10^{24}
	0.7	1.1×10^{24}
Bradfield	0.6	1.9×10^{23}

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OMIT

PRE- AND POST-PERIHELION SPECTROSCOPIC OBSERVATIONS OF COMET KOHOUTEK (1973f)

S. Wyckoff and P. Wehinger

ABSTRACT

Twenty pre- and post-perihelion calibrated image-tube spectrograms (3400-9000A; 75 and 150 A/mm) were obtained of Comet Kohoutek covering a range in heliocentric distances of 0.9 to 0.4 a.u. (30 November 1973 - 14 February 1974). Total band intensities have been measured for the CN, C_2 and NH_2 bands in the coma spectrum, and for the CO^+ and H_2O^+ bands in the tail spectrum. Changes in the total band intensities as a function of heliocentric distance are discussed, as are the pre- and post-perihelion characteristics of the spectra. The line intensity distributions within individual bands of the heteronuclear molecules (with large dipole moments) indicate very low rotational "temperatures" as expected. The measured band intensity ratios of the $A^2\pi$-$X^2\Sigma$ (red) CN bands and the $B^2\Sigma$-$A^2\pi$ (violet) CN bands are compared with predicted band intensity ratios calculated by T. Danks and C. Arpigny (1973 Astron. and Astrophys. 29, 347). Finally column densities are determined for CN and C_2 in the coma and CO^+ in the tail of Comet Kohoutek at various heliocentric distances.

DISCUSSION

W. Jackson: Could you tell us your excitation temperature? How can you define a temperature of a comet when the collision time is long compared to the radiative lifetime of the vibrationally excited H_2O^+?

P. Wehinger: Okay, I got your question.

(Laughter.)

It is a standard question.

The point is that this is a kind of artificial parameter in which the - say the Boltzman equation produces or provides a very good approximation for the line and band intensities. And ideally we would like to do this by calculating the population of each level from a large set of equations. And it rapidly becomes an intractable problem.

W. Jackson: I mean, it looked real good, but I don't know whether that was fortuitous or whether there are enough variations to the parameters that you put in that it will fit no matter what you do.

Voice: Couldn't you say that this is an effective radiation temperature?

B. Donn: I don't quite follow something.

In your first paper you said the H_2O plus is produced by photoionization excitation. And this is what produced the relative intensity that you showed.

Now you are saying that the relative intensities within a band are a temperature effect.

I can't put these two together.

B. Herzberg: Yes, I would also like to comment on that, if I may add to what he said.

It seems to me that if this temperature has any meaning whatever, that is, if there is a radiation temperature, it means that the H_2O^+ ions radiate their rotational energy and therefore bring the temperature down.

If the excited H_2O^+ ions were formed by photoionization you wouldn't see this this temperature, but rather the temperature of the original neutral H_2O molecule.

So I find a little contradiction between those two.

P. Wehinger: Okay.

I appreciate your suggestion.

I should like to ask to explain why we don't see the higher vibronic bands, beyond the 10-0 band.

These should be detectable. They are in a region that is clear of the C_2 Swan bands; particularly the 11-0 band is in a region that has no strong, overlapping contaminants. And if it were there — and we have very well-exposed spectra, and we should be able to see it. We just don't.

We don't see any of the other higher bands.

Voice: Does anyone know what the dissociation energy of H_2O^+ is, because it is just conceivable that they are above the dissociation limit in these particular levels and thus are difficult to observe under low pressure conditions, while in the lab they are observable.

P. Wehinger: Yes.

This may be the case. I could check against the numbers.

Voice: I don't know if anybody knows.

M. K. Wallis: Your slide comparing the observed band intensities with predictions from ionization and fluorescence processes uses the (9,0) band intensity for nomalization. The conclusion favoring ionization would not be so clear if another band were chosen. Is there any good reason for choosing the (9,0) band, such as absence of Greenstein effect?

P. Wehinger: I don't know that there would be. We could have chosen say the 8-0 or 7-0 band, - it wasn't done as any kind of fortuitous argument.

D. J. Malaise: From your computation you conclude that the H_2O^+ is produced directly by photoionization. Now, Benvenuti has shown us that he has taken spectra in the head and in the tail.

And, of course, in the tail it cannot be produced by photoionization of H_2O because for that to be, H_2O should be in the tail, which is not conceivable.

DISCUSSION (Continued)

So, is it possible that Benvenuti can tell us whether the ratio of the lines of the bands is different in the head and in the tail?

And secondly, you surely cannot have H_2O^+ intensity due only to this photoionization.

P. Wehinger: I said that it was primarily photoionization.

D. J. Malaise: Yes, because you observe it in the tail. And in the tail it is surely excited by fluorescence. So it has to be at least partly excited by fluorescence in the head, also.

P. Wehinger: 10 percent.

D. J. Malaise: I don't know.

It should be very interesting to estimate, shouldn't it?

P. Wehinger: Yes.

D. J. Malaise: And then you infer from the intensity of the band and from the process of exciting the bands, the production rate of the ions. But, if you know the cross-section and so on, you should be able also to estimate the density of water, and what the part of the water is photoionized.

Do you have these figures - An estimate of what percentage of the water is ionized to produce these H_2O^+ bands?

P. Wehinger: I don't have them with me at the moment.

D. J. Malaise: The point is that H_2O is already dissociated to account for OH and H, and now if you want to account for H_2O^+ by ionizing it, we need more water.

C. Cosmovici: I think that the ionization potential of water is higher than the dissociation potential. So, in this case you will have a dissociation rate which is much higher than the photoionization rate.

And do you know the percentage of dissociated molecules compared to the photoionized molecules?

DISCUSSION (Continued)

P. Wehinger: I can give you a rough figure, for discussion purposes, something like 10 to 1.

C. Cosmovici: 10 to 1.

But I think more than 1000 kilometers from the nucleus, all parent molecules would be photodissociated. In any case the ionized water, you see, would be formed outside 1000 kilometers from the nucleus.

So it would be very interesting to know how many molecules would be dissociated in this range, and how many would be photoionized. But I don't know, maybe this is not a process for ionization. Maybe collisional ionization— I don't know that.

But I think this question should be discussed a little bit.

W. Jackson: In the first place, most of the water has to be dissociated in the first continuum. It can't be 10 percent.

The solar flux —

P. Wehinger: No, what I was saying is that if you have some amount of water— it is 10 to 1—10 times as much is dissociated as is photoionized.

W. Jackson: That 90 percent, even that is overestimated by maybe one or two orders of magnitude. I think Delsemme can give you the exact number.

A. H. Delsemme: Well I looked crudely into that problem sometime ago already, and 99 plus percent of the water is dissociated and less than 1 percent is ionized.

I have more exact figures, but roughly that is the crude answer — taking into account the wavelength distribution of the solar continuum.

Voice: There is a basic discrepancy with another estimate of the solar production rate of H_2O^+, which is to take the rocket measurements of the H production rate, which we assume is produced by dissociation. You get the same number as saying that the hydrogen production is twice the H_2O production rate. We find that according to his numbers you need all of the H_2O going into H_2O^+.

So I think there is a major discrepancy in the data being presented and the cause of that is probably in the calculation of these source or q factors for computing the rate at which the photoionization takes place.

W. Jackson: When you estimate the total production of H_2O^+, you have to have an oscillator strength. You can't use the relative line strength measurements measured in the lab, to get an estimate of the total amount of H_2O^+.

You have to know what the transition probability is from the excited state to the ground state.

And that number is not known as far as —

G. Herzberg: For H_2O? — Yes it is.

W. Jackson: Yes? It has been measured?

G. Herzberg: The lifetime is known. I believe it is 800 nanoseconds.

W. Jackson: You used that number?

P. Wehinger: And you should also point out that there is a branching ratio that has to be accounted for because of the three lower levels.

And we are only looking at one of the lower levels.

W. Jackson: And when you do all of that you still get as much H_2O^+ — you would require enough water, such that most of the water undergoes photoionization, and that is in direct contradiction with the Lyman alpha measurement in the ultraviolet region.

H. Keller: This table we saw, this is H_2O^+ or H_2O production rate?

P. Wehinger: H_2O^+.

I'm sorry, it is H_2O.

Voice: Oh, okay. Then there is no contradiction.

M. Dubin: Talking about tables, in one of your tables you gave an equivalent of radius of the nucleus.

And you showed in the case of comet Kohoutek, a difference in the radius of the nucleus that was substantial. You show something like 7 kilometers down to a few kilometers, one or two kilometers, after perihelion.

Now that kind of a model won't fit. That kind of a transition in radius doesn't fit, say, the Whipple model.

DISCUSSION (Continued)

How can you adjust that radius to keep it only a very small change, in line with your observation, where the radius is essentially constant?

P. Wehinger: The radius changed by, as I recall the figures, by a factor of two.

Voice: 7.6 kilometers versus 2 kilometers.

M. Dubin: That is still too much.

NEAR-INFRARED SPECTRA OF COMETS BENNETT AND KOHOUTEK

A. E. Potter, T. Morgan, B. Ulrich and T. Barnes

ABSTRACT

Spectra in the range 0.9 to 1.6 microns of Comets Bennett and Kohoutek were obtained at the Coudé focus of the 2.72 meter telescope of McDonald Observatory. Comet Bennett was observed on a number of nights in March and April 1970, while spectra of Comet Kohoutek were taken on two nights in December 1973. The spectrum of Comet Bennett showed a strong continuum, which changed markedly in character during the observations. The surface brightness of Comet Kohoutek was less than the terrestrial hydroxyl airglow. The continuum spectrum could not be distinguished beneath the airglow bands. Spectra of both comets displayed clearly the (0-0) transition of the CN red system at 9115 cm^{-1}, with indications of the (0-1) CN transition visible at the edge of a region of strong atmospheric absorption. Several other possible emission lines were noted in the comet spectra. These were all weak, with signal levels marginally greater than the noise. None were positively identified.

OMIT

OBSERVATIONS OF COMET KOHOUTEK (1973f) WITH A GROUND-BASED FABRY-PEROT SPECTROMETER

D. Huppler, R. J. Reynolds, F.L. Roesler, F. Scherb and J. Trauger

Between 1973 December 1 and 1974 February 2, optical emission lines from the gas cloud surrounding comet Kohoutek were observed using a double Fabry-Perot etalon spectrometer at Kitt Peak National Observatory. The spectrometer had a resolving power of 40,000, corresponding to a velocity resolution of about 7.5 km sec^{-1}. With this resolution it was possible to use the comet-earth relative velocity to resolve faint cometary Hα λ6563, [OI] λ6300 and other emission lines from geocoronal and airglow emissions and to study the cometary line profiles in order to obtain information about the composition, effective temperatures, outflow velocities, and production rates of atoms and ions in the cometary envelope.

The spectrometer was coupled to the McMath Solar Telescope by focussing the primary image of the sky, which has a scale of about 1 arc min per 25 mm, directly onto the 150 mm diameter etalon of the Fabry-Perot spectrometer. Masks could readily be placed just above the Fabry-Perot to restrict the field of view from 5.7 arc minutes down to less than one arc minute as desired. The light passed by the 150 mm Fabry-Perot was coupled by a 3:1 ratio afocal lens system to a lower resolution ($\delta\lambda \simeq 1.5 \mathring{A}$) 50 mm Fabry-Perot which was placed in series with any one of several 50 mm aperture interference filters with band-passes typically 15-20Å. The low resolution Fabry-Perot was used to suppress all but one of the narrow ($\delta\lambda \simeq 0.17 \mathring{A}$) transmission peaks of the large Fabry-Perot which fell within the passband of the interference filter. The Fabry-Perot etalons were housed in separate gas-tight chambers and pressure-scanned over spectral intervals up to 6Å using SF_6 as the scanning gas. An automatic pressure difference control system maintained the tune of the two Fabry-Perot etalons during scans. In order to monitor changes in sky brightness and atmospheric transmittance, about 4% of the light incident on the spectrometer was directed to a reference system containing a 100Å wide filter centered near the wavelength being scanned. The number of photons counted by the spectrometer and reference system during small equal wavelength scan intervals were punched on paper tape on command from an interferometric refractometer scanned in unison with the Fabry-Perot etalons. This method permitted the direct comparison and addition of scans for enhancing the signal-to-noise ratio.

Analyses of Hα line profiles and line intensities indicate that the mean outflow velocity of the hydrogen atoms was $7.8 \simeq 0.2$ km s^{-1} and that the hydrogen atom production rate varied from about 1.0×10^{29} s^{-1} to about 3.5×10^{29} s^{-1} for comet-sun distances between 1 AU and 0.4 AU, respectively. The identification of an H_2O^+ emission feature in certain Hα scans indicates that the H_2O^+ ions were moving in a tailward direction with a velocity of 20 to 40 km s^{-1} with respect to the comet nucleus. An upper limit of 1 part in 100 was found for the D/H ratio in the cometary atomic hydrogen cloud.

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For complete text see Ap. J. 202, 276, 1975

DISCUSSION

W. Jackson: In your slide on the oxygen ^1D you estimate 2×10^{28} as the production of O ^1D?

D. H. Huppler: On December 8, from a scan of oxygen with the two arc minute field of view, we estimate 2×10^{28}, singlet D oxygen atoms per second produced.

W. Jackson: Okay,

From that you can go and calculate what the water production rate should have been on that same day?

D. H. Huppler: If you assume that the only source of singlet D is H_2O, which we are not sure of. If you do that, then there must be the same number of water, right?

W. Jackson: No.

The branching ratio for dissociation into O ^1D and H_2 is roughly only one or two percent of the total dissociation of the H_2O molecule.

And if you do that, and look at your same number for H atoms, you get the same amount of H atoms produced as you get O ^1D.

Now either the O ^1D is produced, as you said, from some other source which either has to have a higher production rate for O ^1D than water or the H atom concentration has been grossly underestimated.

Right now from your measurements, the only way you could have that much O ^1D is if the O ^1D is produced by something else other than water, if you are going to believe your H measurement in terms of absolute measurements.

D. H. Huppler: Right.

Well, we tried to figure out if there was some way of connecting the two. Primary branching, you said was to OH, and what does OH break up into, if it does break up.

And we could not find enough things to determine if OH comes to singlet D. And then there is CO^+, CO, and other molecules containing oxygen for which we couldn't find whether they produced ^1D or not.

DISCUSSION (Continued)

W. Jackson: The O_2 does — we know that. And there is some evidence that CO_2 can produce O ^1D. If that is the case then in a way you have identified the fact that there is a substantial amount of material that could produce O ^1D other than water. Now the critical thing is how accurate is that H measurement? If that H measurement is off by an order of magnitude, and I think it is because it disagrees with the ultraviolet measurement, wouldn't you get about 10^{29} per second? That is just too much O ^1D.

R. Meier: The hydrogen production rates derived from the Balmer alpha observations are only about a factor of 2 lower than those derived from Lyman alpha observations. A solar Lyman beta line with a factor of two less central reversal can account for the difference, since the excitation flux in the wing of the line would be lower requiring a higher production rate by the same factor.

D. H. Huppler: We get 2×10^{28} for oxygen, about 3×10^{29} for hydrogen.

H. Keller: I have another question, concerning your production rate determination.

Did you take into account in your heliocentric dependence slides the field of view effect, and how large was the field of view?

D. H. Huppler: The intensities were 2-arc minute field of view because that was the majority of the data that we had.

And for the scans that we had taken with a 6-arc minute field of view we corrected them to a 2-arc minute field.

H. Keller: And did you change your field of view with geocentric distance?

D. H. Huppler: Yes. We also made geocentric distance corrections.

H. Keller: For the field of view effect?

D. H. Huppler: Yes. And they're both talking about the same thing, how much of the comet in kilometers you're looking at for a particular observation so they're all normalized to the 2 arc-minute field of view at 1 AU.

DISCUSSION (Continued)

H. Keller: Yes. What type of model did you use for it? That depends on the scale length of the species you look at.

D. H. Huppler: Well, for the change from a 6 arc-minute field of view to a 2 arc-minute field of view, we had several days in which both types of scans were taken, so it made it easy for other days when only 6 arc-minutes were taken, and we could just develop the number that we then have to correct the 6 arc-minute scans by, and then we made about the same correction for change in heliocentric distance, and since the scans were only between 0. 8 and 1. 2 AU heliocentric distance, an error in that will not be too great.

H. Keller: An empirical approach.

D. J. Malaise: When you showed the spectra of oxygen, you pointed out that several spectra were displaced by a certain distance in the head. In what direction were they displaced?

D. H. Huppler: You mean the 40 arc-second displacement. We saw nothing to indicate that there was any asymmetry of the head. So I don't know in particular where that scan was, but we looked and saw nothing that would indicate that sunward, tailward, or perpendicular had any asymmetry.

The hydrogen did have the asymmetry only in the tailward direction. If you go perpendicular to the axis - it looked just like the sunward scans.

D. J. Malaise: Yes. Because there was some suspicion that the oxygen line could extend into the tail, which is very funny, but could the O ^1D level be produced by dissociative recombination of some ion, H_2O^+, for instance, in which case you could observe the forbidden line to be asymmetric.

D. H. Huppler: It could potentially be there, but would be less than something like 10 percent of our signal, and so if you're looking for asymmetries of that size, we wouldn't have noticed them.

DISCUSSION (Continued)

M. Oppenheimer: Did you derive the production rate by saying that every produced oxygen atom leads to the emission of one photon?

D. H. Huppler: Yes. Because except for right in the center — right close to the head, the collision time is greater than 100 seconds. The densities get low enough fast enough that you would not have a collision.

M. Oppenheimer: How far from the head are we talking about were these observations?

D. H. Huppler: 40 arc-seconds is something like 20,000 kilometers for the field of view.

M. Oppenheimer: I just think the quenching — the chemical reaction rates for oxygen ^1D are very high, and you have to be very careful about that.

D. H. Huppler: Right. If it hits anything it's gone.

M. Oppenheimer: — and I think that even out at that distance it's possible that you're underestimating the production rate a little bit, depending on what model you use for the neutral densities. Plus the chemical rates are almost gas-kinetic, which means everything just goes.

N76-21062

SPECTROPHOTOMETRY OF COMET KOHOUTEK (1973f) DURING PRE-PERIHELION PERIOD

G. S. D. Babu

INSTRUMENTATION AND OBSERVATIONS

A total of eleven scans of the head of comet Kohoutek (1973f) were obtained during the pre-perihelion period with a photoelectric spectrum scanner (Babu, 1971), mounted at the Nasmyth focus (f/13.1) of the 52-cm telescope, on 7, 10, 11, 13, 14 and 15 December 1973 at the rate of two scans per day, except on 7 December when only one scan was taken. The observational procedure was similar to that for comet Bennett (1969 i) (Babu and Saxena, 1972), excepting that a diaphragm of 3 mm diameter equivalent of 93" of the sky was used at the entrance of the monochromator. The width of the exit slit was equivalent to a spectral window of 3.5 nm. The scans covered the spectral range from 370 to 640 nm. The basic data of the comet during the period of observations is given in Table I.

In addition, two late type stars, π Hya (K2 III) and β Crv (G5 III) were observed on each night to serve as comparison stars. Since β Crv is suspected to be a variable (Hoffleit, 1964), π Hya has been chosen as the comparison star.

The reduction technique is same as that used in the case of comet Bennett (loc. cit.) where all the measurements were normalised to 479 nm. In order to get the normalised relative magnitudes of the comet at each wavelength, the

D/6

TABLE I

Basic data of comet Kohoutek (1973f)

Date Dec.1973 U.T.	Δ (in a.u)	r (in a.u.)	Phase angle	m	Area of the sky at distance Δ admited through diaphram (in sq.km)	Radius of the circular region in sky at dist. Δ (in Km)
7.003	1.262	0.733	$51^{\circ}.2$	$+ 3^{m}.1$	56.72 x 10^{8}	4.249 x 10^{4}
10.011	1.217	0.655	$53^{\circ}.8$	$+ 2^{m}.5$	52.72 x 10^{8}	4.097 x 10^{4}
11.013	1.204	0.628	$54^{\circ}.6$	$+ 2^{m}.3$	51.62 x 10^{8}	4.053 x 10^{4}
13.015	1.181	0.573	$56^{\circ}.1$	$+ 1^{m}.9$	49.68 x 10^{8}	3.976 x 10^{4}
14.005	1.171	0.545	$56^{\circ}.7$	$+ 1^{m}.7$	48.84 x 10^{8}	3.942 x 10^{4}
15.011	1.163	0.516	$57^{\circ}.3$	$+ 1^{m}.3$	48.17 x 10^{8}	3.915 x 10^{4}

differential magnitudes (comet- π Hya)λ were obtained and then converted into intensities.

RELATIVE FLUX DISTRIBUTIONS

Figure 1 shows the mean relative flux distributions of the head of comet Kohoutek (1973 f) on various dates, the vertical lines showing the probable errors. In these the emission features of CN, C_3, CH, the principal Swan band sequences of C_2 and Na have readily been identified. After locating the continuum in the scans, (Swings and Haser, 1956), the areas of the emission band profiles were planimetered. The probable errors in these measurements are found to be less than 5%. These areas, which are identified with the total band intensities, are given in Table II along with the continuum intensities at 479 nm relative to the C_2 ($\Delta V = 0$) band sequence at 516 nm. The total energies streaming out of a cylinder with diameter corresponding to the diaphragm size and extending through the entire comet along the line of sight in C_2 ($\Delta V = 0$) band along with the observed fluxes are also given in the same table. The reduction was made by multiplying the observed flux by $4\pi\Delta^2$ (O'Dell and Osterbrock, 1962).

It is clear from this table that the intensity of Na emission steadily increased with the decreasing r during our observational period. This is similar to the case of comet Ikeya-Seki (1965 f) (Bappu and Sivaraman, 1967). However, it has been reported by Bappu et al. (1973) that in comet Kohoutek (1973 f) the Na emission was first noticed on 8.98 December 1973. But our observations show that Na was in emission even on 7.003 December 1973, though very faintly.

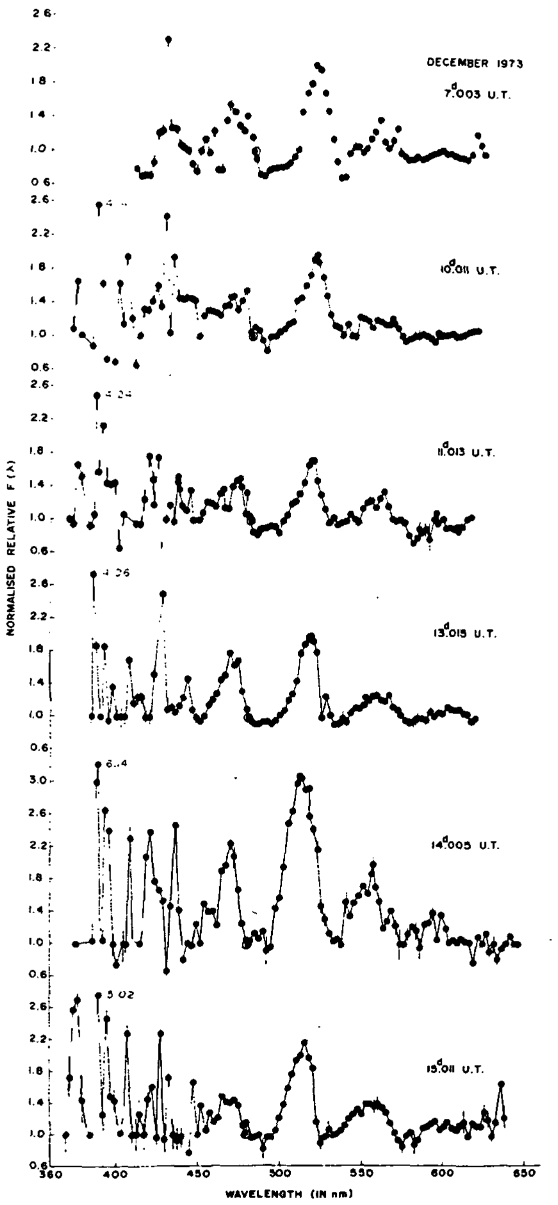

Figure 1: Relative flux distributions of the head of comet Kohoutek (1973 f) on various dates normalised to λ479 nm. The normalisation point is shown as a circle with a dot. Intensity at CN (λ 388 nm) is reduced to fit the plot and is given by the numbers adjacent to the peak. The vertical lines denote the limits of errors.

TABLE II

Relative fluxes of emission band sequences and continuum in the head of Comet Kohoutek (1973f)

Date Dec. 1973 U.T.	Apparent $F(C_2, \Delta V=0)$ (ergs cm^{-2} sec^{-1})	$F/F(C_2, \Delta V=0)$								$4\pi\Delta^2 F(C_2, \Delta V=0)$ (ergs sec^{-1})
		CN (388 nm)	C_3 (405 nm)	CH (428 nm)	C_2			NA (588 nm)	Continuum (479 nm)	
					$\Delta V=-1$ (474 nm)	$\Delta V=0$ (516 nm)	$\Delta V=+1$ (563 nm)			
7.003	2.164×10^{-7}	1.036	-	0.181	0.446	1.000	0.271	0.007	0.516	9.696×10^{20}
10.011	4.919×10^{-7}	0.745	0.093	0.180	0.652	1.000	0.317	0.009	0.566	4.753×10^{21}
11.013	2.173×10^{-7}	0.644	0.110	0.188	0.665	1.000	0.414	0.042	0.622	2.055×10^{21}
13.015	7.305×10^{-7}	0.638	0.110	0.476	0.693	1.000	0.440	0.081	0.535	6.647×10^{21}
14.005	9.369×10^{-7}	0.497	0.118	0.247	0.536	1.000	0.435	0.084	0.344	8.382×10^{21}
15.011	11.459×10^{-7}	0.448	0.146	0.174	0.700	1.000	0.496	0.104	0.543	1.011×10^{22}

Dobrovolskii (1961) has pointed out that the emissions due to C_2 and C_3 are less dependent on r when $r < 1.5$ a.u.. Since all our observations are obtained when r was less than 1.0 a.u., the fluxes due to these two homonuclear molecules are expected to be nearly constant as r decreased. But, in the present case, the absolute flux of C_2 emission at 516 nm and even the relative fluxes of C_2 emissions at 474 nm and at 563 nm show an increase with the decrease in r. Similar is the case with the C_3 emission at 405 nm. This is akin to the case of comet Rudnicki (1966 e) (Mayer and O'Dell, 1968). This increase in the fluxes can be explained only in terms of an increase in the abundances of C_2 and C_3 in the head of the comet due to some internal processes which depend on r.

The relative intensity in the CN band at 388 nm shows a steady decrease with decreasing r. This behaviour matches that of comet Bester (1947 k) (vide Swings, 1965).

The relative continuum intensities at 479 nm are weaker than those found in comet Ikeya-Seki (1967 n), Honda (1968 c) and Thomas 1968 b) as given by Gebel (1970). Even the relative continuum intensities of comet Bennett (1969 i) (vide Babu and Saxena, 1972) were stronger than the present values. Nevertheless comet Kohoutek (1973 f) is not void of continuum, thereby showing the presence of dust particles.

CONTINUUM ENERGY DISTRIBUTIONS

The continuum energy distributions in the head of comet Kohoutek (1973 f) on different dates along with those of π Hya and β Crv have been obtained independently, using γ Gem as a standard star. The calibration of γ Gem was taken from Wolff et al. (1968). The adopted monochromatic values relative to 479 nm are given in Table III and are plotted in Figure 2. The energy distribution of the sun (Arpigny, 1965) is also plotted in the same figure.

On 7 December, when the phase angle was about 51°.2, the energy curve of the comet is found to fall around midway between those of β Crv (G5 III) and the Sun (G2 V). On the later dates, as the phase angle increased, the energy curves of the comet approached that of Sun. During the last three days of our observations, they were found to nearly coincide with that of the Sun. It may be noted here that the phase angle of 57°.3 on 15 December was very close to the preperihelion maximum value of 57°.8 on 17 December. Thus the reddening of the scattered light coming from the head of the comet decreased as the phase angle increased, relative to the energy curve of sun, which compares with the case of Comet Bennett (Babu and Saxena, 1972). However, we have no usable observations available to us to study if this trend continued or not with comet Kohoutek after the comet went past its maximum phase angle on 17 December.

TABLE III

Adopted monochromatic magnitudes of comet Kohoutek (1973f), π Hya, β Crv and Sun normalised to 479 nm

Wavelength (in nm) / Date Dec.1973 U.T.	370	447	479	535	615	Name of the object
	m	m	m	m	m	
7.003	+0.544	-0.065	0.000	+0.087	+0.086	Comet Kohoutek (1973f)
10.011	+0.398 ±0.20	-0.085 ±0.12	0.000	+0.107 ±0.08	+0.116 ±0.12	
11.013	+0.491 ±0.02	-0.022 ±0.18	0.000	+0.130 ±0.05	+0.229 ±0.07	
13.015	+0.256 ±0.25	-0.025 ±0.10	0.000	+0.167 ±0.04	+0.426 ±0.08	
14.005	+0.348 ±0.10	-0.121 ±0.20	0.000	+0.158 ±0.04	+0.374 ±0.05	
15.011	+0.262 ±0.25	-0.122 ±0.00	0.000	+0.215 ±0.03	+0.478 ±0.10	
	+1.012 ±0.15	+0.272 ±0.06	0.000	-0.261 ±0.02	-0.635 ±0.03	π Hya
	+1.544 ±0.08	+0.250 ±0.02	0.000	-0.211 ±0.01	-0.446 ±0.01	β Crv
	+0.51	-0.05	0.000	+0.15	+0.43	Sun

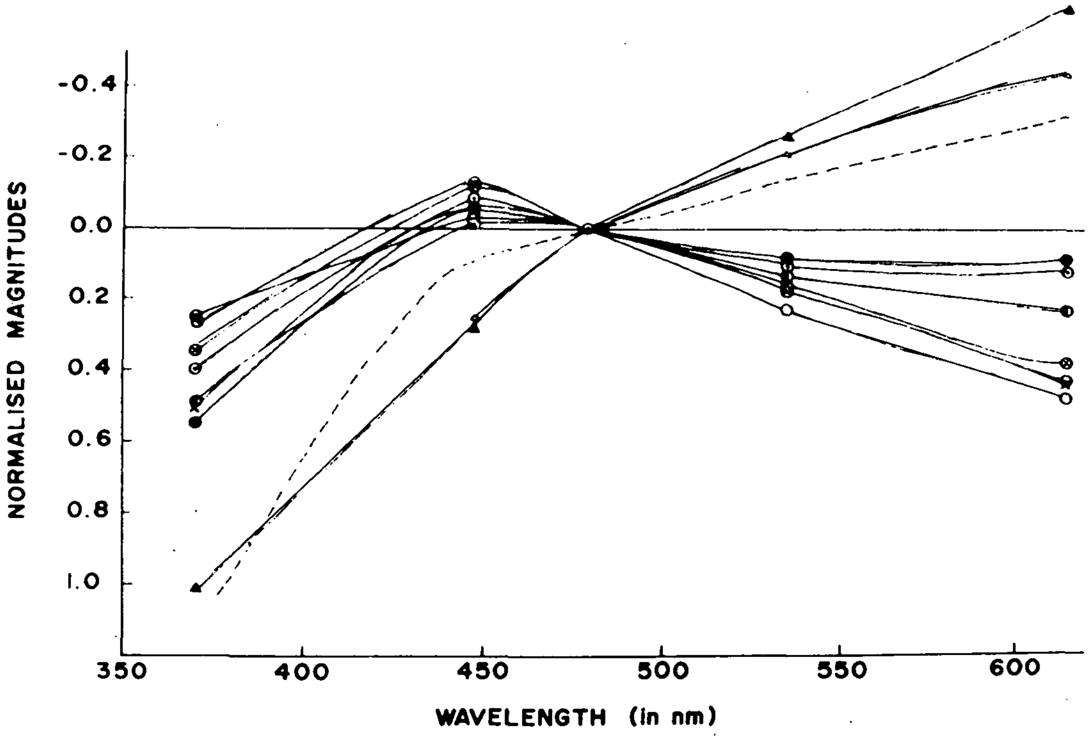

Figure 2: Continuum energy distribution curves of the head of comet Kohoutek (1973 f), which are denoted by circles in the following manner: ● for 7.003 December, ⊙ for 10.011 December, ◐ for 11.013 December, ⊖ for 13.015 December, ⊗ for 14.005 December and ○ for 15.011 December, 1973, compared with those of π Hya (▲), β Crv (△), Sun (X) and solar light scattered according to λ^2 law (------). All curves are normalised to 479 nm and the Balmer discontinuity is smoothed out.

In the previous studies, however, some comets are known to have had a pure reflection continuum, in the sense that the continuum spectra were unreddened with respect to that of the Sun (Arpigny, 1965; Gebel, 1970), whereas some others were found to produce reddened scattered continuous spectra matching those of late type stars around G8 (Bappu and Sinvhal, 1960; Kharitonov and Rebristyi, 1974; Liller, 1960; Vanýsek, 1960; Walker, 1958).

Arpigny (1965) has pointed that the dust grains in comets possibly have a certain range of sizes and the predominant size could be different in different comets. This could produce both reddened and unreddened scattered continuous spectra in the respective comets. Also, assuming dielectric particles and a narrow distribution function of sizes, the selectivity of scattered light depends strongly but not monotonously on the phase angle*. But, it is not known whether the size distribution function and the predominant particle size are varying or not in a given comet along its path around the sun.

To find out the effect due to the variations in the physical parameters only on the intensity in a particular wavelength, the phase angle effect must be separated out from the total. We believe, in principle, it is possible to use appropriate scattering functions for various size distributions of particles and find out the variation of the intensity at a particular wavelength in a given phase angle. This being a complicated program, the same has not yet been attempted.

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N76-21063

RADIO DETECTIONS OF COMETARY MOLECULAR TRANSITIONS: A REVIEW

L. E. Snyder

I. INTRODUCTION

The various radio searches for cometary molecules finally came to fruition with the radio detections of CH, OH, HCN and CH_3CN and several unidentified species in Comet Kohoutek (1973f) and the detection of H_2O emission from Comet Bradfield (1974b). As a result of these detections we have learned something about why past radio searches of other comets for molecules were less than successful. Also, it is now possible to identify and discuss some of the similarities and differences between cometary molecules and interstellar molecules, particularly with regard to the excitation and chemistry. Finally, given the observed projected densities and resulting gas production rates, the feasibility of future radio molecular observations of comets can be discussed.

II. THE IDENTIFIED RADIO MOLECULES

All of the identified radio molecules have been found in two comets, Kohoutek (1973f) and Bradfield (1974b), and are listed in column 1 of table 1. Column 2 gives the quantum numbers of each detected transition and the corresponding rest frequency is in column 3. Column 4 lists the antenna temperature for each line and column 5 shows whether the radio line was detected in emission (E) or absorption (A). The antenna half-power beamwidth (HPBW) is in column 6 and the reported date of the observing period is in column 7. Column 8 has the approximate ratio of the heliocentric distance R to the geocentric distance Δ for the period of observation. Column 9 gives the calculated projected density N (molecular density per cm^{-2}

Table 1
Radio Detections of Identified Cometary Molecules

Molecule (1)	Transition (2)	ν (MHz) (3)	T_A (K) (4)	A/E (5)	HPBW (6)	Date (7)	R (AU)/Δ (AU) (8)	N (cm^{-2}) (9)	Reference (10)
					COMET KOHOUTEK (1973f)				
CH_3CN	J,K=6,0-5,0 (V_8)	110,712.2	0.6	E	67"x63" NRAO	1973,1&5 Dec	0.9/1.4	3×10^{16}*	Ulich and Conklin (1974)
	6,3-5,3 (V_8)	110,709.6	0.4	E	36-ft.				
HCN	J=1-0,F=2-1	88,631.8	0.8	E	75" NRAO	1973,15-16 Dec	0.5/1.2	1.5×10^{13}*	Huebner, Snyder & Buhl (1974)
					36-ft.	1974, 3-6 Jan	0.3/0.9		
CH	J=1/2,F=1-1	3,335.5	0.2	E	14" HCO 25.6-m	1974, 2-7 Jan	0.3/0.9	4×10^{14}**	Black et al. (1974)
OH	J=3/2,F=2-2	1667.4	0.09+	A	3.5'x19'	1973 Dec	<0.7/1.2>	3.3×10^{12}	Biraud et al. (1974)
	F=1-1	1665.4	0.07+	A	Nancay				
	F=2-2	1667.4	0.09+	E	Meridian	1974 Jan	<0.75/0.8>	4.1×10^{12}	
	F=1-1	1665.4	0.05+	E					
					COMET BRADFIELD (1974b)				
H_2O	$J_{K-K+}=6_{16}-5_{23}$	22,235.1	0.15	E	1.5' NEROC 120-ft	1974,9 May	1.22/1.15		Jackson, Clark and Donn (1975)

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* total projected density calculated assuming Boltzmann statistics

** projected density for the ground state lambda doublet

\+ peak antenna temperature

integrated along the line-of-sight) and the detection references are listed in column 10.

Several interesting points are shown by table 1. Three of the cometary molecules were detected in the millimeter wavelength region (CH_3CN at 2.7 mm, HCN at 3.4 mm and H_2O at 13.5 mm) while the remaining two were detected in the older, more developed centimeter wavelength region (CH at 9 cm and OH at 18 cm) of the radio spectrum. Thus the millimeter wavelength region is proving to be very useful for the detection and study of cometary molecules. Given the noise limitations of currently available millimeter and centimeter radio receivers, all of the detected cometary radio lines had antenna temperatures T_A (see column 4) which were close to the detection limit and were weak when compared with most of the current interstellar molecular observations. This suggests that for future comet searches successful molecular detections will require a projected density in excess of about 10^{12} molecules per cm^{-2} averaged over the half-power beamwidth. Of course if the antenna beam is larger than the cometary molecular cloud, the projected density required for detection in the optically thin case will increase in proportion to the square of the ratio of the beam diameter to the molecular cloud diameter. Thus the typically smaller beamwidths in the millimeter spectral region (see column 6) considerably reduce the beam filling factor and allow the detection of polyatomic cometary molecules which have low projected densities. Successful radio molecular observations of Kohoutek were made for R less than 1 AU (see column 8), when the molecular production rate was high, and for Δ no greater than about 1.4 AU so beam dilution was not excessive for the molecular species of interest.

The detections of CH_3CN (Ulich and Conklin 1974), HCN (Huebner, Snyder and Buhl 1974) and H_2O (Jackson, Clark and Donn 1975) were the first radio observations of expected parent or mother molecules in comets (Potter and Del Duca 1974; Huebner 1970) but because of the possibility of nonequilibrium excitation, the projected densities and resulting production rates for these molecules must be interpreted with caution. For example, CH_3CN was detected and observed with good signal-to-noise only in the vibrationally excited $V_8 = 1$ state which is approximately 500K above the zero-point energy. It should be noted that vibrationally excited CH_3CN never has been detected in the galactic molecular clouds; the only remotely comparable microwave transitions observed in galactic sources are the emission lines from rotational transitions of the vibrationally excited SiO maser (Snyder and Buhl 1974; Davis et al. 1974; Thaddeus et al. 1974; Buhl et al. 1974) which originate in circumstellar envelopes of late-type stars. Approximately two weeks after the CH_3CN $V_8 = 1$, $J = 6$-5 transitions were observed by Ulich and Conklin (1974), Buhl, Huebner and Snyder (1975) searched for both $V_8 = 1$, $J = 5$-4 and ground vibrational state $J = 5$-4 lines of CH_3CN. The detected CH_3CN lines were strong enough to confirm the Ulich and Conklin (1974) detection but the signal-to-noise ratio was so low that the new data were not sufficient to serve as an independent identification of cometary CH_3CN (see Figure 2 in Buhl et al. 1975). The ground state lines did not have the intensities which would be expected from a Boltzmann distribution. Hence both the high excitation temperature required by $V_8 = 1$ and the transient nature of the signal strength suggest that the CH_3CN $V_8 = 1$ excitation was time-varying. Therefore the projected density (column 9, table 1) and production rate of $\sim 10^{30}$ obtained by assuming a Boltzmann distribution over vibrational states of CH_3CN probably are too large and a more meaningful production rate is $\sim 10^{27} - 10^{28}$ s^{-1} obtained from the weak ground state signal (Buhl et al. 1975). Evidence of time-varying emission also was found for HCN. The data of Huebner et al. (1974) show multiple HCN Doppler components. A component with zero shift showed increases as well as decreases in the daily average while other components appeared and disappeared during the observations. Because there was no observed evidence for nonequilibrium excitation of HCN and because the observations lacked spatial resolution, the calculated production rates of 1.2×10^{28} s^{-1} (for $r_o = 10^4$ km) to 3×10^{27} s^{-1} (for $r_o = 3 \times 10^5$ km) are based on two assumptions: a Boltzmann distribution and isotropic outstreaming of the gas (Snyder, Huebner and Buhl 1975). The difficulties of calculating an H_2O production rate from the radio observations of Comet Bradfield (Jackson et al. 1975) are due to both the high excitation (447 cm^{-1}) required to populate the 6_{16} level and the relatively long radiative lifetime for the $6_{16} - 5_{23}$ transition. As a result, H_2O production rates found from applying Boltzmann statistics to radio observations tend to give numbers that are too high and a more realistic production rate probably is around 10^{28} (see table 1 of Jackson et al. (1975)).

Radio observations of cometary OH promise to be useful for studying radiative pumping models of OH and hence may be directly applicable to current research on galactic OH source excitation. In 1973 December, Biraud et al. (1974) detected OH absorption in Comet Kohoutek at 1665 and 1667 MHz. Turner (1974) used the NRAO 140 ft. telescope to confirm their observations while the comet was still approaching perihelion. After perihelion, however, Biraud et al. (1974) found that the OH reappeared in emission and that ultraviolet pumping of the ground state lambda doublet could roughly account for the observed OH intensities as a function of time.

III. THE UNIDENTIFIED RADIO MOLECULES

Two groups of radio observers found unidentified lines while searching Comet Kohoutek for other molecules. Giguere and Clark (1975) were using the NRAO 140-ft. telescope to search for the 8190 MHz line of OH when a weak unidentified emission feature at 8188.82 MHz was detected. J.K.G. Watson (1974) has suggested that this line may be one component of the $6_{16} - 5_{23}$ rotational transition of the NH_2 radical. Buhl, Huebner and Snyder (1975) were using the NRAO 36-ft. telescope to search for vibrationally excited SiO when fairly strong unidentified lines at 86,247.1 and 89,010.5 MHz were found. They present arguments that the 86,247 line can not be assigned to nearby transitions of ethanol, acetone or vibrationally excited silicon monoxide and suggest that one or both lines may belong to unstable species which are decay products of more complex molecules.

IV. NEGATIVE RESULTS

In recent years numerous cometary searches have been conducted at several radio observatories but not all of the negative results have been formally reported. The reported negative results (which I am aware of at present) are ordered by frequency in table 2. Column 1 lists each molecule and indicates when a vibrationally excited state was sought; column 2 gives rotational quantum numbers and column 3 the corresponding rest frequency. Column 4 lists the upper limit reached for the peak-to-peak antenna temperature T_A except when noted otherwise; column 5, the radio telescope used; column 6 the half-power beamwidth (HPBW) in arc minutes; and column 7, the reference.

It should be noted from columns 4 and 5 that very low antenna temperature limits were reached for H_2O, H_2CO, NH_3 and $CH_2(CN)_2$ using favorable

Table 2
Reported Negative Results

Molecule (1)	Transition (2)	ν (MHz) (3)	T_A (K) (4)	Telescope (5)	HPBW (6)	Reference (7)
COMET BENNETT (1969i)						
H_2CO	$1_{11}-1_{10}$	4,829.7	0.30	NRAO 140-ft	6.6	Huebner and Snyder (1970)
H_2O	$6_{16}-5_{23}$	22,235.1	2.5	NRL 85-ft	2.3	Clark *et al.* (1971)
COMET KOHOUTEK (1973f)						
H_2CO	$1_{11}-1_{10}$	4,829.7	0.03*	MPI 100-m	2.6	Schroder *et al.* (1974)
OH	1/2,F=1-0	4,765.6	0.03*	" "	"	" "
OH	5/2,F=3-3	8,189.6	0.20	NRAO 140-ft.	3.6	Giguere and Clark (1975)
HC_3N	1-0,F=2-1	9,098.3	0.15	" "	3.2	" " "
$HC_3N(2\nu_7)$	1-0,F=2-1	9,156.1	0.25	" "	"	" " "
$HCN(\nu_2)$	6, ℓdoub.	9,423.3	0.40	" "	3.1	" " "
H_2O	$6_{16}-5_{23}$	22,235.1	1.07	MPI 100-m	0.7	Churchwell *et al.* (1975)
	"	"	0.02	ARO 26-m	1.4	Avery and Andrew (1974)
	"	"	nr**	NEROC 120-ft	1.5	Jackson *et al.* (1975)
NH_3	3,2	22,834.2	0.03	ARO 46-m	1.4	Avery and Andrew (1974)
$CH_2(CN)_2$	$7_{16}-7_{07}$	23,084.2	0.04	ARO 46-m	"	" " "
NH_3	1,1	23,694.5	0.7	MPI 100-m	0.7	Churchwell *et al.* (1975)
CH_3OH	4_2-4_1	24,933.5	0.75	" "	"	" "
CH_3C_2H	5_0-4_0	85,457.2	0.4	NRAO 36-ft.	1.3	Buhl *et al.* (1975)
$(CH_3)_2O$	$2_{20}-2_{11}$	86,222.9	0.4	" "	"	" "
SiO(V=1)	2-1	86,243.3	0.1	" "	"	" "
HNCO	$4_{04}-3_{03}$	87,925.2	0.3	" "	"	" "
HNCO	$4_{13}-3_{12}$	88,239.0	0.4	" "	"	" "
$HCN(2\nu_2)$	1-0,F=2-1	89,087.9	0.3	" "	"	" "
X-ogen(HCO^+)	1-0	89,188.6	0.3	" "	"	" "
"HNC"	1-0	90,665	0.3	" "	"	" "
HC_3N	10-9	90,979	0.4	" "	"	" "
CN	1-0	113,491.0	0.2	NRAO 36-ft.	1.1	Ulich and Conklin (1974)
CO	1-0	115,271.2	0.5	" "	"	" " "

* brightness temperature limits
** not reported

beamwidths without achieving detections in Comet Kohoutek. The well known small error in the topocentric ephemerides used by most radio observers has been discussed by several authors (e.g. Avery and Andrew 1974) and probably it had little effect on the outcome of most observations. However, ephemeris accuracy is most essential for compact sources and the high excitation required by the $6_{16} - 5_{23}$ H_2O line suggests that in most comets it will be found only in a rather compact region. Thus, both the weak intensity of the H_2O emission reported by Jackson et al. (1975) from Comet Bradfield and the generally low elevation of Comet Kohoutek suggest that atmospheric H_2O attenuation coupled with a small pointing error may have been responsible for the negative H_2O results found for Comet Kohoutek.

The upper limit for H_2CO emission found by Schroder et al. (1974) for Comet Kohoutek was at least 100 times more sensitive than the upper limit found by Huebner and Snyder (1970) for Comet Bennett because of the narrower beam width used for the Comet Kohoutek search. Detection of the $1_{11} - 1_{10}$ H_2CO transition in comets may not be as straightforward as it appears, however, because if the excitation conditions are similar to the typical interstellar case, then the H_2CO pumping mechanism may force the absorption mode to predominate. The OH observations and radiative pumping calculations of Biraud et al. (1974) suggest that preperihelion searches for H_2CO absorption may be more successful than postperihelion searches in future comets.

V. SUMMARY

We have learned that successful radio spectroscopy of comets almost always requires going to the detection limits of current instrumentation, which corresponds to a projected number density (in the initial energy level of the transition) of approximately 10^{12} molecules per cm^2. Many of the radio observations appear to be consistent with a straightforward application of the fluid dynamic model (Huebner and Snyder 1970; Clark et al. 1971) with the possible exception of H_2O (as discussed by Jackson et al. (1975)) and other molecules requiring unusual excitation for radio detection. Thus for most molecules of interest, reasonable estimates for the success of future searches can be obtained by starting from an expected production rate estimate, possibly based on the Comet Kohoutek results, and working backward to see if a projected density above $\sim 10^{12}$ cm^{-2} can be reached without excessive beam dilution.

Several of the successful radio detections have demonstrated that not all radio lines lead to a physically meaningful production rate due to the excitation conditions required for detection. Hence, as in the study of galactic molecular sources, non-LTE mechanisms will have to be introduced to explain the radio observations of both high lying transitions (e.g. H_2O and vibrationally excited CH_3CN) and of easily inverted transitions (e.g. OH and possibly H_2CO). As a result, we can now start thinking about using future cometary observations to uniquely test several of the molecular pumping models which have been proposed for galactic molecular sources.

The unidentified lines found in Comet Kohoutek were at least as strong as the identified lines nearby in the spectrum and have not, as yet, been detected in the galactic molecular sources. This suggests that the radical and molecular ion chemistry of comets should be given more attention in the radio spectrum. In fact, it may be more interesting if radio astronomers in the future performed a few frequency scans on comets instead of limiting themselves to grinding away on known transitions of stable molecules.

Finally, as a practical consideration, we have learned that both a good set of radio ephemerides and coordination among various groups of radio observers are essential to success. It is doubtful that I would have as many cometary radio detections to discuss in this review had it not been for the efforts of Drs. T. A. Clark (NASA), D. K. Yeomans (Comp. Sci. Corp.), B. G. Marsden (SAO) and others in preparing and distributing useful ephemerides especially designed for radio observers. The exceptional coordination between various radio observers and observatories optimized the use of valuable radio telescope time and was due mostly to the work of Drs. W. E. Howard (NRAO), S. P. Maran (NASA), and R. W. Hobbs (NASA). Without their efforts, many of the radio molecular observations of Comet Kohoutek would not have occurred.

I wish to thank the many radio observers who sent me their comet results for use in this review and acknowledge partial support for this work from NSF grant GP-34200 to the University of Virginia.

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DISCUSSION

H. Keller: I would like to ask if you would define a flare, and also do you have any idea what the scale length of H_2O was?

L. Snyder: Okay. Your second question, I think should be directed to Jackson, who's sitting here.

The first question - I can define a flare as anything that excites a vibrationally excited state. In this case we think it may have been a knot that started passing from the head of the comet to the tail about the 1st of December. But you can take the usual definition of flare and see what it does in the radio spectrum, or you can take the radio definition and then say if this excitation is unusual, it's certainly flaring in the radio.

L. Biermann: Could you say anything concerning the upper limit for the production rate of CO given by Conklin and Ulich? It's dipole moment is very small.

L. Snyder: They gave upper limits for CN and CO. First of all, I'd just like to say a word about the upper limits. Given the current state of telescope technology and receiver technology, if you can't see a molecule, the upper limit on the projected density for the state of interest usually comes out to be about 10^{11} or 10^{12}, This in turn, given reasonable cometary dimensions and a ground-state rotational transition, will invariably lead to a production rate on the order of 10^{26} or 10^{27}. But what I think happened in the CN upper limit, was that they got a beautiful spectrum of vibrationally excited CH_3CN, two K components. And if I were to guess, I would say that if one could remove the methylcyanide lines, one might see a velocity broadened CN line.

L. Biermann: What about CO?

L. Snyder: A production rate less than 10^{29} would be consistent with the CO negative results.

Voice: Is that a ground state transition?

L. Snyder: Yes. 1-0.

F. L. Whipple: I want to congratulate Dr. Snyder and all the workers here, but I wanted to remove one misapprehension, at least in my opinion. I think that's off the record that we consider cometary astronomy in a very bad state.

(Laughter.)

DISCUSSION (Continued)

L. Snyder: You mean it's come full circle.

F. L. Whipple: It hasn't gotten very far yet.

(Laughter.)

W. Jackson: I wanted to make a few comments about the radio observations. One is that the comet Bradfield production rates, as we realized, are completely ridiculous, in terms of the water production rate. I think that it points up the fact that what we may be seeing is a reflection of the excitation mechanism. Even the production rate for methylcyanide as calculated originally by Ulich and Conklin, and I think that's the original number, is too low if you use reasonable values of the radius of the comet - I mean I think they use something like 10 kilometers or 20 kilometers for the radius of comet Kohoutek, and I think something more reasonable is like 5. The signal goes as the square of the radius of the nucleus, so even that suggests that indeed methylcyanide must be produced either in a flare or in a nonequilibrium mechanism, as the vibrational excitation indicates.

The beam dilution, it turns out, is really a function of the lifetime of the cometary species; the beam dilution in formaldehyde is greater than the beam dilution in water, or it should be.

L. Snyder: It's also a function of wavelength and telescope diameter, so if you put the proper configuration -

W. Jackson: Yeah. Okay, okay, I agree. — But I'm just saying the overall cloud size is going to be dependent upon the photodissociation rate. And it turns out for water the photodissociation rate ought to be almost a factor of 4 lower than the photodissociation rate of formaldehyde.

H. Keller: What is the photodissociation rate for H_2O?

W. Jackson: The lifetime I get is something like 2 times 10^4 seconds. And for formaldehyde it is 5 or 6 times 10^3 seconds.

H. Keller: At one AU?

W. Jackson: One AU. Everything I say is referred to 1 AU.

I've puzzled over why we saw water in Bradfield rather than water in Kohoutek. If I may go to the board for a minute, I think part of it may be due to the way we were pointing in Bradfield.

DISCUSSION (Continued)

I don't know much — I'm not really a radio astronomer, but I was up there for both of the observations, and in Kohoutek, if this is the earth —

We were pointing the telescope at low elevation through a large atmospheric mass. The comet was down close to the horizon all the time.

Bradfield was much higher - near the pole, and was circling around the pole. Now, the noise in the case of Kohoutek increases measurably compared to the noise for Bradfield.

The effectiveness of the integration is much better for Bradfield because even though we may have integrated for 4 or 5 hours on Kohoutek most of it was under conditions where I would say that the signal to noise ratio was poorer than under the 4 or 5 hours for Kohoutek.

L. Snyder: Okay. If you combine this, a τ secant Z for the atmosphere correction, say, with even a quarter of a beam width mispointing, the signal could disappear in the noise very easily. I'd just like to add a little bit to that, and I think that the nonequilibrium detections - methylcyanide, water vapor, HCN - I think are going to prove to be very important for understanding what happens in the interstellar clouds. Because if you consider for a minute — if you get enough telescope time and enough observational time, as the French did on the OH, as you track the comet, and as you can see signal variations with heliocentric distance, it gives you very direct measures, then, on what the UV pumping, for example, is doing to a particular molecule. You just can't do it in the interstellar medium.

I think it's a very promising area of future research, which has come out of this.

G. Herzberg: May I ask to what extent you guard — you have to guard against accidental overlapping of some background source. I mean your comet, while you are averaging for several hours, goes over a lot of the sky. Now, there may by chance be —

L. Snyder: That's right. That's right.

Now, the primary way we guard against this is by looking at each scan as it comes in, before we do any stacking, do very careful editing. The secondary way we guard against it is to make sure that we are clear of the known sources, and then a third way, if any detection is suspect, the common way is just to go back and point in that direction after the comet's gone by. And if there's a source there, then the signal will come in even though the comet's gone.

DISCUSSION (Continued)

E. Ney: Maybe this is crazy, but what makes infrared so easy is that you can find a comet in the daytime, peak up on the signal, get the telescope tracking, and then go integrate on hard wavelengths.

What are the chances that you'll find something bright in the radio to track on? For example, broad band thermal emission from the dust?

L. Snyder: There were several thermal emission experiments tried at various frequencies, and I think the only one that was successful was the interferometer experiment of Hobbs and Maran and Webster and — who else was on it — at Greenbank. And when I talked to Bob Hobbs a few minutes ago, they were still squabbling over the results, because again, it's a very, very weak signal. It's less than 70 flux units, Bob says.

E. Ney: It's just not bright.

L. Snyder: There's nothing bright, given present receivers. Now, if we can cut receiver noise maybe in half, maybe the time will come when we could do that. But given the beam dilution and given the receivers, it's a pretty impossible job. We can't even map now, given our beams and our signal to noise.

We'd like to reach the place where we could map on comets, too, which is a sensitivity problem.

So as far as I know — Dave, did you have something to add to that?

D. Buhl: There was — I believe it was the French group detected the comet at 1 millimeter in the continuum. If the receivers are improved considerably, 1 millimeter might be the frequency for that type of thing.

P. Wehinger: In regard to the background noise that you were commenting on, in the case of Bradfield, it was going through the galactic plane as a background noise. Are there any problems with this compared to the case where Kohoutek was well out of the galactic plane?

L. Snyder: Why don't you ask the man who owns one, sitting in front of you? Jackson did the Bradfield observations.

W. Jackson: Well, the way the radio observations are done, we are looking first where we expect the comet to be 10 minutes later. And then we're looking where the comet is now. So if it was in a galactic noise source, the background signal measured ten minutes earlier would have included the galactic source also. Subtracting the background would eliminate the galactic source.

L. Snyder: All right. You're beam switching there?

W. Jackson: Yes.

B. G. Marsden: I'd just like to distinguish between errors in the ephemeris and errors in the use of the ephemeris.

(Laughter.)

How accurately do you actually want the ephemeris?

L. Snyder: Well, okay. I brought along some numbers. It seems to me that if we're going to probe the nucleus of the comet, we want to probe at millimeter wavelengths.

This means that our largest beam width will be on the order of 80 seconds of arc, and our smallest one, for all practical purposes, given today's telescopes, will be about 40 seconds of arc. So we don't want anything probably more accurate than 10 seconds of arc, because that's the pointing accuracy limit, but if you could take it down to the pointing accuracy —

B. G. Marsden: Down to 30 seconds, say.

L. Snyder: Well, 10 seconds would be great —

B. G. Marsden: Then down to 10 seconds.

L. Snyder: Right.

B. G. Marsden: The custom is, of course, that ephemerides are published by combining the geocentric coordinates of the earth for universal midnight, or ephemeris midnight, with the heliocentric coordinates of the comet for that time. Now, this is absolutely useless, because nobody ever observes that, but this is the convention. What you really want, I suppose, is for us to antedate the heliocentric coordinates of the comet by the light-time, and produce an astrometric ephemeris.

But even then you'd be getting into trouble with parallax, if you aren't already when you're getting down to it at ten seconds. But this is the convention of the IAU; I suppose we have to ask Commission 20 if it will change its convention.

L. Snyder: Yes, well, times are changing in radio, so I think it would be a fair request, because as Jackson points out, when you have a low-lying comet, and you're trying to do water, and in addition you have a half a beam width error, as this pair of slides showed, it can just take the signal right down into the noise. And in fact, there was some hint of a signal on water in Kohoutek; but it really couldn't be proven, couldn't be verified above the noise.

Isn't that correct?

W. Jackson: Yes, There are some measurements that hint that there might have been some water present. But not enough that you could look at it and say with confidence, especially since I'm not a radio astronomer.

L. Snyder: And this optical checking business probably isn't any better than a beam width where it's tracked with the telescope mounted beside the radio telescope, because the axes don't exactly coincide.

B. G. Marsden: Well, we have provided in a few cases on request, specialized ephemerides for certain people, actually for the location of their radio telescope. How useful is it to do this after the event?

L. Snyder: Then it's usually too late. Except for the cases where we have a strong signal of an unidentified feature and we want to get the rest frequency on it and determine whether it's ethyl alcohol or acetone or what have you.

B. G. Marsden: Did you have ethyl alcohol, perhaps?

L. Snyder: I have an announcement from the Washington Post here that I could read, but I won't.

(Laughter.)

W. Jackson: I'd like to make one more comment about the radio measurements in the nonequilibrium excitation mechanism. If you examine the infrared measurements of Meisel as I originally saw them — and I'm quoting from a preprint — the original CN to OH concentration was such — by the infrared measurements — you would predict that there was more CN in the comet than OH.

DISCUSSION (Continued)

And this depended, as I understood the analysis, on a thermal mechanism for the production of the CN infrared emission. That contradicts the UV measurements as we know them, of CN and OH. We understand the excitation mechanism of the CN and OH emission in the UV region.

All I'm trying to say, really, is that one of the exciting things about the possibilities of observing comets in the infrared and radio regions, it may lead to more information about the chemistry of comets, since you are measuring transistions that may be excited by new mechanisms.

M. Mumma: I'd like to say a few words on that, which bear also on the question of the accuracy of the ephemerides. This winter a group of people here at Goddard, and also at NRAO, including Dave Buhl, myself, Ted Kostuk Steve Cohen and Peter von Thuna, from Arthur D. Little, built a new instrument called an infrared heterodyne spectrometer, which promises the ability to measure IR emissions from parent molecules in the inner coma, with 5 arc second resolution in the neighborhood of 10 microns.

This is obviously going to be an important new tool for study cometary processes, and it's one that is now available.

So I would say to Brian that we could use ephemerides that reflect the pointing accuracy that we can now achieve with this instrument.

Voice: I hate to sound skeptical, but I just wonder what criterion you use for the identifications you have in the microwave spectra. For example, can you tell me how many random noise spectra you would feed in for each identified spectrum? In other words, is the chance 1 in 10, 1 in 20 of this being spurious?

L. Snyder: In our own particular data, I think that the unidentified spectra stand alone, in that we have significantly no scans in which they're not showing up above the noise level. So I don't think we have a statistical problem there.

In the HCN data that we report, our common practice is to break the scans into groups, stack the groups and see if we can still see the line, and then try mixing the groups from different days, and see if we can still see the line. In the case of the central features in the HCN, which are all above the noise, we can.

Now, in the case of the methylcyanide data (both the $V_8 = 1$ state and the ground state data) if the features that were appearing at about 2 to 1 or 2.5 to 1 did not match the velocity which had been reported, say, a couple weeks earlier with about 4 to 1 signal to noise by Ulich and Conklin, then we couldn't even report them. I show them here as a confirmation of their detection, but they do not qualify as independent of their detections.

But I don't really think that's the point in identifying a radio line. Or if it is, it doesn't explain enough. In order to identify a radio line, first of all, as we've discussed earlier, you have to make sure the pointing is on the comet and not on some galactic object. And then you have to go through a series of local oscillator shifts, and see if the line moves as you shift the local oscillator. If it moves in your filters or your autocorrelator, because you're moving the box around an absolute spectrum, so as you shift one way the line should move one way, and as you shift the other way the line should move the other. Any real feature that's coming in, say, from the comet or a galactic source, will move, and any noise feature will not move. And when you build up signal to noise on a feature that moves several times. The statistical argument, then, boils down to what the proper intensity is in terms of signal noise.

E. Ney: I'm afraid this may even be almost insulting, but I assume that you handled differential refraction. You have to have your ephemeris, of course, but you have to also put in refraction.

L. Snyder: Well, we take that out with our pointing.

That's integral to our pointing procedure.

E. Ney: But differential refraction, as you track down toward the horizon — what do you do about that?

L. Snyder: Well, as we track down toward the horizon, we try to correct our pointing accordingly.

E. Ney: Toward the differential refraction?

L. Snyder: We know where we're trying to point, and we know where our objects are that we have as standard check objects. I think that question has come up before on Bennett and I think that's the best answer I can give you for now.

E. Ney: But it's big. You go another air mass and it's another minute of arc, so if you're pointing at an ephemeris position you'll be out of the beam.

D. Buhl: (inaudible)

DISCUSSION (Continued)

L. Snyder: What Dave Buhl said was that it's in the telescope pointing program, and it's a problem that you have with any kind of source. It's essentially taken care of in a series of pointing sections every few months and it's programmed in.

Does that answer your question? Okay.

Because — well, yes, that's a good point. We track galactic sources over the horizon, for example, quite commonly, and I must say that the horizon pointing, which takes into account differential refraction, sometimes is much better than the zenith pointing. We sometimes get better signal to noise as the source is going over the horizon than we do at zenith on the 36-foot telescope.

So I'm happy that the corrections are proper from the data that I've seen in the past.

W. F. Huebner: Two models are being proposed for the formation of comets. One of them deals with the formation in the solar nebula. The other one, in a companion nebula, the composition of the comet would therefore be different in both of them.

If the formation of the comet were to occur in the solar nebula, you would expect chemistry which is more like equilibrium. I put the emphasis on "more like," not on "equilibrium."

Can you tell us what the ratios are of the "exotic molecules" to H_2O in interstellar space? Because I think that would be an important criterion to differentiate between the two models.

L. Snyder: Okay, I can give you some numbers. But one thing to keep in mind, which I pointed out before, that given the models, probably the only molecule that we have going here that'll give you a somewhere near legitimate production rate, is one that involves low-lying transitions in the ground-rotational state, and that's HCN at this point.

So in the future we can choose our molecules particularly for production rate calculations, it would seem to me. In terms of comparing the interstellar medium to the comet, of course we get varying numbers as we go around the interstellar medium, but if we pick the Orion cloud, for example, and try to compare projected densities along a given length, we have to say that the molecules along a given length for the heart of the Orion nebula is probably about 10^{+15} integrated column density per centimeter squared.

Now, when we try to compare that with water, we run into exactly the same problem we're running into in the comet, and that is that the water is masering, it's time-varying, and in Orion it has about a dozen velocity components. So you cannot use a direct measurement of water in Orion, but you can say, "If I look around at the other polyatomic molecules that are seen in Orion, and I look at the diatomic molecules that are seen in Orion, quite typically for CO, which is very bright in Orion — it's about 10^{18} per centimeter squared.

And OH, from what can be deduced from absorption measurements, is about 10^{17} per centimeter squared. HCN is about 10^{15}, and then when we drop down to isocyanic acid and molecules of this complexity then we're talking about 10^{12}, approximately, per centimeter squared. I'm a little hesitant on this number, because we just finished this detection. I haven't really completed all the analysis on it.

So let me raise this to 10^{13}, and again, dimethyl ether — in Orion, again is about 10^{13} per centimeter squared.

Okay. So if you bootleg it like that, and say — I don't know of any peculiarity in the interstellar chemistry, given enough hydrogen and given enough oxygen, that would cause water to deviate very much from this scheme — then I think that probably within an order of magnitude either way, water should be about 10^{16}, if you could see thermal water in Orion. You can't, so we don't have a better number than that, and if you wish, for your purposes you can choose 10^{15}, but I don't think you can choose 10^{18} at this point.

B. Donn: This is a point I was going to discuss in my paper, on Wednesday, on the origin of comets. It seems to me this is an important way of looking at the origin. One can, in a sense, divide the composition of comets, including new comets, into a number of different classes, depending on the ratios CO^+ and N_2^+ : CN, C_2, C_3, NH, etc: continuum and try to fit this into some formation pattern which I will do on Wednesday.

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DETECTION OF MOLECULAR MICROWAVE TRANSITIONS IN THE 3 MM WAVELENGTH RANGE IN COMET KOHOUTEK (1973f)

D. Buhl, W. F. Huebner* and L. E. Snyder

Introduction

We have recently reported detection of hydrogen cyanide and the first quantitative observations of the velocities of neutral gas jets in the inner part of the coma while the comet was at small heliocentric distances (Huebner, et al., 1974). Now we report the detection of two line transitions from unidentified cometary molecules, provide further evidence of the variability of neutral gas jets, and give a summary of our search program for microwave transitions in molecules of cometary origin.

The observations presented here were made with a 3-mm line receiver mounted on the 11-m NRAO** radio dish at Kitt Peak. Observations were carried out before perihelion (15 to 20 December 1973) and after perihelion (3 to 7 January 1974). During these periods the comet was between 0.3 and 0.5 AU heliocentric distance. The antenna half-power beam width at 3 mm wavelength is $\theta_B \approx 80$ arc s. The observations are based on data obtained from filter banks with a resolution of 250 kHz and 100 kHz. Small local oscillator frequency offsets were made to check for system-generated signals. Searches at off-comet positions were carried out to obtain comparison spectra for noise determination. Comet velocity and position was obtained from ephemerides calculated independently by T. Clark (Goddard Space Flight Center) and Rh. Lüst (Max-Planck-Institut für Astrophysik,

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Munich). The two sets of ephemerides agreed to within the pointing accuracy (10 arc s) of the telescope.

Table 1 summarizes the observational data. The columns, in order, list the UT date of observation, average comet position (RA and Dec) during each period of observation, molecular transition searched for, total integration time (δt), single-sideband r.m.s. system temperature (T_S^*) obtained from all calibrations made during the integration interval, heliocentric distance (r) of the comet, geocentric distance (Δ) of comet, geocentric radial velocity component ($\dot{\Delta}$) of comet, and the rest frequency (ν_o) of the theoretically strongest component of the molecular transition.

Hydrogen Cyanide

The detection of HCN has been reported earlier (Huebner, et al., 1974). Here we present the spectral data of the $H^{12}C^{14}N$ J = 1 - 0 transition with more time resolution to show the variability of the gas jets and consistency of this phenomenon in other mother molecules. Figure 1(A) illustrates the average composite spectrum obtained December 15 and 16. In Figs. 1(B) and 1(C) the same transitions are presented as observed on January 3 and 6. The bars above each spectrum indicate the frequencies of the three hyperfine quadrupole components F = 0 - 1, 2 - 1, and 1 - 1, belonging to the same Doppler shifted velocity group measured with respect to the rest frame of the comet's nucleus. These laboratory frequencies as measured by DeLucia and Gordy (1969) are 88.63394 GHz, 88.63185 GHz, and

TABLE 1

Observational Data

UT Date	Comet (1950) RA [h m]	Dec [° ']	Transition	ΔT_{pp} [K]	r [AU]	Δ [AU]	$\dot{\Delta}$ [km/s]	ν_o [GHz]
Dec 15.8	15 41.4	-25 41	HCN (1-0)	--	.49	1.16	-12.5	88.631847
Dec 16.7	15 51.4	-25 51	CH_3CN (v_8=1,5_K-4_K)	--	.46	1.15	-10.5	92.261440
Dec 16.8	15 52.5	-25 52	HCN (1-0)	--	.46	1.15	-10.3	88.631847
Dec 17.7	16 02.9	-25 58	CH_3CN (v_8=1,5_K-4_K)	--	.43	1.14	- 8.3	92.261440
Dec 17.8	16 04.1	-25 59	CH_3CN (v_8=1,5_K-4_K)	--	.43	1.14	- 8.0	92.261440
Dec 17.9	16 05.3	-26 00	X-ogen	0.5	.43	1.14	- 7.8	89.189
Dec 18.6	16 13.6	-26 03	X-ogen	0.2	.40	1.14	- 6.2	89.189
Dec 18.6	16 13.6	-26 03	CH_3CN (5_K-4_K)	--	.40	1.14	- 6.2	91.98705
Dec 18.7	16 14.8	-26 03	HNC (1-0)	0.3	.40	1.14	- 6.0	90.665
Dec 18.7	16 14.8	-26 03	HNCO ($4_{04}-3_{03}$)	0.3	.40	1.14	- 6.0	87.92524
Dec 18.8	16 16.0	-26 03	CH_3C_2H (5_K-4_K)	0.4	.40	1.14	- 5.8	85.45729
Dec 18.8	16 16.0	-26 03	HNCO ($4_{13}-3_{12}$)	0.4	.40	1.14	- 5.8	88.23905
Dec 18.9	16 17.2	-26 03	HCN ($2\nu_2$,1-0)	0.7	.40	1.14	- 5.6	89.08792
Dec 19.7	16 27.1	-26 03	HCN ($2\nu_2$,1-0)	0.3	.37	1.14	- 3.8	89.08792
Dec 19.8	16 28.3	-26 03	CH_3CN (v_8=1,5_K-4_K)	--	.37	1.14	- 3.6	92.261440
Dec 20.7	16 39.8	-25 59	HC_3N (10-9)	0.4	.34	1.14	- 1.6	90.981
Jan 3.9	20 07.6	-16 42	HCN (1-0)	--	.30	0.94	-41.8	88.631847
Jan 4.8	20 18.4	-16 00	SiO (v=1,2-1)	0.3	.33	0.92	-38.3	86.24328
Jan 4.9	20 19.6	-15 55	$(CH_3)_2O$ ($2_{20}-2_{11}$)	0.4	.34	0.92	-37.9	86.22804
Jan 4.9	20 19.6	-15 55	SiO (v=1,2-1)	0.4	.34	0.92	-37.9	86.24328
Jan 5.0	20 20.8	-15 51	SiO (v=1,2-1)	0.3	.34	0.92	-37.5	86.24328
Jan 6.8	20 42.2	-14 22	HCN (1-0)	--	.39	0.88	-30.6	88.631847
Jan 6.9	20 43.4	-14 17	SiO (v=1,2-1)	0.8	.40	0.88	-30.1	86.24328
Jan 7.0	20 44.6	-14 12	SiO (v=1,2-1)	0.3	.40	0.88	-29.8	86.24328

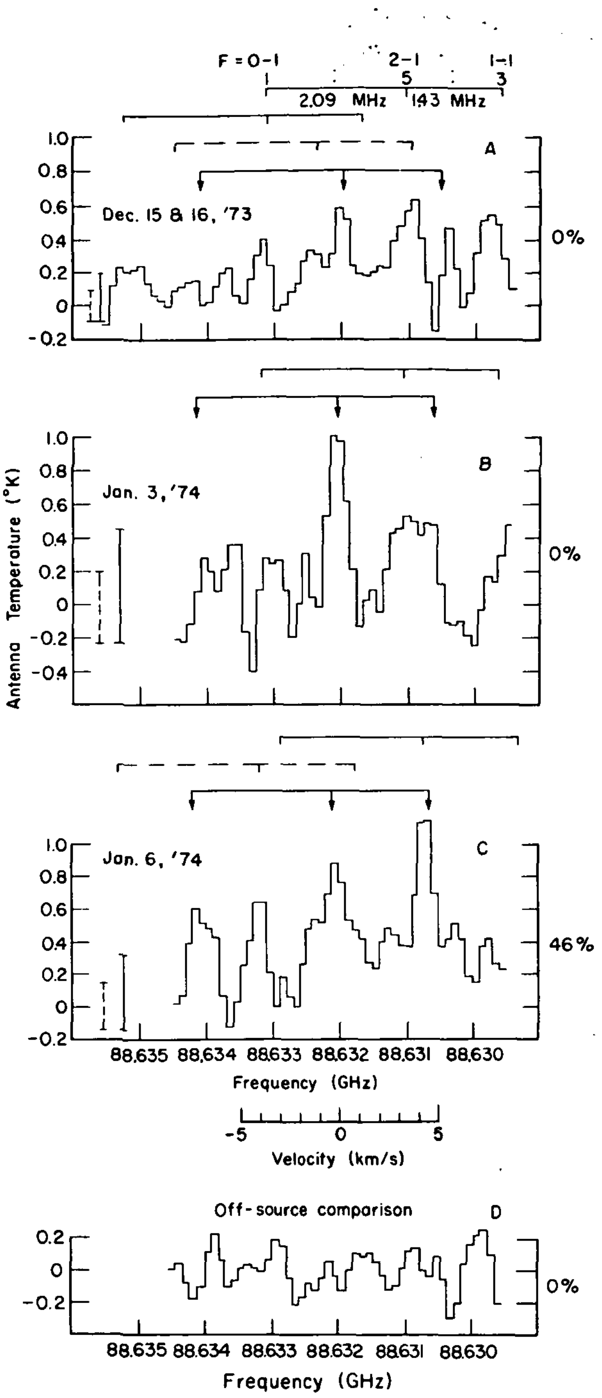

Figure 1: Emission spectrum of the HCN J = 1-0 transition observed in comet Kohoutek (1973 f) before perihelion (A) and after perihelion (B) and (C).

88. 63042 GHz. Within each group the observed intensities follow closely the predicted theoretical values (2F + 1) indicated above the top bar. The triplet with zero Doppler shift (within the width of a channel) with respect to the nucleus is indicated by arrows. It appears to be present in each spectrum, but fluctuates with time. The intensity of the other triplets also fluctuates with time, but in addition they change their number and frequency shift. The transitions with zero Doppler shift can be interpreted as a quiescent outstreaming of slowly released gas, however, their time variation suggests that they are also outbursts with velocities consistent with the other Doppler shifts, but close to the plane perpendicular to the earth-comet direction. There is no discernable decrease of intensity in the post-perihelion observations. Only the strongest Doppler shifted components of the spectrum are identified, possible weaker ones are indicated by dashed bars. Doppler shifts up to ~1.3 MHz (~4 kms^{-1}) can be measured. Figure 1(D) is a spectrum taken while tracking ~7.5 arc min off the comet nucleus and was used to determine the peak-to-peak noise which was found to be ~0.3°K. The peak-to-peak noise is indicated by two error bars in Figure 1. The dotted error bar indicates the noise with the dome open, the solid error bar indicates the increase in noise due to dome attenuation. The percentage of time during which observations were made with the dome open is given to the right.

Methyl Cyanide

Following the unexpected detection of $^{12}CH_3{}^{12}C^{14}N$ in its $v_8 = 1$ excited state, transition $J_K = 6_3 - 5_3$ by Ulich and Conklin (1974) on 1 and 5 December, 1973, we searched for the next lower rotational transition in the same vibrational state on 16, 17, and 19 December. Although signals 3 to 4 times peak-to-peak noise were detected in the 100 kHz filter bank the variability in intensity and frequency of the Doppler shifted lines resulted in identification problems: Doppler shifts similar to those measured in HCN could also be infered in the CH_3CN spectrum, but since the spacing of its K-component lines is bigger than the hyperfine splitting of the HCN spectrum one or the other of two K-components was frequently shifted out of the range of the 100 kHz filter bank. For this reason we present the analysis of the CH_3CN spectrum in the 250 kHz filter banks.

The average of the spectra obtained by Ulich and Conklin on 1 and 5 December with the 100 kHz filter banks are presented in Fig. 2(A). The frequency scale has been reversed to facilitate comparison of their observation of the $J_K = 6_0 - 5_0$ and $6_3 - 5_3$ transition with our $J_K = 5_0 - 4_0$ and $5_3 - 4_3$ observations.

Figure 2(B-D) presents our observed spectrum of $^{12}CH_3{}^{12}C^{14}N$ in the $v_8 = 1$ excited state. The transitions correspond to $J_K = 5_2 - 4_2$, $5_0 - 4_0$, $5_3 - 4_3$, and $5_1 - 4_1$. The corresponding frequencies as measured by Bauer and Maes (1969) are 92.26399 GHz, 92.26144 GHz,

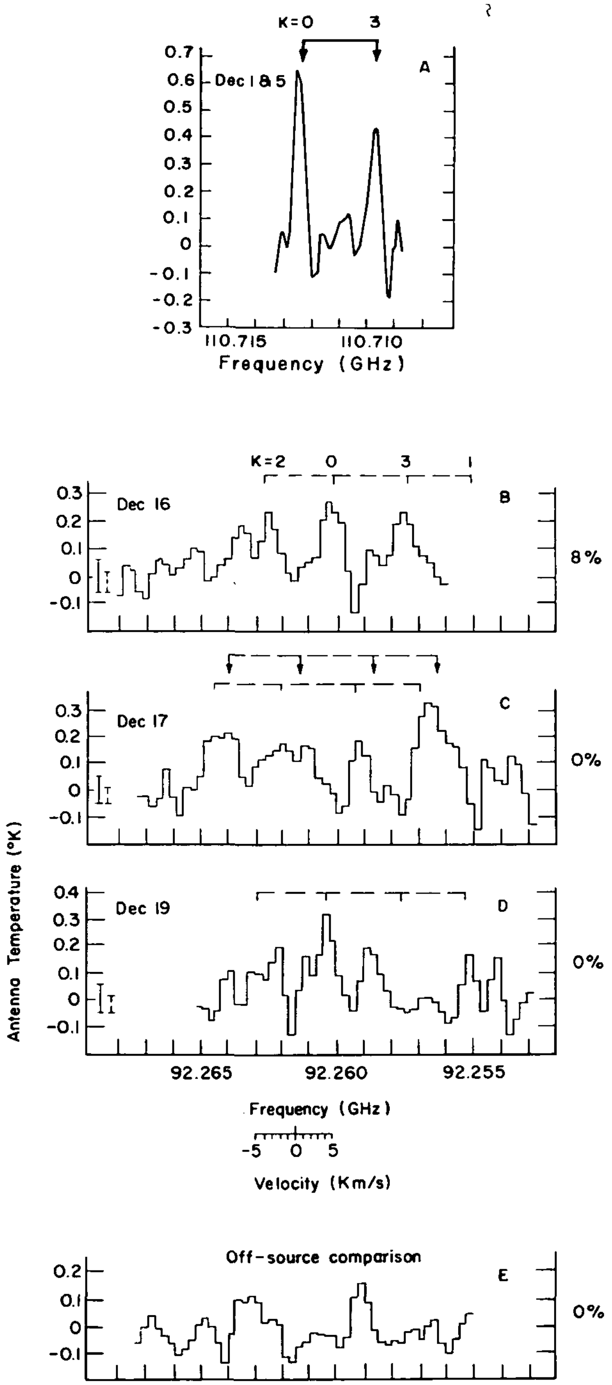

Figure 2: Emission spectrum of the CH_3CN $v_8 = 1$ state observed in the comet in the $J_K = 6_0 - 5_0$ and $6_3 - 5_3$ transitions (A) and the $J_K = 5_K - 4_K$, K = 0, 1, 2, and 3 transition (B), (C), and (D).

92.25841 GHz and 92.25629 GHz. Doppler shifts up to about ±1.0 MHz are measured. The zero point of the velocity scale below Fig. 2(D) indicates the expected position of the K = 0 component under quiescent conditions. Bars above each spectrum connect K-components exhibiting the same Doppler shift; the bar with arrows pointing downward indicates transitions of the "quiescent" state with nearly zero Doppler shift. It should be noted that the "quiescent" state is not always present, which strengthens the interpretation that it is due to jets in a plane perpendicular to the line of sight rather than a uniform outgassing. The spectra as presented in Fig. 2(A-D) get progressively weaker. Only our 16 and possibly 17 December spectra are strong enough to serve as confirmation of the detection of CH_3CN by Ulich and Conklin. The signal to noise ratio is insufficient for a direct and independent identification of the molecule.

On 18 December we made a search for $^{12}CH_3{}^{12}C^{14}N$ vibrational ground state $J_K = 5_K - 4_K$ transitions simultaneously with a search for X-ogen (Buhl and Snyder, 1970) in the other side-band of the receiver. There was a possible detection of weak components ($|K| = 3, 2, 0,$ and 1)at about $T_A^* = 0.4K$. The corresponding rest frequencies measured by Bauer and Maes (1969) are 91.97137 GHz, 91.98000 GHz, 91.98528 GHz and 91.98705 GHz.

Two unidentified lines

On 3 January Snyder and Buhl (1974) discovered a peculiar masering transition with several frequency components as a point source in Orion. A search for these lines was made in the comet on 4,5,6, and 7 of January with several shifts of the local oscillator frequency. As a result of this search two lines were acquired one in the upper side-band of the 250 kHz filter bank receiver at 89.0105 GHz and one in the lower side-band at 86.2471 GHz. The summary of these observations is presented in Fig. 3(A and B). The interstellar lines were later identified as Doppler shifted components of SiO with rest frequency 86.24328 GHz corresponding to the transition v = 1, J = 2 - 1 (Snyder and Buhl, 1974) and cannot be brought into agreement with the lines observed in the comet. There are no known transitions in the neighborhood of 89.0105 GHz. The frequency of the other line (86.2471 GHz) is close to that of ethanol (86.2474 GHz) and acetone (86.2479 GHz), but probably cannot be identified with either one of these molecules for the following reasons: (A) The line is too broad, indicating an approximately isotropic expansion velocity of ~ 3 kms^{-1}. This requires the additional assumption that an exothermic process took place. (B) The line does not exhibit the resolvable Doppler shifted components and thus is not consistent with the HCN and CH_3CN observations made at about the same heliocentric distance. (C) If the molecule were acetone one would also expect to find a line at 86.2447 GHz which is not observed. The source of the two unidentified lines is probably a radical which during the process of decay of its mother molecule received an excess of kinetic energy as, e.g., can occur during photodissociation.

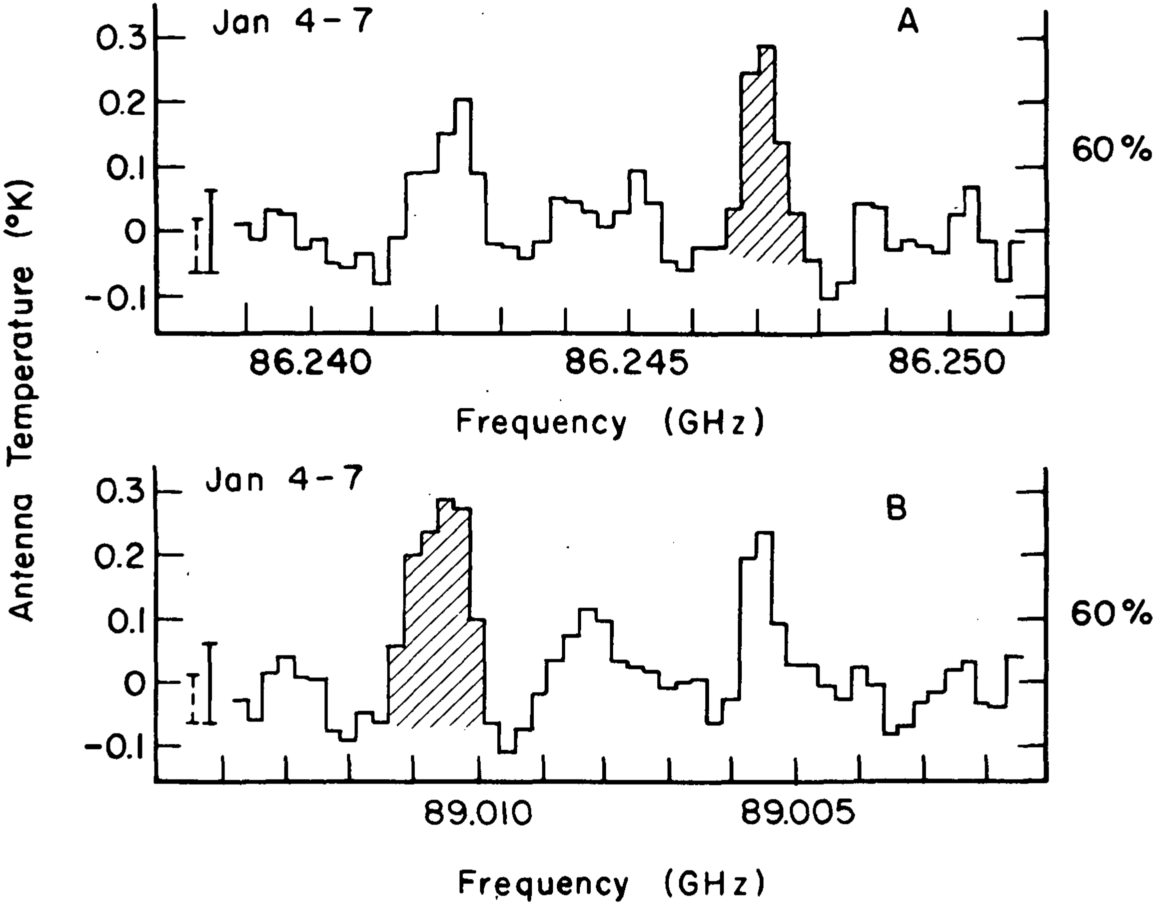

Fig. 3. Two unidentified line transitions found during the Si 0 search in the lower side band (A) at 86.2471 GHz and in the upper side band (B) at 89.0105 GHz. Since lower and upper side band of the receiver are super imposed in the display but with frequencies increasing in opposite directions the line transitions show up in both spectra (A) and (B) but the side band to which they belong can be assigned uniquely through shifts in the local oscillator frequency.

Production Rates

Figure 4 presents the earth's orbit and the projection of the comet's orbit on the ecliptic and indicates the times and heliocentric distances when the above-mentioned observations were carried out. Ulich and Conklin observed between 1 and 5 December when the comet was at heliocentric distances between 0.87 and 0.79 AU. Their spectra indicate a quiescent production of methyl cyanide. Our observations of methyl cyanide were made when the comet was between 0.46 and 0.37 AU heliocentric distance before perihelion. By that time the production was very weak and getting weaker. Discrete jets with speeds of several km/sec with respect to the nucleus are measured from Doppler shifts. These indicate an inhomogeneous structure of the nucleus (Huebner, 1974, 1975). Observation of the spectrum in the vibrationally excited state ~640 °K above the ground state, the lack of a Boltzmann distribution, and the action of jets make estimates for the abundance very difficult. In the absence of detailed knowledge about the excitation mechanism and the cross sectional area of the jets we apply a quiescent state fluid dynamic model (Huebner and Snyder, 1970) to our ground state observation.

The fluid model is valid as long as:

$$A < n\,v\sigma \quad (1)$$

where A = Einstein emission coeff. for microwave transition in $\sec^{-1}$, n = number density of molecules/cm^3, v = escape velocity $\approx$ thermal velocity $\approx 3 \times 10^4$ cm/sec and σ = collision cross section $\approx 10^{-15}$ cm^2.

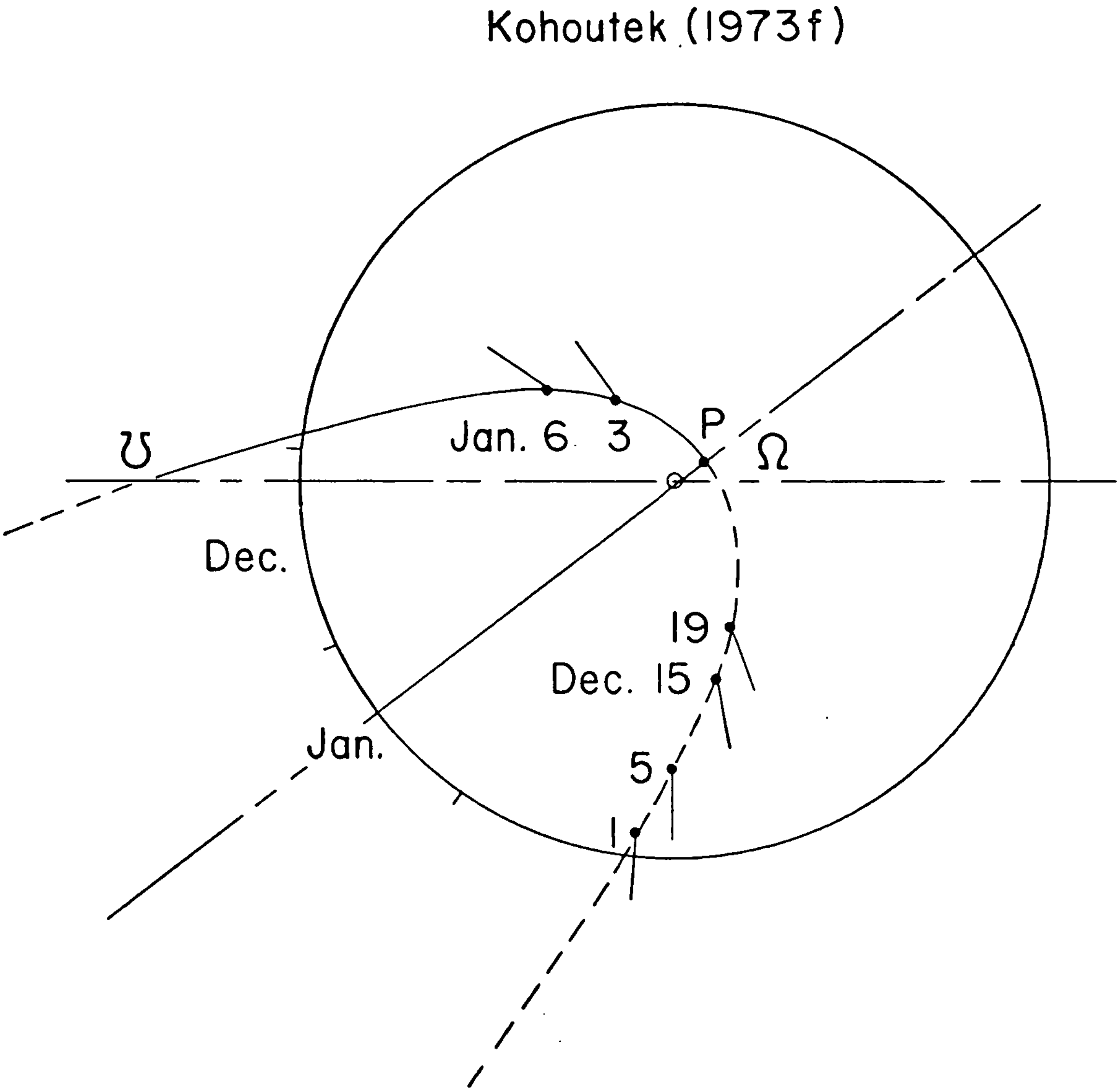

Fig. 4. Projection of the orbit of the comet onto the ecliptic. Earth positions for December 1, January 1, and February 1 are indicated on the circle. Comet positions corresponding to the dates of observations by Ulich and Conklin and by us are shown on the parabola.

For our fluid dynamic model

$$n = \frac{Z}{v} \left(\frac{R}{r}\right)^2 \tag{2}$$

Where Z = gas production rate of comet ≈ $(10^{18}/r_h^2)$ molecules sterad^{-1} cm^{-2} sec^{-1} for $r_h \leq 1$ AU where r_h = heliocentric distance in AU; R = radius of nucleus ≈ 3 to 5 x 10^5 cm for Kohoutek, and r = radial distance of molecules in the coma as measured from center of nucleus.

$$\therefore A < \frac{Z\sigma}{r_h^2} \left(\frac{R}{r}\right)^2 \approx (10^{18}/r_h^2) \times 10^{-16} (10^{5.5}/r)^2$$

$$A < 10^{13}/(rr_h)^2 \tag{3}$$

In our calculations $r_h \approx 0.3$ to 0.5 AU. We assumed two cutoff values for r: $r_o = 10^4$ km $= 10^9$ cm and $\bar{r}_o = 10^5$ km $= 10^{10}$ cm.

$$\therefore A < 10^{-3} \text{ sec}^{-1} \text{ for } r_o = 10^4 \text{ km} \tag{4a}$$

$$A < 10^{-5} \text{ sec}^{-1} \text{ for } r_o = 10^5 \text{ km} \tag{4b}$$

The fluid model breaks down when the collision mean free path becomes larger than the distance traveled, i.e., it breaks down at $r \approx 1/(n\sigma)$, or $r \approx ZR^2\sigma/v \approx 10^{10}$ cm. Hence, within the cutoff radius which we consider the fluid model is valid.

The optical depth, frequency-averaged over the full width ($\Delta\nu$) of a line at one-half the maximum line intensity, for a symmetric top molecule is

$$(\tau) = \frac{16\pi^2 <N> f_v h^{3/2} \mu^2 \nu^2 (ABC)^{1/2}}{3c \; \Delta\nu \; (kT)^{5/2}} \cdot \frac{(J + 1)^2 - K^2}{J + 1} e^{-W/T} , \qquad (5)$$

for $(J + 1)_K \rightarrow J_k$.

The effects of beam dilution, β, have been included, i.e.,

$$<\tau> \equiv \beta \bar{\tau} , \qquad (6)$$

and

$$<N> \equiv \beta N . \qquad (7)$$

Here N is the column density of the total number of CH_3CN molecules, μ is the dipole moment (3.92×10^{-18} esu·cm for CH_3CN), ν is the transition frequency, and A, B, and C are the rotational constants (A = B = 9.199 GHz, C = 158.0 GHz and CH3CN). The rotational energy of the upper level W = 13.2 °K for $J_K = 5_0 - 4_0$ in CH_3CN enters the assumed Boltzmann distribution for the vibrational ground state for which the partition function is $f_v \approx 1$.

If the comet coma is optically thin and its 3 mm continuum emission is negligible then the antenna temperature, T_A^*, as measured by chopper wheel calibration is related to the optical depth, Eq. (5), by

$$T_A^* = T <\tau> . \qquad (7)$$

If emission is not enhanced (which is apparently not true for the $v_8 = 1$ state) by collisional or radiative excitation, then the temperature is determined by the vaporization equilibrium, $T \approx 150\ ^{o}K$. An upper limit for the K = 0 component is $T_A^* \approx 0.4\ ^{o}K$. This gives for the optical depth including beam dilution $\langle\tau\rangle \approx 0.0027$. Although smoothing gives the lines a much broader appearance, the total half-intensity line width $\Delta\nu \approx 200$ kHz. Substitution into Eq. (1) gives for the column density including beam dilution $\langle N\rangle \approx 1.6 \times 10^{13}$ cm^{-2} as an approximate upper limit. The range of the methyl cyanide molecules before they are destroyed by photodissociation or photoionization is not known. Two typical values will be assumed for the cutoff range, $r_o = 10^4$ and 10^5 km. The column density uniformly distributed over the antenna beam is

$$\langle N\rangle = \frac{4Q'}{\pi v \Delta^2 \theta_B^2} \left[s \cos^{-1} \frac{s}{r_o} - (r_o^2 - s^2)^{1/2} + r_o \right] \qquad (9)$$

with

$$s = \min[r_o, \Delta \cdot \theta_B/2]. \qquad (10)$$

Here Q' is the total production rate of the molecule under consideration, $v \approx 0.3$ kms^{-1} is the average (thermal) expansion velocity of the escaping gas, θ_B is the half-power antenna beam width, and Δ is the geocentric distance of the comet. Using $\Delta = 1.14$ AU an upper limit for the production rate of CH_3CN at r = 0.40 AU heliocentric distance is $Q' = 1.7 \times 10^{28}$ s^{-1} for $r_o = 10^4$ km and $Q' = 3.6 \times 10^{27}$ s^{-1} for $r_o = 10^5$ km.

The production rate of HCN based on observations of the J = 1-0 vibrational ground state transitions was reported earlier by Huebner, et al., (1974) to be $Q' = 1.2 \times 10^{28}\ s^{-1}$ for the cutoff range $r_o = 10^4$ km and $Q' = 3 \times 10^{27}\ s^{-1}$ for $r_o = 10^5$ km. No spectrum could be detected in the vibrationally excited 2ν state. Upper limits for production rates of other molecules listed in Table 1 can be obtained, taking into account the appropriate molecular symmetry properties in the calculation of the optical depth (see, e.g., Townes and Schawlow, 1955). The results are summarized in Table 2.

Production rates are related to abundances of the constituents in the frozen state, but latent heats of vaporization and likely inhomogenities in the structure of the nucleus must be considered in such an analysis. It should be noted that, with the sole exception of water, only molecules with strong transition probabilities in the radio range have been detected. Other molecules may be more abundant, yet their detection is more difficult because of weak transition probabilities or high latent heats of vaporization. The difficulties encountered with the detection of water by Jackson, et al., (1975) is a typical example.

Acknowledgements

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Table 2

Summary of Production Rates, Q', and Related Quantities

Molecule	T_A^* [°K]	< τ >	A [s^{-1}]	< N > [cm^{-2}]	Q' [s^{-1}] for $r_o=10^4$km	$r_o=10^5$km
HCN (1-0)	0.8	0.0054	$2.4x10^{-5}$	$1.5x10^{13}$	$1.2x10^{28}$	$3x10^{27}$
CH_3CN (5_K-4_K)	0.4	0.0027	$9.4x10^{-5}$	$1.6x10^{13}$	$1.6x10^{28}$	$4x10^{27}$
X-ogen	<0.3					
HNC (1-0)	<0.3	<0.002				
HNCO (4_{04}-3_{03})	<0.3	<0.002	$8.9x10^{-6}$	$<4x10^{13}$	$<5x10^{28}$	$<1x10^{28}$
CH_3C_2H (5_K-4_K)	<0.4	<0.003	$2.8x10^{-6}$	$<3x10^{15}$	$<3x10^{30}$	$<1 x 10^{30}$
HC_3N (10-9)	<0.4	<0.0025	$6.3x10^{-5}$ $2.9x10^{-5}$	$<3x10^{12}$	$<4x10^{27}$	$<1x10^{27}$
Si O (v=1,2-1)	<0.1	<0.001	$2.2x10^{-6}$	$<7x10^{16}$	$<6x10^{31}$	$<2x10^{31}$
$(CH_3)_2O(2_{20}$-$2_{11})$	<0.4	<0.003				

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RADIO DETECTION OF H_2O IN COMET BRADFIELD (1974b)

W. M. Jackson, T. Clark and B. Donn

The present authors (Clark et al, 1971) previously attempted to detect the 1.35 cm microwave line of water in Comet Bennett (1969i) using the 26 m Maryland Point radio telescope of the Naval Research Laboratory. An upper limit for the H_2O column density of 10^{17} molec/cm^2 was obtained assuming the rotational levels were in thermal equilibrium. A more recent search in Comet Kohoutek using the 37 m radio telescope of the Haystack Observatory with a low noise traveling wave maser preamplifier was also unsuccessful. In this comet the identification of H_2O^+ in the visible spectrum gave strong support to the idea of water as a major parent molecule. The radio detection of HCN (Heubner et al, 1974) and CH_3CH (Uhlich and Conklin, 1974) in Comet Kohoutek suggested that the attempt to detect H_2O should be repeated in a suitable comet.

The present paper discusses the successful detection of H_2O in Comet Bradfield (1974b) using the Haystack telescope when the heliocentric and geocentric distances were 1.22 A.U. and 1.15 A.U. respectively. At 1.35 cm this antenna has a main-beam half-width of 1.5 arc min. and an efficiency of 0.33. The traveling wave maser was used with a 100 channel autocorrelator operating at a 667 KHz bandwidth. The average system temperature for these observations was 158°K. An observing sequence of 10 minutes on the comet

D13

and 10 minutes off was employed. Each off source scan was taken along the azimuth evaluation path on the sky that the comet would traverse ten minutes later. This procedure compensated for gross atmospheric and instrumental effects and sky background. Some on source runs were made with the antenna intentionally displaced one half beam width on the sunward or tailward side of the comet. Cometary positions for pointing purposes were based on ephemerides supplied by B. Marsden.

The results are summarized in Figure 1 for runs taken when pointing at the comet position and in Figure 2 for runs with the telescope pointed one half beam width on the sun or tailward side. All twelve 20 minute on-off scans on the comet show some signal excess at the -0.82 km/sec feature which we identify as the H_2O transition. It is therefore unlikely that this feature is an artifact. Figure 2 also shows the H_2O feature although the signal is weaker. Because of reduced integration time the noise is worse.

This data supplies strong evidence for the detection of the 1.35 cm (22.2 GHz) emission line of water in Comet Bradfield with a peak antenna temperature of $0.15^{\circ}K$ and a FWHM of 0.4 km/sec. The -0.82 km/sec line shift from Marsden's ephemeris is several orders of magnitude larger than any possible errors in the calculations. The decrease in signal by $\sim 1/3$ when the telescope is shifted 1/2 beam width from the predicted position of the comet indicates an intrinsic source size of $\leqslant$ 10-15 arc sec.

There are serious difficulties with the interpretation and further analysis of these results. Reliable column densities and in turn water production rates, Q, can be readily obtained only if the rotational levels are in thermodynamic equilibrium with a Boltzmann distribution over rotational states. This is questionnable in the case of comets as the density is low near the nucleus and falls off rapidly. The treatment of Clark et al (1971) based on the equilibrium assumption yields an average column density <N> of 2 x 10^{16} molec/cm^2. A temperature of $240^{\circ}K$ calculated from the measured FWHM was used.

Heubner and Snyder (1970) have derived a relationship between <N> and Q:

$$Q = \frac{v\Delta^2 \theta^2 <N>}{16r_o} \qquad (1)$$

Where Δ = geocentric distance, v = expansion velocity, θ = half power beam width and r_o = radius of molecular cloud. All of these are known or may be reliably estimated except r_o. They defined r_o as $v\tau$ where τ is the photodissociation lifetime. Bertaux et al (1974) obtained a value of approximately 30 hours which makes r_o = 5.7 x 10^4 km. Equation (1) yields a water production rate of 3.4 x 10^{29} molec/ster sec. A comparison with other derivations of production rates of parent molecules is given in Table 1. It is seen that our value is an order of magnitude larger except for the CH_3CN result. The two other water results are based on ultraviolet observations of H and OH fragments. As the photochemistry of water and the optical excitation of the fragments are well understood, it seems likely that these results are substantially correct. HCN is detected by the J = 1-0

<u>TABLE 1</u>

Production Rates of Parent Molecules

Molecule	A.U.	Molec/sec sterad.	Comet	Method	Reference
H_2O	1.0	$2.6x10^{28}$	Bennett (1969i)	OGO-5 H atom profiles	Bertaux et al (1974)
H_2O	0.43	$2x10^{28}$	Kohoutek (1973f)	Sky Lab	Carruthers et al (1974)
H_2O	1.2	$3.4x10^{29}$	Bradfield (1974b)	Radio Observation	This work
CH_3CN	0.8	10^{30}	Kohoutek (1973f)	Radio Observation	Uhlich & Conklin (1974)
HCN	0.4	$\sim 5x10^{26}$	Kohoutek (1973f)	Radio Observation	Heubner et al (1974)

transition and no excitation problem occurs. Methyl cyanide is detected by emission from excited state comparable to that of water and a similar, as yet unknown, excitation process occurs.

A more careful analysis of the excitation of water and methyl cyanide in comets is required and preliminary considerations are now given. The upper level of the $6_{16} - 5_{23}$ H_2O transition lies 447cm^{-1} above the ground rotational level. In order to maintain thermodynamic equilibrium, collosional pumping rates of all levels must be larger than the radiative decay rates. The principal mode of radiative decay of the 6_{16} level is via the $6_{16} - 5_{05}$ transition with a lifetime of about 1 sec (Buhl et al., 1969).

To a first approximation the steady state condition is given by equating radiative and collisional lifetimes. The approximation neglects the details of the system in which there are numerous rotational levels with radiative and collisional transitions among them. It also cancels Boltzmann factors for rotational and translational populations. We write for the lifetime τ_c of collisional processes:

$$\tau_c = (v\sigma n)^{-1} \lesssim 1 \text{ sec} \qquad (2)$$

where v is the thermal velocity.

As the principle constituent is assumed to be water, rotational excitation will be governed by a dipole-dipole potential. This leads to cross-sections for rotational excitation of the order of $1000\mathring{A}^2$ (Levine and Bernstein, 1974).

With $v = 10^4$ cm/sec, the water density must be greater than 2.5×10^8 cm^{-3}. The fluid dynamic model of comets (Jackson and Donn, 1966) predicts densities of this order at 1600 km from the nucleus for water production rates of 10^{29} molec/sec ster. This radius for the cloud is a factor of 40 less than that used to calculate the water production rate from Equation (1). The assumption of thermodynamic equilibrium leads to an inconsistency and production rates for molecules detected in excited rotational states may not be calculated on such an assumption.

Some other mechanism of rotational excitation than molecular collisions is required. Recent calculations by Itikawa (1972) have yielded cross-sections for rotational excitation of water by 0.01 ev electrons of the order of 10^{-13} cm^2. Even this large cross-section would require an electron density comparable to the particle density. An anomalous excitation of the $6_{16} - 5_{23}$ water transition is observed in the interstellar water masers requiring a non-equilibrium excitation mechanism. A suggestive process is infra-red pumping as described by Litvak (1972). Such a scheme may also work for comets. The cometary system is known in considerable detail and a comprehensive analysis for cometary H_2O and CH_3CN emission would be very valuable.

The more favorable observing conditions with Comet Bradfield compared to Comet Kohoutek appear to account for the detection of water in Bradfield for the first time. Comet Bradfield was nearly circumpolar (δ=87°) at the time of our observations. Hence we were able to observe for longer times without suffering extensive atmospheric attenuation. Comet Halley will also be favorably located and will be a good candidate for further water observations.

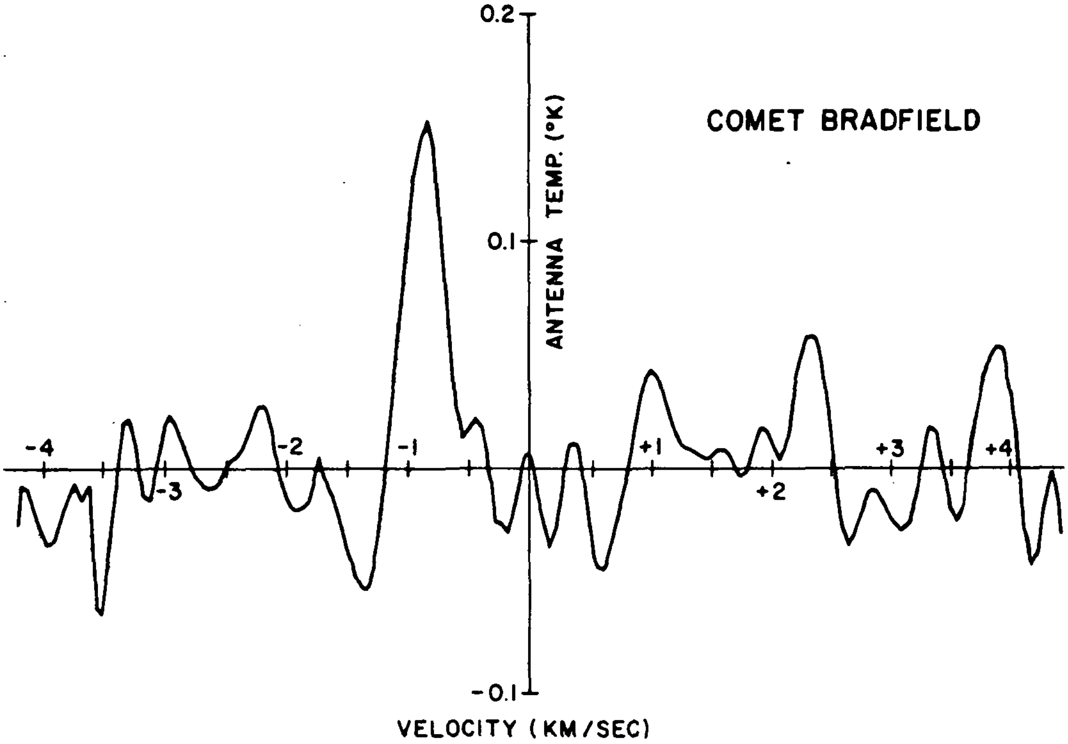

Figure 1. 1.35 cm (22.2 GHz) water transition. Sum of all scans centered on comet position.

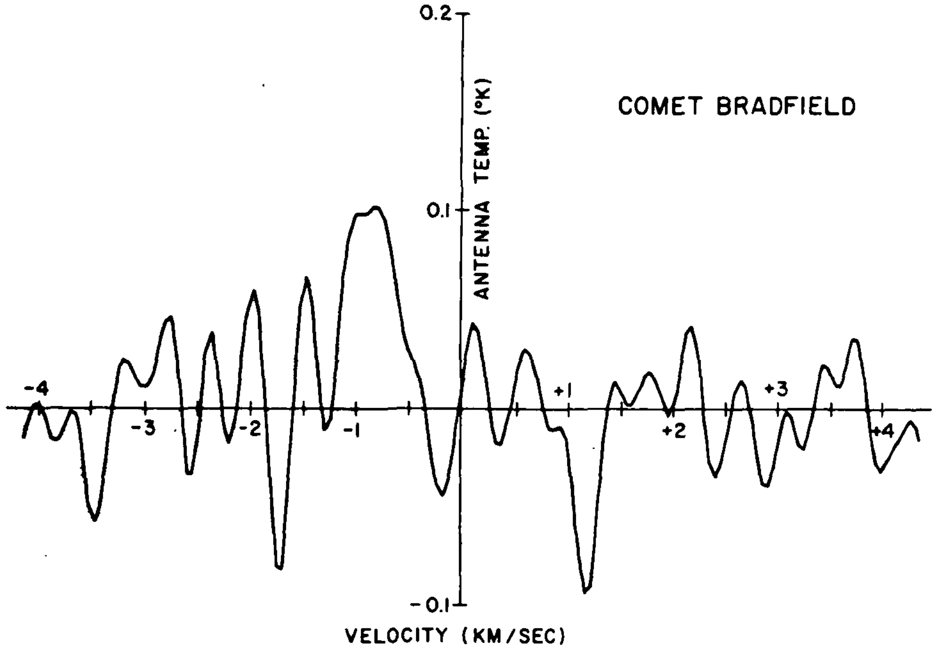

Figure 2. 1.35 cm (22.2 GHz) water transition. Sum of scans displaced 1/2 beam width in sun or tail direction.

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A SEARCH FOR MOLECULAR TRANSITIONS IN THE 22-25 GHZ BAND IN COMET KOHOUTEK 1973f

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Introduction

According to current theories, the radicals optically identified in cometary spectra stem from more complex parent compounds which have no transitions at visible wavelengths. In recent years radio transitions of likely molecules have repeatedly been searched for but were never found (e.g., Huebner and Snyder, 1970; Clark et al., 1971). Only in Comet Kohoutek 1973f have microwave lines of three molecules been detected, OH (Biraud et al., 1974; Turner, 1974), CH_3CN (Ulich and Conklin, 1974), and HCN (Snyder et al., 1974). Here we report on our search for transitions in the 22-25 GHz band of the molecules H_2O, NH_3, and CH_3OH in this Comet and give upper limits on line temperatures and column densities.

Observations

The observations of Comet Kohoutek 1973f have been made with the 100-m radio telescope of the Max-Planck-Institut für Radioastronomie in Bonn, West Germany. The antenna half-power beam width (HPBW) was ~40 arc sec and the aperture efficiency was ~0.17 (not accurately measured). The receiver was an uncooled tunnel diode mixer system with a double side band system temperature of ~2500 K. The observations were made by beam-switching with the signal beam on the electrical axis of the telescope and the comparison beam offset by 2 arc min; the switch rate was 1 cps. A calibration signal from a noise diode was injected into the signal channel every second cycle. The temperature equivalent of the noise diode was measured in the laboratory and checked periodically throughout the observations against NGC 7027. The pointing accuracy of the telescope was ≤10 arc sec.

The observations were carried out in two periods, the first on January 7 and 8, 1974, when the Comet had passed perihelion (perihelion passage, $T = 1973$, Dec.28.4; perihelion distance, $q = 0.14$ AU) but had a high enough angular separation from the sun so that the sun was outside the beam pattern; the second on January 14 and 15, 1974, when the Comet reached its closest approach to the Earth (Jan. 15, 1974, $\Delta = 0.81$ AU), thus giving the best ratio of source size (head of the Comet) to beam size.

The essential observational data is listed in Table 1. The ephemeris was calculated by Stumpff from elements communicated by Marsden (1974). The first six columns of Table 1 list the time of observation, position of the Comet, its heliocentric and geocentric distance, radial velocity, and the observed frequency. The total number of scans is given in column 7. Each scan lasted for 10 minutes. Since the Comet's position was not known with high accuracy on January 7 and 8, 1974, the telescope was pointed at the presumed position of the cometary nucleus and also at 4 positions surrounding it with $\alpha' = \alpha_o \pm 30''$ and $\delta' = \delta_o \pm 30''$, respectively (with α_o, δ_o the predicted position of the nucleus). In searching for H_2O on January 7 and 8, four scans each were made at the presumed nucleus' position as well as at $\alpha' = \alpha_o + 30''$ and $\delta' = \delta_o - 30''$. At each of the remaining two positions $\alpha' = \alpha_o - 30''$ and $\delta' = \delta_o + 30''$, three scans were made. During the search for NH_3 on January 8, three scans were made at the nucleus and two scans each at $\alpha' = \alpha_o \pm 30''$ and $\delta' = \delta_o \pm 30''$. Since the Comet's orbit had been confirmed before the second observation period on Jan. 14/15 started, the telescope was pointed only at the predicted position of the nucleus.

Table 1
Observational Data

Date (1974) UT	Comet Position (1950) R.A.	Decl.	Heliocentric Distance (AU)	Geocentric Distance (AU)	Geocentric Radial Velocity (km/sec)	Observed Frequency (MHz)	No. of Scans
Jan. 7.71	$20^h44^m06^s.4$	$-14^\circ14'06''$	0.422	0.866	-27.07	22235.08	7
Jan. 8.54	20 55 55.1	-13 22 54	0.447	0.854	-24.25	22235.08	11
Jan. 8.71	20 55 55.1	-13 22 54	0.452	0.851	-23.34	23694.48	11
Jan.14.67	22 05 43.0	-07 47 48	0.621	0.807	- 2.71	23694.48	28
Jan.15.63	22 17 00.8	-06 49 01	0.647	0.806	0.25	24931.54/ 32.04	39

It was attempted to detect radio lines in the 1.3-cm band of three molecular species which had been detected in interstellar space but not in a comet.

NH_3 (ammonia) is chemically very stable and a common end product of reactions where polymers or hydrogen bonded molecules are pyrolyzed. This process is expected to take place during the Comet's closest approach to the sun. Also this molecule presumably has one of the greatest extents around the nucleus of any molecule observable at this frequency. It may be noted that the (1.1) transition at 23694.48 MHz is energetically the lowest in para-ammonia, whereas the (3.3) inversion transition at 23870.11 MHz is the lowest in orth-ammonia.

At the time of the search, H_2O (water) had not directly been observed in a comet. Although high excitation energies are required to observe the H_2O rotational transition line, the chemical stability of the molecule in conjunction with the high abundance of cometary OH and H seemed to warrant a search for this species. H_2O was subsequently found in Comet Bradfield 1974b (Clark et al., 1974).

CH_3OH (methyl alcohol) is a rather common molecule in the interstellar medium. The lines (2,2-2,1; 3,2-3,1; 4,2-4,1) lie within a very narrow frequency interval (24928.7 - 24934.4 MHz), but they arise from energy levels (unfortunately only of species E 1) with rather different energies. Thus they are expected to be sensitive to excitation conditions.

Discussion

No lines were detected above the noise. However, the observed noise can be used to derive an upper limit on the column densities, N_m which is given by

$$N_m = \frac{3k}{8\pi^3|\mu_{ij}|^2 \nu} \int B\nu dv$$

Table 2 is a summary of the results. A line width $\Delta V_L = 0.53$ km/sec was assumed which is equivalent to that found for CH_3CN (Ulich and Conklin, 1974) when corrected for the half-intensity full width rather than half the 1/e-width. Listed are the molecules with corresponding transition and transition frequency, and upper limit on the mean column densities.

Table 2
Results

Molecule	Transition	Frequency (MHz)	ΔT_{pp} (K)	T_{A_L} (rms) (K)	T_{B_L} (3σ) (K)	N(molecules/cm^2)
H_2O	$6_{16} - 5_{23}$	22235.08	1.07	≤ 0.2	≤ 2	$\le 5.6 \times 10^{14}$
CH_3OH	$4_2 - 4_1$	24933.47	0.75	≤ 0.15	≤ 1.5	$\le 6.6 \times 10^{12}$
NH_3	(1,1)	23694.48	0.7	≤ 0.14	≤ 0.47	$\le 1.7 \times 10^{12}$

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ON THE COMETARY HYDROGEN COMA AND FAR UV EMISSION

H. U. Keller

I. INTRODUCTION

Comet Tago-Sato-Kosaka (1969 IX, hereafter TSK) was the first medium bright comet passing by in the era of ultraviolet satellites. The Orbiting Astronomical Observatory (OAO-2), observed in January 1970 the strong Lyman alpha signal at 1216 A which led to the first detection of cometary hydrogen. The peak signal in the photometer field-of-view (FOV) of 10' diameter was about 70 kR (Code _et al_., 1970). The resonance scattering emission of hydrogen was optically thick in the central part of the coma. A rocket experiment of Jenkins and Wingert (1972) using an objective grating spectrograph confirmed the OAO-2 observations. Later in Spring 1970 comet Bennett (1970 II) was observed in Lα by OAO-2 and by two photometers onboard the Orbiting Geophysical Observatory (OGO-5) (Bertaux and Blamont, 1970; Keller and Thomas, 1973). A single observation of the short periodic comet Enke was also achieved (Bertaux _et al_., 1973). Comet Kohoutek (1973XII) triggered a variety of ultraviolet experiments using satellites, Copernicus (Bohlin _et al_., I. A. U.) and Skylab (Keller _et al_., 1975; Carruthers _et al_., 1974), as well as rockets (Feldman _et al_., 1974; Opal _et al_., 1974) and the spaceprobe Mariner 10 (Broadfoot _et al_., 1974) on its way to Mercury.

For hydrogen coma interpretations this review will rely heavily on recently published data of comet Bennett. Many observations of comet Kohoutek are still being analyzed.

The cometary hydrogen observations are reviewed, and theoretical interpretations of the results are followed by a brief summary of UV observations other than Lα.

II. Lα OBSERVATIONS

A spectrometer with a FOV of 2' x 8' onboard OAO-2 was used to construct a Lα isophote map of the central region of the hydrogen cloud of comet Bennett on April 16, 1970 (Code _et al_., 1972). The roughness in the contours --extending out to 2 kR -- is partly explained by contamination of the Lα signal by resonance oxygen emission at 1304 A (Lillie, 1974). The observed diameter was about 3×10^6 km. The apparent heliocentric velocity of the comet forms an angle of 52° with the antisolar direction (and not of more than 90° as indicated in the map). A comparison with recent Lα isophote maps of comet Kohoutek (Opal _et al_., 1974) shows the OAO-2 isophotes appreciably more irregular. The details are probably not physically relevant.

The French OGO-5 observations, which yielded twelve maps (Bertaux _et al_., 1973), were made during a special spin-up (spin axis parallel to apparent sun-comet direction) in April 1970. These photometer observations showed the hydrogen coma extending out to 250 R or a length (in antisolar direction) of 15 x 10^6 km, several orders of magnitude larger than its visible counterpart. In these observations the influence of the Lα radiative pressure force is dominant. The resolution is somewhat worse than the FOV diameter of 40' would have permitted. Because the special spin-up motion of the satellite complicated the data reduction, the location of the cometary nucleus is not known.

A different set of observations were achieved by the University of Colorado photometer onboard OGO-5 when the comet passed fortuitously through the FOV during the normal satellite operation in late March 1970 (Keller and Thomas, 1973). Four tracks across the cometary hydrogen cloud revealed that the Lα intensity as far out as 30 x 10^6 km in antisolar direction still reached a value of about 70 R above the sky background (∿400 R). A relatively large FOV of about 3° diameter increased the sensitivity of this instrument.

The Mariner 10 satellite made similar observations of comet Kohoutek in January 1974. The multichannel spectrometer of the Kitt Peak Observatory scanned the comet out to about 25 x 10^7 km in tail direction (Broadfoot et al., 1974). The data evaluation is still in progress.

By far the best Lα isophotes (Fig. 1) resulted from an observation of comet Kohoutek by an electrographic camera flown on a rocket on January 8, 1974 (Opal et al., 1974). The resolution was about 2' or 10^5 km; the comet's heliocentric distance was 0.43 a.u., and the influence of the Lα radiation pressure was strong. The innermost isophotes show optical thickness effects on the antisolar side not visible on the Bennett isophote maps. Thirteen maps were achieved by a similar camera onboard Skylab between 26 November 1973 and 2 February 1974 (Carruthers et al., 1974). Some of the pictures are, unfortunately, degraded by several adverse technical circumstances. An interpretation is difficult because of the proximity of the comet to the sun and because the absorption of the geocorona must be considered on several occasions. A knowledge of the cometary emission line profile is necessary to make these corrections. Some observational progress was achieved improving the coarse determination of the line profile of TSK by Code et al. (1970) who found a linewidth corresponding to a Doppler velocity $v_D \simeq 5$ km s^{-1}. The narrow geocoronal absorption line scanned across the cometary emission at the comet's perigeum.

The EUV spectrograph of the Naval Research Laboratory on Skylab received Lα line profiles of the central optically thick parts of comet Kohoutek's hydrogen coma shortly after

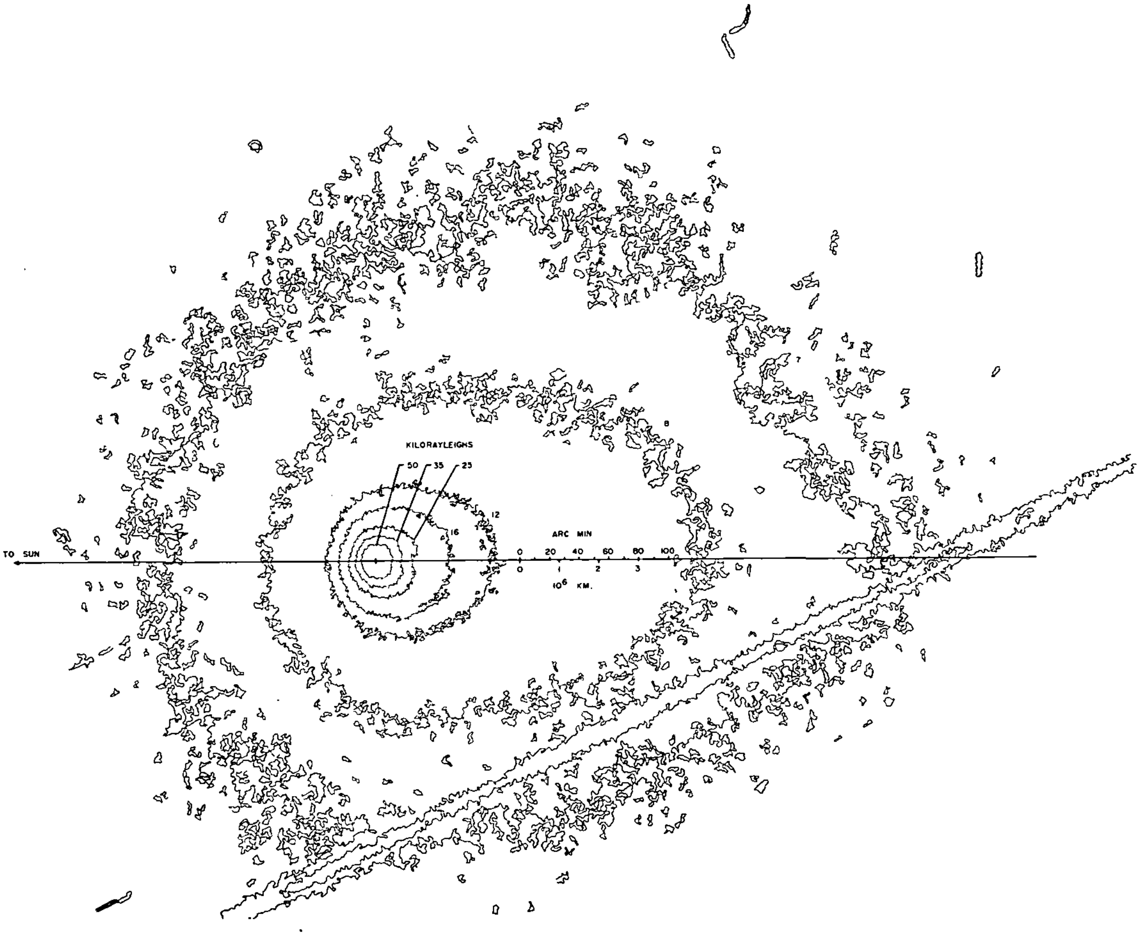

Figure 1 Lα isophotes of comet Kohoutek, 8.1 January 1974, observed by Opal et al. (1974). The isophotes are represented by microdensitometer tracings converted to absolute emission rates (kR). Linear and angular scales are indicated. Resolution in the inner parts is about 10^5 km (2 arc min). The outer isophotes in the lower part are deteriorated by a scratch on the film.

perihelion. The observed broadened linewidth (FWHM = 0.14 A or v_D = 34 km s^{-1}) agrees with the hydrogen outflow velocity $v_H \simeq 8$ km s^{-1} if the small instrumental broadening and opacity effects are considered. The observations were not good enough to deduce the actual cometary line profile (Keller et al., 1975). The Princeton University spectrometer onboard Copernicus (OAO-3) made observations in late January 1974, when the comet's heliocentric distance was about 1 a.u. (Bohlin et al., I. A. U.). The observed cometary linewidth corresponds to about v_D = 9 km s^{-1} since even the central region was predominantly optically thin.

High resolution observations with a Fabry-Perrot interferometer of comet Kohoutek detected the Hα emission of hydrogen. The determined linewidth corresponded to v_D = 8 km s^{-1} (Huppler et al., I. A. U.).

III. INTERPRETATION

Biermann (1968) described the overall features of the then still-hypothetical cometary hydrogen based on the dissociation of parent molecules like water and other hydrogen compounds. He called attention to the strong influence of the solar Lα radiation pressure force and the limiting interaction with the solar wind. Keller (1971) pointed out that the photodissociation of hydrogen-containing parent molecules in many cases (including H_2O) yields high excess energies of more than 1 eV. These excess energies are almost completely transformed into kinetic energy of the liberated hydrogen atoms providing velocities of more than 10 km s^{-1}. Depending on the overall gas production rate of a comet and, therefore, its heliocentric distance, r, these fast atoms are partially cooled by collisions. The inner region where collisions are possible has a radius on the order of 10^4 km, assuming a gas production rate on the order of 10^{30} molecule s^{-1} (typical for comet Bennett), and is therefore smaller than the region of dissociation which is about 10^5 km at r = 1 a.u. (Keller, 1973a). The source of hydrogen is small if compared to the dimensions of the OGO-5 observations. Keller (1971) suggested using Haser's (1966) fountain model -- originally developed for the visible coma -- for the interpretation of the hydrogen cloud. This model assumes a point source at the cometary nucleus with radial outflow velocity distribution and includes the effects of solar radiation pressure and of a finite lifetime. The major drawback of the fountain model is the neglect of the cometary motion during the lifetime of the hydrogen atoms (about 10 days at r = 1 a.u.). Bertaux et al. (1973) and Keller (1973b) used this model for the interpretation of the French OGO-5 data of comet Bennett.

The outflow velocity of the hydrogen atoms determines the extent of the sunward part of the isophotes (Fig. 2); $v_H = 8 - 9$ km s^{-1} was found for the mean velocity of an assumed radial maxwellian velocity distribution. The finite hydrogen lifetime, t_H, decreases the intensity of the isophotes the most on the down-sun side. t_H was about 2×10^6s (reduced to r = 1 a.u.) in early April 1970. Bertaux et al. (1973) found a decrease for later dates. This was attributed to an increase of the solar wind flux at solar latitudes higher than 45°. About 80% of the hydrogen atoms are ionized by charge exchange with solar wind protons; the rest are photoionized. The hydrogen production rate, Q_H, -- the third free parameter of the fountain model -- is determined from the absolute calibration. An average value for Q_H was 8×10^{29} H atom s^{-1} for r = 0.8 a.u.

Opal et al. (1974) also used the fountain model for a preliminary interpretation of their Kohoutek Lα isophote maps. The value for v_H was confirmed.

The comparison of the computed isophotes with the observations of comet Bennett (Fig. 2) reveals some qualitative differences, particularly in antisolar direction (Keller 1973b). The tapering of the observed isophotes is not reproduced by the model. The model shifts too much weight to the far down-sun parts, probably because of the incompleteness of the observations and the relatively

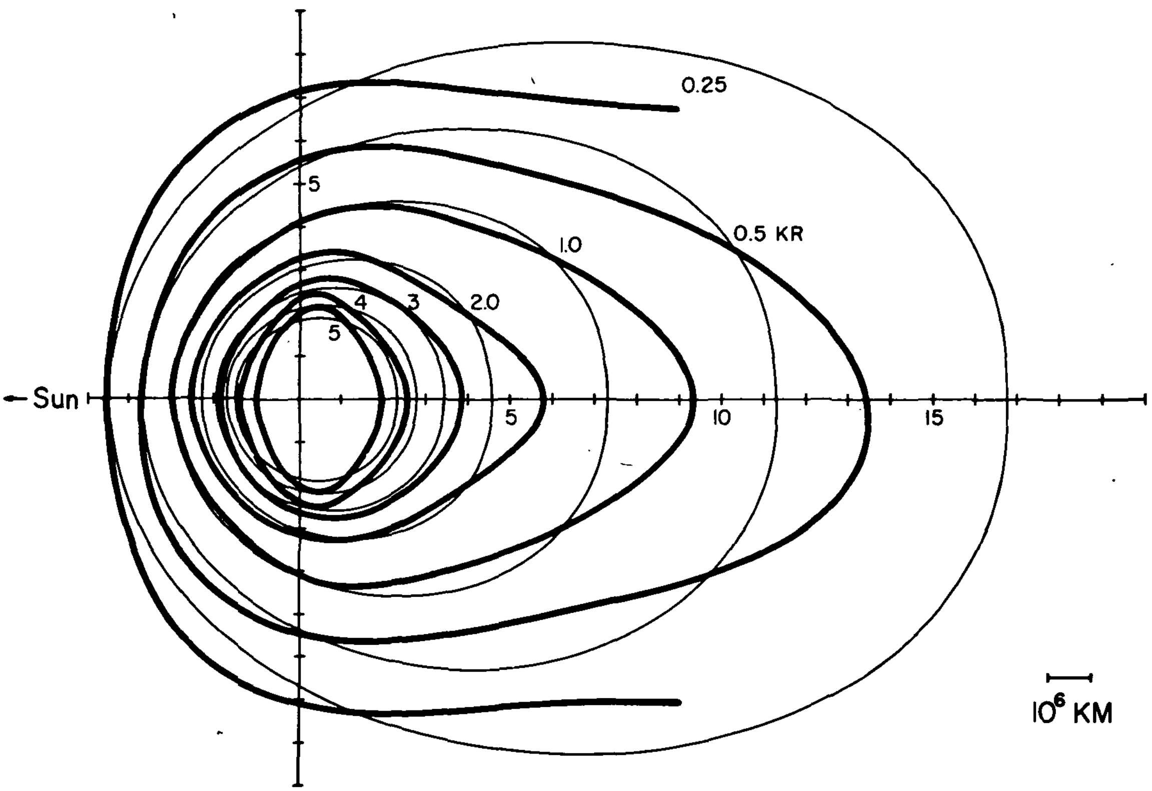
Ly α Isophotes Comet Bennett (1970II) April 1, 1970

Figure 2 The observed Lα isophotes (Bertaux et al., 1973), -, are compared to model calculations by Keller (1973b), —. The model parameters are: Q_H = 1.2×10^{30} atom s^{-1}, v_H = 8 km s^{-1}, $t_H = 2.5 \times 10^6$ s, and a solar Lα center flux of 3.2×10^{11} ph s^{-1} cm^{-2} A^{-2} is assumed.

primitive model. The Kohoutek observations (Fig. 1) resemble the calculated isophotes better but do not match perfectly.

Recently a more elaborate model was developed by Keller and Thomas (1975 and I. A. U.). This model uses methods similar to the dust tail calculations. Hydrogen atoms leaving the nuclear region with zero ejection velocity form a curve in the orbital plane of the comet -- the syndyname -- at observation time. The shape of the syndyname depends on the radiative pressure force and the cometary orbital elements. The points on the syndyname are interpreted as fictitious sources contributing to the line-of-sight density integral. This model accounts for the motion of the comet and the change of the hydrogen lifetime and production rate.

If the line-of-sight of the observations is nearly perpendicular on the orbital plane, the curvature of the hydrogen coma can be used to determine the solar Lα flux independent of any instrumental calibration. Keller and Thomas achieved the following results from the University of Colorado photometer observations of comet Bennett shortly after perihelion in March 1970: $Q_H = 5.9(\pm 2) \times 10^{29}$ atom s^{-1}, $t_H = 1.3(-0.3, +0.7) \times 10^6$ s both reduced to $r = 1$ a.u. These agree well with all the other Bennett results. The data at the outer boundaries of the hydrogen coma required a 50:50 mixture of two maxwellian velocity distributions, v_H = 7 and 21 km s^{-1}, for a good fit. The high velocity component is hard to detect on the antisolar side, it is masked by the low velocity H atoms. The central solar Lα flux was determined to $5(\pm 1) \times 10^{11}$ ph s^{-1} cm^{-2} A^{-1}.

Keller (1973a) investigated the properties of the optically thick central parts of the cometary hydrogen coma. The radiative transfer problem was solved for a purely radial outflow velocity distribution using Monte-Carlo techniques. Emission line profiles were determined for multiple and single scattering. This type of model calculation will have increasing importance for the interpretation of high resolution -- spatial and wavelength -- observations. A comparison with the OAO-2 isophotes confirmed the interpretations of the fountain model for Q_H and v_H.

The physical parameters for particular observations of the hydrogen coma have been established, and their variation with heliocentric distance must be investigated now. The lifetime increases with r^2 since the limiting effects of both solar wind and solar flux are diluted. However, the effect on the outflow velocity is not clear. The French OGO-5 data of comet Bennett did not yield evidence for a systematic variation of the outflow velocity in the heliocentric distance interval from 0.61 to 1.0 a.u. A systematic change in the hydrogen production rate was hardly detectable either, probably because the uncertainties of the observations were too large.

OAO-2 photometer observations of comet Bennett in the heliocentric distance interval from 0.75 to 1.25 a.u. show a parallel decrease of the hydrogen and hydroxyl (OH) production rates with an r-exponent of -2.3($\pm$0.3) (Keller and Lillie, 1974; Lillie and Keller, I. A. U.). These results are unique because of the simultaneous H and OH observations with similar instruments and because they include the greatest heliocentric distance yet observed. The parallel decrease and an H/OH ratio of about 2 suggest a mutual parent molecule, probably water. The relatively small exponent 2.3 does not exclude more volatile molecules. No indication of a sudden drop of the vaporization of the parent molecule due to the re-radiation term in the equilibrium equation was found. These results allow conclusions on properties of the nucleus, e.g., its albedo (see Delsemme and Rud, 1973, and Keller and Lillie, 1974, for a more detailed discussion).

Delsemme (1973) had investigated similar, less complete OAO-2 data of comet TSK and found the variation of the production rates of the mutual parent moelcule of H and OH governed by the exponent -2.8. He concluded that only water evaporation can explain the data.

Table I summarizes the results of the hydrogen observations of comet Bennett. The preliminary results of comet Kohoutek observations do not show any significant differences. The hydrogen outflow velocities determined from Lα isophotes (Opal _et_ _al_., 1974) and line profile (Bohlin _et_ _al_., I. A. U.) seem to be equal.

The available hydrogen production rates of the comets TSK, Bennett, Kohoutek, and periodic comet Encke are illustrated in Fig. 3. The agreement for the Bennett observations are excellent. Undoubtedly, production rate determinations of cometary hydrogen based on the ultraviolet observations are by far more reliable than results for most other constituents.

TABLE I

Comet Bennett (1970 II)

Hydrogen

Production Rate at 1 a.u.	$Q = 5.4(\pm 2) \times 10^{29}$ atom s^{-1}
Lifetime at 1 a.u.	$1 - 2.5 \times 10^{6}$ s
Outflow velocity	$7 - 9$ km s^{-1}
and component with	~ 20 km s^{-1}
Production rate variation	$Q \propto r^{-n}$ $1.5 < n < 2.6$
for	$0.55 < r < 1.25$

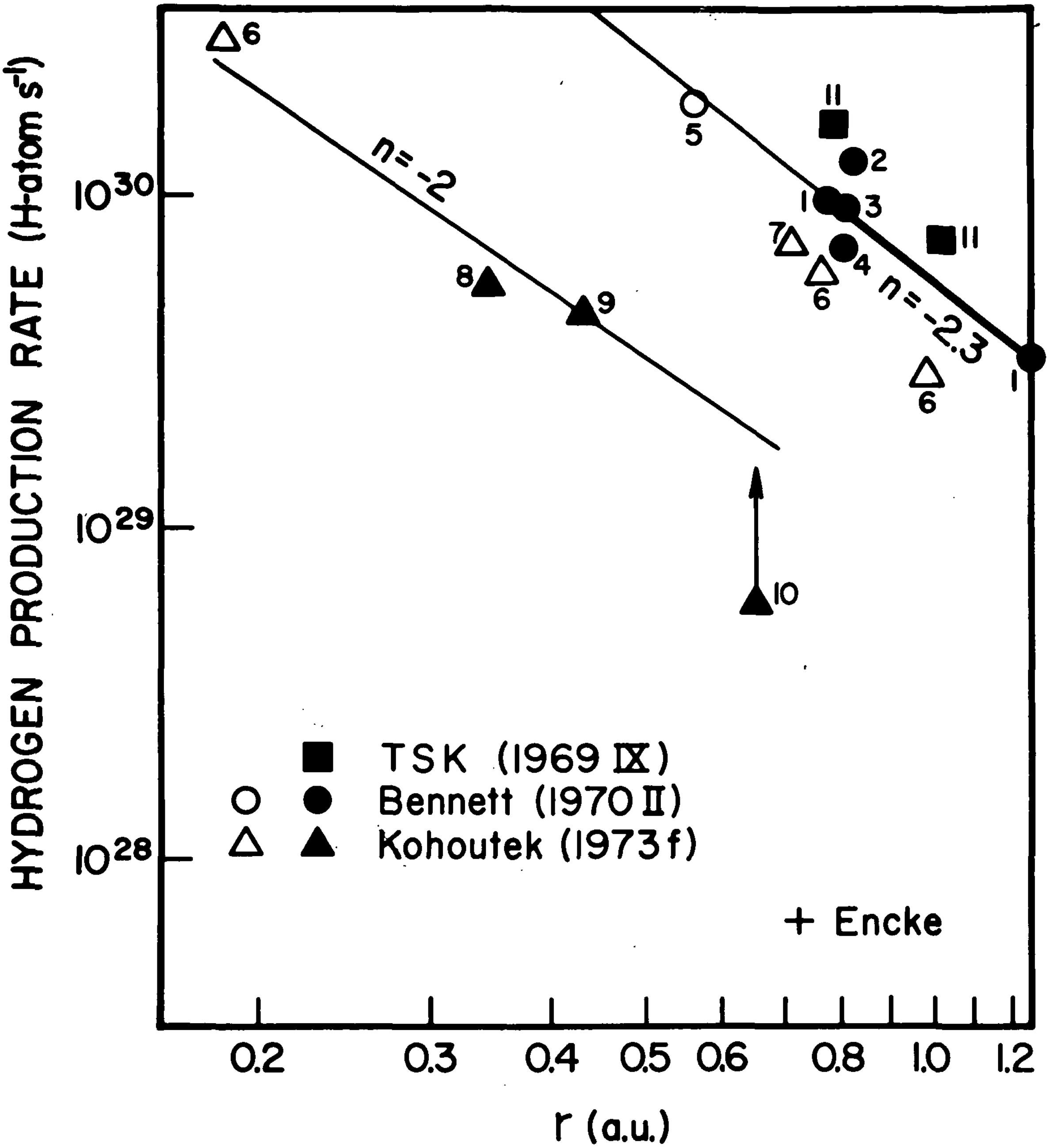

Figure 3 Hydrogen production rates of all observed comets: Open signs refer to the pre-perihelion, the filled ones to post-perihelion orbit. The ordinate is the heliocentric distance.

Figure 3 Legend

1. OAO-2, Keller and Lillie (1974) observations cover the interval between the edge points (heavier line). Observed slope, n = -2.3.
2. OAO-2, Keller (1973a).
3. OGO-5, French Photometer, Bertaux *et al*. (1973). A typical value is chosen. Observation interval from 0.6 to 1.0 a.u.
4. OGO-5, French Photometer, Keller (1973b). A typical value, representing the maximum deviation from average.
5. OGO-5, University of Colorado photometer, Keller and Thomas (1975).
6. Skylab, electrographic camera, Carruthers *et al*. (1974).
7. Hα observations, Huppler *et al*. (I. A. U.).
8. Spectrometer on rocket, Feldman *et al*. (1974).
9. Electrographic camera on rocket, Opal *et al*. (1974).
10. Mariner 10, UV spectrometer, Broadfoot *et al*. (1974).
11. OAO-2, Lillie (1974).

Comet Encke was observed by the French photometer on OGO-5, Bertaux *et al*. (1973).

Pre-perihelion comet Kohoutek's hydrogen production seemed to be slightly less than Bennett's; the Lα and Hα observations agree well. The hydrogen production rate was down by about a factor of five after perihelion as compared to comet Bennett. Thus, this decrease of the gas production (lessening the dust production too) explains comet Kohoutek's fainter visual brightness after perihelion. The hydrogen production peaked at perihelion and the exponent was approximately -2 ($Q_H \propto r^{-2}$). The final results of all Kohoutek observations (Skylab, Mariner 10, and Copernicus) will provide the hydrogen production rate variation from about 1 a.u. to perihelion and back to the same heliocentric distance.

Also included in Fig. 3 are two points referring to comet TSK. These are unpublished, preliminary results from OAO-2 observations. Surprisingly, the hydrogen production of comet TSK surpassed (about 50%) that of comet Bennett whose intrinsic visual brightness was three magnitudes brighter. The superior visual brightness of the latter comet obviously stems from its tremendous dust production. Comet Encke's hydrogen production rate was smaller by about two orders of magnitude.

The questions remain how the hydrogen atoms are created and what their parent molecules are. These large amounts of hydrogen atoms cannot be directly stored in the nucleus; the same holds for molecular hydrogen. Clearly, the recently detected parent molecules, HCN, CH_3CN, and H_2O and other observed radicals contribute to the amount of atomic hydrogen. We shall not discuss in detail whether water (H_2O) is dominating; only arguments directly connected with the ultraviolet observations will be mentioned. The strongest hint for the important role of water is based on the observations of the large OH production. The OAO-2 results for comet Bennett (Keller and Lillie, 1974) show that nearly all the hydrogen comes from water as assumed parent molecule of OH, or at least one third in the extreme of the error limits. The Kohoutek observations yielded similar results. Equally important, the H and OH production rates of comet Bennett decreased parallel between $r = 0.75$ and 1.25 a.u. Probably, OH could not be synthesized efficiently enough by ion-molecule reactions in the inner coma (Oppenheimer, I. A. U.) and must be a dissociation product.

The conclusions from the values of the hydrogen outflow velocities observed and interpreted by several different methods are somewhat controversial. Table II shows the probable photodissociation processes connected with water. Several laboratory experiments (e.g., Welge and Stuhl, 1967;

TABLE II

H_2O Dissociation

$H_2O + h\frac{c}{\lambda}$

λ: 1365 - 1860 A	70% →	$H + OH(X^2\pi) + E_{kin}\left\{\begin{matrix} >1.5\text{ eV} \\ v_H > 16\text{ km/s} \end{matrix}\right\}$	60%
		$H_2 + O$	10%
λ < 1365 A	30% →	$H + OH(X^2\pi) + E_{kin}\left\{\begin{matrix} \sim 5\text{ Ev?} \\ v_H \sim 30\text{ km/s?} \end{matrix}\right\}$	28%
		$H + OH^*(A^2\Sigma^+) + E_{kin}\left\{\begin{matrix} < 0.4\text{ eV} \\ v_H < 9\text{km/s} \end{matrix}\right\}$	<1%
		$H_2 + O$	2%

OH Dissociation

$$OH + h\frac{c}{\lambda} \rightarrow O + H + E_{kin}(?)$$

Carrington, 1964; and Stief, 1966) deal with the various dissociation branches of water; however, no measurements exist for OH. The important H_2O dissociations yield excess energies of more than 1.5 eV which are nearly completely converted into translation energies of the H atoms. The observed hydrogen velocity of 8 km s^{-1}, however corresponds to only about 0.4 eV. Bertaux et al. (1973) estimated, based on a polytropic coma model of Mendis et al. (1972), that only about 20% of the hydrogen atoms stemming from water dissociation are cooled, whereas the second generation H atoms from OH dissociation undergo practically no collisions. They concluded that the kinetic energy from this photodissociation must yield only 0.4 eV or less. Most theoretical estimations, however, are 1 eV or even more (Solomon, 1968). Wallis (1974) included the heating by dissociative excess energies in the inner coma more realistically, but his approximation also yielded only 30% thermalized hydrogen atoms.

If thermalization determines the outflow velocity, v_H should vary from comet to comet and with heliocentric distance. The sphere of collisions is proportional to the production rate and decreases in radius when the comet recedes. In addition, hydrogen atoms are created at a greater nuclear distance and live longer. An alternative is that all hydrogen atoms with $v_H \approx 8$ km s^{-1} are completely thermalized requiring a total gas production rate essentially higher than that observed of the H atoms (Keller, 1971; 1973a). The recent OH radio observations of comet Kohoutek (Biraud et al., 1974) seem to exclude collisional damping and result in rather large hydroxyl Doppler velocities of 3-4 km s^{-1}.

A small variation of the observed hydrogen outflow velocity cannot be excluded by the existing data but is not supported either. A large portion of the hydrogen atoms may have high velocities (Keller and Thomas, I. A. U.). This high velocity component is difficult to observe. More knowledge of the H_2O and OH dissociation is badly needed to determine whether the observed hydrogen atom velocities are in agreement with the water photodissociation. A stochastic treatment of the collision dominated inner coma region taking into account the partial relaxation of the initial non-thermal velocity distribution will make a detailed interpretation possible.

IV. NON-Lα UV OBSERVATIONS

In the ultraviolet an identification of cometary constituents other than hydrogen is difficult. The emission rates are more than two orders of magnitude weaker than

Lα because of the low exciting solar flux and the smaller oscillator strengths of the transitions. The abundances are smaller too. Feldman et al. (1974) made observations of comet Kohoutek on January 5, 1974, using two spectrometers covering the wavelength region 1200 to 3200 A (Table III). The figures are uncertain by at least a factor of two. The radial heliocentric velocity of the comet was large enough that the cometary atoms absorbed in the wings of the narrow solar emission lines (for $\lambda < 1800$ A) introducing an additional uncertainty. This situation could be improved in future experiments by a series of observations at different cometary velocities (Feldman et al., I. A. U.).

Feldman et al. (1974) concluded that their results are consistent with the assumption that water vapor dissociation is predominant. The emission of carbon, CI, at 1657 and 1561 A was observed for the first time. The fact that CI is only slightly less abundant ($Q_O/Q_C \simeq 3$) than oxygen and hydroxyl is one of the most important results of all Kohoutek observations. Lillie (I. A. U.) confirmed the O:C ratio for comet Bennett from OAO-2 data. Earlier, oxygen (1304 A) was found in about the same amount as hydrogen in comet Bennett (Code et al., 1972). Carbon is obviously by more than an order of magnitude more abundant than CN ($Q_H:Q_{CN} \simeq 200$ for comet Bennett, Code et al., 1972). It is probably not a minor constituent. Improved UV observations in future comets are important and might lead in addition to the

TABLE III

UV Emissions of Comet Kohoutek (1973f)*

5 January 1974 r = 0.34 a.u.

Species	λ [A]	Q[s^{-1}]
HI	1216	3.6×10^{29}
OI	1304	1.4
CI	1657	0.6
CO	1510	$\leq$ 2.7
H_2	1607	$\leq$ 0.3
CO_2	2890	$\leq$ 10.1
OH	3090	0.8

*Table from Feldman et al. (1974).

Some values are revised.

Species with UV emissions to be detected:

He, N, N_2, N_2^+, NO, C^+, CN^+, O^+, S, Si, and metals.

detection of some of the constituents listed on the bottom of Table III.

V. OUTLOOK AND SUMMARY

Ultraviolet observations of more comets are badly needed to confirm our conclusions and to find which values are typical to all comets and which ones are specific to the individual comet or a group of comets. A new generation of UV instruments is available to make Lα observations of comets down to about 10th visual magnitude. We should try to duplicate the synoptic and simultaneous observations of the hydrogen and hydroxyl production rate variations of a comet and expand the heliocentric distance interval as far as possible in order to determine the sudden drop off point of the water evaporation. More difficult, but at least equally interesting, is the observation of the ratio of water dissociation products to the rest of the molecules and atoms and its variation with heliocentric distance. Lα observations with good spatial resolution together with observations of the actual cometary emission profile will provide the information to determine the velocity distribution using models that include the relaxation of the hydrogen atoms.

In summary, the cometary Lα observations have, without a shade of doubt, confirmed the relatively high overall gas production rates on the order of 10^{30} molecule s^{-1} of medium bright comets suggested by other observations and calculations in the last decade. Additional observations of oxygen and hydroxyl favor water to be one of the most abundant molecules in the coma at cometary heliocentric distances of about 1 a.u. and less. Water does not seem to outnumber other constituents by orders of magnitude in comet Kohoutek. The hydrogen production rate of comet Kohoutek was about a factor 5 less after perihelion and probably only slightly less pre-perihelion when compared to comet Bennett. The observed outflow velocities of the hydrogen atoms of both comets were about 7-10 km s^{-1}, a value not yet understood. If the high velocity component of 20 km s^{-1} or more comprises a larger amount, some of the quoted hydrogen production rates are actually higher. The intrinsic cometary brightness is only a very crude indicator of a comet's actual gas production rate as shown by the comparison of comets Bennett and TSK. The strength of the Lα emission favors these measurements as a standard procedure for observing future comets since they also provide the most accurate results on the total gas production rate and its variation with heliocentric distance.

Acknowledgements: This work was supported by a grant from the National Aeronautics and Space Administration, NGR 06-003-179.

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DISCUSSION

D. J. Malaise: I have three comments on this review paper.

1. From what I have heard of stellar observations by OAO, the absolute calibration of the spectrometer and of the photometer was somewhat unreliable, and even relative calibration between the different experiments was not satisfactory. Here, moreover, you have to take into account the integration in the entrance aperture. What kind of uncertainty does that introduce in the relative production rates you have deduced?

2. I don't agree that these results are another proof that H_2O is the main constituent of the comet. In fact, they seem to disprove it in two respects. First, the dissociation of H_2O yields only the high velocity component of H ($v > 10$ km/sec), so that about half the hydrogen observed in the coma (the low velocity component, $v \sim 9$ km/sec) needs another mother molecule than H_2O. Second, you showed that the variations of both H and OH with perihelion distance were remarkably parallel, while the production of H (the low velocity component for instance) through the dissociation of OH would give a H/OH production rate greater at smaller perihelion distances.

3. You showed an observed profile for H and a 2-component (9 km/sec + 21 km/sec) computed profile which was adjusted to fit the observations. I want to make a general comment about the fitting procedure in view of information theory. The two limits of the observed profile are essentially due to accidental errors, while there is a systematic deviation of the computed profile from the mean of the observed profiles. It is not relevant in the fitting procedure that the systematic deviation be kept within the accidental errors, because these two errors are of quite different nature.

As a matter of fact, if the correct physics were used to derive the theoretical profile, such large systematic deviations should not appear. If you allow such a misfit, a good mathematician will show you that there exists an infinite number of solutions to your problem. To choose one particular solution, you need to use additional constraints (other than your observed curve). These constraints can be simple hypothesis or personal views of how the model should be, etc. These constraints are used in parallel to the observations to define or select the fitting curve, but then it is an error of principle to claim that the observations prove the model. The model is an input and not an output of the fitting procedure; it can not be both.

W. Jackson:

1. The latest laboratory data for H_2O is reviewed in my paper. However, it shows that in the first continuum 99% of the H_2O dissociates into H + OH ($X^2\pi$), while in the second continuum 99% of the H_2O dissociates into H + OH,

while 10% of the products are $H_2 + O(^1D)$. Further, the present data indicate that the excess energy is deposited into translational energy of the H product in both regions.

2. It seems unlikely that CO is the parent of C atoms, because laboratory data indicate that CO doesn't photodissociate in its first absorption band. This means that the lifetime against photodissociation is very long, since CO will only dissociate in a region below 1100Å.

P. D. Feldman:

1. CO as a source of C is only an educated guess.

2. The new value for Q_{OH} is 0.5×10^{29} sec^{-1} (Feldman, et al., paper 51). This gives $Q_{OH}/Q_H \sim 0.1$, which is probably outside experimental errors.

3. $CH_4 \rightarrow C + 4H$ would give a good fit to the data.

4. With a factor of 10 better sensitivity in UV observations, next time we should be able to see if CO is really present.

F. L. Whipple: It should be pointed out that the high production rates of some material like H_2O was explicit in the early non-gravitational forces in comets. The necessary mass was unobserved at that time and had to have a vapor pressure something like H_2O to confine the non-gravitational forces, as well as general comet activity, to the perihelion regions. The current evidence for many carbon compounds in comets relieves the need to postulate CH_4, which seems to be incompatible with the presence of CO and CO_2.

M. Festou: The velocity of the H-atoms is obtained by comparing fountain-model and data, so we must use an experimental profile which is very dependent on this velocity, that is to say, the sunward profile. All observations fit with an 8 km/sec component. If we use the anti-solar profile, we can see that the velocity is only a factor of proportionality, and the model fits the data when using a short lifetime for the H-atoms; the velocity does not play any role. This is illustrated by the fact that we find both a short lifetime ($\sim 1.5 \times 10^5$ secs) when using two different velocities (20 km/sec and 8 km/sec). Another way to fit the data when using a higher lifetime of the H-atoms is to take into account a complementary source in the anti-solar direction. I think the dissociation of H_2O^+ can be this additional source, because H_2O^+ is produced in a very small solid angle, which compensates its relatively low production rate.

omit

HIGH RESOLUTION LY-α OBSERVATIONS OF COMET KOHOUTEK BY SKYLAB AND COPERNICUS

J. D. Bohlin, J. F. Drake, E. B. Jenkins and H. U. Keller

ABSTRACT

The Ly-α emission line of Comet Kohoutek was observed with two high spectral resolution instruments yielding consistent results. The first set of measurements occurred on 5 dates from 19 December 1973 to 6 January 1974; these measurements were made with the Naval Research Laboratory's S082B spectrograph from the Skylab Apollo Telescope Mount. The second set of measurements occurred on 29 January and 2 February 1974; these measurements were made with the Princeton telescope-spectrometer on the Copernicus satellite (Orbiting Astronomical Observatory - C). Both measurements were made with the instruments pointed at the cometary nucleus. The FWHM (full width at half maximum) of the emission line profiles so obtained exceeded in all cases the instrumental profiles expected. The calculated Skylab instrumental profile FWHM is 0.055 Å at Ly-α while the Copernicus FWHM determined by geocoronal Ly-α observations is 0.068 Å. The residual FWHM due to the comet is 0.13 Å for the Skylab data and 0.063 Å for the Copernicus data. If these line widths are interpreted as Doppler velocity effects and if optical depth effects are considered, then both sets of data are consistent with a Doppler velocity of about 10 km/sec. The uncertainties in both the Skylab and Copernicus data correspond to Doppler velocities of the order of ±3 km/sec.

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A HIGH-VELOCITY COMPONENT OF ATOMIC HYDROGEN IN COMET BENNETT (1970 II)

H. U. Keller and Gary E. Thomas

The Lyman alpha emission from Comet Bennett (1970II) was measured near perihelion (March 1970) by the University of Colorado ultraviolet photometer experiment on OGO-5. The spectrometer field of view of about 3° crossed the cometary hydrogen coma four times. The hydrogen coma was observed to extend more than 30×10^6 km in the antisolar direction.

A model for the hydrogen density was developed which took the actual cometary motion and the gradients of the forces of gravitation and radiation pressure into account. Exact trajectories of atoms in the orbital plane representing the column densities perpendicular to the plane were calculated. The variation of the hydrogen lifetime along the trajectory as well as the solar Lα profile were considered. The strong curvature of the hydrogen cloud in the orbital plane of the comet was used to determine the solar Lα flux independent of instrumental calibration. Figure 1 illustrates the observational geometry and the calculated Lα isophotes. In general, the values for the cometary hydrogen parameters: production rate, outflow velocity and lifetime, determined from different satellite observations (Keller, 1973a,b; Bertaux _et al_., 1973) based on Haser's (1966)

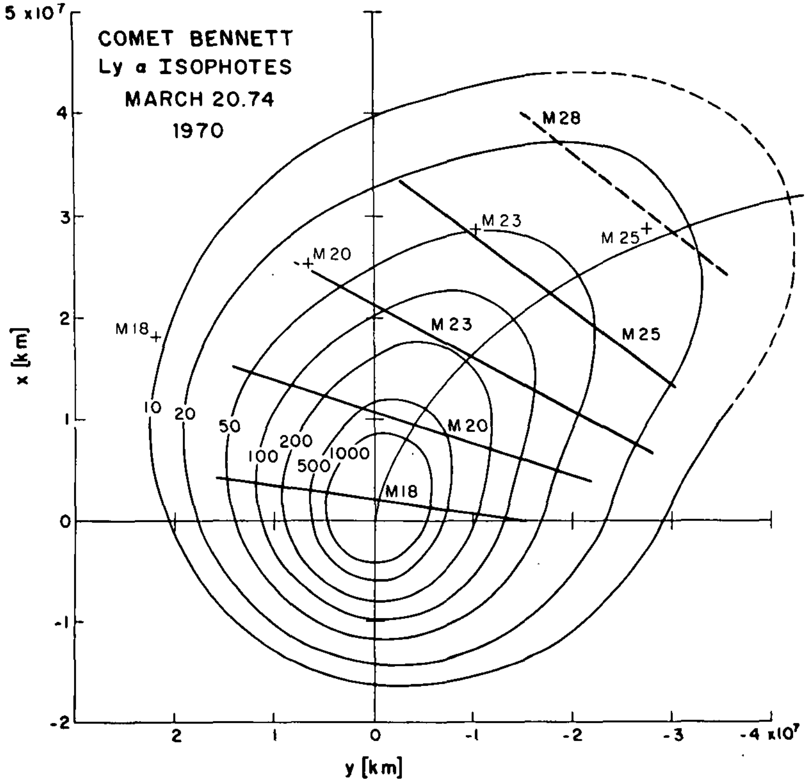

Figure 1. Lα isophote map of a model calculation for 20.74 March. The x coordinate points in antisolar and the y coordinate in the direction of the cometary motion. x and y lie in the orbital plane of the comet. The cometary nucleus is located at the origin. Two velocity components, $v_H = 7$ and 21 km s^{-1}, $F_o = 5 \times 10^{11}$ ph s^{-1} cm^{-2} A^{-1} and $t_H = 1.3 \times 10^6$ s are used. The isophotes are labeled with relative apparent emission rates. 10 corresponds to 8.86 R for $Q = 5.9 \times 10^{29}$ H atom s^{-1} at 1 a.u. $(n = 2)$. Heavy lines are scans of the OGO-5 University of Colorado photometer at their particular geometrical position depending on the observational date (M28 dashed). The crosses (+) are defined by the x and y coordinates of the earth at the times when the maximum intensities were observed. The curved line is the syndyname.

fountain model were confirmed by this investigation. A significant discrepancy of the model calculations using the established outflow velocity of about 8 km s^{-1} with the observations was detectable at the wings of the field of view tracks, i.e., on the outermost parts of the hydrogen coma; especially on the leading edge (Fig. 2). An additional high velocity component of about 20 km s^{-1} was necessary to fit the data. Under the assumption of a radial maxwellian velocity distribution a best fit was found using a 50:50 mixture of hydrogen atoms with mean outflow velocities of 7 and 21 km s^{-1}. Figure 2 illustrates very well how difficult the detection of this high velocity component is. Both of the computed profiles agree closely in the inner part of the hydrogen coma. The low velocity component masks the high velocity portion. The subsolar parts of the coma would be much more sensitive to the value of the outflow velocity.

The hydrogen atoms are created with non-thermal velocities stemming from the excess energies of the dissociation processes. The region where collisions are important around the nucleus is smaller than the hydrogen source region (Keller, 1973b). Hence, we cannot expect the hydrogen atoms to be thermalized. The high velocity component of about 20 km s^{-1} might well be directly connected with such a dissociation process. The first dissociation of H_2O, for

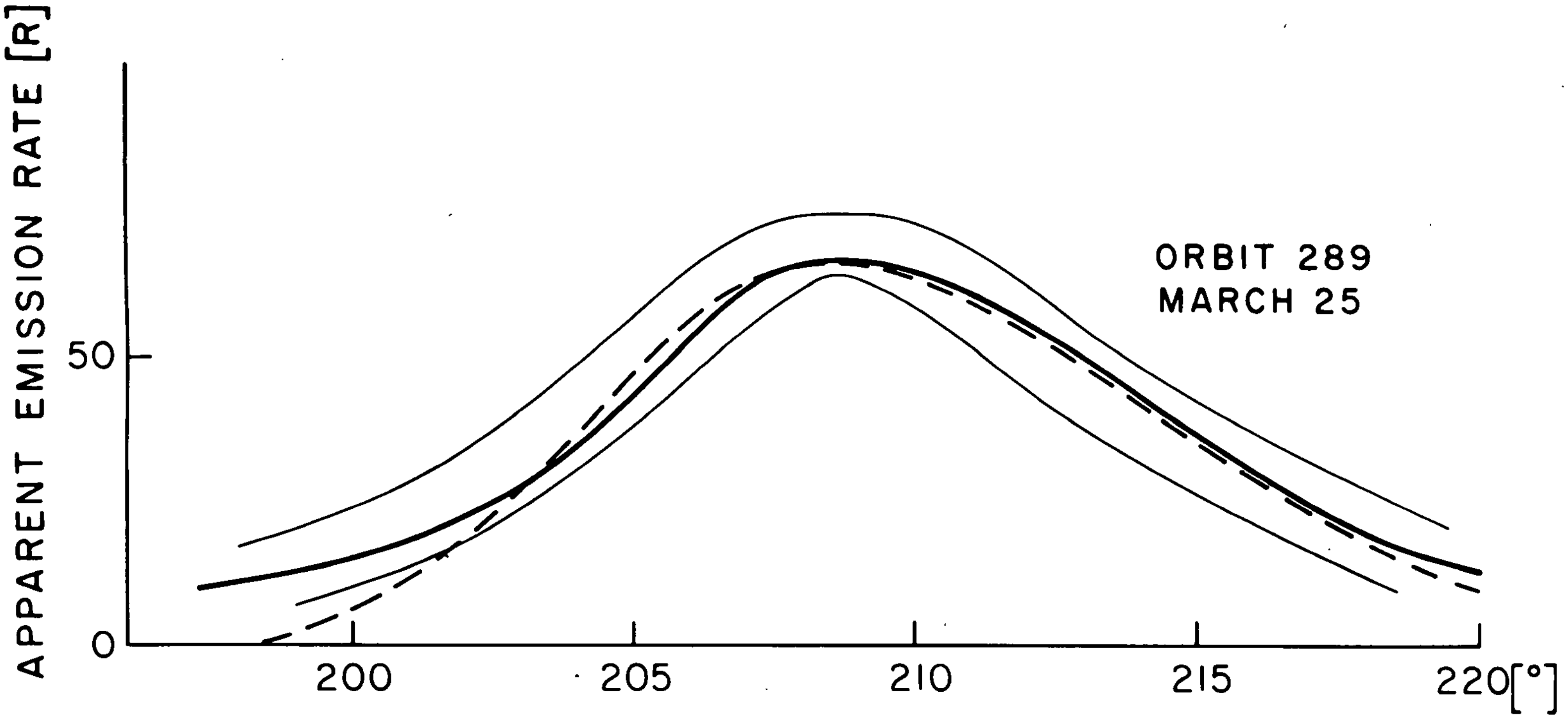

Figure 2. The abscissa is the true anomaly of the satellite orbit in degrees. The ordinate is the Lα emission rate. The light curves represent the probable error boundaries of the observational data of the scan on March 25, 1970; heavy line — the "best fit" calculated model using two maxwellian velocity distributions with mean velocities of $v_H = 7$ and 21 km s^{-1}. Dashed line (--) a single velocity model with $v_H = 9$ km s^{-1}. The remaining model parameters are: solar Lα flux, 5×10^{11} ph s^{-1} cm^{-2} A^{-1}; lifetime, 1.3×10^{6} s; and hydrogen production rate, 5.9×10^{29} atom s^{-1} (all at 1 a.u.)

example, yields hydrogen atoms with a velocity of at least 16 km s^{-1} (Keller, 1971).

The comparison of the model calculation with the observed data further yielded the following values for the hydrogen quantities: production rate, 5.9 (±2) x 10^{29} H atom s^{-1}; lifetime, 1.3 (-0.3 + 0.7) x 10^{6} s (both at 1 a.u.). The solar Lα flux in line center was determined to be 5.0 (±1.0) x 10^{11} photon s^{-1} cm^{-2} A^{-1} independent of any instrumental calibration. For more details of the model calculations and results, see Keller and Thomas (1975).

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OMIT

SPECTROPHOTOMETRY OF COMET BENNETT FROM OAO-2

C. F. Lillie

ABSTRACT

In addition to the strong emission features of H(1216Å) and OH(3090Å), a number of weaker features, such as OI(1304Å) and CI(1657Å) are present in spectral scans of Comet 1970 II which were obtained with the Orbiting Astronomical Observatory (OAO-2) spacecraft. Observed emission rates and column densities or upper limits are presented for molecules with transitions in the 1000-3000Å region which are expected to be present in the nucleus of a comet. The apparent emission rates at different wavelengths measured with the stellar photometers on OAO-2 are shown to be in good agreement with the spectrometer data. The ultraviolet scattering efficiency of dust in Comet Bennett will be discussed.

omit

THE GAS PRODUCTION RATE OF COMET BENNETT

C. F. Lillie and H. U. Keller

Comet Bennett (1970 II) was observed with the ultraviolet photometers on OAO-2 from April 13.39 to May 13.88, 1970, while its heliocentric distance increased from R = 0.77 to 1.26 a.u. An analysis of the photometer data for the emission features of OH $\lambda 3090$ and H $\lambda 1216$ indicates the production rates of OH and H were 2.0×10^{29} molecule sec^{-1} and 5.4×10^{29} atom sec^{-1}, respectively, at R = 1 a.u. During this period the production rates of H and OH varied as $R^{-2.3}$. This is consistent with the assumption that water vaporization controls the production rate of gas in comets at small heliocentric distances.

The OAO spacecraft was stabilized in three-axes and pointed to the nucleus of the comet with a nominal accuracy of ±1'. The comet was observed during the 10 minute period between comet-rise and sun-rise, as seen from the spacecraft. The OAO-2 photometers consisted of an off-axis parabolic mirror, aperture, fabry lens*, and photomultiplier tube. The aperture provided a 10 arc min diameter field-of-view. Each filter isolated an ∿300 A bandpass in the 1050 - 4600 A region. Figures 1 and 2 show the measurements

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*no Fabry lens was used in the Lyman-alpha photometer.

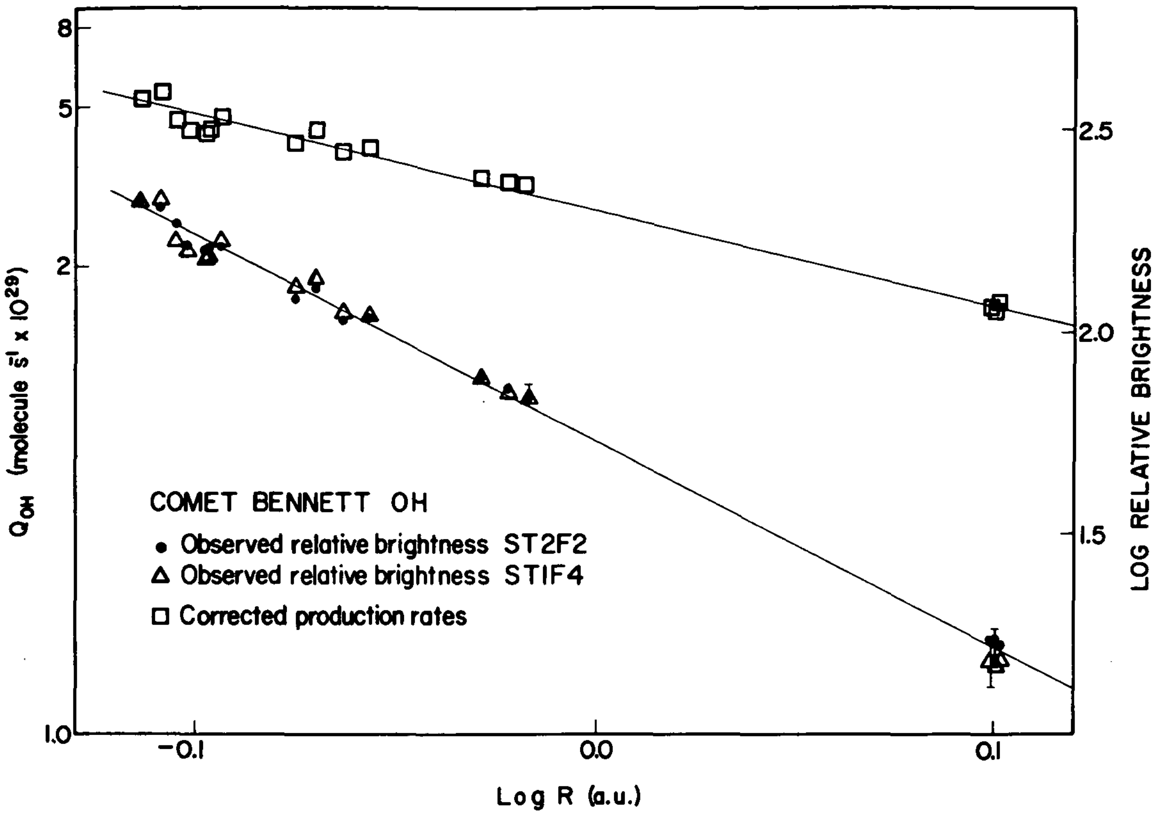

Figure 1 The OH λ3090 photometer observations of comet Bennett from April 13 to May 13, 1970. The lower curve shows the logarithm of the observed brightness (right ordinate) from two different photometers, ST 1 F4 (Δ) and ST 2 F4 (●), versus the logarithm of the heliocentric distance, R. The upper curve (□) shows the observations, corrected for field-of-view effects, in terms of the production rate of OH (left ordinate) versus log R.

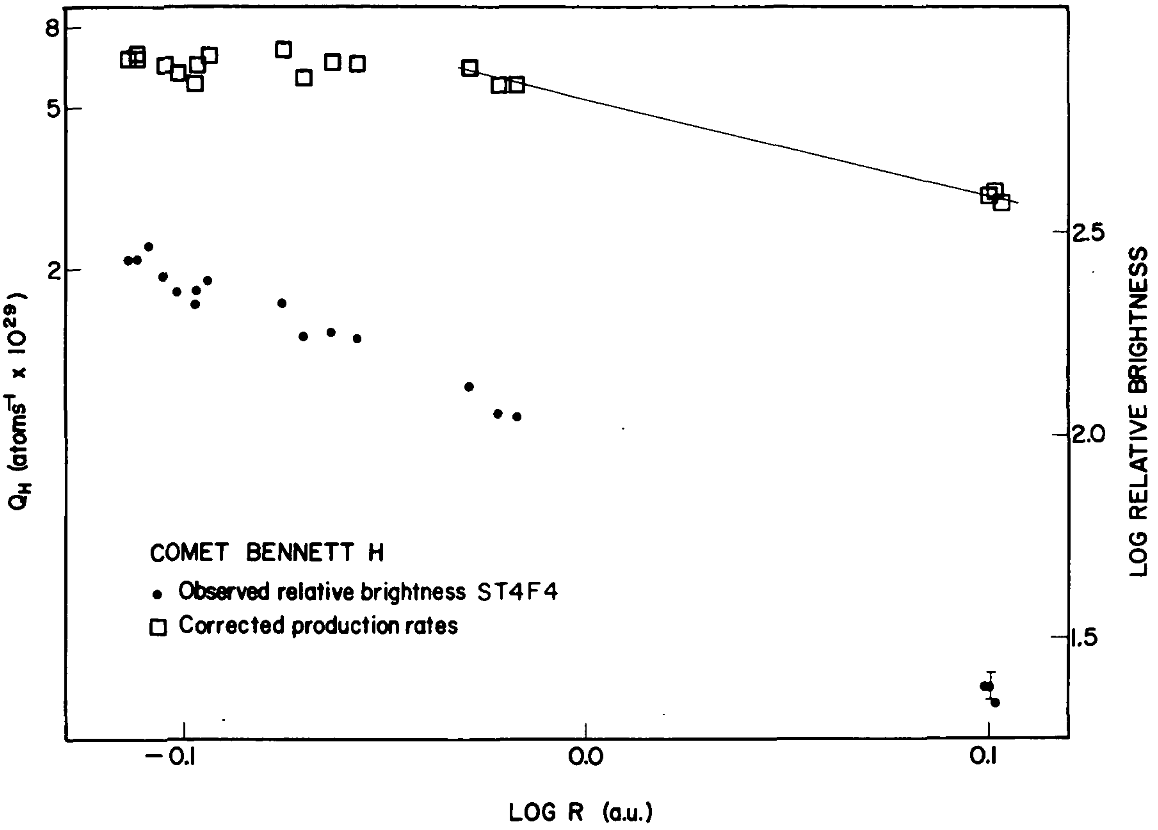

Figure 2 The hydrogen Lα photometer observations of comet Bennett from April 13 to May 13, 1970. The logarithm of the brightness observed with ST 4 F4 in relative units is shown versus the logarithm of the heliocentric distance, R, by filled circles (●). The production rate of hydrogen derived from the observations, corrected for field-of-view effects, versus log R is shown by open squares (□).

obtained with the bandpasses centered on 2980 A and 1260 A, respectively. The lower curve shows the logarithm of the observed brightness plotted versus the logarithm of heliocentric distance. An examination of the spectrometer data for Comet Bennett (Lillie, 1975) indicates that 85% of the signal in the long wavelength bandpass is due to emission from the (0-0) band of OH ($A^2\Sigma^+ - X^2\Pi_i$), and ∿95% of the signal in the short wavelength bandpass is due to the Lyman-alpha line of atomic hydrogen.

Our observational material only provides the mean column densities of OH and H in a 10' field-of-view centered on the nucleus of the comet. In order to convert these observed intensities of H and OH into production rates, we adopted Haser's (1957) parent-daughter model for the radial distribution of atoms and molecules in the head of a comet.

If we assume the coma is optically thin, its average brightness in a field-of-view of radius s will be:

$$B(s) = \frac{gQ_p t_d}{\pi s^2} \; f$$

where g is the photo-excitation factor in photon molecule^{-1} sec^{-1}, Q_p is the production rate of parent molecules in molecule sec^{-1}, t_d is the lifetime of the daughter molecules and f is a function which corrects for the limited field-of-view of the instrument. This correction depends on the scalelength of parent and daughter molecules.

We can understand the data qualtitatively if we assume the parent molecule production rate, Q_p, is proportional to R^{-2}. The excitation rate, g, is proportional to the incident solar flux which goes as R^{-2}; the lifetime of a molecule, t, is inversely proportional to the solar wind and solar radiation flux and goes as R^2; the size of the field-of-view, s, is proportional to geocentric distance, Δ, which in this case increases monotonically with R, and, therefore, the field-of-view factor $f \rightarrow 0$ as $\Delta \rightarrow \infty$. Detailed calculations for the field-of-view factor (Keller and Lillie, 1974) show that f was roughly proportional to R^{-1} during the period of observations. Thus, we may write

$$B(s) \propto \frac{R^{-2} \times R^{-2} \times R^2 \times R^{-1}}{R^2} \propto R^{-5}$$

An examination of Figures 1 and 2 shows the observed brightness goes as $R^{-5.1}$, and $R^{-5.4}$ for OH and H, respectively.

The upper curves in Figures 1 and 2 show the production rates of OH and H derived from the observations after a rigorous correction for field-of-view effects. In the log Q_{OH} versus log R diagram the points lie close to a straight line with a slope of -2.3 ± 0.2, while the slope of the Q_H variation was -2.2 ± 0.35 from April 13 to 25, 1970.

Using the OAO calibration data and assuming $g_{OH} = 1.2 \times 10^{-3}$ photon sec^{-1} and $g_H = 2.5 \times 10^{-3}$ photon sec^{-1}

for the mean solar flux, we find $Q_{OH} = (2.0 \pm 0.8) \times 10^{29}$ molecules sec^{-1} and $Q_H = (5.4 \pm 2.7) \times 10^{29}$ atoms sec^{-1} at 1 a.u. The production rates for OH and H run parallel, suggesting a mutual formation process and a mutual parent molecule, presumably water. This conclusion is supported by the ratio of the production rates $Q_H/Q_{OH} = 2.7$, close to the expected ratio of 2. The hydrogen production rates are in excellent agreement with the French OGO-5 observations of Comet Bennett (Bertaux et al., 1973; Keller, 1973). The production rates of H and OH can be combined to find the production rate of water

$$Q_{H_2O} = (2.2 \pm 0.9) \times 10^{29} \text{ molecule sec}^{-1}$$

at R = 1 a.u.

We may use these results to compute the mass loss by Comet Bennett during perihelion passage. Assuming the exponent for the production rate of water, $E_{H_2O} = 2.3$, was constant for $R < 2.5$ a.u., the loss of water was $\sim 2 \times 10^{14}$ g, neglecting the water molecules (<10%) which were ionized before they could be dissociated. If we take a radius of 3.8 km for the comet (Delsemme and Rud, 1973) and a density of 1, the total mass of water ice was $\sim 2.4 \times 10^{17}$ g. Consequently, Comet Bennett lost about 0.1% of its total mass and its radius decreased by $\sim$1 meter during perihelion passage. The presence of an appreciable amount of dust does not change these figures significantly. From their dust tail model for Comet Bennett, Sekanina and Miller (1973) estimated the maximum dust production at perihelion was ∿0.5 of the gas production by mass.

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OMIT

THE SCALE LENGTH OF OH AND CN IN COMET BENNETT (1970 II)

H. U. Keller and C. F. Lillie

Comet Bennett (1970II) was observed with an ultraviolet spectrometer on the OAO-2 spacecraft during April 1970. The instrument consisted of a plane grating, a parabolic mirror, a slit, and a photomultiplier tube. The exit slit provided a 2' x 8' rectangular field-of-view and a 23 A bandpass. At this resolution emission features such as OH $\lambda 3090$ and CN $\lambda 3883$ were essentially monochromatic. Since the instrument had no entrance slit, movement of the grating produced a shift in the field of view, with 1 arc min of spatial offset corresponding to a 10 A wavelength shift.

The strongest cometary UV emission feature was the (0,0) band of OH at 3090 A. Figure 1 presents a comparison of six observed intensity profiles of OH with calculations based on Haser's (1957) parent-daughter-molecule model with purely radial outflow. The observed OH coma had an extent of $\sim$20' or a diameter of 9×10^5 km when the comet's heliocentric and geocentric distances were about 0.8 a.u. and 1 a.u., respectively. The scale length of the parent molecule of OH could not be determined, but a lower limit of 5×10^4 km was indicated.

The OH scale length, however, was, for the first time, determined to $2(+0.5 - 1.0) \times 10^5$ km at a cometary helio-

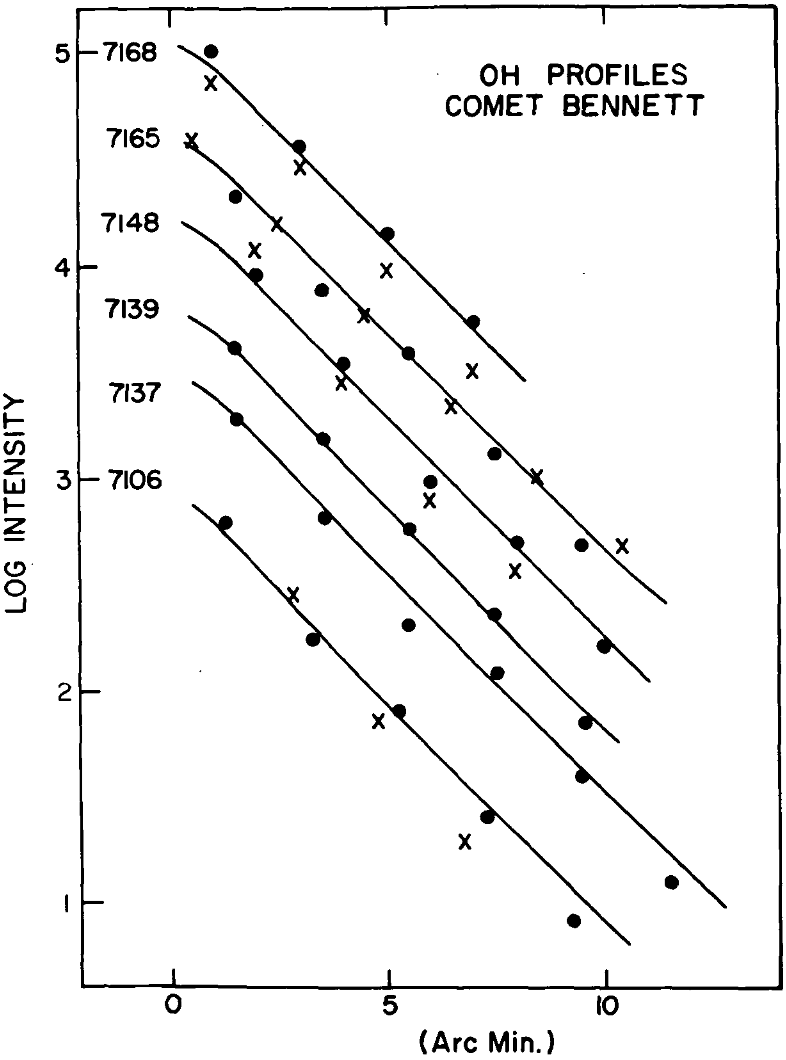

Figure 1 A comparison of model calculations with OH observations for six orbits in April 1970. The long wavelength wing is indicated by filled circles (●) while the short wavelength (sun-ward) wing is indicated with (X). The theoretical profiles (solid line) are for scale lengths of the parent molecule of 10^5 km and 2×10^5 km for the OH radical.

centric distance of 1 a.u. This value is smaller than expected. The photodissociation cross section of OH is too small to yield such a short scale length (Dalgarno 1974). Since an excitation into high rotational energy levels of OH is not observed, one would also expect the efficiency of predissociation to be small (Smith 1970). The results presented for the OH scale length need further theoretical explanation.

Similar observations were made of the (0-0) CN band at 3883 A which is less intense than the OH emission. Good agreement between the observed and calculated profiles was obtained using a CN scale length of 1.4×10^5 km (compare Delsemme and Moreau 1973).

The results are presented in more detail by Keller and Lillie (1974).

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N76-21067

PHOTOMETRIC OBSERVATIONS OF RECENT COMETS

E. P. Ney

The first infrared observations of a comet were made by Becklin and Westphal (1966) who studied Comet Ikeya Seki (1965f). Their data at wavelengths of 1.6 to 10 microns revealed that this comet was a bright infrared object because of thermal radiation by dust grains in the coma. This is just another example of the importance of dust in infrared astronomy. The success of infrared is largely due to the extreme visibility of dust which reveals itself by reradiation in the infrared and by scattering or extinction in the visible. Optical opacities are $\chi = 10^4 \mathrm{cm}^2/\mathrm{gm}$ for one micron dust particle, $\chi = 1 \frac{\mathrm{cm}^2}{\mathrm{gm}}$ for plasma free electrons, $\chi = 10^{-4}\ \mathrm{cm}^2/\mathrm{gm}$ for neutral molecules. By the time Bennett came along (1969i) infrared techniques were well developed, and the presence of an emission feature at 10 and 20 microns had been discovered in the infrared energy distributions of late type luminous supergiant stars (Woolf and Ney, 1969, for a summary see Ney (1972)). This feature is now widely believed to be due to the presence of Fe and Mg silicates condensed in the outer atmospheres of these stars and blown into the interstellar medium by their stellar winds. We believe that carbon and SiC condense in the atmospheres of carbon stars and silicates in the atmospheres of oxygen rich supergiants and giants. From the cosmological point of view, comets differ from the interstellar material because they represent a sample of the solid material without the "contamination" of all that hydrogen and helium.

D15

Because of the thermal emission by the atmosphere, infrared observations are made by beam switching on the sky to cancel this emission. Liquid helium cooled bolometers at 1°K can be used at all wavelengths in the atmospheric windows from visual wavelengths (.5μ to 18 microns). The limiting noise is the statistical noise due to radiation within the bandpass of the filters. These techniques work equally well day or night except that at wavelengths shorter than 1 micron the scattered sunlight degrades the performance in daytime.

A comet can be acquired on the meridian by pointing the telescope to the ephemeris position and scanning for it.

The principal results that I will review come from the Arizona group, the Cal Tech group, and the Minnesota group. Comet Bennett was the first comet in which the silicate emission feature was seen (Maas, Ney and Woolf, 1970) and this comet taught us that we needed observations at all wavelengths preferably made with the same diaphragm geometry to untangle the scattered light and separate it from the thermal emission.

In these broadband $\frac{\lambda}{\Delta\lambda} = 10$ observations, the cometary observations are dominated by the scattered sunlight from the dust at short wavelengths and the thermal emission by the dust at long wavelengths. The interesting lines that we have heard so much about are only a minor contaminant. Also dust is its own parent molecule, being evaporated from the nucleus and flowing out into the coma and tail.

Figure 1 shows the observing record for Comet Kohoutek. Figure 2 shows what some solid objects in the solar system look like. I show this because cometary dust has a similar energy distribution.

Figure 3 shows a comparison of Comet Bennett and Kohoutek at the same distance from the sun. The principal features are scattered sunlight at short wavelengths and thermal emission at long wavelengths with a superimposed silicate dust bump at 10 and 18 microns.

Because different observers use different beam sizes, it is important to know how comet brightness depends on beam size. All three groups have studied this and shown that the flux is proportional to beam diameter at least between about 10 seconds of arc and 100 seconds. This fact of course also makes it possible to correct observations to the same geocentric distance. Figures 4 and 5 show the intercomparison of the three groups, and also indicate the excellent absolute agreement among the three groups.

Figure 4 shows the comparison between Cal Tech (Gatley et al. 1974) and Minnesota (Ney 1974). The former used a 35 arc second diaphragm and the latter a 27 arc second diaphragm. The 40% increase in diaphragm size is reflected in a 40% increase in observed brightness. Figure 5 shows the comparison between Arizona (Rieke and Lee 1974) and Minnesota. The factor of five in diaphragm diameter produces about a factor of five in observed brightness. Flux proportional to beam diameter observed at all wavelengths is to be expected in a simple model of the coma which is optically thin in dust, which has surface brightness proportional to $\frac{1}{r}$; r is distance from the

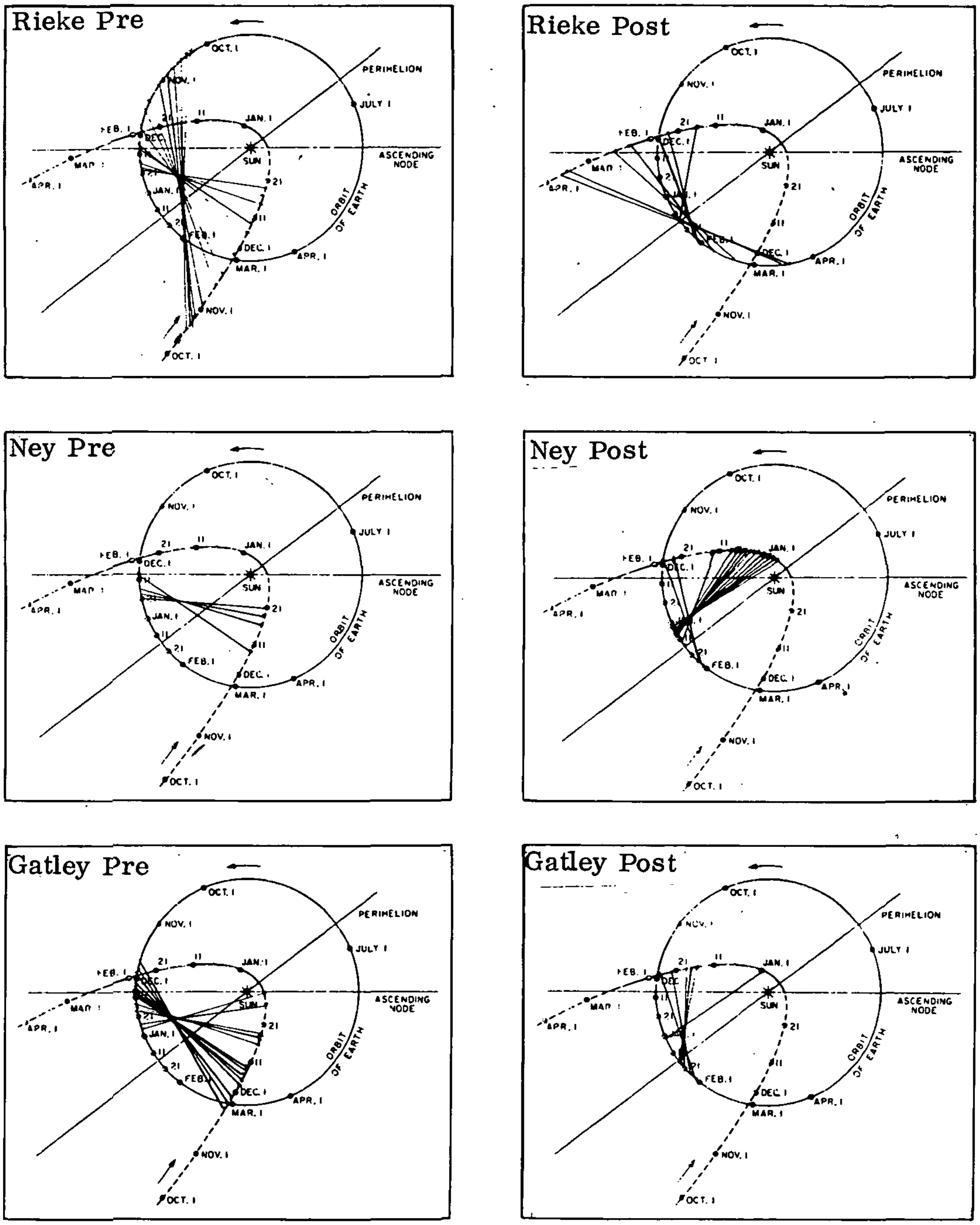

Figure 1. Graphical representation of those days on which the comet was observed at some wavelengths by each of the three groups. The observations are divided into pre and post perihelion.

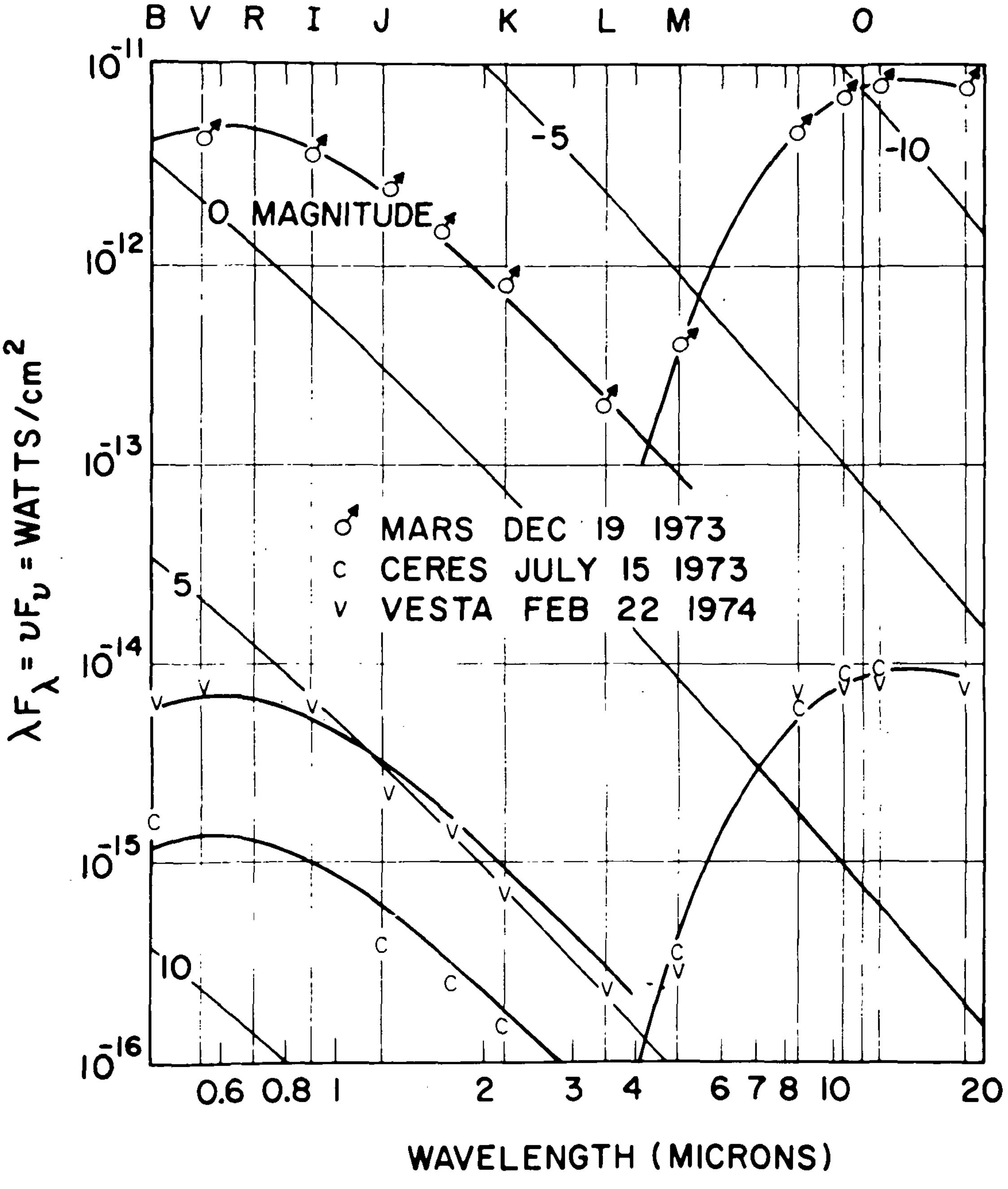

Figure 2. The infrared energy spectra of Mars and the asteroids Vesta and Ceres. The quantity plotted is λF_λ which is proportional to energy/area octave against the wavelength.

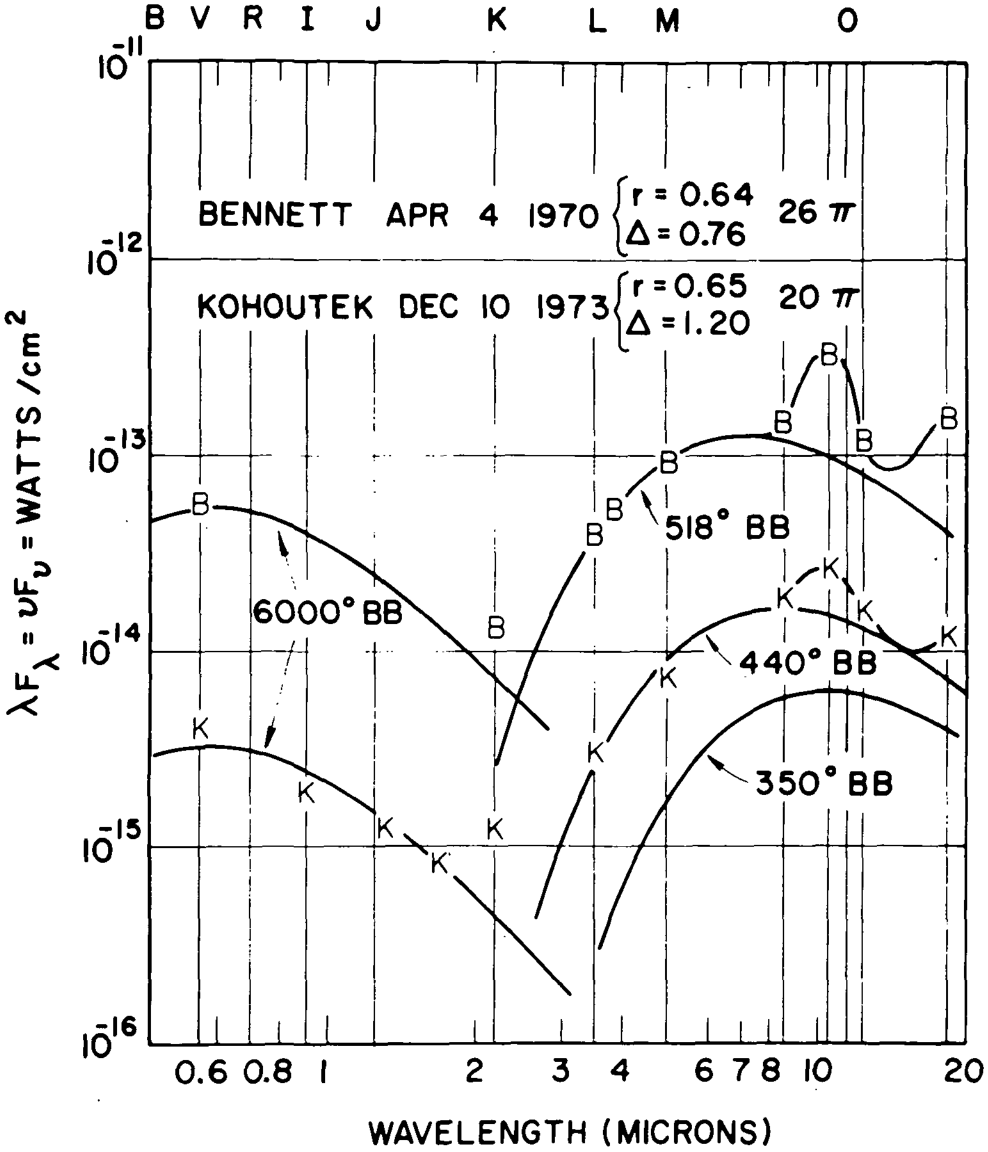

Figure 3. Comparison of the energy spectra of Comet Bennett and Comet Kohoutek, both at the same distance from the sun. Comet Bennett has a more pronounced silicate signature and also has a larger temperature excess above the grey body temperature at the appropriate distance.

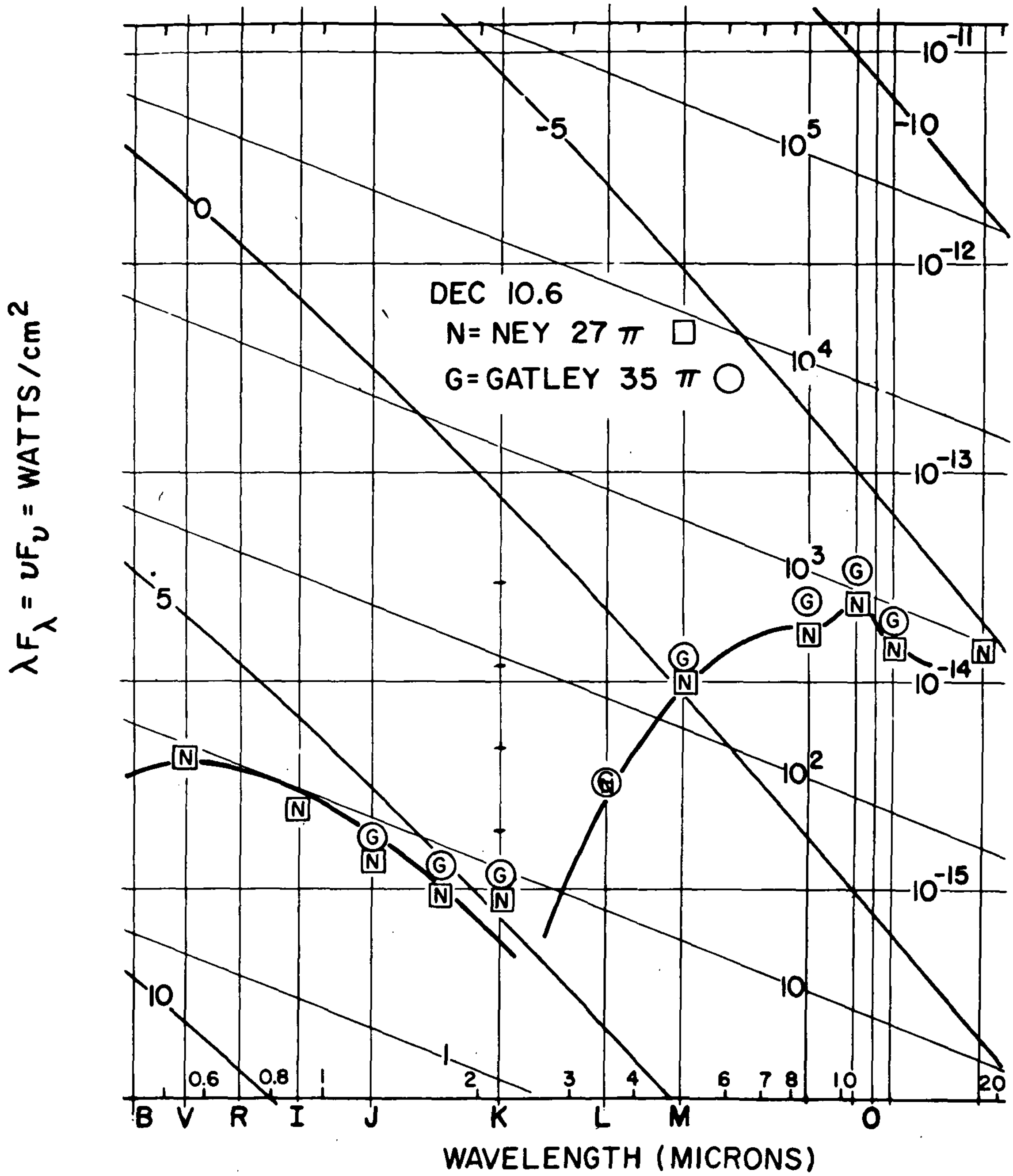

Figure 4. Comparison of the Cal Tech data and the Minnesota data on December 10.6. The larger diaphragm of Gatley et al. produces a proportionally larger signal.

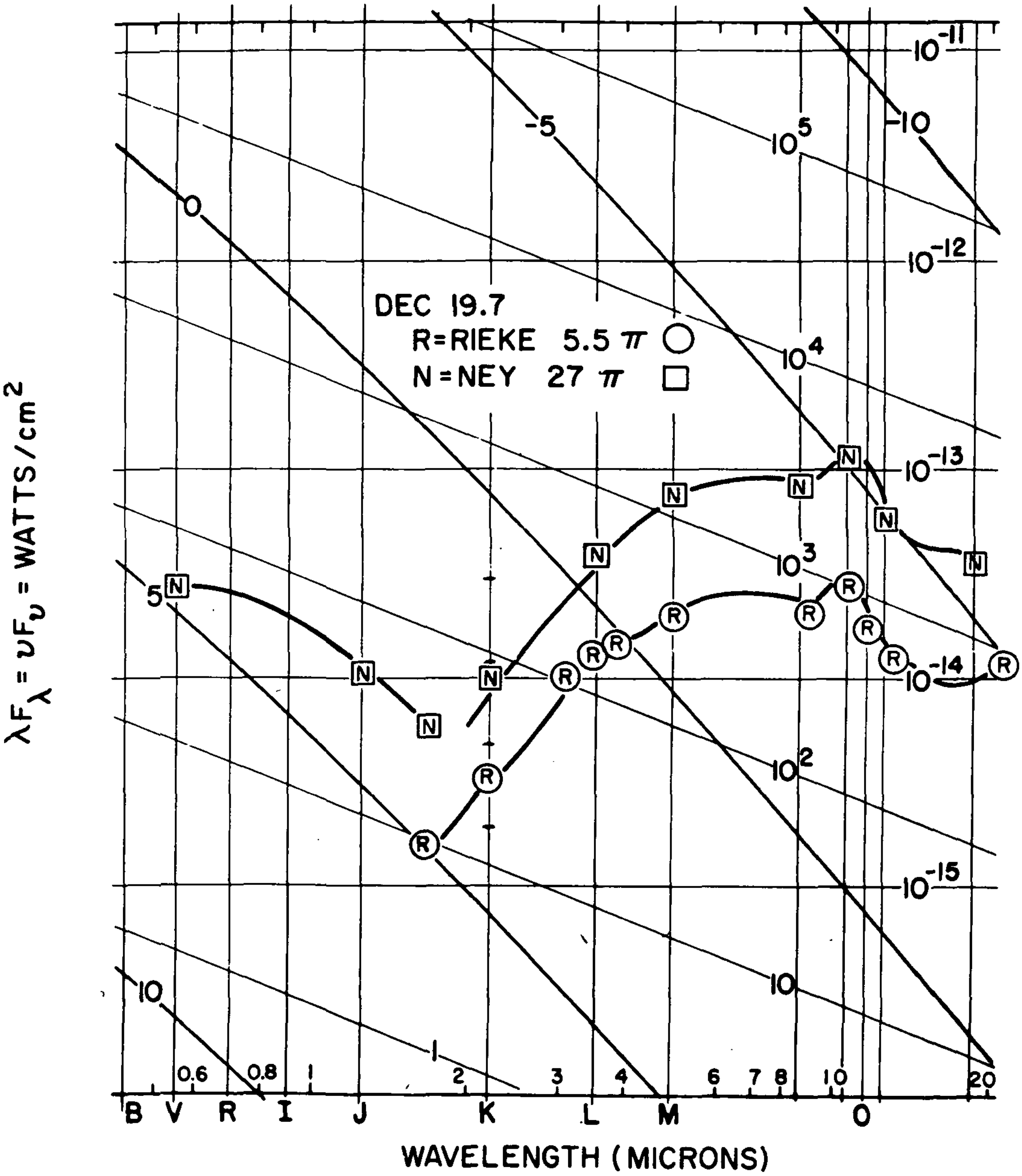

Figure 5. Comparison of results from the Arizona group with the Minnesota data. The diaphragm used by Rieke and Lee. is 5.5 sec of arc in diameter. Ney used a square diaphragm 27 arc seconds on a side. The measured fluxes are proportional to the diaphragm diameters.

nucleus and in which the particle number densities are proportional to $\frac{1}{r^2}$.

Figure 6 shows Comet Kohoutek and the planet Mercury at the same distance from the sun and earth and on the same day. The absence of any 10 micron feature in Mercury proves its real existence in the comet. Both the comet grains and the mercurian surface are hotter than a fast rotating black body at this distance from the sun. In the case of the comet it is because the grains are small and in the case of Mercury it is because the back side is cold and the thermal reradiation is principally from the heated surface.

Shortly after perihelion passage of Kohoutek an anti tail was discovered on the comet. Figure 7 shows the coma tail and anti tail observed at 3.5 microns. The remarkable thing about the anti tail is that its infrared energy distribution shows that it is cooler than the coma and tail and it does not have the silicate signature. This tells us a lot about the particles and connects these observations with the elegant analysis of Zdenek Sekanina (1974) who shows that the particles in the anti tail must be large and old (i.e. ejected at a much earlier time). There are three separate physical effects.

1) For the silicate feature to appear the grains must be small enough so that at 8 to 12 microns a single grain is optically thin. This means thatthe grain diameter must be less than about 1 micron.

2) The presence of the temperature excess means that the grains are small compared to the plankian maximum of the thermal radiation they must emit.

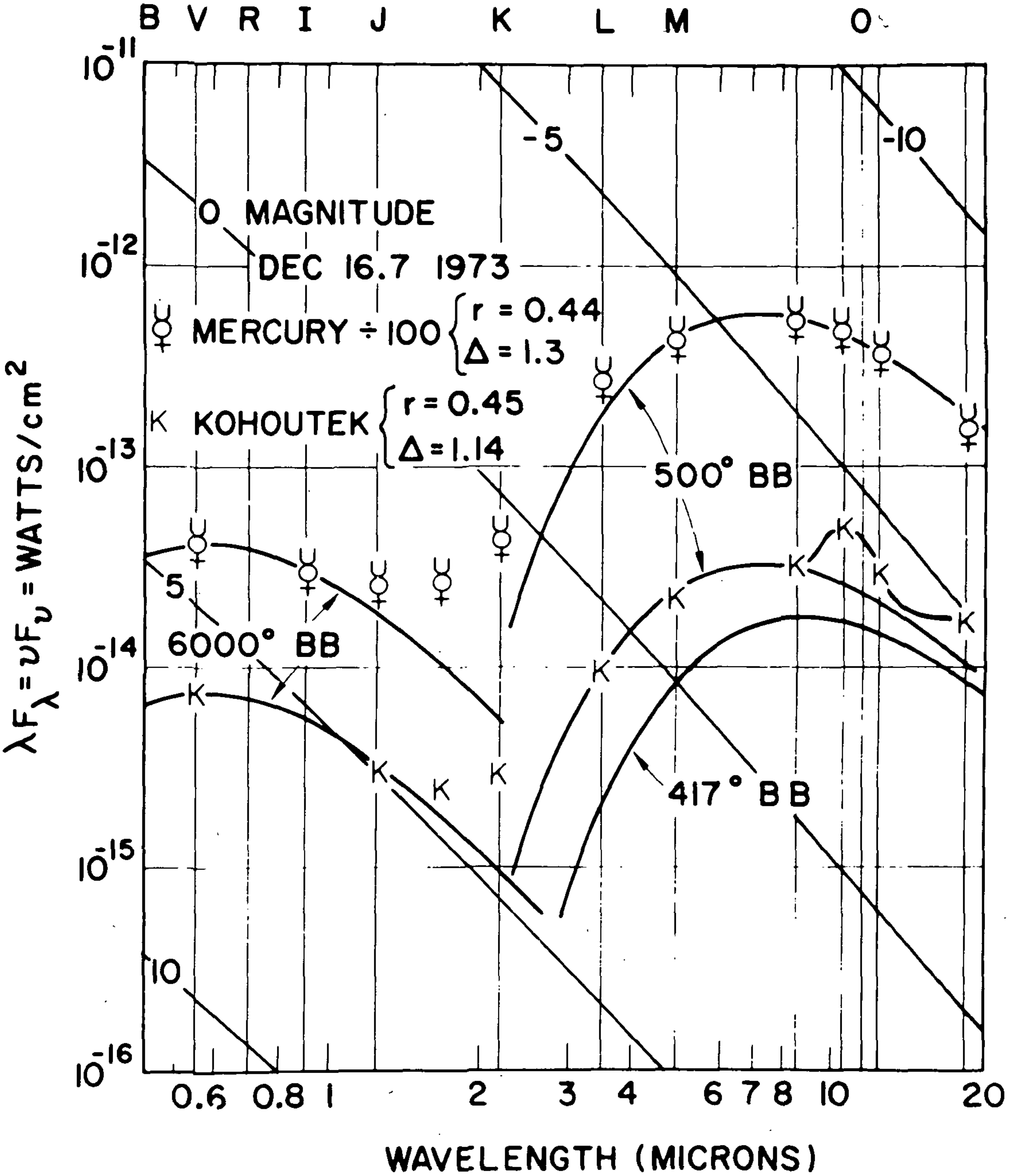

Figure 6. Comet Kohoutek and the planet Mercury at the same distance from the sun and on the same day. Note that the reflected energy by the planet is a smaller fraction of the energy in thermal emission than is the case for the comet.

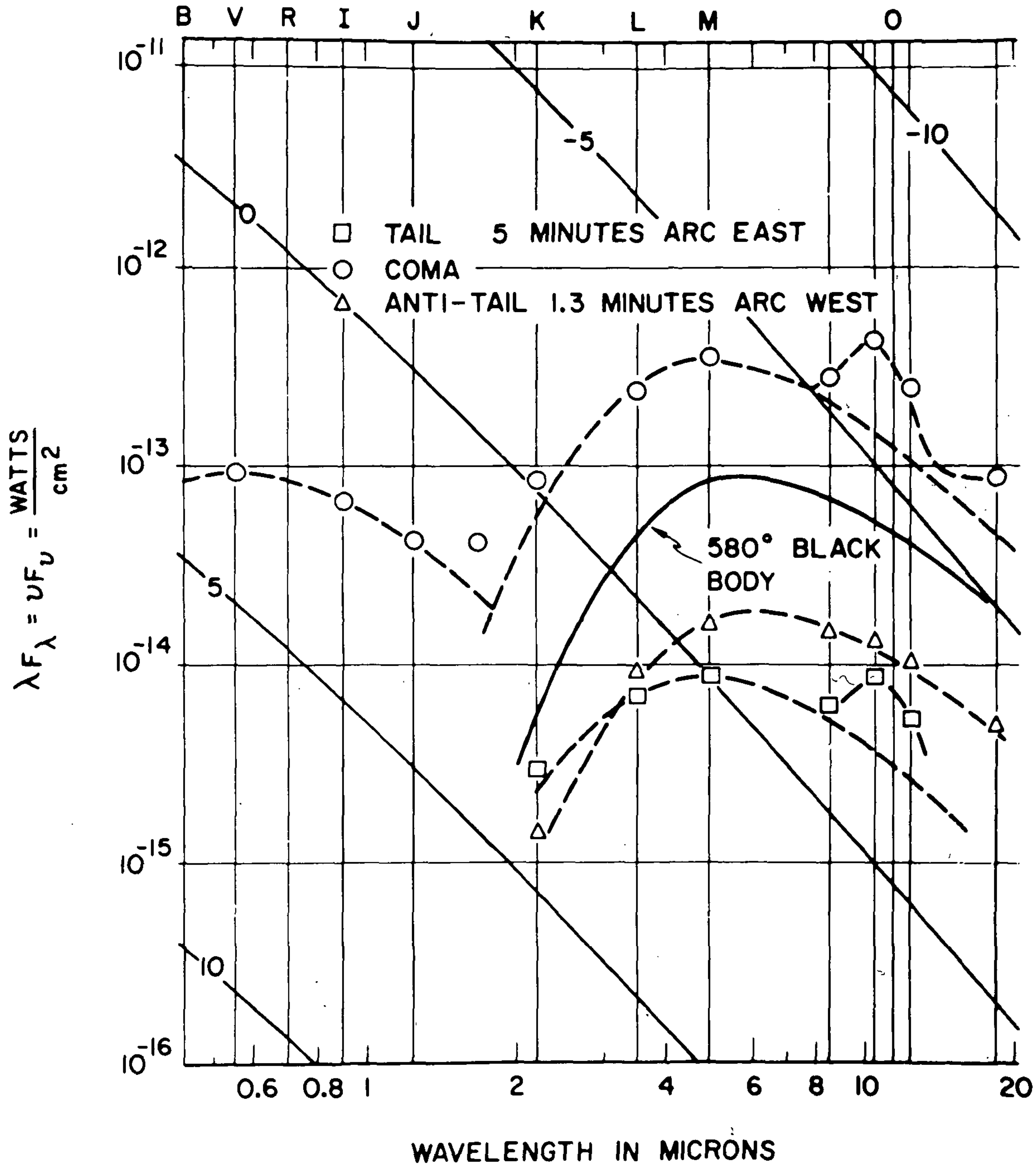

Figure 7. The coma, tail and anti tail of Comet Kohoutek on New Year's day. The coma and tail have very similar energy distributions. The anti tail is very different and is a good match for a grey body at the given distance from the sun.

3) The grains in the coma and tail cannot be too small or they would Rayleigh scatter the short wave radiation which is seen to have the solar colors. Finally,

4) the particle albedo is rather high $\gamma=0.2$. O'Dell (1971) was the first to point out for Comet Bennett that the grain albedo is determined by the ratio of the infrared thermal emission to the scattered sunlight.

For the anti tail particles, the same arguments show that unless they are of a different material they must have diameters greater than about 20 microns, although they could be as large as baseballs. Sekanina will discuss his analysis of the anti tail ballistics, but it is exciting to see his predictions confirmed by the infrared observations. There is of course a tantalizing connection between Sekanina's large particles and the shower meteors.

In the connection of particle size in the coma, the Japanese observers at Kyoto and Nagoya (Noguchi, 1974) have measured the polarization at visual and near infrared wavelengths and find that the polarization is 15 to 20% at wavelengths from visual to 1.6 microns. The direction of the polarization is correct for scattered sunlight and the wavelength independence of the polarization argues for a mixture containing small particles.

Figure 8 shows the way the comet changed after perihelion passage. The data are corrected to $\Delta=1$.

Figure 9 shows Comet Bradfield at the end of March and in early April.

Table 1 gives the Minnesota data on Comets Bennett, Kohoutek, Bradfield and Encke.

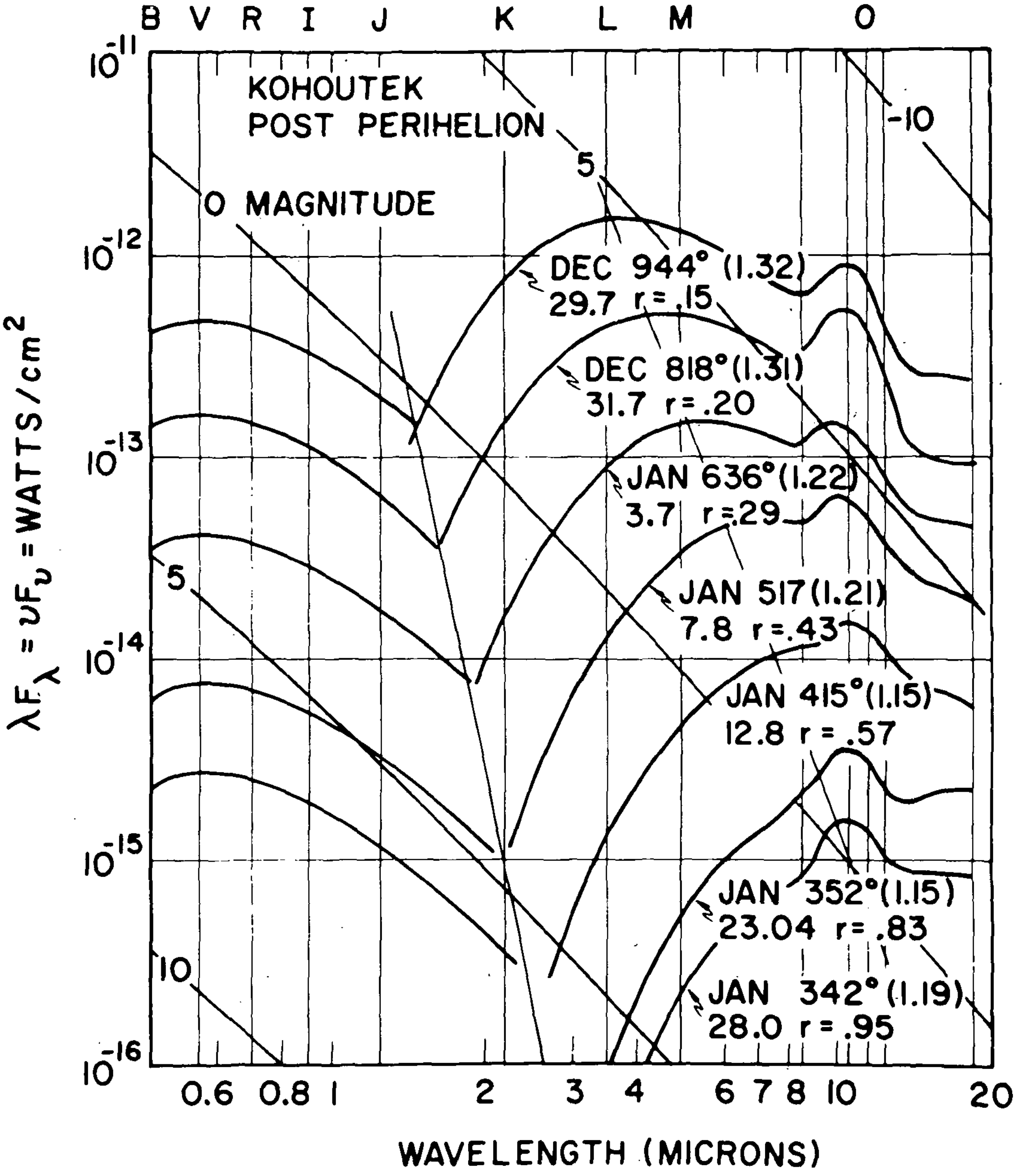

Figure 8. Some examples of the spectra of Kohoutek after perihelion passage. The temperatures of the fitted black bodies are indicated along with the factor by which the temperature exceeds the black body temperature. The relative strength of the silicate feature varies.

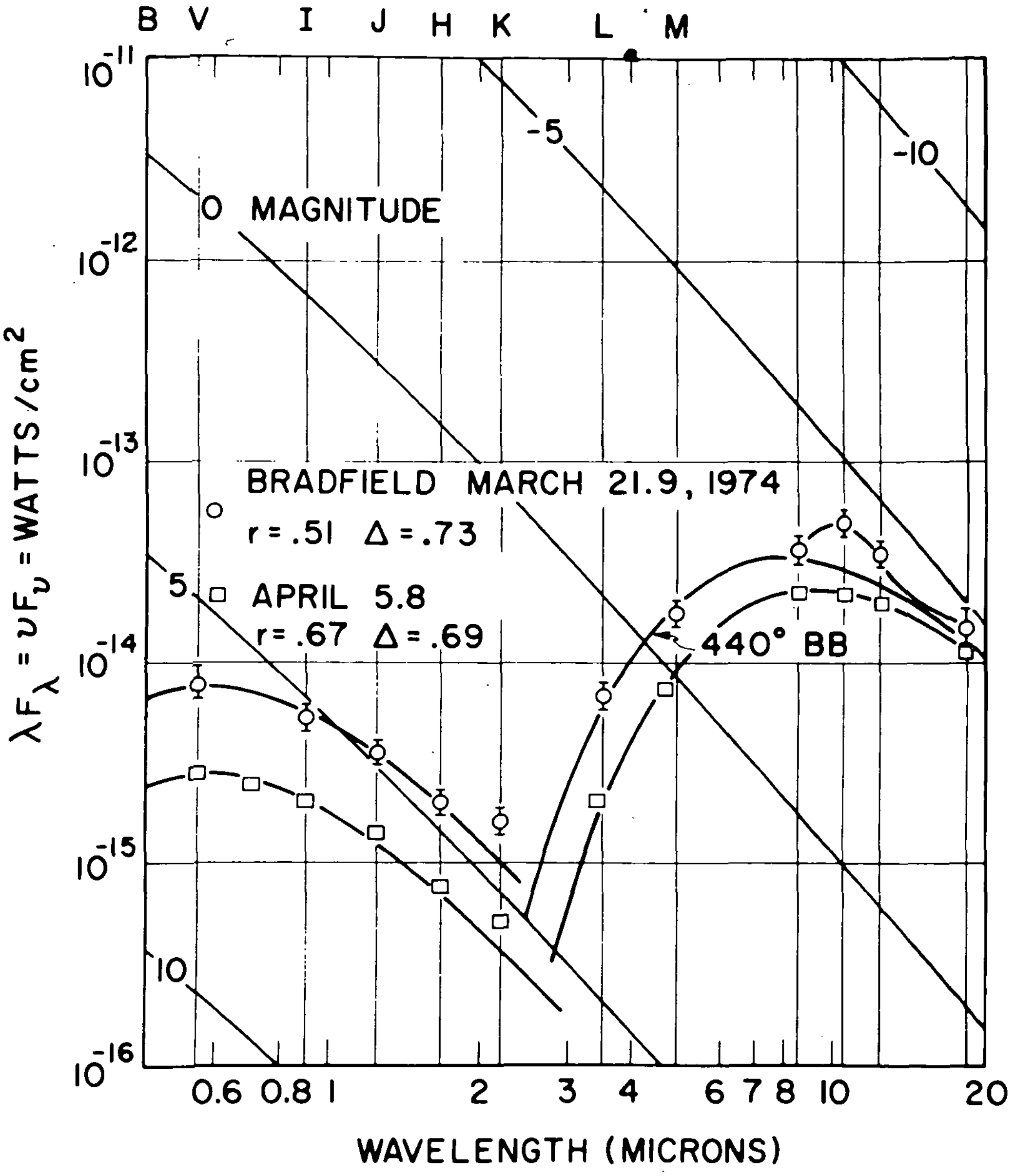

Figure 9. Comet Bradfield between r=.51 and r=.67. On the earlier date this comet had an energy distribution much like Comet Kohoutek. However, between the two dates the albedo decreased and the dust bomb disappeared.

TABLE 1

MINNESOTA OBSERVATIONS OF COMETS

				Magnitudes											
Date	Diaphragm	r	Δ	V	R	I	1.2μm	1.6μm	2.2μm	3.5μm	4.8μm	8.5μm	10.6μm	12.5μm	18μm
Comet Bennett (1969i)															
April 4, 1970	26π	0.64	0.8						1.8	-0.9	-2.6	-4.9	-6.2	-5.8	-7.2
April 24, 1970	26π	0.94	1.1						5.2	2.8	0.9	-1.6	-3.5	-3.3	-5.1
May 5, 1970	26π	1.1	1.4						6.1	5.9	3.1	-0.9	-2.5	-1.9	
Comet Kohoutek (1973f)															
Dec. 10.7, 1973	27π	0.65	1.2	6.6		6.4	5.8	5.5	4.4	2.0	0.0	-2.6	-3.4	-3.6	-4.4
Dec. 16.7, 1973	27π	0.48	1.1	6.3		6.0	4.8	4.5	3.6	0.8	-1.0	-3.2	-4.1	-4.1	-4.8
Dec. 19.7, 1973	27π	0.37	1.1	4.6		4.4	3.9	3.4	2.2	-0.6	-2.1	-4.1	-5.0	-5.0	-5.7
Dec. 20.7, 1973	27π	0.34	1.1	4.8		4.1	3.6	3.0	1.8	-1.0	-2.6	-4.4	-5.4	-5.4	-5.9
Dec. 29.7, 1973	27π	0.15	1.1						-2.5	-4.5	-5.5	-6.3	-7.2	-7.1	-7.9
Dec. 29.7, 1973	60π	0.15	1.1							-5.9	-6.9	-7.8	-8.6	-8.4	
Dec. 30.7, 1973	27π	0.19	1.1	2.0		1.8	1.4	0.1	-1.7	-4.0	-5.1	-6.2	-7.1	-7.0	-7.3
Dec. 30.7, 1973	60π	0.19	1.1							-5.0	-6.3	-7.3	-8.1	-8.1	
Dec. 31.7, 1973	27π	0.20	1.0	2.6		2.2	1.8	0.8	-0.8	-3.3	-4.5	-5.7	-6.6	-6.5	-7.2
Jan. 1.7, 1974	27π	0.23	1.0	3.3		2.6	2.1	1.2	-0.2	-2.7	-4.0	-5.5	-6.6	-6.6	-6.7
Jan. 2.7, 1974	27π	0.26	1.0	4.3		3.4	2.6	2.4	0.8	-2.1	-3.6	-5.0	-5.9	-5.9	-6.8
Jan. 3.7, 1974	27π	0.29	0.9	4.4		3.5	2.9	2.4	1.3	-1.6	-3.0	-4.6	-5.5	-5.6	-6.7
Jan. 3.7, 1974	60π	0.29	0.9						0.1	-2.8	-4.3	-5.9	-6.7	-6.8	
Jan. 4.8, 1974	27π	0.33	0.9	4.7		4.2	3.3	2.9	1.9	-1.1	-2.7	-4.6	-5.6	-5.5	
Jan. 5.8, 1974	27π	0.36	0.9			5.0	3.8	3.5	2.5	-0.3	-2.1	-4.1	-4.9	-4.8	-5.8
Jan. 6.8, 1974	27π	0.39	0.9	5.6		5.0	4.5	4.1	3.0	0	-1.9	-3.9	-4.8	-4.8	-5.7
Jan. 7.8, 1974	27π	0.43	0.9	6.0		5.2	4.9	4.4	3.6	0.5	-1.4	-3.6	-4.4	-4.5	-5.0
Jan. 9.8, 1974	27π	0.48	0.8						4.4	1.4	-0.6	-2.8	-3.9	-3.9	-4.8
Jan. 12.8, 1974	27π	0.57	0.8						5.2	2.7	0.7	-2.3	-3.0	-3.2	-3.8
Jan. 23.0, 1974	27π	0.85	0.8							5.1	3.9	-0.3	-1.2	-1.2	
Jan. 28.1, 1974	27π	0.92	0.9							6.7	4.2	0.7	-0.6	-0.5	-1.6
Comet Bradfield (1974b)															
March 21.9, 1974	27π	0.51	0.73	5.6		5.2	4.8	4.7	4.1	1.2	-0.7	-3.2	-4.2	-4.4	-4.8
March 24.9, 1974	27π	0.52	0.70							1.5	-0.3	-2.8	-3.9	-4.0	

TABLE 1 (Continued)

Date	Diaphragm	r	Δ	Magnitudes											
				V	R	I	1.2μm	1.6μm	2.2μm	3.5μm	4.8μm	8.5μm	10.6μm	12.5μm	18μm
<u>Comet Bradfield (1974b) (Continued)</u>															
April 5.8, 1974	27π	0.66	0.69	7.1	6.8	6.2	5.7	5.6	5.3	2.5	0.3	-2.9	-3.5	-3.8	-4.7
April 7.8, 1974	27π	0.69	0.70				6.7	6.7	6.5	3.9	1.3	-2.0	-2.8	-3.0	-4.0
April 9.8, 1974	27π	0.72	0.73									1.4		-0.4	
April 16.8, 1974	27π	0.83	0.82								4.8	1.0	0.1	-0.4	
<u>P/ENCKE</u>															
April 16.7, 1974	27π	0.46	1.2							5.9					
April 23.8, 1974	27π	0.35	1.0							5.8					
April 25.8, 1974	27π	0.35	1.0						8.6	5.3	3.0	1.2			
<u>Calibration Stars</u>															
α Sco				1		-1.7	-3.1	-3.8	-3.8	-4.1	-3.9	-4.3	-4.8	-4.8	-4.8
α Lyra				0	0	0	0	0	0	0	0	0	0	0	0
NML Cyg (Cygnus)							4.8	2.5	0.4	-1.9	-3.2	-5.0	-5.5	-6.0	-6.8
α Boo (Bootes)				0	-1.05	-1.7	-2.3	-3.0	-3.1	-3.15	-3.05	-3.05	-3.2	-3.2	-3.2

In contrast to the smooth decrease in brightness of Comet Kohoutek something drastically different happened to Comet Bradfield as its heliocentric distance increased.

Between March 21 and April 5 the dust bump disappeared and the albedo decreased. I interpret this to mean that the size or the chemical nature of the grains changed, as if the comet were layered like an onion.

Then between April 7 and April 9 the brightness of Comet Bradfield decreased abruptly. This decrease in the infrared was paralleled by a decrease in the visible light shown in the photometry of Minton (1974) at LPL and reported in the I. A. U. Circular 2674. In a matter of two days the 8 and 12 micron fluxes dropped 3 magnitudes and the V magnitudes decreased 2 magnitudes. The dust just went away.

Figure 10 shows the behavior of $(\lambda F_\lambda)_{max}$, the total energy radiated as a function of distance from the sun for Bennett, Kohoutek and Bradfield.

To summarize:

1) many comets contain silicates.

2) the particles in the coma and tail of Comet Kohoutek were small $.2\mu < d < 1\mu$ and the temperatures exceed the black body temperature.

3) the particles in the anti tail were large and the temperature is close to the black body temperature.

4) the strength of the silicate feature varies from comet to comet and can change even in the same comet.

5) the albedo of the cometary dust is relatively high $\gamma=0.2$.

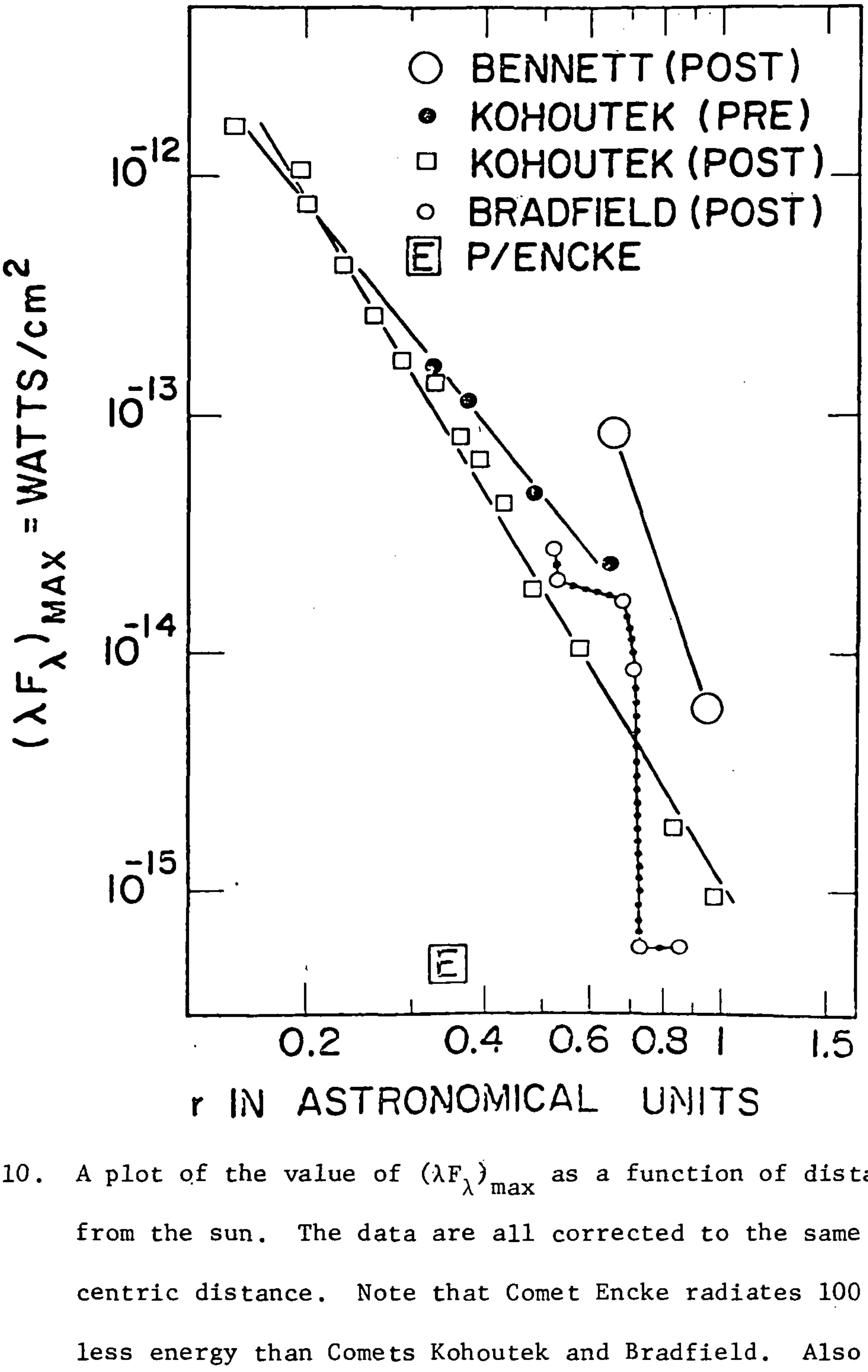

Figure 10. A plot of the value of $(\lambda F_\lambda)_{\max}$ as a function of distance from the sun. The data are all corrected to the same heliocentric distance. Note that Comet Encke radiates 100 times less energy than Comets Kohoutek and Bradfield. Also shown is the abrupt drop in brightness of Comet Bradfield at a heliocentric distance of about 0.7 astronomical units.

6) the composition and/or sizes of particles can change from comet to comet and in the same comet.

Several observations on future comets are suggested.

1) The changes in brightness, strength of the silicate feature and albedo should be well documented.

2) The polarization at ten microns should be measured. It would be expected to be small, because this radiation is thermal radiation, but any effect of aligned grains could produce polarization.

3) Most important to measure is the albedo of the anti tail particles. The data at the short wavelengths were not obtained on Kohoutek, but could be acquired on a comet as bright as Kohoutek just after perihelion passage.

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DISCUSSION

Z. Sekanina: In regard to our yesterday's discussion of the investigation of comets at large heliocentric distances, I believe that application of the methods of the type professor Ney was describing should be strongly encouraged. Since, however, the distant comets are considerably fainter than the ones that have so-far been studied in the infrared, I wonder what magnitude could be reached by the currently used techniques.

E. Ney: If you look at the data on these comets, you will find that we are getting into trouble between 1.5 and 2 A.U. on Comets Bradfield and Kohoutek, and the 100 times down on Encke was misery at the distance it was. There are, however, prospects for improved detectors. I suspect the time will come when we may be able to do infrared observations on comets that are this dirty at perhaps 3 A.U., but not tomorrow. Two, one-and-a-half to two A.U. tomorrow.

F. L. Whipple: Doesn't the relative efficiency correlation with particle dimension produce a distortion in the flux/wavelength curve to change the λ_{max} and hence the calculated temperature?

E. Ney: What you say is entirely correct, and I think if the effect were to move it very much you would in fact have to change it, because the physics is that instead of radiating like black bodies, small particles have an additional factor that multiplies the Planck function which depends on the ratio of the particle size to wavelength. In addition to shifting the maximum, it should in fact change the shape.

W. F. Huebner: Making a reasonable assumption about the size distribution of the particles, can you make some estimate about the relative abundance of silicates to other materials?

E. Ney: No. I can only say that there is kind of a black body component of the comet which could be carbon or it could be big silicate particles. We just can't make any estimates of the relative abundance because it depends so much on particle size. It was different in Bennett and Kohoutek, but it is an appreciable amount of the material. It is not a negligible fraction of the dust in the coma that are silicates.

K. S. Krishna Swamy: I have tried to get the variation of grain temperture as a function of heliocentric distance from the observations of Rieke and Lee for Comet Kohoutek. I used the measured refractive index of some Lunar samples to get the absorption coefficient. The emission curves for the grain sizes of 0.2 and 1.0 microns were calculated. The general shapes of the two curves are the

C 5

same. From a comparison of the observed energy distribution with those of the calculated ones, the temperature of the grains was obtained. The process was repeated for different heliocentric distances. I get a grain temperature variation of 225°K to 550°K for distances between 1. 34 and 0. 37 A. U. The temperature of 580°K at 0. 23 A. U., as given by Ney, fits well the relation I get. As a typical case, calculations were done for two Lunar core samples. The results are the same.

Next thing is to calculate the absorption property of the dust in the UV and visible region which gives the above observed grain temperature variation. Unfortunately, detailed refractive index measurements are not available covering the whole wavelength region, so I did calculations for different silicate materials for which refractive index measurements are available. I did so for olivine, enstatite, and magnetite. I also did calculations assuming for the refractive index a value of 1. 3-0. 05i and of 1. 6-0. 05i. The expected grain temperatures for olivine and enstatite are very low compared to the observed one, which means they do not absorb much in the UV and visible regions. Magnitite could give the observed variation, but the temperature is larger than the observed one. This may be because it is a pure iron type material, which is very unlikely in comets. The temperatures obtained with 1. 3-0. 05i and 1. 6-0. 05i can give the observed temperature distribution. This shows that we require the complex part to be of the order of 0. 05 in the UV and visible regions.

C. R. O'Dell: The solar-direction distance at which the IR emission ceases is a measure of the distance the particles travel before being reversed by radiation pressure. This is $v^2/2a$ (v is velocity of ejection, a is acceleration) and is a function of the mass loss rate and the particle size. Have any sunward scans been made in the coma?

E. Ney: I agree with what you say. These data are representative of what we had, and I realized afterwards that we should have done more to use the anti-tail as a kind of mass spectrometer for particle sizes, based on the kind of analysis that you and Sekanina have done. The anti-tail got pretty hard for us after three days.

M. Mumma: Your observation of an IR flux for Encke of 10^{-2} of that for bright comets, together with the production of H-atoms which is also down by a factor of 100, suggests that the gas/dust production ratios are similar for this very old comet and for some newer ones. We know that the visual continuum emission is very weak for Encke, suggesting that any dust production is primarily in the form of large particles. Since the total mass of particles required to produce a given scattered brightness goes as $\sim R^3/R^2 = R$ (R is the particle radius), we can conclude that the proportion of total mass flow in the form of dust is much greater for Encke than for new comets.

B. Donn: The fact that you see in the visible almost no continuum of Encke means that the small particles that are very efficient in scattering are not there. We could have larger particles that could contribute in the infrared but would not scatter efficiently, as the cross-section to mass ratio would be low. If that is the case, the silicate signature should be very low, so the determination of whether Encke really shows a silicate bump would be a very important measure of the particle size.

Z. Sekanina: If Comet Encke produced a significant amount of rather large particles in recent times, it should have displayed anti-tails on a number of occasions. A tentative comparison of favorable visibility conditions with available reports suggests that no such anti-tail has been observed. This conclusion is not in any apparent conflict with the existence of the extensive stream of Taurids, whose origin is put back at a time several thousand years ago.

M. Mumma: The dependence of visual magnitude on heliocentric distance follows an R^{-2} law from ~0.8 A.U. to perihelion, based on the observations of Bayer and Bortle. Hence the measured H-atom rate at 0.7 A.U. should scale as R^{-2}, so that one can compare dust brightness measurements at 0.34 A.U. with the H-atom production rate scaled to 0.34 A.U.

B. Jambor: I would like to point out the importance of Comet Encke in connection with such infrared measurements. It has to do with the contribution that periodic comets can make to the "permanent" interplanetary dust—the zodiacal cloud. Only particles larger than 10 microns can stay in the inner portion of the solar system if ejected from Comet Encke, for example. How many such particles are ejected by Encke strongly influences the total contribution to the Zodiacal light. As pointed out by Dr. Sekanina, a large quantity of such particles would create an anti-tail at certain times.

F. L. Whipple: The comments by Mumma regarding the substantial quantity of observed particles in Comet Encke brings me to the "gospel" that I have been preaching for more than two decades, viz., the predominance of gas spectra in periodic comets does not disprove large solid particle contribution by those comets. Comet Encke is responsible for the largest known meteor stream—the Taurid meteors, dating back for thousands of years. Simply stated, the periodic comets. expel larger particles than the newer comets, such as Bennett, etc. The optical ratio of band to continuum spectrum is no measure of the gas/particle ratio. We very much need IR measures of Encke in order to plan space missions more efficiently.

OMIT

COMET KOHOUTEK: GROUND AND AIRBORNE HIGH RESOLUTION TILTING-FILTER IR PHOTOMETRY*

C. Barbieri, C. B. Cosmovici, S. Drapatz, K. W. Michel, T. Nishimura,
A. Roche and W. C. Wells

ABSTRACT

Because of Comet Kohoutek's anticipated large gas production, which seemed to offer a unique chance to reveal parent molecules, two Fabry-Perot Tilting Filter Photometers were designed with the purpose to detect and study the behaviour of CH_4 and its photolysis product H_2. The importance of these two molecules is well known and their detection would have given valuable indications about the structure of the nucleus, its thermal history and conditions of formation.

Similar to CH_4, H_2 has no dipole moment and cannot be detected by radioastronomy. The most obvious way for measuring H_2 in extended cometary comae is certainly on the basis of fluorescence from the Lyman bands around 1000Å; there are, however, vibrational quadrupole transitions within the overtone bands of the ground electronic state which give rise to emissions in the near infrared, accessible by means of ground based telescopes. Three of the stronger lines are: $\lambda = 0.8748\ \mu$; $0.8560\ \mu$ and $0.8497\ \mu$. Methane is more readily detectable in the infrared, since it has strong fundamental (1-0) infrared vibration rotation bands at $3.3\ \mu$ (ν_3). In order to measure both the CH_4 concentration and its rotational temperature, a very high resolution (~3.7Å) high throughput instrument was designed which could isolate several individual vibration-rotation lines in the ν_3 band, namely the P_2, P_3 and P_9 lines. The instrument consisting of a Fabry-Periot Tilting Filter Photometer with InSb detector interfaced with the 30 cm f/30 Dahl-Kirkham Telescope is described in detail elsewhere.(1). The observations were made in January from the NASA Convair 990 (Galileo II) at an altitude of 13 km, where atmospheric methane absorption can be minimized but not avoided. Doppler shift of cometary and atmospheric lines with respect to one another by at least a few Å caused by the orbiting velocity of the comet would be sufficient to allow for high transmission measurements. Though long integration time measurements with Lock-In-Amplifier technique have been carried out, no signals from the CH_4-rotational lines of the comet coma could be detected. Using the planet Venus as a calibration source for the photon flux and as a result of delicate laboratory measnrements an upper limit of

$$Q_{CH_4} \leqslant 5 \cdot 10^{28} \text{ molecules/sec sr}$$

could be derived. This value is several orders of magnitude less than the original predictions for Kohoutek during close approach. Therefore, one could conclude that volatile components like CH_4 boiled off the comet well before perihelion, at large (~4 AU) distances from the sun and were responsible for the high brightness of the comet at that time. Such a fractionation is only possible if the nucleus was composed of relatively loose, porous ice, rather than compact ice. This hypothesis was strongly supported by the second experiment for search of H_2 in the near infrared at the 182 cm telescope of Asiago. Also in this case a Fabry-Perot tilting filter photometer was designed to match with the f/9 optics of the telescope. The instrument (2) consists in a high resolution (~0.7Å) tilting filter system with photon counting technique which allows phase-sensitive background subtraction. On the basis of the best

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*The full text of this paper has appeared in ICARUS 23, No. 4 (1974).

data achieved between January 10 and 15 the occurrence of H_2-lines with an intensity larger than 2% of the continuum could be excluded, viz. the flux averaged over the field of view was less than 4.10^5 photons/cm^2 sec sr Å. Since the pre- and post-perihelion measurements were not affected by molecular fluorescence, they represent only the light scattering flux from dust particles. The data display that the comet's dust coma was definitely brighter during approach than during recession from the sun. However, the quantity of more fundamental interest is the difference in dust production rates, and a derivation of the mass-production rate of dust could be derived. The study shows that both the dust and gas production rate differ greatly in the pre-perihelion period as compared to the post-perihelion period, as conjectured previously for "virgin" comets. (Dust production rate/gas production rate: pre-perihelion 0.1, post-perihelion 1). The pronounced asymmetry in the production rates strongly suggests that fractionation and dust entrainment effects have to be considered in brightness predictions of young comets, the nucleus of which will generally consist of a multi-component mixture of parent molecules.

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[1] Roche, A., Cosmovici, C. B., Drapatz, S., Michel, K. W., and Wells, W. C., Icarus (in press) 1975

[2] Barbieri, C., Cosmovici, C. B., Michel, K. W., Nishimura, T., and Roche, A., Icarus (in press) 1975

DISCUSSION

H. Keller: $\dot{M}_D/\dot{M}_G$ should be the same for pre- and post-perihelion, due to infrared and H-gas production rates.

C. Cosmovici: The gas production rates are not our measurements; we just took the gas production from other people's measurements.

W. F. Huebner: I wish to point out that a group from Los Alamos also made aircraft observations of Comet Kohoutek on six different occasions before and after perihelion, starting in mid-December. The aircraft used was a Boeing 707 type jet. The aircraft was flown at altitudes up to 13.5 km. The infrared range covered was from about 1 to 14 microns. Our upper limit for the CH_4 molecule production rate is somewhat higher than the one reported here. The work has not been published since the upper limit is so high. A number of visual instruments were also on board, including a spectrograph that covered part of the near IR, and a polarization experiment. Guiding was accomplished with an on-board computer electronically connected to image intensifier cameras.

D. D. Meisel: Measurements with our Fabry-Perot on the 1.1 micron $J = 0$ lines agree that CH_4 appears to be absent.

H. Keller: H_2 as a dissociation product of CH_4 should lead to an extended source for H-Lyα, which should be detectable in the intensity distribution.

M. Mumma: I would like to comment on the general problem of detecting molecular emissions in the infrared in comets. One of the serious problems is that the molecular line profiles that you expect to see are only on the order of 50 MHz wide. What this means, essentially, is that if you have an instrument such as an iris interferometer that has a resolution of one wave number, you are trying to look for a molecular line that has a half-width of, say, a milli-wave-number, so the intensity dilution factor is more than 1000 to 1. The problem is even worse if you have a broad band filter. If you go to a tilting filter, where you have a resolution perhaps on the order of 10^{-2} wave numbers at 3 to 5 microns, then the dilution factor is only 10 to 1. In principle, the new technique of heterodyne spectroscopy gives you the ability to measure these IR emissions at resolutions that are 10 to 15 times narrower than the line widths.

M. K. Wallis: What is the significance of your upper limit on CH_4? It is larger than the production rates of H and C given earlier by Keller, by a factor of 2 or 3. The CH_4 limit therefore seems interesting.

DISCUSSION (Continued)

G. S. D. Babu: In my observations of Comet Kohoutek from 7 to 15 December 1973, I found a large deviation of the flux in $C_2(\Delta V = 0)$ on 11.013 Dec., 1973 (UT) as compared to the other dates. It seems to agree with the IR magnitude deviation on the same date obtained by yourself. Perhaps we can relate it to some process that took place in the comet.

C. Cosmovici: I think that is a very interesting comparison, since the two observations have been made, one in India and one in Italy, in two different regions of the spectrum, so that experimental errors can be excluded. I propose also to check photographs taken between the 10th and the 12th of December, in order to try to obtain some conclusions from this peculiarity.

L. Biermann: Before closing this session I would like to draw attention to the work of Rank, Towns, and associates, on their attempt to measure CO emission at 4.7 microns in Comet Kohoutek. Though bad weather and other transient difficulties prevented real observations being made before the comet had reached a solar distance of 1-1/2 A.U., and thus only an upper limit could be established, there seems to be every reason to hope for positive results for future medium-bright comets, provided the relative production rate of CO is of the order of 10% or more of what would be expected on the basis of recent work.

N76-21068

REVIEW – OBSERVATIONS OF RECENT COMETS - ION TAILS

John C. Brandt

In this review, we concentrate on an aspect of the physics of ion tails stimulated by observations of Comet Kohoutek (1973f), namely, the nature of moving structures in the tail. These motions could be bulk motions themselves or waves moving at the information speed of the medium; the resolution of this question from simple photographic data alone may not be possible.

We do not discuss the principal problem of ion tails, namely, the physical mechanism responsible for the creation of CO^+ ions. Indeed, results from studies of gas phase chemistry presented at this Colloquium indicate that the solution may be quite complex. Also, we do not discuss either the details of the solar-wind comet interaction or dust tails.

An extensive series of plates of Comet Kohoutek was obtained at the Joint Observatory for Cometary Research (JOCR) with a Schmidt camera expressly designed for large-scale photography of tails. An 8° x 10° field is recorded on 4" x 5" plates or film. The JOCR plates were also a major part of the movie of Comet Kohoutek prepared by Jockers, Roosen, and Cruikshank and shown at this Colloquium. The features under discussion are best seen in movies.

Jockers, Roosen, and Cruikshank have studied the movie of Comet Kohoutek and conclude that the pattern speeds are essentially the speeds of material motion along the tail. This is the generally prevailing view and has been presented in some detail by Jockers, Lüst, and Nowak (1972) for the case of Comet Tago-Sato-Kosaka.

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An alternate view has been suggested by Hyder, Brandt, and Roosen (1974) in a preliminary discussion of the JOCR plates*. We draw heavily on this paper in the following discussion and use structures observed on one day as an example.

On January 13, 1974, photographs of Comet Kohoutek showed an (apparently) helical structure (Figure 1) which moved down the tail at approximately 200 km/sec (the observed speed was approximately 250 km/sec and the apparent geocentric speed of the comet was approximately 50 km/sec) as illustrated schematically in Figure 2. Circumstances of the observations are: $r = 0.58$ a.u., $\delta = 0.81$ a.u., and $\csc\beta = 1.00$ (i.e., the tail was nearly face-on). The helix was approximately 16×10^6 km from the nucleus and had wavelength and radius of 1.4×10^6 km and 2.3×10^5 km, respectively. The length of the helical structure sketched in Figure 2 is 3.6×10^6 km.

Hyder et al. (1974) have suggested that this structure might be the result of a "kink instability" resulting from currents flowing along the tail axis. On their interpretation, the phase speed would be the Alfvén speed in the cometary plasma. This interpretation implies a cometary field of roughly 100γ. If the field configuration is essentially cylindrical away from the head, the decrease in density of CO^+ ions from $\sim 10^3$ cm^{-3} near the head to ~ 10 cm^{-3} well into the tail could produce a variation in Alfvén speed from ~ 20 km/sec to ~ 200 km/sec, and allow the extreme view that most moving features observed in cometary ion tails are waves moving at the Alfvén speed (see Ness and Donn 1966).

These divergent viewpoints for the case of Comet Kohoutek are based to a large extent on the same observational material. Hence, tests of the two hypotheses not based on simple, direct photography would be most desirable.

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*Full publication of the plates will be in "The JOCR Atlas of Comet Kohoutek" (Roosen and Brandt, in preparation).

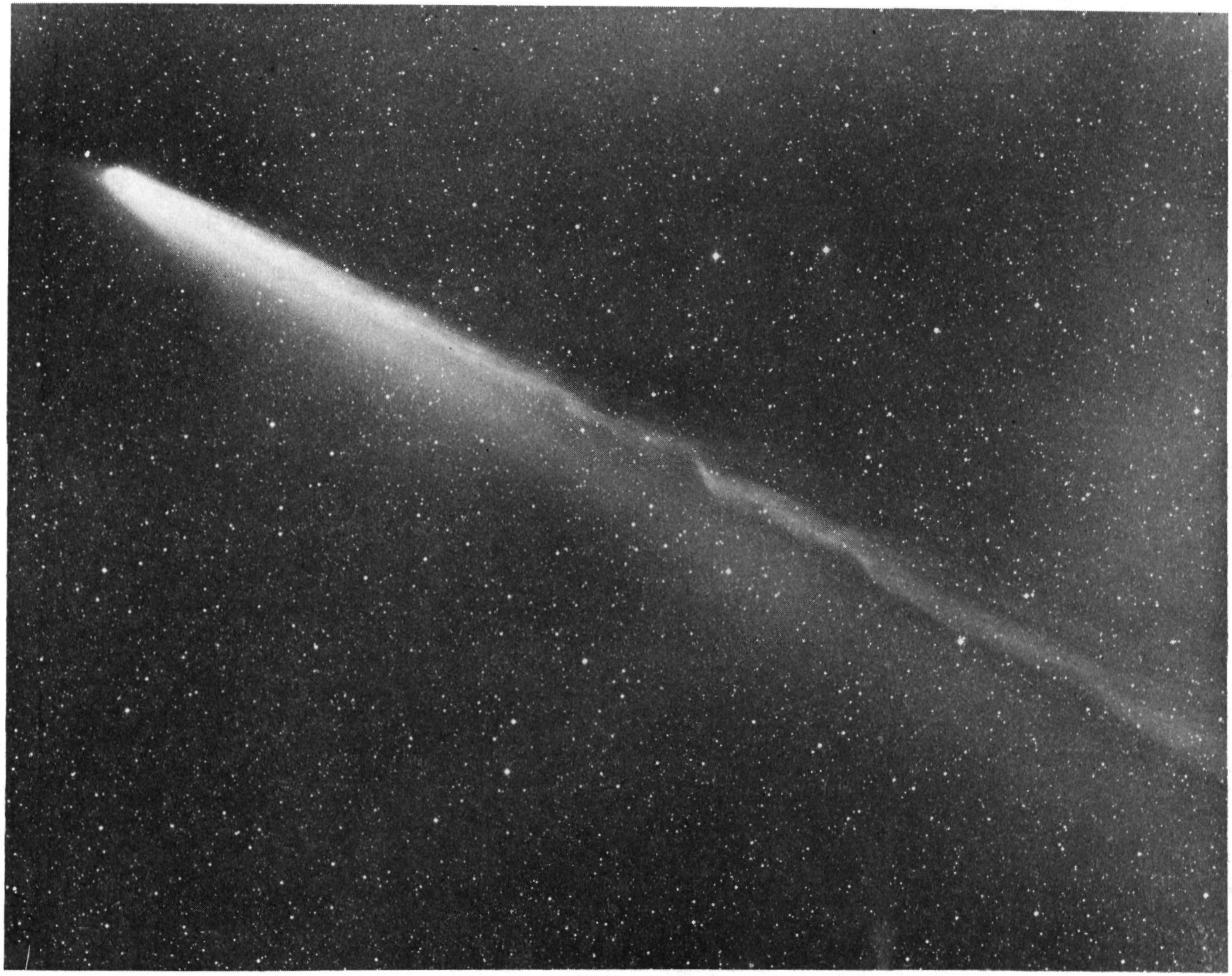

Figure 1. JOCR photograph of Comet Kohoutek on January 13, 1974. Compare with Figure 2.

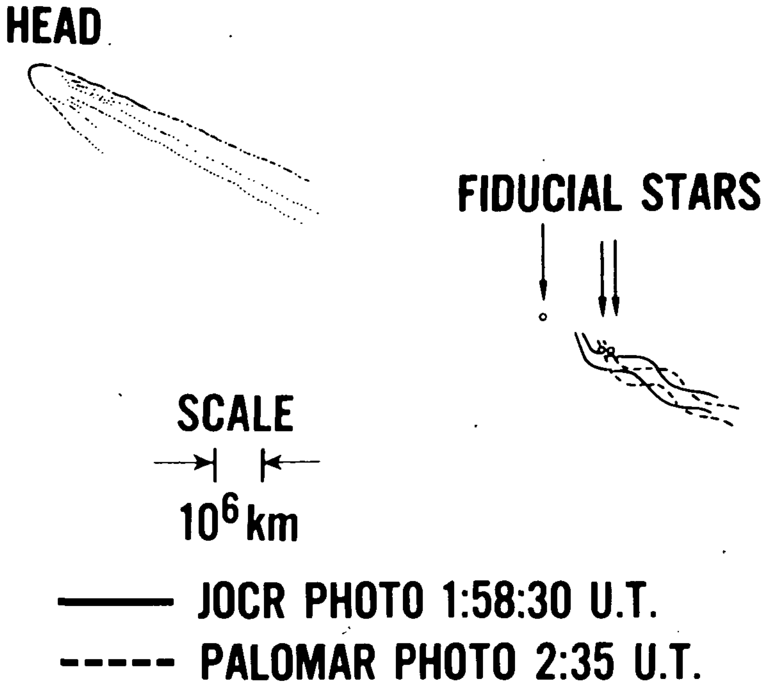

Figure 2. Schematic diagram showing the helical structure on January 13, 1974 (Figure 1) and its motion.

The most convincing test would be to observe the motion of the material spectrosocopically by means of the doppler effect. This might be carried out in two ways. (1) The material speed could be determined by observations made at a small angle with respect to the tail axis and compared with the pattern speeds. Such observations have been discussed many times but, to this reviewer's knowledge, have never been successfully carried out. (2) Observations nearly perpendicular to the tail axis could also provide a test as suggested by Hyder (1974, private communication). If the structure seen in Comet Kohoutek on January 13, 1974 is in fact a helical wave moving much faster than the material speed, then during the passage of one wavelength of the pattern the material must traverse a circle of radius $r = 2.3 \times 10^5$ km in approximately 7×10^3 sec; see above for input numbers.

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The most convincing test would be to observe the motion of the material spectroscopically by means of the doppler effect. This might be carried out in two ways. (1) The material speed could be determined by observations made at a small angle with respect to the tail axis and compared with the pattern speeds. Such observations have been discussed many times but, to this reviewer's knowledge, have never been successfully carried out. (2) Observations nearly perpendicular to the tail axis could also provide a test as suggested by Hyder (1974, private communication). If the structure seen in Comet Kohoutek on January 13, 1974 is in fact a helical wave moving much faster than the material speed, then during the passage of one wavelength of the pattern the material must traverse a circle of radius $r = 2.3 \times 10^5$ km in approximately 7×10^3 sec; see above for input numbers. Thus, the material in the helix is performing circular motion at approximately 200 km/sec and speeds of this size should be observed at the crests and troughs of the pattern. Very little motion perpendicular to the axis of the tail would be expected if the speed of the material is about the same as the pattern speed. Thus, observations perpendicular to the tail axis may provide a clear distinction between the two viewpoints. Nearly perpendicular viewing conditions may be fairly common and were available for Comet Kohoutek for several days in mid-January 1974. Photography through shiftable, high efficiency, narrow-band filters may be the best method of observation. Speeds of 200 km/sec would produce shifts of nearly 3Å in the blue CO^+ bands, and hence, the filters needed should not be difficult to obtain. Hence, the problem reduces to finding a line of sufficient strength and suitable isolation in (say) the $A^2\Pi - X^2\Sigma$ (comet tail system) bands of CO^+.

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Jockers, K., Lüst, Rh., and Nowak, Th. 1972, Astron. and Astrophys., **21**, 199.

Ness, N. F., and Donn, B. D. 1966, Nature et Origine des Comètes, (Liège), p. 343.

DISCUSSION

D. J. Malaise: This is surely an impressive way of showing the variability of tail features, but it is not easy to follow up the details, because it is going too fast. You repeated each image twice. To my knowledge, this is the standard in high quality cartoons (Walt Disney, for instance), but repeating each picture four times does not change the quality of the motion picture by an amount appreciable to the eye. This factor of two in the speed of motion would certainly make the show more comfortable to follow. Another point is that if the motion of the comet could be taken out, it would be much easier to follow the structure change, even if the stars are shooting back and forth.

K. Jockers: There is a repetition of each sequence 20 times. In the sequence every picture is shown twice, and sometimes there are small time gaps, so that two pictures are separated not by ten but by fifteen minutes. Then the picture is repeated three or four times.

F. Scherb: How did you separate the Alfvén wave speed from the speed of the underlying plasma which is streaming outward? The apparent motion of the wave to the observer is the result of the wave motion through the tail plasma at the Alfvén speed plus the motion of the tail plasma.

J. C. Brandt: We calculated the Alfvén velocity would be the same as the pattern speed, and we have the pattern speed to within 10%.

K. Jockers: How do ions not detectable in visible light contribute to the density needed to evaluate the Alfvén speed?

J. C. Brandt: We took the density to be solely, for the purposes of calculation, what it is for CO_+. I'll simply point out that it is not terribly sensitive to that, because it appears as the square root unless we're just completely mistaken.

K. Jockers: In the cometary movie we see secondary tail rays emerging from tail condensations and moving through the main tail. If Alfvén's model of cometary tail rays is correct, that means that magnetic field lines generate in the whole tail and get hooked up at condensations. So one would expect that a comet tail is not a more or less homogeneously magnitized rod but has a rather complicated magnetic field structure.

J. C. Brandt: I would certainly argue that the magnetic field model is not complicated. On the other hand, one has to start somewhere, and we can get some insight as to what the tail configuration might be by looking, for example, at the geomagnetic tail, where a cylindrical model is not perfect, but it's not unreasonable, either. The field strength in the geomagnetic tail decreases very slowly—I think it is the cube root of the distance, or something like that—so that is not an unreasonable approximation.

We spent a great deal of time looking rather hard at a lot of days in which the field is fairly quiet, and the cross section does not seem to change terribly much going from fairly close to the head to a more distant part of the tail, obviously excluding the region in the immediate vicinity of the head, where a great deal of activity is going on. That's why I prefaced this discussion by mentioning that this clearly is very simple, and very simpleminded. But I have not yet seen anything of this nature that's been discussed extensively in the literature, with exceptions here and there.

L. Biermann: As I described in the paper I referred to yesterday, the visible ions are rather likely to be transformed by ion-molecule reactions into other invisible ions before being eliminated by dissociation, recombination, or complete decomposition. In any case, the visible cometary ions give only a lower limit to the actual density, though the total density may not be more than several times larger.

B. Donn: The important and impressive feature of the paper we have just heard is that Brandt and his colleagues and Jockers have done what many of us have talked about for a long time, i.e. observations of an ion tail at short time intervals over appreciable intervals of time. This procedure will certainly lead to important results in the future.

M. K. Wallis: The region of the solar wind disturbed by the cometary gas is surely much more limited than the extent of the H-coma. For a comet of the size of Bennett, the H-coma appears thin to single protons outside 10^4 km. Taking heavy ions and general streaming into account, the distance may be increased to a few times 10^5 km, but far smaller than the 10^7 km scale of the H-coma or of the tail. This provides good reason for not devaluing the significance of comet tails as indicators of the solar wind.

J. C. Brandt: I think you should take your position and discuss it with the Munich group, and when you decide what the answer is, let me know. I tend to feel, however, that the flow is disturbed over a rather large distance. To what extent it is disturbed, I think, is still a valid question.

G. H. Herbig: Is it certain that such rapidly moving structures occur only in plasma tails, and never in dust tails?

DISCUSSION (Continued)

J. C. Brandt: Yes, I think that is almost surely the case. There is fine structure that does occasionally show up in Type II tails, the so-called synchronic band structure, but I don't think it has any relation to this phenomenon whatsoever.

R. Lust: I have two questions. One concerns the ecliptic latitude of Comet Kohoutek when the tail showed the swan structure, the second with respect to a relationship with geomagnetic data.

J. C. Brandt: The comet was so close to Jupiter and Venus in the sky that it had to be at a low ecliptic latitude, and any relationship should show up. We searched our hearts out to find a solar event or a solar wind event. The spacecraft solar wind data is simply not available at the present time. We looked very hard at geomagnetic indices, and we found nothing we would like to have our names associated with at the present time.

R. Lust: Some velocities, especially those measured in the rays (wave structure) might not be velocities of material, but there are definitely structures (knots, condensations) for which material velocities of 10-100 km/sec must be established.

J. C. Brandt: Obviously, there have to be motions of the tail. It is only when I see the type of structure, such as the two I specifically described today, that I become convinced that at least some of the structures must be wave patterns. Then I ask myself the question—let's be ridiculous, could they all be, in some not too exact way. The answer is, in terms of getting kinds of velocity variations that one finds—yes, indeed, they could possibly be. I think the best way to sort this matter out is with a spectrograph, and I think it would resolve it unambiguously. It is clear that if you have a more or less semi-cylindrical tail, that one of the ways to get the density to decrease is for the plasma to be accelerated down the tail, and if we ever get a good calibration point, we may be able to map that out fairly carefully.

D. A. Mendis: If we accept the value of B($\sim$100γ), the question arises as to its origin. It is difficult to understand how the ambient interplanetary field establishes contact with the plasma in the tail, let alone be amplified. It may be suggested that the field is in fact intrinsic, being produced by the usual hydromagnetic conversion of turbulent energy to magnetic energy during the period of coma activity. Indeed, there is no difficulty energetically or with regards to the time scales for decay.

N76-21069

A KINEMATOGRAPHIC STUDY OF THE TAIL OF COMET KOHOUTEK (1973f)

K. Jockers, R. G. Roosen, D. P. Cruikshank

Introduction

By combining observations of Comet Kohoutek (1973 f) made in the Southwest US, Alaska and Hawaii, a cometary tail movie has been made. Parts of the movie were shown at the conference and some frames of the movie are reproduced in Fig. 1. In this paper we give some details of the observations and describe what we see on the movie.

Observations

Observers who contributed to the movie are listed in Table 1 with their institutions, instruments, and site locations. In all but one case, fast Schmidt cameras were used; high-speed optics are needed for this work because the interval between successive pictures should not exceed 15 minutes if plasma tail motions are to be properly visualized. The 36 cm f/2 Schmidt camera of the Joint Observatory for Cometary Research (JOCR) is clearly well-suited because of its flat field of about 8 x 10°. JOCR is located at an altitude of 3235 m at a site having frequent high transparency of the sky. In Alaska and Hawaii we used the comparatively inexpensive and easily portable Celestron 20 cm Schmidt cameras. The Celestron proved especially effective at the high altitude site in Hawaii where relatively fine grain Kodak RAR 2498 emulsion was used (Crump and Cruikshank 1974).

D/7

Table 1

Sources for Comet Photographs

Number of Pictures	Institution	Location		Instrument	Observers
		Long.	Lat.		
47	JOCR	107.10	33.59	36 cm f/2 Schmidt	R. G. Roosen J. C. Brandt T. Armijo
4	Lunar and Planetary Lab.	110.72	32.40	46 cm f/3 Schmidt	S. Kuturoff R. B. Minton
5	Lowell Obs.	111.66	35.20	33 cm Astrograph 13 cm f/5 Cooke lens	H. L. Giclas
28	Sac Peak Obs. Observations from College, Alaska	147.50	64.50	20 cm Celestron Schmidt	K. Jockers
20	Mauna Kea Obs. University of Hawaii	155.47	19.82	20 cm Celestron Schmidt	D.P. Cruikshank P.C. Crump

Table 2

Time Intervals and Distances

Date	Time (UT) Covered in the Movie		Heliocentric Distance of Comet (a.u.)
Jan 11	1:42-2:04*	2:04-3:07	.52
Jan 12	2:42-3:21	3:50*	.55
Jan 13	1:59-2:52	3:32-4:35*	.58
Jan 14	1:40-2:47	3:45-4:08*	.60
Jan 17	1:38-2:32	3:31-5:57	.68
Jan 19	1:41-2:10	3:13-3:23	.74
Jan 20	1:19-3:01	5:24-6:44*	.76
Jan 21	2:24-2:34	5:05-6:39	.79
Jan 22	2:44-6:27		.81
Jan 23	1:35-3:25	5:25-6:35	.84

*An asterisk indicates that, because of small field, the pictures in these time intervals were used only for the sequence nearest to the cometary head.

The resolution obtained in the photographs with the small Schmidt cameras seemed to be somewhat more sensitive to sky transparency than in those made with the larger instruments. This may be related to the dependence of resolution on the contrast of the object being photographed. The bending of the 35 mm film pieces to the strongly curved focal plane of the Celestron Schmidt cameras introduces noticeable image shifts which vary from frame to frame, therefore making precise alignment of the frames in the movie impossible.

The dates and time intervals covered in the movie are given in Table 2 together with the heliocentric distance of the comet. During the observation period the comet was always near its minimum geocentric distance of about 0.8 a.u. and the phase angle was near 90°.

Arrangement of the Movie

A typical sequence in the movie consists of about ten individual frames. To ease perception of these short sequences the pictures for each day are repeated 20 times forward and backward in time. Most of the individual frames have been printed twice on the movie. Since the original pictures were taken at intervals of about 10 min., with a projection speed of 24 frames per second 10 minutes of real time are compressed into somewhat less than 1/10 of a second in the projection. To ensure a constant time reduction in case of minor gaps in the data, some frames have been repeated on the movie up to four times. No attempt has been made to smoothe out the data gaps of about 1 hour which sometimes occur between the JOCR and the Alaska/Hawaii pictures. To preserve the resolution of the original data on the copy movie, the tail was divided into several parts so that the long side of the frame covers about 3° on the sky or 6 million km at the comet's distance.

The frame including the comet's head is denoted A, while frames offset to the northeast along the tail are designated B, C., etc. In order to properly display particular tail features the offsets have varying amounts of overlap. Because of the small field of the Celestron camera virtually all of the offset information comes from the JOCR observations. The alignment of the frames has been done with respect to the star background, i.e., the proper motion of the comet has not been removed.

Description of the Kinematic Behavior of the Cometary Tail

In this description we refer to the different sequences of the movie by a number denoting Greenwich date in January 1974 and a letter indicating the part of the tail concerned, i.e., 21 A means the sequence of January 21 of the first tail section, which includes the cometary head.

a. Tail Rays

Plasma comets show tail rays emerging from the coma and moving towards the main tail (Wurm 1963 p. 574f, Wurm and Mammano 1972). Long rays of this type can be seen on sequences 13A and 19A-C. The present observations show side rays originating from almost every tail condensation or kink (11B, 12C, 20B, 20C, Fig 1a, 1d). A few cases of this kind, but in rather strong condensations, have been seen in the tails of Comets Morehouse 1908 III (Bobrovnikoff, 1928) and Tago-Sato-Kosaka 1969 IX (Jockers et al. 1972). If Alfven's (1957) model of cometary tail rays is correct, this observation suggests that magnetic field lines penetrate the whole plasma tail and cause a rather complicated field structure.

b. Wave Trains

Features looking like wave trains are frequently seen in cometary plasma tails. In the movie they appear in the center of the tail (13B) and on its edge (12B, 20B, 20C, Fig 1d). In the latter case there is a large-scale kink in the tail. Similar wave trains in a large-scale tail disturbance have been seen in Comet Bennett 1970 II (see pictures of the April 3/4 1970) event reproduced in Jockers and Lüst, 1973). The wave trains show little differential motion relative to condensations. Hence, if the wave trains represent real waves, their phase velocity must be rather low. During one hour they change shape only slightly.

c. Condensations and Kinks

Condensations can be seen in the main tail and in the tail rays. Jockers et al. (1972) report a case where higher velocities of the condensation were measured in the tail rays than in the main tail. In the present movie condensations in tail rays are seen most frequently adjacent to condensations in the main tail (11A, 11B and many other examples, Fig 1a). They move with almost the same velocity as the adjacent main tail structure. It appears that the flow in the tail ray was restricted by the main tail condensation. An interesting example of the development of a large condensation far from the cometary head is seen in sequence 21B (Fig 1e). Sequence 23A (Fig 1f) shows a condensation being ejected from the coma. Kinks can steepen during their evolution (19C, Fig 16) or be flattened out (20A, Fig 1c). Due to the short interval of time coverage the development of the large-scale kink in the cometary tail on January 20 and its possible correlation with the evolution of wavy structures cannot be studied from the available data.

In view of the limited observational material available, the above description necessarily remains subjective and has to be considered as a first attempt to describe what requires independent confirmation in observations of future comets.

Acknowledgments

We are grateful to Messrs S. Kuturoff and R. B. Minton (Lunar and Planetary Laboratory), H. L. Giclas (Lowell Observatory) and P. C. Crump (University of Hawaii), who contributed to the observations. Dr. H. U. Schmidt (Max Planck Institute for Astrophysics) made the two Celestron Schmidt cameras available and gave encouraging advice. Dr. J. W. Evans (Sacramento Peak Observatory) and Dr. K. B. Mather (Geophysical Institute, College, Alaska) made the trip to Alaska possible. The staff of Sacramento Peak Observatory and the Geophysical Institute in College provided invaluable help in support of the observations.

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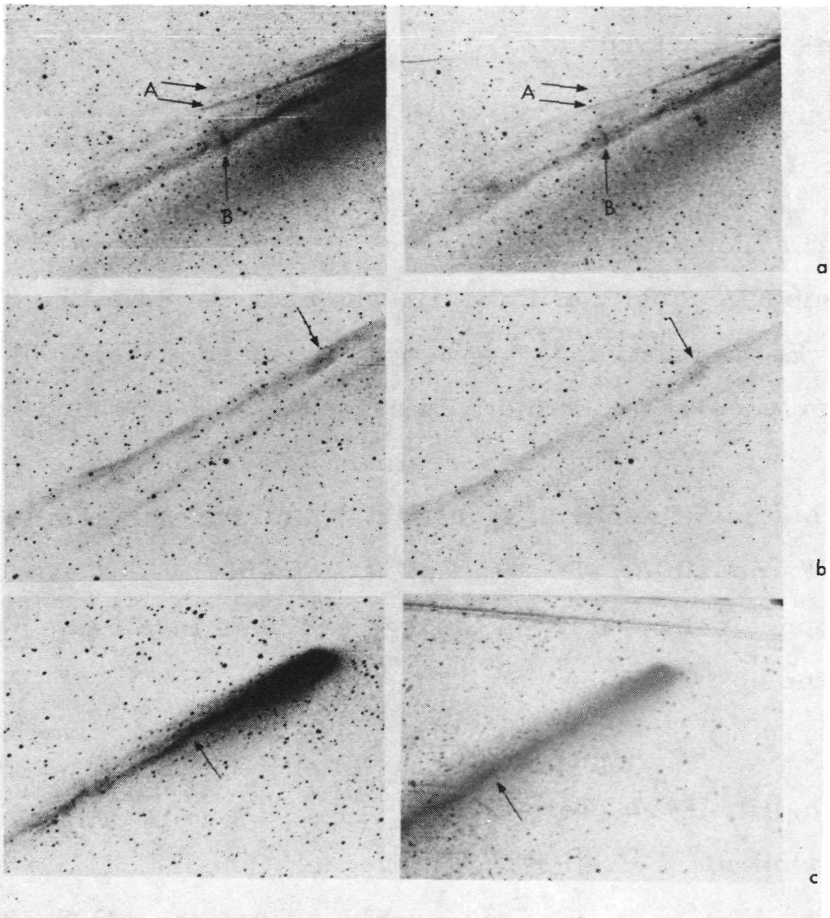

Fig. 1a-c

Fig. 1 Some frame pairs of the movie showing interesting time changes:

a) Jan 11: Time difference between frames 21 min. Two condensations in tail rays (A) remain adjacent to a condensation in the main tail (B). On the early picture (left) two small side rays leave condensation B at both sides at almost right angles to the tail axis. These angles have diminished appreciably in the late (right) frame by motion of the side rays toward the tail axis.

b) Jan 19: Time difference between frames 66 min. A kink develops.

c) Jan 20: Time difference between frames 223 min. A kink flattens out.

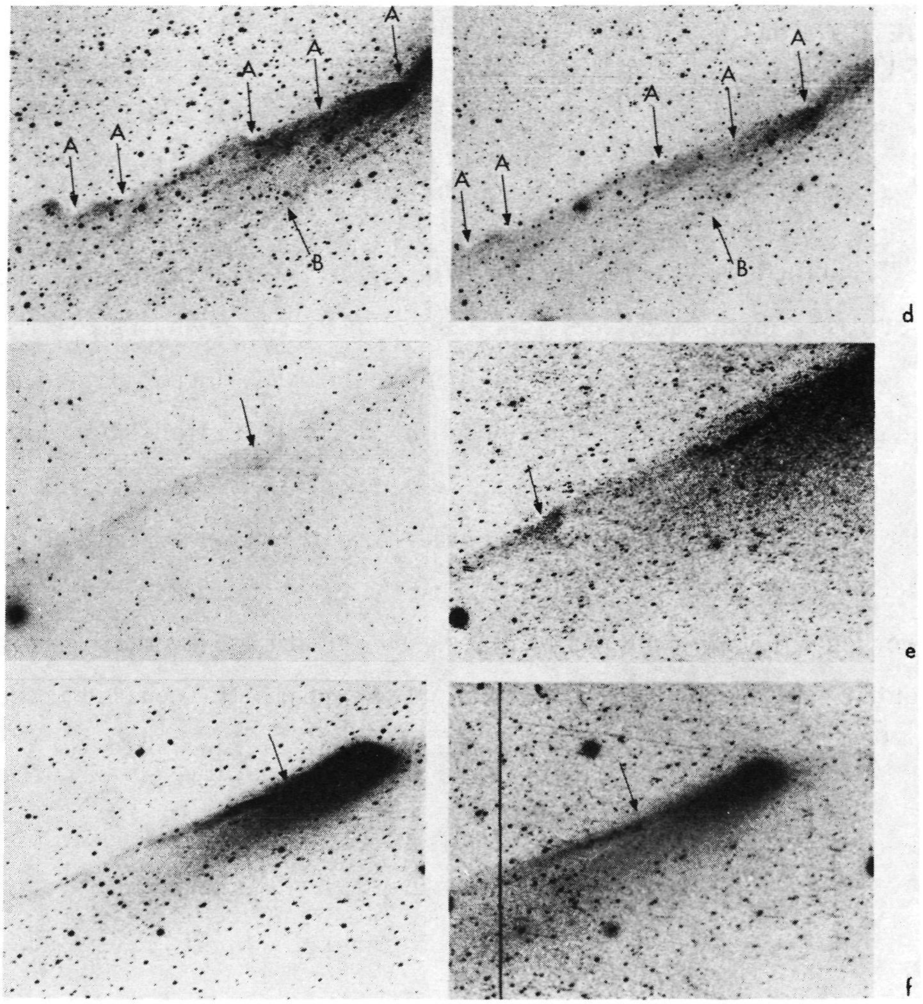

Fig. 1 (Continued)

d) Jan 20: Time difference between frames 55 min. The structure of the wave train (wave troughs marked A) remains remarkably constant. Attached side rays move towards tail axis (most prominent tail ray is marked B).

e) Jan 21: Time difference between frames 198 min. A condensation develops far from the cometary head.

f) Jan 23: Time difference between frames 208 min. A condensation leaves the dust envelope around the coma.

omit

POSSIBLE DETECTION OF COLLIDING PLASMOIDS IN THE TAIL OF COMET KOHOUTEK (1973f)

R.G. Roosen and J.C. Brandt

ABSTRACT

Six JOCR photographs of Comet Kohoutek taken on January 19, 1974 (UT) show concentrations of plasma about ten degrees from the head of the comet which are very similar to the "barred spirals" reported by Bostick (IAU Symposium No. 6: Electromagnetic Phenomena in Cosmical Physics, B. Lehnert, (ed.) Cambridge Univ. Press, 1958) from laboratory observations of colliding plasmoids. The photographs were taken about one day after a solar magnetic sector boundary crossed the comet's head. Also, the comet's plasma tail splits near the head into two distinct segments. It appears that the two segments reconverge and form the plasma concentrations by collisions. This represents an increase in scale over Bostick's work of about 10^{14}. Possible historical observations of similar phenomena are discussed.

DISCUSSION

G. H. Herbig: Can it be that this object is due to an internal reflection in your optical system? In Schmidt systems, reflection from the emulsion (or filter, or field flattener) back through the system and off the correcting lens and thus to the focal plane again can produce an out-of-focus image of a bright star. These ghosts are symmetrical with respect to the field center. I notice that on your first slide the comet head is located with respect to the lower left corner just as your feature is placed with respect to the upper right.

R. G. Roosen: First of all, we took plates with and without a filter, so if it were reflection, the reflection would have to be the same both with and without a filter. That's a fine suggestion, and I'll be happy to embarrassingly publish a retraction if it turn's out that that's it, and I will go back and measure the plates for this distance.

F. L. Whipple: I hate to be the "devil's advocate," but in tens of thousands of plate inspections I have found so many false images that I have a built-in suspicion of peculiarly shaped images that move for a short duration.

R. G. Roosen: We've examined all our other plates and don't find anything like this on any of the other nights. Klauss Jockers said that he thought that he found one on another plate (he's examined all of our plates, too), but we went to look for it and couldn't find it. So on this night it showed up on every plate, and it never showed up on any of the other nights, even though we had this same orientation.

P. M. Millman: In regard to cross-axis inverted images, these do not necessarily depend on the closeness of the original image and the cross-axis image to the edge of the plate. The important fact is that the two images should be the same angular distance from the optical axis of the lens system.

B. G. Marsden: Peculiar tail features of this kind have been reported before, of course, and I mention in particular one appearance in a photograph of Comet Bennett by McClure. The fact that your feature also appears on a red plate makes one wonder whether some of the cometary objects occasionally reported visually near bright comets are perhaps manifestations of the same phenomenon. Barnard is said to have dreamt one night, during his comet-hunting period, that the sky was filled with comets. On waking and going outdoors, he found that it was, with a dozen or so "comets" seen to be surrounding the great comet of 1882. Similar objects were also reported by Brooks and Schmidt.

N76-21070

LUMINOSITY AND ASTROMETRY OF COMETS: A REVIEW

Elizabeth Roemer

Visual Brightness

By far the greatest number of observations of the brightness of comets, and the only ones that cover a long enough time span for investigation of secular effects, have been made by visual methods, mostly with small instruments. Such observations record the contribution of a large part of the coma, and possibly some light from the tail, at wavelengths to which the eye is sensitive. Three distinct observational techniques have been defined:

1) Comparison of similar-appearing extrafocal images of comet and comparison stars for equal apparent brightness. (Most observations have been made by this method.) The technique has been described by Bobrovnikoff (1941a, 1941b).
2) Comparison of the in-focus image of the comet with extrafocal images of comparison stars for equal apparent brightness. This method has been described by Sidgwick (1955).
3) A method used extensively by Max Beyer (1950), in which grossly out-of-focus images of the comet and comparison stars are examined for similarity of extinction against the sky.

Each of these techniques is subject to systematic errors depending upon a variety of factors: the observer and the instrument employed; the observing circumstances, most particularly the brightness of the sky background; and the character of the comet, especially the degree of central condensation. The several techniques, including differences in their susceptibility to systematic effects, and physical interpretation of the observational data are considered in some detail by Meisel and Morris (1975).

Photographic Brightness

Magnitude estimates can also be made from photographic observations. Those derived from photographs taken with small instruments of relatively short *f* ratio so not differ grossly from visual determinations of "total" brightness. But determinations made from photographs taken with large, relatively long-focus reflectors for astrometric purposes, tend to give much fainter magnitudes. Such photographs are usually taken with the motion accurately compensated, and the images of comets are small, round, and generally quite sharply condensed. These images are often nearly stellar in appearance, so that direct eye comparisons can be made with images of stars on similarly exposed plates of one of the star fields in which photoelectrically calibrated magnitude sequences have been established. The writer has regularly applied a mean correction of 0.3 mag per air mass (blue light) to compensate for differential extinction. Magnitudes derived in such a way are always fainter than those that refer to the brightness of the central condensation observed visually with the same instrument. Typically they are as much as 5-6 magnitudes fainter than visual estimates made with small telescopes using one of the techniques described above.

To determine appropriate exposure times for photographic observations with the large instruments, it has been the practice for some time to compute ephemerides of "nuclear" magnitudes (Roemer 1961). The distinction between "total" (m_1) and "nuclear" (m_2) magnitudes was introduced into the IAU telegram code some years ago, and its general use was recommended by resolution of IAU Commission 20 in 1970 (*Trans. IAU* XIVB, p. 156, 1971).

Actual observations of individual comets will generally fall somewhere between "total" and "nuclear" magnitudes. For visual observations there is a well-known and rather pronounced dependence of the observed magnitude on the size of the telescope, the "aperture effect" discussed by Bobrovnikoff (1941a, 1942, 1943). Comets appear systematically fainter the larger the telescope with which they are observed. But it is clear that the *f* ratio plays a role as well (see, e.g., Morris 1973). "Total" magnitudes fall short of the ideal in that not all of the light from the coma and tail of a well-developed comet is included in observations made visually, even with very small, wide-field instruments. And "nuclear" magnitudes will rarely be free from contamination by light from the inner coma, the amount apparently being dependent on the *f* ratio of the telescope and on the characteristics of the comet. Even quite large Schmidt cameras give brightnesses appreciably greater than do the long-focus reflectors. An *f*/4 208-cm reflector gives magnitudes of the order of 1 mag brighter for typical comets than does a 229-cm *f*/9 instrument.

Interpretation of Nuclear Magnitudes

Not surprisingly it is found as an empirical fact that "nuclear" magnitudes are less sensitive to heliocentric distance than are "total" magnitudes. For a very few comets, direct solution from observed "nuclear" magnitudes over an adequate range of distances has led to an asteroidal-type magnitude law, P/Arend-Rigaux being the outstanding example (Marsden 1974; see also Sekanina 1975). The sensitivity to the heliocentric distance seems to be correlated with the photographic appearance of the comet, in that the more nearly stellar the appearance the closer the brightness behavior is likely to be to a simple reflection law.

Conformity of actual observations to an asteroidal law has been used, supplementing nearly stellar appearance, as a test of the degree of resolution of true "nuclear" magnitudes. The investigation by Sekanina (1975) suggests that this may not be a sufficient condition of resolution.

A comet is likely to be of most nearly stellar appearance if observed at large distance from the sun, when it is relatively inactive. But some bright and active comets may be nearly stellar in appearance on short-exposure photographs, particularly if high-contrast photographic emulsions are used. It is, however, a very rare comet that is not immediately recognizable as a comet, whatever the observational circumstances. P/Arend-Rigaux is such an object.

Plates I - VI show the appearance of a number of comets as photographed with long-focus reflectors. Both short- and long-period comets are included, and observations span a considerable range of heliocentric distances. The minor planet (1580) Betulia is shown in Plate VII for comparison.

To the extent that the cometary image is not absolutely stellar in appearance, the "nuclear" magnitudes clearly do not refer exclusively to light reflected from a monolithic nucleus. Dimensions of nuclei calculated from observations of brightness that include any unresolved contribution from the inner coma will be too large, perhaps considerably so. Even interpreted in a rather uncritical way, the "nuclear" magnitudes determined with the large reflectors have proved that the radii of comet nuclei are in the range from fractions of a kilometer to a few kilometers for typical objects (Roemer 1966). Such dimensions are far below the limit of optical resolution in ordinary circumstances.[1]

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[1] Delsemme and Miller (1971) have shown that the brightness profile of continuum light reflected from grains of an icy halo falls off very sharply with distance from the nucleus. Recalling that a radius of 725 km subtends an angle of 1 arcsec at a distance of 1 a.u., it is clear that a significant contribution of light from a grain halo may be included unrecognized in nuclear magnitude estimates when such a halo is present.

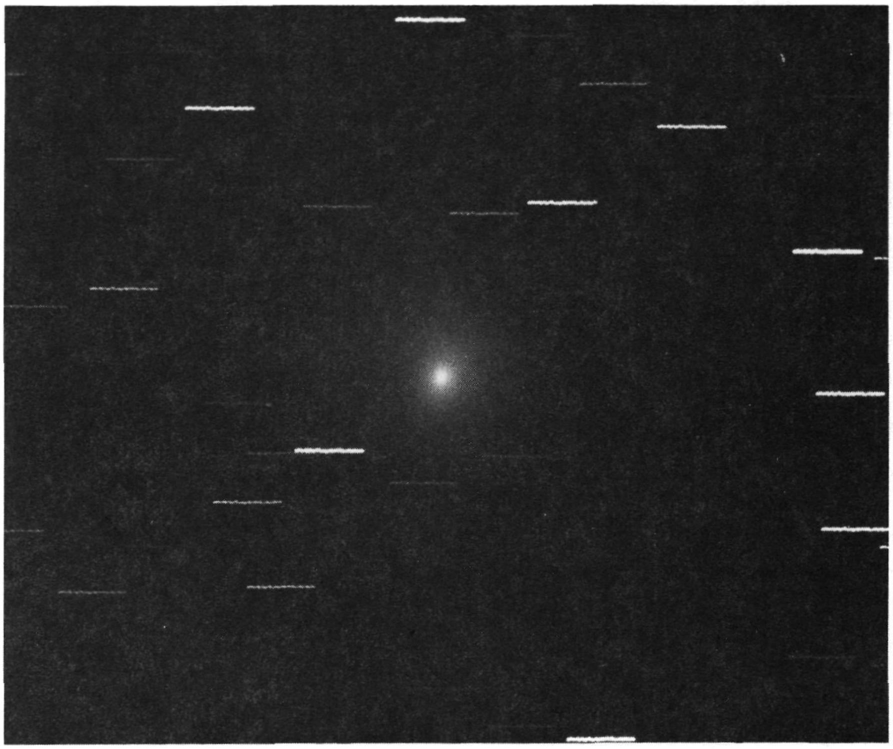

Plate I. P/Tuttle-Giacobini-Kresák, 1962 V, 1962 Apr. 5. $\Delta = 0.27$ a.u., $r = 1.15$ a.u. 102-cm f/6.8 reflector, 30-min exposure on Kodak 103a-O emulsion. "Very strongly condensed, essentially stellar nucleus in a faint asymmetrical coma at least 1' in diameter." An m_2 estimate of 16.5 was made from a shorter exposure taken the same night. Note that the quoted descriptions were all made from examination of the original plates. Contrasts are recorded differently in reproductions.

Official U.S. Navy Photograph

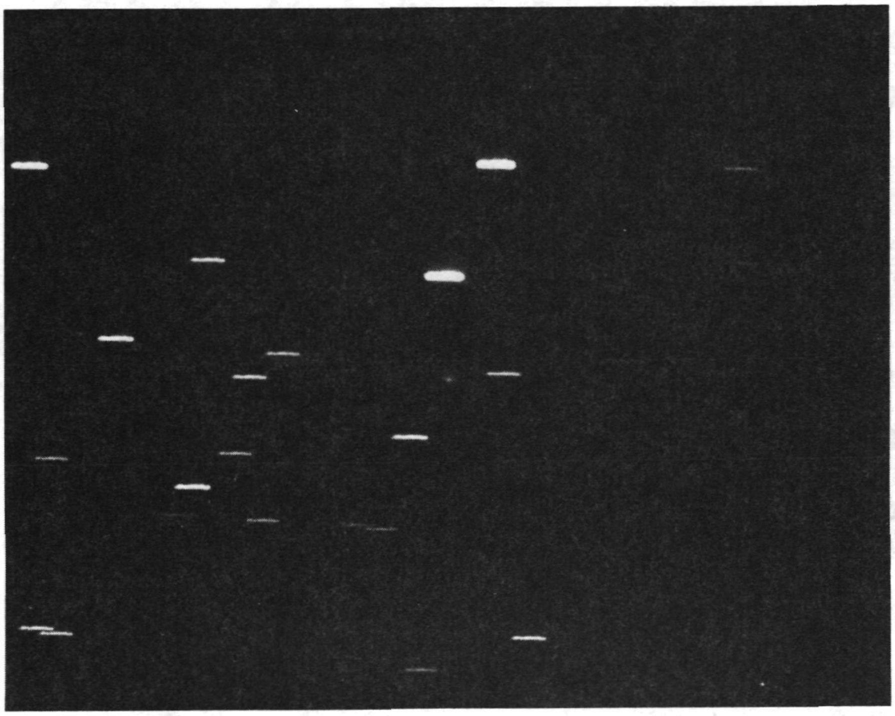

Plate II. P/de Vico-Swift, 1965 VII, 1965 Aug. 4. $\Delta = 0.81$ a.u., $r = 1.64$ a.u. 102-cm f/6.8 reflector, 30-min exposure on Kodak 103a-0 emulsion. "Practically stellar condensation of m_2 near 18.7, with a faint trace of trail . . . WSW."

Official U.S. Navy Photograph

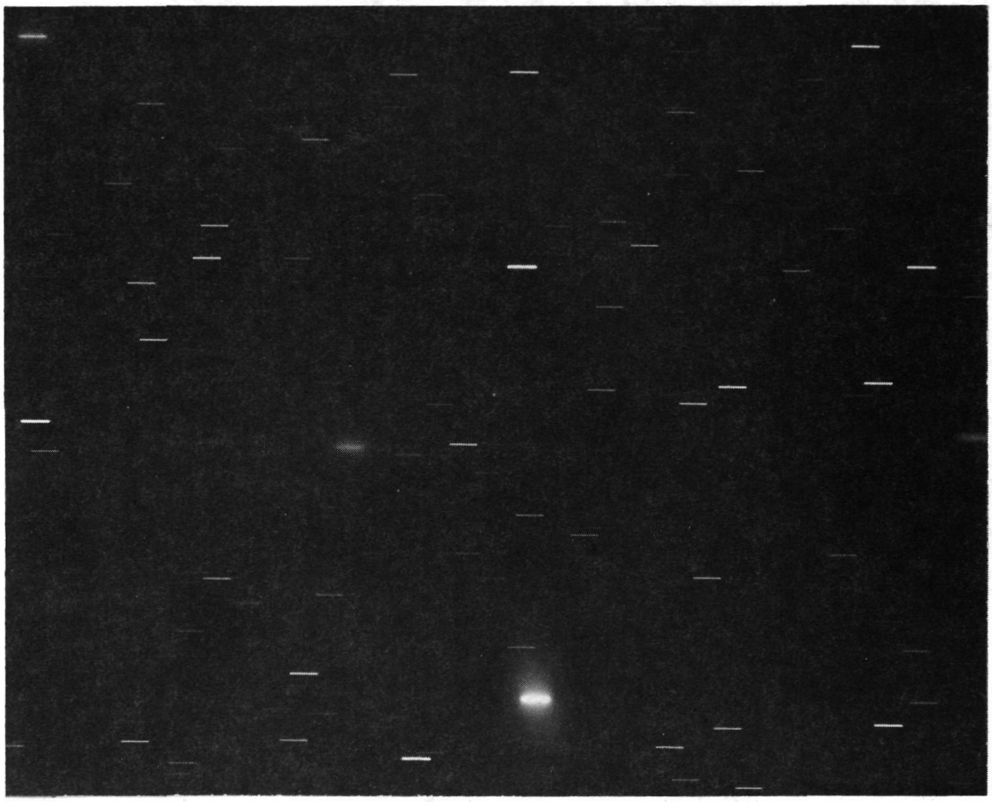

Plate III. P/Tempel 1, 1972 V, 1972 Jan. 11. Δ = 1.78 a.u., r = 2.28 a.u. 229-cm f/9 reflector, 60-min exposure on Kodak 103a-O emulsion. "Strong image; nearly stellar nucleus embedded in a very small, slightly asymmetric coma."

Steward Observatory Photograph

Plate IV. Comet Wirtanen, 1957 VI, 1957 June 27. $\Delta = 3.75$ a.u., $r = 4.48$ a.u. 102-cm f/6.8 reflector, 10-min exposure on Kodak 103a-O emulsion. (Shows the long-enduring double nucleus.) "Nuclei not quite stellar; m_2's about 16.3 and 18.0; sep. about 8".5."

Official U.S. Navy Photograph

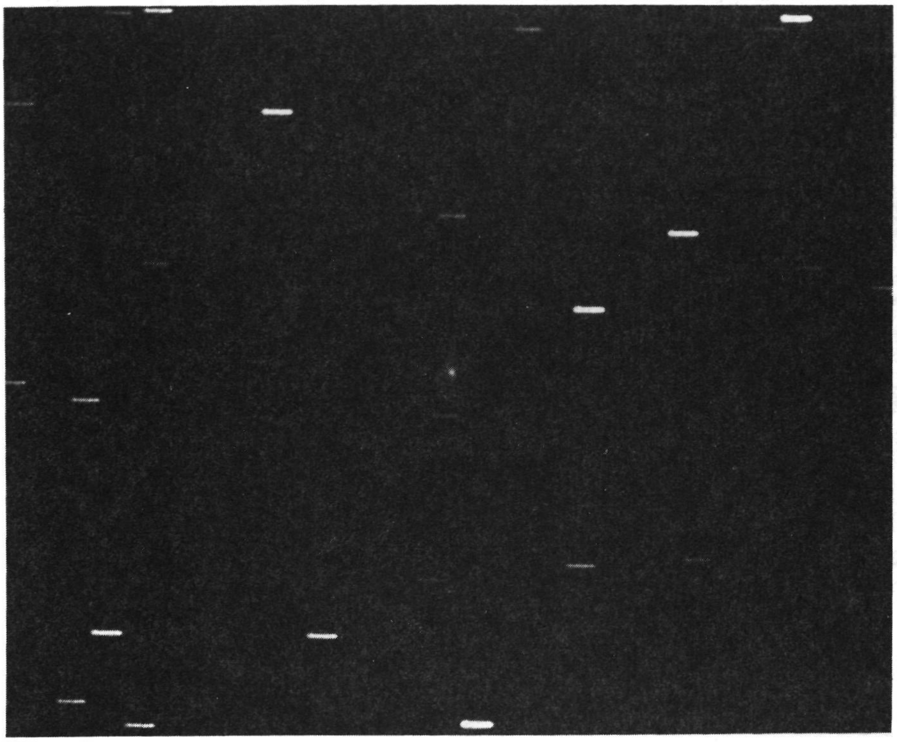

Plate V. Comet Humason, 1962 VIII, 1964 May 12. $\Delta = 5.24$ a.u., $r = 5.70$ a.u. 102-cm f/6.8 reflector, 120-min exposure on Kodak 103a-O emulsion. "Practically stellar nuclear condensation of m_2 about 17.8 in a weak, almost featureless coma 0.'4 in diameter."

Official U.S. Navy Photograph

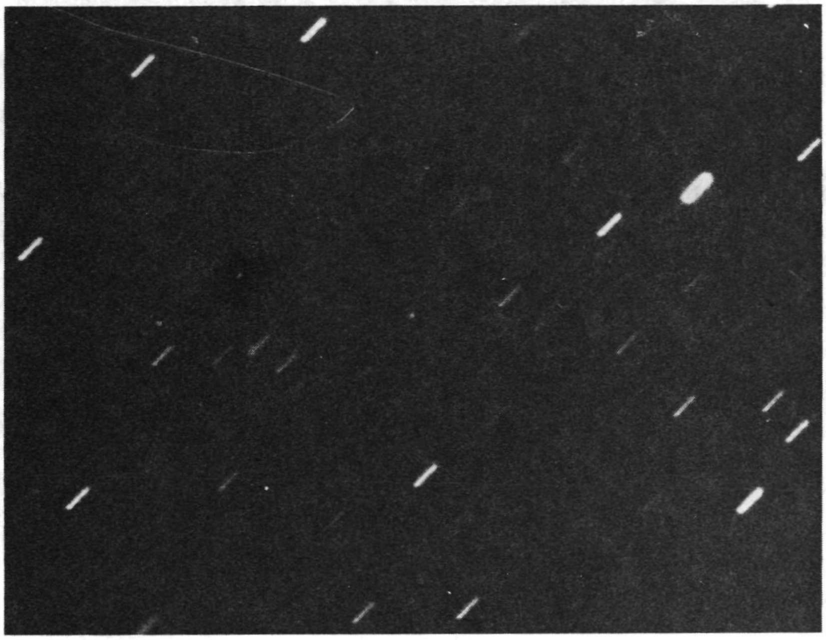

Plate VI. P/Arend-Rigaux, 1957 VII, 1958 May 12. $\Delta = 2.04$ a.u., $r = 2.77$ a.u. 102-cm f/6.8 reflector, 90-min exposure on Kodak 103a-O emulsion. "Stellar image of m_2 about 19.8."

Official U.S. Navy Photograph

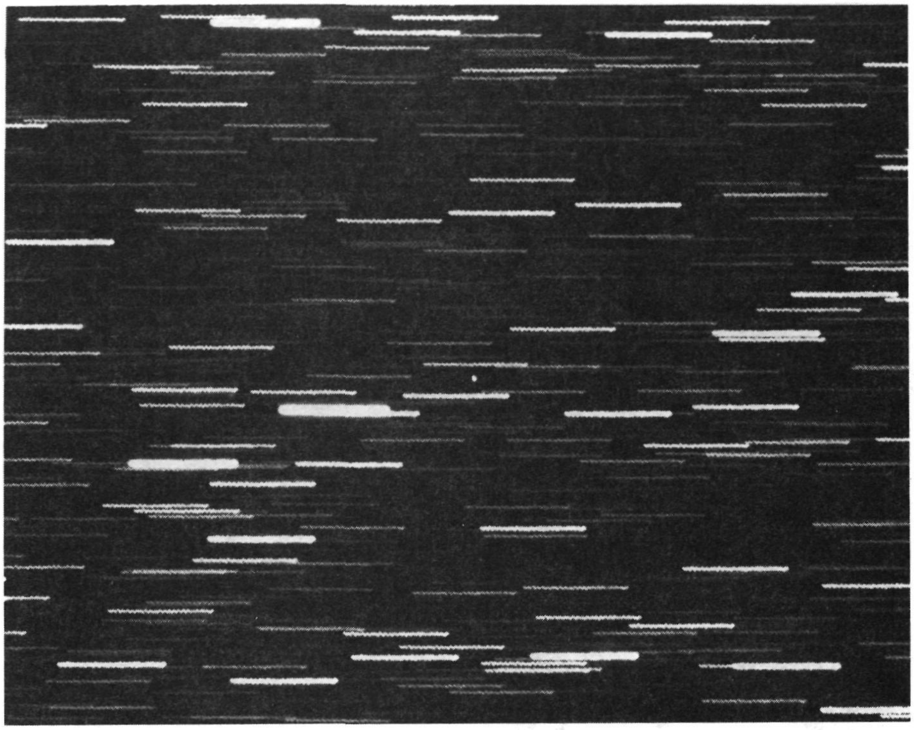

Plate VII. Minor planet (1580) Betulia, 1963 Apr. 25. Δ = 0.42 a.u., r = 1.12 a.u. 102-cm f/6.8 reflector, 60-min exposure on Kodak 103a-D emulsion, without filter, prolonged in an effort to record any possible trace of coma that might be present around this close-earth-approach asteroid. "Stellar appearance, magnitude about 16."

It should be noted that the nuclear dimensions published by the writer were derived from individual magnitude observations, not from absolute magnitudes. The degree of contamination from an unresolved inner coma will vary with time as the intensity of the gas and dust emission fluctuates, and will generally be less at large heliocentric distances. A nuclear absolute magnitude calculated from a collection of observations made over a considerable range in heliocentric distance will include a fit to this contamination. Nuclear radii calculated from absolute magnitudes are likely, therefore, to depend to some degree on the particular range of distances over which the individual objects were observed and the level of their physical activity. Since the overwhelming majority of nuclear magnitude estimates refer to comets at geocentric and heliocentric distances greater than 1 a.u., reduction to unit distance will have the effect of exaggerating the contamination from the coma and will lead to spuriously large figures for nuclear dimensions.

Brightness Ephemerides

The apparent brightness of a comet as it depends on geocentric and heliocentric distance is commonly represented by the relation

$$I = I_o \Delta^{-2} r^{-n} . \qquad (1)$$

The nuclear brightness of some comets may show in addition a dependence on phase angle, but such dependence appears to be negligible for total brightness. For ephemeris purposes, the relation (1) is most frequently used in the form

$$m = m_o + 5 \log \Delta + 2.5 n \log r \qquad (2)$$

where m is now usually specified as referring to "total" magnitude, m_1, or "nuclear" magnitude, m_2. The exponent n thus represents in an average way characteristics of the comet itself and of its response to the solar radiation field. The "absolute magnitude", m_0, corresponds formally to $\Delta = r = 1$ a.u., but it is not a clear-cut intrinsic property of a comet. For comparison, the conventional form for magnitude ephemerides for minor planets is

$$m = g + 5 \log \Delta + 5 \log r + 0.023\, \alpha^\circ. \qquad (3)$$

Extensive analyses of the total brightness behavior of observed comets have been made by many investigators (e.g., Bobrovnikoff 1941a, 1942, 1943; Schmidt 1951; Vsekhsvyatskij 1958) and have led to identification of several general patterns. "New" comets, defined as those moving in original orbits so nearly parabolic that they are not likely to have passed previously through the inner solar system, are found to be responsive to solar radiation at relatively large distances. Further brightening is comparatively slow on closer approach to the sun. The average value of $\underline{n}$ in (2) is about 3. "Old" comets, including those in definitely elliptical orbits, are more sensitive to decreasing heliocentric distance, and the average value of $\underline{n}$ is found to be larger, nearly 4 for long-period comets, and approaching 6 for short-period comets. Values of $\underline{n}$ found for individual comets in all classes span a wide range, some comets even fading out on approach to perihelion.

For a comet that becomes relatively bright at perihelion but is observed photographically over a long arc, many estimates of m_1 will be made while the comet is bright, while measures of m_2 will predominate at large $\underline{r}$. Very few comets are observed visually when $m_1 > 12$, while m_2 observations generally fall in the range $15 < m_2 < 21$. Fits have sometimes been made to the two kinds of magnitudes indiscriminately by adjustment of the parameters in a single formula. When this is done, an exaggerated value of $\underline{n}$ is likely to emerge, along with an m_0 that is quite uninterpretable.

When a new comet is discovered visually, the long-focus photographic observer normally expects m_2 to exceed m_1 by four to six magnitudes, the amount being sensitive to the diffuseness of the object.

Conversely, it has sometimes been necessary to predict the near-perihelion visual brightness of a comet when only photographic observations at large heliocentric distance are available. This was the situation with Comet Kohoutek in March and April 1973. To arrive at some estimate of the probable development, ephemerides were calculated on the basis of two assumed magnitude laws, one with $\underline{n} = 4$, and one with $\underline{n} = 6$, each with m_0 determined so as to fit the available photographic observations. The more conservative prediction, which turned out to be rather accurate, seems to have been largely overlooked in the excitement that followed. The near-perihelion m_1 observations of Comet Kohoutek as reported in the IAU *Circulars* are shown in Fig. 1, with an $\underline{n} = 4$ magnitude ephemeris represented by the full curve. A one-magnitude asymmetry in the preperihelion vs. postperihelion brightness behavior is fairly common, but most comets tend to be somewhat brighter after perihelion passage than before. Although some comets have been followed after perihelion to distances comparable with that at which Comet Kohoutek was discovered, no comet ever before was followed from discovery at a heliocentric distance of nearly 5 a.u. through a perihelion passage less than 0.2 a.u. from the sun. The experience, therefore, was highly instructive.

Summary

The rate of secular fading of short-period comets continues to be a topic of interest. Visual estimates of total brightness made with small telescopes are the only data comparable with old observations. Interested

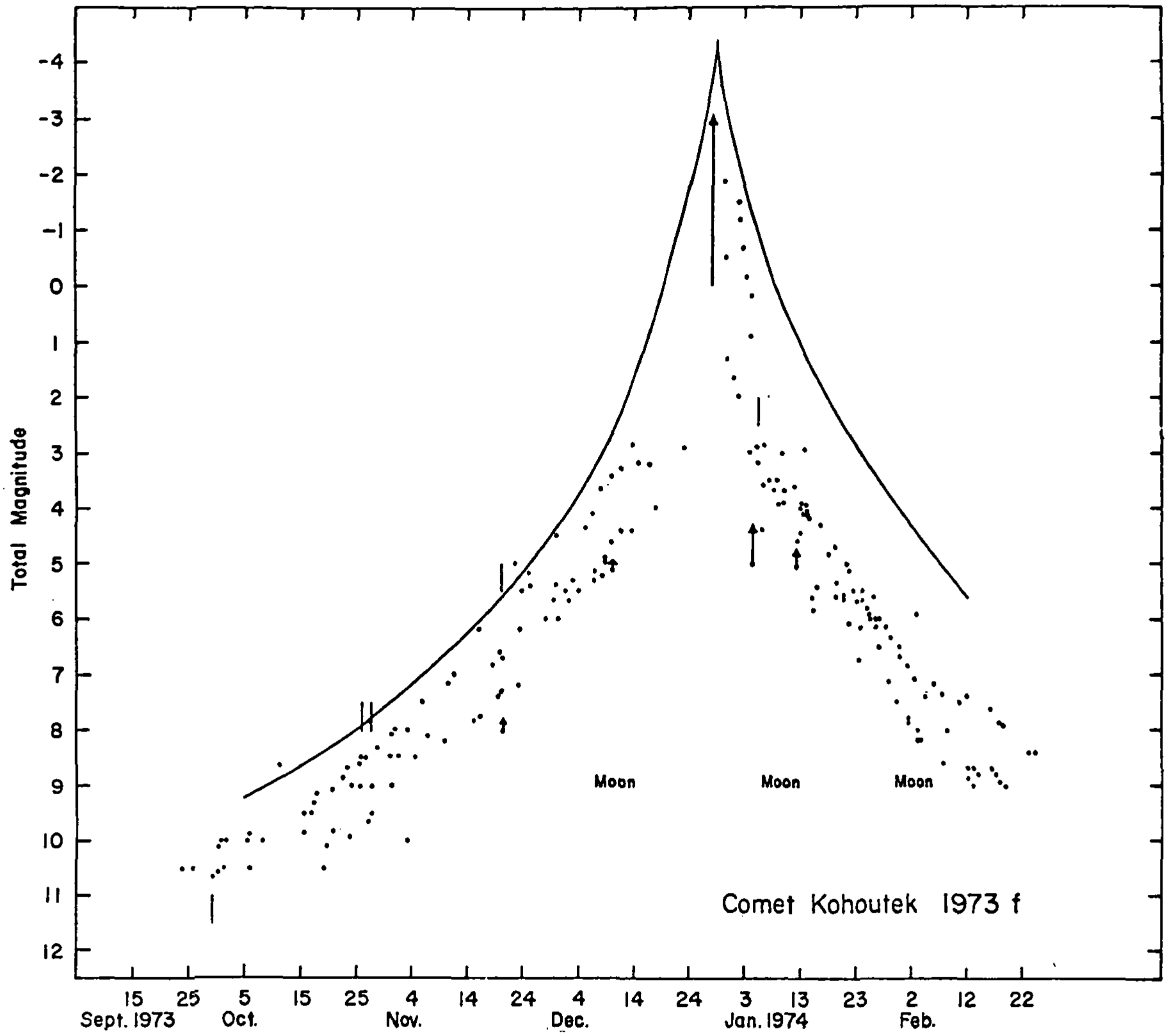

Fig. 1 Near-perihelion uncorrected visual estimates of total magnitude (m_1) of Comet Kohoutek, taken from the IAU Circulars. Observations subject to greater than average uncertainty are represented by vertical lines. Intervals when moonlight may have interfered are marked. The full curve represents a magnitude ephemeris calculated according to an inverse 4th power dependence on heliocentric distance.

amateurs have made very useful contributions in this area, and hopefully will continue to do so.

Estimates of nuclear magnitudes seem to have a usefulness beyond that of determining appropriate exposure times for photographic observations, and it appears desirable to encourage activity in this area, particularly since m_2's are an easily obtained by-product of badly needed astrometric observations. Their limitations should be kept in mind, however, when they are used for calculation of dimensions of cometary nuclei. Comparison of results with data obtained by other methods, such as from gas/grain production rates, will give a better idea of the meaning of radii derived from nuclear magnitudes when those are the only data available.

For adequate understanding of the many aspects of physical activity of comets, much more exactly definable data will be needed than have been discussed here.

ASTROMETRY

Observations

Accurately observed right ascensions and declinations as functions of time are the fundamental data for determinations of the orbits of comets. Ephemerides, calculated from orbital elements, are needed even for bright comets if precise physical observations are to be made, and highly accurate predictions of positions in space will be required if spacecraft are to be guided to proper location for in situ experiments. Orbital characteristics of the observed population of comets constitute the basic data for a wide variety of studies of the dynamics of comets, including nongravitational effects, and evolution of orbits.

Precise positions now are determined almost exclusively from measures of photographic plates or films taken either with relatively short-focus, wide-field astrographs or Schmidt cameras, or with large, long-focus reflectors of limited field. With short-focus instruments, direct exposures guided at the sidereal rate often are sufficient. The image of the comet on such photographs will be more or less trailed, the amount depending on the total motion relative to stars during the exposure.

With the open scale of the long-focus instruments, or if observations are pushed to the limit with small astrographs, it generally will be advantageous to compensate for the motion of the object during the exposure. The moving object will then appear small and round, while stars are recorded as regular, parallel trails. Basic techniques have been described by Roemer (1963, 1971).

With astrographs and Schmidt cameras, which are guided with an auxiliary telescope, it may be possible to sight directly on the comet, if a sharp condensation can be seen well enough. Or offsetting can be done differentially with respect to a star by use of an eyepiece micrometer, the requirement being that the guide star is brought back after each increment to crosswires systematically displaced by a small amount.

Guiding with large instruments always must be accomplished by offset from a suitable star at the edge of the field being photographed. The direction and rate of motion are calculated in advance from the ephemeris, and the capability must be provided at the telescope for displacement of either the crosswires or the plate by small, accurately definable amounts. It is usually convenient to turn the tailpiece of the telescope so that the displacement is in only one coordinate. Although it is easy in principle to make the offsetting procedure completely automatic by motorizing the guide eyepiece motion and employing an automatic guider, very few telescopes are so equipped at the present.

In extreme situations it may be possible to take adequately compensated plates without corrective guiding if accurately calibrated tracking systems are available in the two telescope coordinates. By careful calculation of the changing effect of refraction on apparent sidereal rate, as well as of the differential motion of the object with respect to stars, satisfactory plates were obtained of Icarus at low altitude in June 1968, completely unguided, when the apparent motion of the minor planet was as great as 24 arcmin/hr. The star trails on the 8-min exposures were 16 mm long.

At the two telescopes used for observations of faint comets at the University of Arizona, the offsetting and guiding are done by hand. Increments of $0\overset{\prime\prime}{.}5$ are set off at the 229-cm *f*/9 reflector, and steps of $0\overset{\prime\prime}{.}4$

at the 154-cm *f*/13.5 reflector at the signal of an automatic timer. Typical intervals between such offsets lie in the range 10 - 90 sec. Most exposures are of duration 10 - 60 min, but some 90-min exposures have been taken in critical circumstances. The uniformity of the star trails (or the lack of it!) gives valuable information on the smoothness of the tracking and offsetting, and of changes of seeing, transparency, and focus during the exposure. Each of these effects will be recorded quite differently in the star trails and in the image of the faint moving object.

Considerable advantage derives from taking plates in pairs whenever possible, the second observation providing immediate verification of the reality of weak images and a check on the identification of the object through comparison of the observed and computed motions between the exposures.

Photographic Materials

At long *f* ratios, one generally must use the fastest available photographic emulsions to compress adequate exposures into the time during the night that the faint objects may be in accessible position for observation. At short *f* ratios, enough time may be available to expose fully such efficient but relatively slow plates as hypersensitized Kodak IIIa-J Spectroscopic plates. The best plate for instruments of *f* ratio as long as nine still seems to be the blue-sensitive Kodak 103a-O emulsion. The quality of images on plates sensitive to a wider wavelength passband is likely to be impaired by atmospheric dispersion, and the use of a filter costs too much light except when observations have to be obtained in difficult special circumstances, such as in bright moonlight. An excellent source for information on available photographic materials, and for guidance on special techniques for hypersensitization, handling, and processing, has been compiled by the Eastman Kodak Company (1973). Useful new information on hypersensitization has been published more recently by Scott and Smith (1974) and by Babcock et al. (1974).

Image Tubes and Television-type Sensors

Until recently the field of view obtainable with image tubes was of too limited extent to make such detectors practical for astrometric applications of the kind considered here. Although the cost of the new very large tubes is high, they appear to open the way to some interesting possibilities. A pair of critical observations of the XIIIth satellite of Jupiter were made in September 1974 by R.H. Cromwell, R.J. Weymann, and R. A. McCallister with an image tube having a photocathode nearly 150 mm in diameter, attached to the 229-cm reflector of the Steward Observatory. Exposures of 90 sec were sufficient to produce adequately exposed images of the satellite, which was of photographic magnitude close to 21.0 at the time of the observations. Two plates were taken to permit identification of the satellite by blink comparison, since the motion was not sufficient during a single exposure to permit recognition of the image of the satellite. Scaled semiaccurate positions suggest that the field characteristics of the ITT F-4094 tube are not a source of gross errors. It would appear that developments in this field of instrumentation, which has been reviewed recently by Livingston (1973), bear close watching.

Measurement

Whether the motion is compensated, or the comet is allowed to trail, the centers of gravity of the images of comet and reference stars give coordinates referred to the mid-time of the exposure. Measurement may be accomplished by direct bisection of the images, if they are small enough, using a suitable coordinate comparator. On long-focus plates it is often necessary to measure the two ends of the star trails, the end coordinates then being averaged to determine those of the center of each star trail. In some cases the trails may be so long, as much as 1 - 2 cm in exceptional circumstances, that they cannot be seen in their entirety within the field of view of the optical system of the measuring engine. Obvious problems are likely to arise with measurement of such images.

An impressive variety of measuring machinery has become available within recent years. Some models of coordinate comparators incorporate a considerable degree of automation, but long star trails are beyond the capability of most of the automatic or semi-automatic machines, at least in their normal mode of operation. Weak images or heavy background fog from moonlight, twilight, or prolonged exposure will pose difficulties with other measuring engines, particularly those in which the viewing is by projection. The comet observer soon becomes accustomed to pursuing his objects under much less than ideal observing conditions, and as a consequence he often acquires material that presents problems during data reduction.

Reduction Techniques

Astrometric reduction methods as applied to determination of positions of comets and minor planets are fairly well standardized, and a brief review has been given recently by Roemer (1971). Within the field of at least 1° diameter readily available on plates taken with astrographs and Schmidt cameras, it is generally possible to find a suitable configuration of reference stars of reliably known coordinates. A very convenient source for star positions is the Smithsonian Astrophysical Observatory Star

Catalog (1966). For the Northern Hemisphere, the AGK3, presently available in machine-readable form, offers reference star coordinates and proper motions of even higher precision.

With the limited field of the long-focus instruments (30 arcminutes diameter at a scale of 10"/mm for the two Arizona telescopes), the only adequate direct source of reference star coordinates is the Astrographic Catalogue. An excellent compendium of detailed information on this, as well as on other standard star catalogs, has been compiled by Eichhorn (1974).

Special problems arise when the Astrographic Catalogue has to be used as the source of reference star positions. For most declination zones in that monumental catalog, only rectangular coordinates measured from photographic plates taken many years ago are directly available for the individual stars. These coordinates can be reduced to right ascension and declination by use of plate constants tabulated in the Catalogue for each field. These preliminary plate constants depend on observations of "repère" stars made as long ago as the 1870's in the Northern Hemisphere, and mostly between 1915 and 1935 in the Southern Hemisphere. These "repère" star positions were used, generally without correction for proper motions, to determine the plate constants referred to the epochs of the plates of the Astrographic Catalogue.

Definitive plate constants are now available for the Northern zones of the Astrographic Catalogue from declination +90° to +32° (Günther and Kox 1970, 1972). And work by P. Lacroute and A. Valbousquet on new constants for the remaining zones of the Northern Hemisphere is in progress at Strasbourg. The new constants are based on the accurate star positions and proper motions that have become available with completion of the AGK3.

With use of these constants, coordinates for stars of the Astrographic Catalogue are referred consistently to the system of the FK4. New constants for the Northern Hyderabad zone have been published by Eichhorn and Gatewood (1967), and for the Bordeaux zone by Herget (1973) as results of earlier investigations. Improvement in the Southern Hemisphere is not immediately possible, pending further work on the Southern Reference Star program.

Somewhat higher accuracy may be obtainable through direct determination of coordinates of secondary reference stars by measurement of a "field" plate. Such a plate is taken with an instrument that records an area large enough to include an adequate set of SAO Catalog stars, and coordinates of selected reference stars within the field of the long-focus instrument are determined from it. This technique of field transfer is a standard one, regularly used, but it requires observations with a second instrument and measurement and reduction of an additional plate. In sparsely populated star fields around the galactic poles, and in the very limited fields that can be photographed with most image tubes, it is the only possible way to obtain accurate positions.

With coordinates of reference stars known from some source catalog, measured coordinates of these stars on the comet plate are used to set up transformation equations between the measured coordinate system and the catalog coordinate system of the reference stars. Then measured coordinates of the comet can be transformed to coordinates in the reference system. Details depend on the nature of the instrument with which the comet has been observed--astrograph or Schmidt camera, Ritchey-Chrétien or classical Cassegrain reflector, with or without correcting optics. A review of classical procedures of both plate constant and dependence types has been given by König (1962). Special formulae applicable to the Schmidt have been published by Dixon (1962, 1963). Eichhorn (1974) summarizes information about more sophisticated modern methods.

Accuracy of Positions

Coordinates of stars in the best reference catalogs may approach or somewhat exceed a systematic accuracy of 0".2 over much of the sky. The accuracy of star positions in the Astrographic Catalogue, referred to the epoch of observation, may approach 0".3. Proper motions, neglected over time spans of more than 70 years in some instances, lead, however, to frequent occurrence of residuals of individual star positions of as much as 1-2".

Limits on positional accuracy derivable from the comet plate arise from several factors connected to the offsetting of motion, as well as from the common fact that observations are obtained under less than ideal conditions--at low altitude (refraction, poor seeing), weak images of intrinsically very faint objects, or with available exposure time limited by the position of the object in twilight. Large differences in the character of the images of comet and reference stars, which often are much brighter than the comet and have long, trailed images arising from the differential motion, lead inevitably to a variety of systematic errors. Even if every offset increment is put on regularly and in precisely the right way, and corrective guiding is done accurately, an intrinsic limitation of half the increment size is imposed on precision of the measured position of the comet. Any error in offsetting will lead to incorrect positions of the ends of reference star trails, often without affecting in a noticeable way the image of the comet. Improvement in accuracy is possible by use of stepping motors, by which very small increments can be set off nearly continuously.

The short exposures possible with image tubes have the advantage that images of both comet and reference stars are nearly round, but the consequence that effects of the frequent large difference in brightness between comet and reference stars are likely to be aggravated. On prolonged exposures during which motion is offset, the images of the reference stars consist effectively of an aligned series of short exposures. Thus image growth from overexposure is lessened, and the detailed structure of trailed images of even rather bright stars may remain clearly resolvable.

Adequacy of Current Astrometric Programs

The usefulness of observations of position over the longest possible arc for every comet that appears seems to be generally recognized among workers interested in either the physical or dynamical properties of these bodies.

A typical potential observing list in recent years has contained some 12 to 15 objects, at least potentially within the reach of large instruments at any given time. Only three or four of these comets, at most, would be as bright as magnitude 16 or 17, and thus accessible to very many of the wide-field instruments. Two-thirds or more would be the exclusive responsibility of the observers who use the large, long-focus reflectors. Particularly since the interval of observability amounts to no more than a few months (in some instances, only a few weeks), for some comets, it seems a reasonable goal to try to obtain a few observations of each object each month, in sum total.

Astrometric observations of comets with instruments that reach to magnitude 16-17 are in generally satisfactory state in the Northern Hemisphere, with fairly regular participation of at least 20 observatories and of several enthusiastic amateurs who report valuable positions of good accuracy. The situation is less satisfactory in the Southern Hemisphere, even for relatively bright comets. Fairly regular work on comets is included on the programs only at Córdoba, Perth, Wellington, El Leoncito, and at Cerro Tololo. The closing of the Republic Observatory, Johannesburg, has resulted in a serious loss through curtailment of the important observational program on comets and minor planets carried out for many years at the Hartbeespoort Station of that observatory. Northern observers, particularly in Japan, have been very diligent in efforts to obtain observations of objects moving far into the southern skies, so as to lighten the burden that must rest solely on our too few colleagues in the Southern Hemisphere.

The situation for observations of faint comets is more precarious, with regular programs underway only at the University of Arizona, at the Center for Astrophysics (Harvard-Smithsonian), at the Tokyo Observatory, and at Cordoba. Important discoveries and some critical observations come as well from the 122-cm Palomar Schmidt telescope.

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DISCUSSION

B. G. Marsden: I do think that image tubes provide one possible solution to the problem of persuading more observers to do astrometry of faint comets. It is useful to point out that, even though the plates were scaled rather than accurately measured, the Arizona image-tube observations of Jupiter XIII give (O-C) residuals of no more than about 1.5".

B. Donn: Regarding nuclear magnitude measurements, there are two possibilities of distinguishing coma contribution from monolithic nuclear magnitude. True nuclear magnitude will be independent of exposure time, whereas a faint coma will show up more on longer exposures. The second, which is more remote, is the measurement of polarization. A dust scattered coma not at opposition will be polarized to some degree, and with a more or less predictable wavelength dependence. What is the observational situation with regard to this?

E. Roemer: I think the second point certainly is well taken, because the fact that you have to keep in mind is that practically everything on my observing list is fainter than 17th magnitude, and I am hard pressed to get any kind of an image, let alone sort out the ones that might be polarized.

Now, on the occasions where for one reason or another there have been exposures with different exposure times, it is usually a factor of 2, or something of that sort. On the whole there has been no effect that I can be confident of separating from experimental error–I think there is a 0.2 or 0.3 of a magnitude uncertainty. These are just eyeball estimates; they are comparisons of images with images of stars in the four selected area sequences where there are photoelectric magnitudes down to the 22nd magnitude. Just in compensating for differences in seeing conditions, I do normally put in 0.3 of a magnitude per air mass to account for the differential air mass, but it is kind of a crude comparison. There have been experiments, as Tom Gehrels has gotten rather interested in using an iris photometer on some of the asteroid plates, and, in fact, the quality of those magnitude determinations is poorer than the eyeball, because you simply could not compensate adequately for the difference in the character of the image with the seeing.

Now, there is generally a correlation of these magnitudes with the f-ratio, which is a sign of trouble. The 24-inch at Yerkes and the 82-inch at McDonald that Van Biesbroeck used to use so much are both f/4, and on the whole Van B's magnitude estimates were the same as those made photographically. I have had some experience with the 24-inch at Yerkes, and I would say estimates are a magnitude brighter than the magnitude estimates that came from the Crossley at f/5.8 (by Jeffers and some of the people that worked with him).

DISCUSSION (Continued)

The Naval Observatory 40-inch at f/6.8 I think does lead to magnitudes that are a little bit brighter than the Stewart and Catalina telescopes. I do not get convincing differences between the latter two instruments, at f/9 and f/13.5, so at some stage for a typical sample you do apparently get a long enough f-ratio beyond which you don't get gross differences. However, shorter than, say, f/7 there is enough of a diffuse character to those images where the f-ratio does make a difference much of the time.

P. Wehinger: The 40 and 90 mm ITT image tubes have resolution well below the seeing disk. The use of such tubes with intermediate band filters is suggested in order to detect fainter comets.

E. Roemer: The trouble is that those fields are too small for us. Our scale in the focal plane on both those telescopes is 10 arc seconds to the millimeter, so it takes us 8 inches to get a 0.5 degree diameter field. We just have to have these huge tubes.

Z. Sekanina: I wonder whether you expect that there are any systematic differences between the "nuclear" magnitudes from your Crossley plates and your 40-inch Ritchey-Chretien plates.

E. Roemer: It is f/5.8 against f/6.8. I wouldn't expect a great difference, but it would be in the sense of Crossley brighter. That, by the way, is undoubtedly one of the sources of error in the early estimates of Comet Kohoutek, in that it was Schmidt observations, and then the long focus observations after there already was significant coma development. The Schmidt is running f/2.5, f/3, f/3.5. Those are always going to be less than pure nuclear magnitudes—they are somewhere in between m_1's and m_2's.

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COMET BRIGHTNESS PARAMETERS: DEFINITION, DETERMINATION, AND CORRELATIONS

David D. Meisel and Charles S. Morris

Introduction

Visual estimates of comet total magnitude have been made for well over one hundred years. In this paper no attempt has been made to review all previous work on comet magnitudes. Instead we prefer to concentrate on developing a conceptual framework upon which previous work can be evaluated. We have tried to unify the approach as much as possible by filling in gaps that occur between previously published accounts. The present work represents an extension and revision of an earlier attempt at understanding comet magnitudes (Meisel, 1970).

Part I. Comet Brightness Formulae

Comet total brightness (luminosity) is usually defined by a power-law formula

$$B_{\text{☄}} = B_0 r^{-n} \quad \Delta^{-2}$$

which can be directly converted to an expression using stellar magnitudes.

$$m = m_0 + 2.5n \log r + 5 \log \Delta \qquad (1)$$

where m = total apparent comet magnitude, r = the comet heliocentric distance, Δ = the comet geocentric distance, n = the parameter "index of variation" (n = 2 for pure reflection), and m_0 is the unit or "absolute" magnitude of the comet. Least-squares solutions of the power-law formula occur throughout astronomical literature in numbers far too numerous to mention explicitly here.

Levin (1943) proposed an alternative formula originally based on the desorption of gases,

$$m = A + B\sqrt{r} + 5 \log \Delta \qquad (2)$$

While desorption processes are no longer considered relevant to the comet problem, this formula can be used for interpolation purposes and Bobrovnikoff (1951) and Meisel (1970) have shown the conditions under which expression (2) converges to (1). Oort and Schmidt (1951) used the Levin formula in an attempt to distinguish photometrically between "old" and "new" comets. Because solutions using (2) appear from time-to-time in the literature, we have developed a formalism to convert the parameters of such solutions to m_0 and n sets.

First, note that (1) can be written (ignoring the geocentric variation) as

$$m = m_0 + 2.5 \times 0.43 \times n \times \ln r$$

which is the integral $m = m_0 + \int_1^r \frac{\partial m}{\partial r} dr$. Then (2) can be written as

$$m = A + B\sqrt{r}$$

which is the integral $m = A + \int_q^r \frac{\partial m}{\partial r} dr$. Comparing the integral expressions

$$m_0 = A + \int_q^1 \frac{\partial m}{\partial r} dr \text{ and } m = A + \int_q^1 \frac{\partial m}{\partial r} dr + \int_1^r \frac{\partial m}{\partial r} dr$$

These imply that $m_0 = A + B$ and

$$B = \int_q^1 \frac{\partial m}{\partial r} \text{ with } \int_1^r \frac{\partial m}{\partial r} dr = \sqrt{r} \int_q^1 \frac{\partial m}{\partial r} dr$$

by formal definition. The above expression predicts that B (and by implication n and m_0) is q dependent in accord with the empirical findings of Oort and Schmidt (1951). By differentiation we obtain

$$n = \frac{r}{2.5 \times 0.43} \frac{d}{dr} \left[\sqrt{r} \int_q^1 \frac{\partial m}{\partial r} dr \right]$$

Taking average values for n and B gives the direct variable transformation

$$n = 0.43\ B \left\langle \sqrt{r} \right\rangle$$

while $m_0 = A + B$ as the formal transformation equations.

In the case of an elliptical orbit the computation of $\left\langle \sqrt{r} \right\rangle$ can be a problem. In the case of a parabola, the expressions are complicated, but straightforward. We have adopted the parabolic assumption for our parameter conversion (because of its simplicity) even in the case of most periodic comets. The error involved is largest for orbits of small eccentricity at aphelia. Even for Comet Encke, the worst case in our list, the maximum possible error in $\left\langle \sqrt{r} \right\rangle$ is only 25%. In the appendix, the average $\sqrt{r}$ expressions are given for a parabolic orbit. Exact conversion of least-squares $m = A + B\sqrt{r}$ and $m = m_0 + 2.5n \log r$ solutions is also given, but the additional complexity of the exact conversion does not appear to be necessary at least for the several test cases that have been investigated.

While the physical reasons for originally adopting the Levin formula are invalid in the light of modern research, expression (2) can be useful for avoiding the mathematical singularity encountered with least-squares solutions using the power-law formula when $r \rightarrow 1$ A.U. Because the association of Levin's name with expression (2) sometimes connotes a physical interpretation in terms of adsorption, we suggest that the notion of a $\sqrt{r}$ variation be dropped and near $r = 1$ A.U. a generalized <u>series formula</u> be adopted to avoid the singularity: $m = C + Dr^{n_0}$ where C and D are found by least-squares assuming a value of n_0. The final C, D values are found by trial values of n_0 until minimum solution residuals are obtained. The usual (m_0, n) set can then be compared with the corresponding transformed parameter set defined as $n_1 = 0.4\ n_0 D$ and $m_1 = C + 2.5(n_1/n_0)$ to see if solution divergence due to the small log r values and fluctuations in the magnitude data (either real or observational) are present. The possibility of this type of solution divergence is obviously greatest for objects which have q → 1 and the power-law parameters derived when r → 1 and/or q → 1 should always be suspect. Divergences due to small ranges in log r values may also be present and these are not as easily identified in a consistent manner. However, solutions based on observations made over a short time period should always be considered less certain.

Early work by Bobrovnikoff (1941a, 1941b) showed the necessity of investigating the possibility of instrumental systematic effects thoroughly before applying expression (1). Later Öpik (1963) proposed a modification of the usual power-law formula (1) which attempted to correct explicitly for instrumental effects.

$$\begin{aligned} m = m_0 &- 2.5(s-2) \log(D/67.8) \\ &+ 2.5s \log \Delta + 2.5n \log r \end{aligned} \qquad (3)$$

where D is the telescope diameter (in millimeters) and s is the index of variation of brightness within the comet coma such that the comet surface brightness has a radial dependence $B(\rho) = B_0 \rho^{-s}$ where ρ is the projected distance from the comet central condensation. When s = 2, the Öpik formula (3) reduces to (1). In a previous investigation (Meisel, 1970) with two comets, an attempt was made to justify empirically (3), but this failed presumably because s → 2 for both objects. Delsemme (1973a) and O'Dell and Osterbrock (1962) have cited many reasons for adopting an exponential decay model to describe a comet coma. Haser (1957) investigated this model in some detail with the result that no single value of s can describe the entire coma. In view of the lack of theoretical as well as empirical justification for the Öpik formula, continued use of expression (3) only compounds the difficulty of interpreting the derived comet photometric parameters.

We believe that expression (1) still represents the best approximation to visual comet brightness behavior. Bobrovnikoff's method of comparison and reduction appears to give consistent results even when reflecting telescopes are used although the mean aperture correction for reflectors has been shown by Morris (1973a) to be less than Bobrovnikoff's value for refractors. Meisel's (1970) earlier work suggested aperture corrections result from clipping of the object spatial frequencies by telescope apertures, but only for certain radial coma brightness distributions will analytical expressions be obtained. In an equivalent analysis for the fixed field stop case, Delsemme (1973a) has derived expressions which take into account the aperture effect without the need for correction of individual observations.

We have investigated the possibility that Delsemme's theory might be applicable to photometric solutions derived from visual magnitude estimates where the size of the effective field stop is not predetermined. In the case of solutions based on estimates made with a single instrument such as those given by Beyer, the connection with the fixed field stop theory is straightforward and empirical systematic corrections can be applied to m_0 and n with confidence as will be done later for the Beyer data. In the cases where a variety of instruments and apertures have been used, averaging in Fourier transform space must be carried out before the Delsemme results can be applied. For two well-studied cases (Meisel, 1970) the preliminary results of a direct conversion using Delsemme's theory and an inversion of the statistical distribution of apertures shows no significant advantage of a direct correction of (m_0,n) values based on visual magnitude estimates either statistically or computationally. At the present time we see no reason to abandon the simpler procedure of instrumental correction using linear aperture correlations prior to least-squares solution in favor of a more direct approach. Only if a significant improvement in accuracy of the individual visual magnitude estimates could be made would the complicated Fourier inversion procedure be worthwhile. One final point should be noted about comet brightness formulae. Over the past several decades there have been numerous attempts at interpreting the (m_0,n) parameters in terms of unique physical processes. However, if evaporative processes predominate in comet gas production as argued by Delsemme (1973c) and Huebner (1965) such attempts are largely futile since the number of possible mechanisms is much greater than the number of distinct parameters which can be determined empirically from visual magnitude estimates. [Recall the difficulty of deriving Öpik's "s" parameters directly from observation. (Meisel, 1970)] Traditional interpretations of n have centered around two mechanisms--fluorescence (n → 4) and dust reflection (n → 2). But it is quite clear that many other influences may be involved and until some means of establishing the possible heliocentric variations of these other mechanisms is available no physical interpretation of n (or even m_0) should be attempted. All that can be concluded at this point is that the n coefficient somehow characterizes an unknown combination of the following physical processes.

(a) Gas Evaporation Rate
(b) Dust Production Rate
(c) Dust Destruction Rate
(d) Parent Molecular Dissociation Rates
(e) Daughter Molecular Dissociation Rates
(f) Fluorescence $\propto r^{-4}$
(g) Dust Reflection $\propto r^{-2}$
(h) Gas and Dust Velocity Fields

How m_0,n values relate to these various processes is a topic for future investigations.

Part II. Treatment of Instrumental Effects

There are three main methods of comet-star comparison in the literature. We summarize these here:

(a) "In-Out Method" - Sidgwick (1955)

[Memorize to compare focused comet and out-of-focus star]

(b) "Bobrovnikoff Method" - Bobrovnikoff (1941a, 1941b)

[Compare out-of-focus star with (same size) out-of-focus comet image and apply empirical aperture corrections]

(c) "Beyer Method" - Beyer (1952)

[Observe relative extinction of grossly out-of-focus star and comet images]

The Sidgwick method requires considerable skill unless binoculars with individual focus mounts are available. This method can have systematic effects if aperture corrections are ignored. The Bobrovnikoff method is the easiest to do consistently for relatively inexperienced observers. Always requires "aperture" corrections when comparisons between different instruments are made. The Beyer method is quite sensitive to sky background illumination. As shown later this method leads to systematic effects unless aperture corrections are applied.

Bobrovnikoff (1941a, 1941b) first introduced the notion of systematic "aperture" corrections in a purely empirical way. Meisel (1970) has demonstrated that the Bobrovnikoff and Sidgwick extrafocal comparison methods produce a flux mismatch in the focal plane. Furthermore it was demonstrated that this mismatch is really an effect of focal ratio. However, since focal length and aperture are frequently correlated, Bobrovnikoff's empirical use of aperture as the correlation parameter can be justified. Using numerous visual observations, Morris (1973a) has demonstrated a definite difference of mean aperture correction between reflecting and refracting telescopes for the Bobrovnikoff method. It is straightforward (but tedious) to show that the Bobrovnikoff method of equal image-size comparison gives the smallest possible aperture correction for a given optical configuration. Only when the star and comet are put out-of-focus with the same apparent size are the instrument entrance and exit pupils in a maximum flux transmitting configuration. The subject of aperture corrections has been very controversial and Bobrovnikoff's work criticized. But his investigation along with that by Morris (1973a) has shown the persistence of the correlation. It is easy to forget that in optical imagery one is dealing with diffraction patterns which involve Fourier transforms of apertures and not the apertures themselves. It is this lack of understanding of the image formation process that has made acceptance of instrumental corrections in visual comet photometry very slow. We therefore digress to present the following theoretical development outlining the nature of the problem.

First we define a function ψ which gives the comet/star flux ratio in the instrument focal plane.

$$\psi = \frac{\int_0^\infty r' I_f^{\text{☄}}(r')_g \, dr'}{\int_0^\infty r' I_f^{*}(r')_g \, dr'} .$$

where r' is the radial coordinate in a plane perpendicular to the optical axis, the f subscript indicates the intensities are those in the focal plane. The subscript g indicates that these are geometrical optics projections of the objects.

If the intensities all have circular symmetry we may use Fourier-Bessel (F-B) transforms defined as

$$B\Big(I(r')\Big) = G(\rho') = 2\pi \int_0^\infty r' I(r') J_0(2\pi r'\rho')\,dr'$$

and

$$I(r') = B\Big(G(\rho')\Big) = 2\pi \int_0^\infty \rho' G(\rho) J_0(2\pi r'\rho')\,d\rho'$$

where ρ' is the spatial frequency. Thus ψ becomes

$$\psi = \frac{\displaystyle\int_0^\infty r' \left[\int_0^\infty \rho' G^{\text{☄}}(\rho)_g J_0(2\pi r'\rho')\,d\rho'\right] dr'}{\displaystyle\int_0^\infty r' \left[\int_0^\infty \rho' G^{*}(\rho)_g J_0(2\pi r'\rho')\,d\rho'\right] dr'}$$

The relationships between the geometrical $G(\rho)_g$ and the instrumental $G(\rho)_i$ in the focal plane are given by

$$G^{\text{☄}}(\rho)_i = H_0(\rho) G^{\text{☄}}(\rho)_g$$

and $$G^{*}(\rho)_i = H_0(\rho) G^{*}(\rho)_g$$

Here $H_0(\rho)$ is the so-called optical transfer function (OTF) of the instrument. Since a star is a point source, we assume by definition that $G^{*}(\rho)_g = P$ and

$$H_0(\rho) = G^{*}(\rho)_i/P$$

where P is a scalar. Then ψ becomes

$$\psi_f = \frac{\displaystyle\int_0^\infty r' \left[\int_0^\infty \rho' G^{\text{☄}}(\rho)_g J_0(2\pi r'\rho')\,d\rho'\right] dr'}{\displaystyle P\int_0^\infty r' \left[\int_0^\infty \rho' J_0(2\pi r'\rho')\,d\rho'\right] dr'}$$

and with $G^{\text{☄}}(\rho)_g = \Big(G^{\text{☄}}(\rho)_i/G^{*}(\rho)_i\Big)\,P$, we finally obtain

$$\psi_f = \int_0^\infty r' \left[\int_0^\infty \rho' \Big(G^{\text{☄}}(\rho')_i/G^{*}(\rho')_i\Big)_f J_0(2\pi r'\rho')\,d\rho'\right] dr'$$

In the cases of real optical systems there is always band limiting in ρ'

such that

$$\psi_f = \int_0^{r'_L} \left[\int_0^{\rho'_0} \rho' \left(G^{\text{☄}}(\rho')_i / G^*(\rho')_i \right)_f J_0(2\pi r'\rho')d\rho' \right] dr'$$

where $\rho'_0 = R/\lambda f$ with R = aperture, λ = wavelength and f = focal length.

Each method has its own criteria for determining a match between star and comet.

(a) Sidgwick Method

$$\int_0^{r'_0} r' I^*_{\Delta f_1}(r')dr' = \int_0^{r'_0} r' I^{\text{☄}}_f(r')dr'$$

(b) Bobrovnikoff Method

$$\int_0^{r_1} r' I^*_{\Delta f_2}(r')dr' = \int_0^{r_1} r' I^{\text{☄}}_{\Delta f_2}(r')dr'$$

(c) Beyer Method

$$\int_0^{R_L} r' I_{sky}(r')dr' = \int_0^{R_L} r' I^*_{\Delta f_3}(r')dr' = \int_0^{R_L} r' I^{\text{☄}}_{\Delta f_3}(r')dr'$$

Note that Δf_1, Δf_2 and Δf_3 are such that

$$0 \le \Delta f_1 \le \Delta f_2 \le \Delta f_3$$

In the focal plane, we have the spectral ratio

$$\Phi_f(\rho') = \left(G^{\text{☄}}(\rho')_i / G^*(\rho')_i \right)_f$$

If the star and comet are both thrown out of focus, then the spectral ratio is different.

$$\Phi_{\Delta f}(\rho') = \left(G^{\text{☄}}(\rho')_i / G^*(\rho')_i \right)_{\Delta f}$$

The defocusing process is one which attempts to make the comet image identical in appearance to that of the star. Thus in both the Beyer and Bobrovnikoff method, the aim is to make

$$\Phi(\rho')_{\Delta f} = \left(G^{\text{☄}}(\rho')_i / G^*(\rho')_i \right)_{\Delta f} \Rightarrow \text{constant for all } \rho'.$$

If the match is to be perfect then

$$\Phi(\rho')_{\Delta f} = 1 \quad \text{for all } \rho' \quad 0 \text{ to } \infty.$$

This condition then requires the "defocus" function $\sigma(\Delta f,f)$ to be such that

$$G^{☄}(\rho')\Delta f = \sigma(\Delta f,f)G^{☄}(\rho')f$$

and $$G^{*}(\rho')\Delta f = \sigma^{-1}(\Delta f,f)G^{*}(\rho')f$$

These imply that

$$\left(\frac{G^{☄}(\rho')\Delta f}{G^{*}(\rho')\Delta f}\right) = \sigma^{2}(\Delta f,f)\left(\frac{G^{☄}(\rho')f}{G^{*}(\rho')f}\right)$$

It can be shown [Goodman (1968)] that a misfocused system requires as a first approximation

$$\sigma^{2} = \exp\left[-2\pi j\left(\frac{\Delta f}{f}\right)\lambda(\rho')^{2}\right]$$

Because this involves $\Delta f(\rho')^{2}$ it can be seen that as Δf increases there will be a corresponding decrease in the system bandwidth.

Thus while there is an advantageous degree of spectral smearing in extrafocal methods of comparison (i.e., comet and star can be smoothed to look identical), the further one goes out-of-focus, the more the effective system bandwidth is cut. It is this decrease of effective system bandwidth which is responsible for the net "aperture" effect in extrafocal comparisons. Since the Bobrovnikoff method requires the least amount of Δf for a given focal ratio, it will always have the smallest instrumental correction.

It also should be noted that objects which have different brightness profiles will have different Δf distances before the star and comet match can be made. However, because the Bobrovnikoff method has minimum Δf, it will also display minimum sensitivity to the effective s parameter (exponent of the change of coma brightness with distance from the nucleus).

Explicit proofs for the above are too involved to give here, but the lesson of the above discussion is clear. IN ANY EXTRAFOCAL METHOD OF COMPARISON, SYSTEMATIC EFFECTS ARE MINIMIZED IF IMAGES ARE THROWN OUT-OF-FOCUS BY THE LEAST AMOUNT NECESSARY TO MAKE THE EXTENDED OBJECT LOOK SIMILAR TO THE STAR. In all the methods of extrafocal comparison there is an approximation of

$$\left.\frac{G^{☄}(\rho')\Delta f}{G^{*}(\rho')\Delta f}\right]_{\rho'_0} \quad \text{by} \quad \frac{\left.G^{☄}(\rho')f\right]_{\rho'_0}}{\left.G^{*}(\rho')\Delta f\right]_{\rho'_i}}$$

where

$$\rho'_i = R/\lambda(f + \Delta f_i)$$

The instrumental corrections thus depend inversely on two ratios

(a) f/R = 2 x focal ratio

(b) $\Delta f/R$ = "defocus" ratio

For a given optical system $\Delta f \approx kf$ and hence

$$\rho'_i \approx R/\lambda f(1 + k)$$

In Bobrovnikoff's scheme the lowest possible eyepiece magnification is recommended. If the magnification is below a certain critical amount, the focal ratio will be determined by the pupil of the eye not the aperture of the telescope. At the critical magnification there is a perfect flux match often referred to as the "richest-field" condition. A suitable descriptive parameter Z is obtained by normalizing to this condition (assuming the pupil of the dark-adapted eye is 7.6 mm)

$$Z = (\rho'_i/\rho'_k) \approx \frac{\text{(f-ratio) minimum } (1 + k \text{ min})}{\text{(f-ratio) actual } (1 + k)}$$

upon substitution

$$Z = 0.13\ (1 + k\ \text{min})\ D\ (\text{min})/(1 + k)M$$

where M = instrument magnification. To a sufficient approximation, $(1 + k'/M) = 1+k$ and as $M \to 0$ we have $(1 + k) \to M^{-1}$ with the result that $Z \propto D$.

Thus for instruments used visually the minimal defocusing process effectively renders the appropriate parameter to be the aperture alone. THIS IS IN

ACCORD WITH FINDINGS OF BOBROVNIKOFF AND DEMONSTRATES WHY IT IS VALID TO USE APERTURE CORRECTIONS WHEN DISCUSSING VISUAL MAGNITUDE ESTIMATES.

Since the above derivation does not depend explicitly on the method of extrafocal comparison used, we conclude that no method will be free from aperture effects.

It is important to remember that the aperture correlation only applies to a fixed exit pupil situation near the focal plane. For photographic extrafocal magnitudes the appropriate correlation parameter is focal ratio, not aperture.

Obtaining analytical expressions for aperture corrections is difficult. In all realistic cases of interest, numerical convolutions must be carried out. However, the mathematical procedures are simplified if we take $B = B_0 \rho^{-s}$ (as first proposed by Öpik) as a zero order approximation. Under that assumption (even if it is a bit unrealistic), it can be shown that the aperture effects of the three principal methods of obtaining comet magnitude are simply related.

(a) Slopes of Linear Aperture Correlation

$$\left(\frac{\Delta m}{\Delta D}\right)_{\text{In-Out}} \approx 2s+1 \left(\frac{\Delta m}{\Delta D}\right)_{\text{Bobrovnikoff}}$$

$$\left(\frac{\Delta m}{\Delta D}\right)_{\text{Beyer}} \approx 2s \left(\frac{\Delta m}{\Delta D}\right)_{\text{Bobrovnikoff}}$$

where s = index of the radial brightness relation.

(b) Intercepts of Linear Aperture Correction

(D_0) In-Out ≈ (2s+1) x (67.8 mm)

(D_0) Beyer ≈ (2s) x (67.8mm)

These relationships, however, are of little use in practice because:

(a) Random errors contribute to wide scatter.

(b) The Bobrovnikoff aperture-effect parameters are sensitive to instrument type as well as aperture (Morris, 1973a).

(c) It is not clear how to determine the effective s value to be used in these expressions since the validity of the Öpik formula has been questioned.

It is therefore simpler to derive empirical (mean) aperture corrections for each object when possible. Otherwise mean corrections for all available comets should be applied. If s ≈ 2 the above relations reduce to

$$\left(\frac{\Delta m}{\Delta D}\right)_{\text{In-Out}} \approx 5\text{x} \left(\frac{\Delta m}{\Delta D}\right)_{\text{Bobrovnikoff}}$$

with $(D_0)_{\text{In-Out}} \approx 340$ mm and

$$\left(\frac{\Delta m}{\Delta D}\right)_{\text{Beyer}} \approx 4\text{x} \left(\frac{\Delta m}{\Delta D}\right)_{\text{Bobrovnikoff}}$$

with $(D_0)_{\text{Beyer}} \approx 270$ mm.

It is therefore expected that on the average, Beyer method will lead to fainter estimates with "large" telescopes and brighter estimates with "small" telescopes compared with those made on the Bobrovnikoff system at the same heliocentric and geocentric distances. Therefore magnitude reductions using only those m's obtained with the Beyer method should give n values which are systematically higher than those obtained using the Bobrovnikoff system. With the proper aperture corrections, individual Beyer estimates could probably be reduced to the Bobrovnikoff system but such an approach for past observations is time-comsuming because of the need for re-doing the least-squares or graphical solutions. As will be shown later, however, the Beyer (m_0,n) values show systematic differences which enable mean corrections to be made without explicit derivation of aperture correlations. Such a systematic effect follows directly from the above discussion since Beyer used essentially the same instruments for all the estimates upon which his solutions are based.

Part III. Lists of Photometric Parameters

We have been able to locate 150 separate sets of comet brightness parameters that appear to be on (or convertible to) a common photometric system. Prior to the year 1963, we have drawn from the lists of Bobrovnikoff (1941a, 1941b), Beyer (1970, 1972) and Schmidt (1951). After 1963, both published and unpublished values by Morris, Meisel, Bortle, Minton, and Beyer have been used. Each comet appearance has been listed separately regardless of whether the sightings represent a reappearance of the same object or not. All values given as Levin (A,B) sets have been converted using the parabolic conversion equations listed in the appendix. The original data have been separated into three categories -- (a) solutions where pre-perihelion observations dominate (Table I); (b) solutions where perihelion falls in the middle of the observational period (Table III); and (c) solutions where post-perihelion observations predominate (Table II). In our lists we give the comet designation, its perihelion distance, the appropriate m_0 and n values, the number of observations upon which the solution is based, the span of the observation period in months, the mean sunspot number over that observation period, and notes giving the source of the solution, the Oort-Schmidt orbit classification, and possible solution divergence. Finally a solution weight defined as the product of the time span in months and the number of points is given as a rough guide to the likelihood that the (m_0,n) are characteristic of the comet behavior.

Although it is difficult to distinguish between "normal" and "abnormal" brightness behavior, cases where it is obvious that observational bias or intrinsic brightness flares (or fading) have rendered the solution completely unreliable are omitted. In spite of this prior screening there however may be certain solutions where spurious values have gone unrecognized.

Instrumental corrections are known to have been applied before trying a least-squares or graphical solution for all but the Beyer values. Since the previous Fourier transform discussion of aperture effect suggests that the Beyer method leads to systematic effects, we have tested these for the available material by comparing means and standard deviations for the two groups.

Parameters	Beyer Values	Non-Beyer Values
$\langle n \rangle$	5.2 ± 2.5	3.7 ± 2.1
$\langle m_0 \rangle$	6.9 ± 2.5	6.3 ± 1.9
$\langle q \rangle$	1.1 ± 0.7 A.U.	1.0 ± 0.7 A.U.
Object N$^{\underline{o}}$s	67	83

The $\langle n \rangle$ difference is significant at a 99.9% level and the $\langle m_0 \rangle$ difference is significant at an 85% level. WE THEREFORE ADJUSTED THE ORIGINAL BEYER DATA BY $\Delta m_0 = -0.6$ and $\Delta n = -1.5$ for use in the statistical discussions. However, both the original and adjusted values have been listed.

The limitations of the mean correction to individual Beyer data is illustrated by the entry for Comet 1968I in Table II where both the Bortle-Morris solution and the Beyer solution are given. The n value differences for this one comet in common are in agreement with the mean adjustment relation but the m_0 values do not agree very well. In several other cases where direct comparisons can be made (but where the Beyer solutions have not been included in our lists because of relatively low precision), the systematic tendency of Beyer's n values to be too high persists, but the m_0 negative correction does not. Thus while we are confident that the n correction is generally valid, the m_0 correction term needs to be investigated further as indicated by the somewhat lower confidence level (85%) found for the $\langle m_0 \rangle$ differences.

LIST OF VISUAL BRIGHTNESS PARAMETERS

Table I. Pre-Perihelion Dominated Solutions (Original Beyer Data in Parentheses)

Comet	q(A.U.)	m_0	n	N	Δt (mos.)	$\hat{R}$	Wt	Notes
1858 VI	.58	3.39	3.49	25	1	64.3	25	B, 0
1874 III	.68	6.24	4.78	48	1	66.8	48	B, 0
1882 I	.06	7.6	2.9	13	1	59.4	13	S, N
1884I	.78	5.21	3.13	103	5	72.9	515	B, 0
1886 II	.48	6.66	2.05	76	3	31.1	228	B, N
1886 IX	.66	4.79	2.63	27	2	14.2	54	B, N
1902 III	.40	6.77	2.63	89	2	7.4	178	B, N
1903 IV	.33	6.49	2.38	128	2	24.8	256	B, N(P)
1908 III	.95	4.00	5.00	109	3	51.7	327	B, N, d
1911 VI	.79	6.31	3.55	81	1	4.5	81	B, 0
1915 II	1.00	5.65	1.66	58	4	43.3	232	B, N, d
1919 III	.48	10.44	5.76	64	1	62.3	64	B, 0
1919 V	1.12	10.8	6.6	6	3	60.5	18	S, N, d
1925 III	1.63	5.9	2.0	3	3	57.3	9	S, 0
1930 II	.67	8.34	4.27	53	1	55.3	53	B, N
1932 IX	1.62	7.5 (8.1)	3.0 (5.5)	9	1	11.9	9	Be, 0
1937 VI	.33	9.4 (9.96)	4.5 (5.95)	10	4	110.8	40	Be, (Encke) 0
1941 I	.37	5.2 (5.81)	0.5 (1.99)	32	2	58.6	64	Be, 0
1947 XI	.34	9.3 (9.90)	4.8 (6.32)	20	1	145.6	20	Be, (Encke) 0
1951 III	.34	9.2 (9.83)	1.2 (2.73)	15	2	70.6	30	Be, 0
1952 VI	1.20	8.3 (8.87)	4.2 (5.68)	28	1	29.5	28	Be, N, d
1954 VII	.77	4.1 (4.66)	2.8 (4.33)	76	6	6.6	456	Be, 0
1954 X	.97	5.3 (5.86)	2.1 (3.65)	76	6	4.7	456	Be, N(P)
1956 IV	1.18	4.1 (4.68)	4.9 (6.38)	46	5	118.2	230	Be, 0
1959 VIII	.94	9.6 (10.18)	7.9 (9.43)	28	2	143.7	56	Be, 0
1960 II	.50	7.2 (7.78)	2.3 (3.80)	37	4	122.4	148	Be, N
1960 III	1.20	7.2 (7.83)	9.1 (10.56)	24	4	122.4	96	Be, 0, d(hn)
1961 I	.34	9.6 (10.19)	2.0 (3.52)	14	1	53.5	14	Be, 0
1962 III	.03	5.6 (6.24)	0.8 (2.30)	11	1	45.4	11	Be, N(P)
1962 V	1.12	10.7 (11.31)	8.8 (10.32)	35	3	43.5	105	Be, 0, d(hn)

Table I. Pre-Perihelion Dominated Solutions
(cont.) (Original Beyer Data in Parentheses)

Comet	q(A.U.)	m_o	n	N	Δt (mos.)	$\hat{R}$	Wt	Notes
1962 VIII	2.13	1.5 (2.14)	2.0 (3.49)	51	11	42.0	561	Be, 0
1963 I	.63	5.7 (6.29)	3.2 (4.70)	20	2	42.7	40	Be, 0
1965 VIII	.01	6.10	3.28	59	1	18.8	59	Milon, Solberg Minton 0
1967 II	.42	9.44	2.53	18	2	88.3	36	Bortle, N(P)
1969 VII	.77	7.70	3.75	11	1	86.3	11	Bortle, 0
1970 II	.54	5.41	4.31	20	2	115.6	40	Bortle, 0
1970 ℓ	.34	9.75	4.23	10	1	83.8	10	Bortle, Encke, 0
1973 f	.14	5.37	2.52	63	3	34.0	189	Morris & Bortle, N

B = Bobrovnikoff, Be = Beyer, S = Schmidt, N = New comet, 0 = old comet, N(P) = parabolic comet, d = solution divergence possible, d(hn) = solution divergence, high n, d(ln) = solution divergence, low n, hn = high n group, ln = low n group.

LIST OF VISUAL BRIGHTNESS PARAMETERS

Table II. Post-Perihelion Dominated Solutions

Comet	q(A.U.)	m_0	n	N	Δt (mos.)	$\hat{R}$	Wt	Notes
1853 III	.31	5.7	3.3	2	5	26.1	10	S, N
1858 VI	.58	4.3	4.5	21	1	67.6	21	B, O
1861 I	.92	6.5	11.7	4	5	79.0	20	S, O, d(hn)
1861 II	.82	5.08	0.47	66	2	77.0	132	B, O, ln
1862 III	.96	5.35	8.63	80	2	58.0	160	B, O, d(hn)
1881 III	.77	5.65	2.40	106	4	56.7	424	B, O
1882 II	.01	0.8	3.2	3	5	56.8	15	S, O
1890 II	1.91	5.47	2.55	30	8	11.1	240	B, N
1892 I	1.03	3.3	1.9	2	10	73.8	20	S, N, d(ln)
1893 II	.68	6.42	2.24	35	1	85.7	35	B, N
1893 III	.67	6.2	2.8	4	4	85.6	16	S, O
1894 II	.98	5.8	7.4	3	2	79.3	6	S, O, d(hn)
1896 III	.57	9.0	5.1	11	2	43.8	22	S, N
1898 I	1.10	4.62	5.93	53	3	26.5	159	B, O, d(hn)
1898 VIII	2.28	4.3	4.9	3	7	17.4	21	S, O
1899 I	.33	6.49	3.77	56	4	13.5	224	B, N
1900 II	1.02	8.62	6.55	59	2	7.5	118	B, N, d(hn)
1904 I	2.71	3.36	3.45	146	8	46.2	1168	B, N
1905 IV	3.34	5.3	2.0	3	1	62.6	3	S, N
1906 VII	1.22	7.58	6.89	37	1	60.9	37	B, N, d(hn)
1907 I	2.05	6.9	2.2	2	11	55.2	22	S, N
1907 IV	.51	4.32	3.58	98	7	54.6	686	B, O
1910 I	.13	4.7	3.8	3	3	29.6	9	S, N(P)
1911 II	.69	7.90	4.14	58	1	5.3	58	B, O
1912 II	.72	6.28	3.21	113	3	3.0	339	B, N
1913 IV	1.25	5.71	9.56	58	2	2.4	116	B, N, d(hn)
1915 II	1.00	6.19	2.99	20	3	55.2	60	B, N, d
1917 I	.19	5.1	1.8	2	0.5	95.2	1	S, O
1922 II	2.26	7.6	0.2	2	10	6.3	20	S, N, ln
1925 I	1.10	5.88	3.28	39	2	44.0	78	B, N, d
1925 VII	1.57	5.8	1.6	4	7	63.2	28	S, N
1927 IV	3.68	4.3	2.2	23	48	83.3	1104	S, N
1930 III	.48	8.67	4.67	99	2	45.6	198	B, O
1930 IV	2.08	8.2	0.4	2	3	34.0	6	S, N, ln
1931 III	1.04	4.3	5.2	3	9	15.7	27	S, O
1932 I	1.26	9.3	2.8	3	1	12.1	3	S, O
1932 V	1.04	7.36	11.40	130	2	11.8	260	B, O, d(hn)
1932 VI	2.31	5.08	2.46	28	4	7.7	112	B, N
1932 X	1.31	8.92	2.09	47	2	8.1	94	B, O
1933 I	1.00	9.3 (9.92)	1.9 (3.39)	11	1	7.7	11	Be, N(P), d(ln)
1937 II	.62	10.21	3.74	32	2	119.1	64	B, O
1941 II	.94	10.3 (10.86)	0.64 (2.14)	14	1	54.7	14	Be, O*
1947 I	2.41	2.5 (3.12)	4.2 (5.71)	22	13	141.6	286	Be, N

*Badly placed

Table II. (cont.) Post-Perihelion Dominated Solutions

Comet	q(A.U.)	m_o	n	N	Δt (mos.)	$\hat{R}$	Wt	Notes
1948 I	.75	5.7 (6.31)	1.5 (2.97)	52	3	138.2	156	Be, N
1948 IV	.21	6.9 (7.54)	3.9 (5.39)	36	2	137.7	72	Be, N(P)
1948 V	2.11	3.8 (4.37)	2.9 (4.44)	132	12	139.2	1584	Be, N
1948 X	1.27	5.4 (6.01)	5.0 (6.48)	8	4	136.8	32	Be, 0
1948 XI	.14	4.8 (5.36)	2.2 (3.66)	29	5	137.5	145	Be, N
1949 IV	2.06	5.0 (5.59)	4.0 (5.53)	79	9	118.3	711	Be,N
1950 I	2.55	4.3 (4.94)	3.9 (5.36)	33	4	102.7	132	Be, N*
1950 VII	1.39	8.3 (8.87)	7.1 (8.59)	11	1	69.5	11	Be, 0*, hn
1951 II	.72	8.8 (9.40)	2.0 (3.47)	30	10	80.3	300	Be, N(P)
1951 IV	1.12	9.6 (10.23)	9.5 (11.05)	20	1	70.0	20	Be, 0, d(hn)
1952 I	.74	8.3 (8.88)	2.8 (4.33)	6	1	40.8	6	Be, N
1954 III	.56	12.2 (12.78)	4.6 (6.06)	11	1	4.2	11	Be, 0
1954 VIII	.68	3.3 (3.94)	6.9 (8.42)	10	2	7.6	20	Be, N*, hn
1955 III	.54	6.3 (6.85)	3.7 (5.21)	13	1	35.1	13	Be, 0
1955 IV	1.43	4.2 (4.79)	5.7 (7.24)	25	4	60.0	100	Be, 0
1955 V	.89	6.2 (6.85)	3.2 (4.67)	35	3	59.8	105	Be, N(P)
1956 IV	1.18	4.4 (5.02)	2.4 (3.93)	15	3	150.6	45	Be, 0
1957 V	.36	3.0 (3.63)	0.7 (2.21)	23	2	198.4	46	Be, N
1958 III	1.32	6.2 (6.75)	5.8 (7.25)	27	2	191.7	54	Be,N
1959 I	1.63	6.5 (7.10)	3.4 (4.86)	46	6	174.8	276	Be, N
1959 VIII	.94	9.6 (10.18)	7.9 (9.43)	28	2	143.7	56	Be, 0, hn

*Badly Placed

Table II. (cont.) Post-Perihelion Dominated Solutions

Comet	q(A.U.)	m_o	n	N	Δt (mos.)	$\hat{R}$	Wt	Notes
1961 II	1.06	5.9 (6.53)	7.5 (8.95)	21	4	48.5	84	Be, N(P), d(hn)
1961 V	.04	8.6 (9.19)	4.5 (6.02)	19	2	52.3	38	Be, N
1962 III	.03	4.5 (5.12)	2.1 (3.55)	15	1	44.0	15	Be, N(P)
1962 IV	.65	9.9 (10.47)	3.7 (5.21)	15	2	41.8	30	Be, N(P)
1963 I	.63	5.7 (5.36)	3.2 (3.56)	32	2	33.9	64	Be, O
1963 VIII	2.21	8.6 (9.23)	0.5 (2.00)	55	3	15.7	165	Be, O
1964 IX	1.26	5.7 (6.29)	4.5 (6.03)	63	4	8.1	252	Be, N(P), d
1965 VIII	.01	6.43	3.63	55	3	24.0	165	Morris, O
1966 IV	.88	6.7 (7.26)	1.9 (3.44)	10	1	58.0	10	Be, N(P)
1968 I	1.70	3.87	4.85	243	9	107.7	2187	Morris & Bortle, N
1968 I	1.70	2.52 (3.12)	4.35 (5.85)	86	9	107.7	774	Be, N
1968 VII	1.77	7.5 (8.08)	1.2 (2.74)	17	2	107.1	34	Be, N(P)
1967 VII	.18	7.27	2.8	67	1	85.8	67	Meisel, N(P)
1969 IX	.47	5.8 (6.39)	1.6 (3.06)	29	5	117.4	145	Be, O
1970 II	.54	3.42	3.54	31	6	86.0	186	Bortle, O
1970 X	.41	7.9 (8.49)	3.0 (4.48)	8	2	88.0	16	Be, N(P)
1971a	1.23	6.67	4.12	66	5	62.6	330	Morris, N, d
1972d	.99	9.57	4.22	33	5	70.4	165	Morris, O, d
1973f	.14	6.47	2.51	120	3	26.6	360	Morris & Bortle, N

B = Bobrovnikoff, Be = Beyer, S = Schmidt, N = New comet, O = old comet, N(P) = parabolic comet, d = solution divergence possible, d(hn) = solution divergence, high n, d(ln) = solution divergence, low n, hn = high n group, ln = low n group.

LIST OF VISUAL BRIGHTNESS PARAMETERS

Table III. Combined Pre- and Post-Perihelion Periods

Comet	q(A.U.)	m_0	n	N	Δt (mos.)	$\hat{R}$	Wt	Notes
1873 V	.38	7.2	4.9	3	3	54.3	9	S, N
1886 I	.64	8.1	5.4	14	8	30.7	112	S, N
1889 I	1.81	4.9	1.8	5	8	6.0	40	S, N
1889 II	2.26	8.2	0.3	2	5	6.3	10	S, N, ln
1898 VII	1.70	6.5	2.0	3	6	24.0	18	S, N
1907 IV	.51	4.32	3.58	98	7	54.6	686	B, O
1910 II	.59	5.70	3.71	254	8	27.5	2032	B, O (P/Halley)
1910 IV	1.95	7.1	1.6	2	9	12.4	18	S, N
1911 V	.49	5.60	3.43	466	5	4.3	2330	B, O
1914 V	1.10	1.78	3.50	260	3	16.3	780	B, N
1917 III	1.69	8.29	1.97	67	6	100.9	402	B, N
1921 II	1.01	6.94	5.53	96	2	28.1	192	B, N, d
1932 VIII	1.87	8.7	3.0	8	1	11.9	8	Be, O
		(9.3)	(5.5)					
1935 I	.81	9.81	2.88	51	3	22.4	153	B, O
1936 II	1.10	6.75	4.62	346	3	77.8	1038	B, O, d
1937 IV	1.73	6.18	3.25	121	7	115.8	847	B, N
1937 V	.86	6.20	0.72	349	2	111.7	698	B, N, ln
1941 VIII	.88	6.3	2.1	50	6	48.1	300	Be, N(P)
		(6.91)	(3.62)					
1943 I	1.35	4.6	1.4	494	6	19.4	2964	Be, O
		(5.22)	(2.93)					
1946 VI	1.14	4.4	2.3	19	9	111.7	171	Be, N, d
		(4.98)	(3.81)					
1951 I	2.57	6.6	0.0	35	11	74.6	385	Be, N
		(7.15)	(1.54)					
1952 III	1.19	6.8	5.1	57	5	37.7	285	Be, O, d
		(7.39)	(6.57)					
1953 I	1.67	-0.2	12.2	26	5	25.3	130	Be, N, hn
		(0.43)	(13.73)					
1953 III	1.02	7.0	9.0	7	1	17.2	7	Be, O, d(hn)
		(7.61)	(10.47)					
1955 VI	3.87	2.4	2.8	60	1	58.8	60	Be, N(P)*
		(3.05)	(4.33)					
1957 III	.32	4.6	2.8	60	10	181.8	600	Be, N
		(5.15)	(4.35)					
1966 V	2.39	1.3	5.2	40	3	47.2	120	Be, N
		(1.86)	(6.67)					
1968 IV	.68	10.7	4.1	10	1	121.5	10	Be, N(P)
		(11.28)	(5.56)					

*Badly placed

Table III. Combined Pre- and Post-Perihelion Periods
(cont.)

Comet	q(A.U.)	m_0	n	N	Δt (mos.)	$\hat{R}$	Wt	Notes
1968 VI	1.16	5.2 (5.78)	2.5 (3.98)	74	5	106.7	370	Be, N(P), d
1970 XV	1.11	5.0 (5.56)	1.1 (2.60)	61	4	97.3	244	Be, N(P), d

B = Bobrovnikoff, Be = Beyer, S = Schmidt, N = New comet, O = old comet, N(P) = parabolic comet, d = solution divergence possible, d(hn) = solution divergence, high n, d(ln) = solution divergence, low n, hn = high n group, ln = low n group.

Part IV. Statistical Analysis of Comet Brightness Parameters

(a) Photometric Groups

Various authors have attempted to use visual brightness parameters to classify comet behavior. Oort and Schmidt (1951) and Oort (1951) established that there was a significant statistical difference in the photometric parameters for "old" and "new" comets as well as a noticeable perihelion distance correlation. Unfortunately their analysis was based on the erroneous Levin model. We have re-examined the available power-law parameters not only for a q correlation and the "old" and "new" comet distinction, but also for a possible statistical difference between pre-perihelion and post-perihelion parameters. In addition to these groupings we have also examined two others of possible significance--one group of unusually high n values and one group of unusually low n values. The mean and standard deviations characteristics of these groupings are summarized in Table IV. NOTE THAT THESE STATISTICS INCLUDE THE CORRECTED BEYER VALUES. If the uncorrected Beyer values are used instead, somewhat different means are obtained.

Comparison of the data in Table IV shows that grouping according to perihelion distance is even more significant than the "old" and "new" distinction. While the pre-perihelion/post-perihelion behavior of single comets may be very different, groupings according to period of visibility produces only slight changes in the parameter means.

The high n and low n groups appear to be quite distinctive when means are compared but it remains to be demonstrated that these groups are not simply the result of least-squares solution divergence.

Table IV. Grouped Data Means and Standard Deviations of Comet Brightness Parameters

GROUP	MEANS AND STANDARD DEVIATIONS	GROUP	MEANS AND STANDARD DEVIATIONS
All (m_0,n) sets $(N = 150)$	$\langle n\rangle = 3.6 \pm 2.3$ $\langle m_0\rangle = 6.3 \pm 2.2$ $\langle q\rangle = 1.0 \pm 0.7$ A.U.	Pre-perihelion Dominant $(N = 38)$	$\langle n\rangle = 3.6 \pm 2.0$ $\langle m_0\rangle = 6.9 \pm 2.2$ $\langle q\rangle = 0.7 \pm 0.5$ A.U.
New Comets $(N = 85)$	$\langle n\rangle = 3.2 \pm 2.0$ $\langle m_0\rangle = 6.1 \pm 2.0$ $\langle q\rangle = 1.2 \pm 0.8$ A.U.	Post-perihelion Dominant $(N = 82)$	$\langle n\rangle = 3.9 \pm 2.3$ $\langle m_0\rangle = 6.3 \pm 2.1$ $\langle q\rangle = 1.1 \pm 0.3$ A.U.
Old Comets $(N = 65)$	$\langle n\rangle = 4.2 \pm 2.5$ $\langle m_0\rangle = 6.6 \pm 2.5$ $\langle q\rangle = 0.9 \pm 0.5$ A.U.	Both pre-and post-perihelion periods $(N = 30)$	$\langle n\rangle = 3.4 \pm 2.4$ $\langle m_0\rangle = 5.9 \pm 2.1$ $\langle q\rangle = 1.3 \pm 0.8$ A.U.
$q > 1.25$ A.U. $(N = 40)$	$\langle n\rangle = 3.1 \pm 2.2$ $\langle m_0\rangle = 5.6 \pm 2.3$ $\langle q\rangle = 2.0 \pm 0.6$ A.U.	High n group $(N = 13)$	$\langle n\rangle = 8.7 \pm 2.4$ $\langle m_0\rangle = 6.6 \pm 2.7$ $\langle q\rangle = 1.1 \pm 0.2$ A.U.
$q < 1.25$ A.U. $(N = 110)$	$\langle n\rangle = 4.4 \pm 2.7$ $\langle m_0\rangle = 6.6 \pm 2.1$ $\langle q\rangle = 0.7 \pm 0.4$ A.U.	Low n group $(N = 11)$	$\langle n\rangle = 0.5 \pm 0.2$ $\langle m_0\rangle = 6.8 \pm 1.9$ $\langle q\rangle = 1.3 \pm 0.9$ A.U.

(b) Residual Systematic Effects

The most striking differences due to grouping occurs for the perihelion distance q as might have been expected on the basis of the Oort-Schmidt (1951) results. However, as pointed out in Part I of this paper, an empirical dependence on q for n and m_0 is expected on purely pedigogical grounds. The dependence of the solutions on q for our data is significant at the 99.5% level. For the combined list (N = 150), the relationship is $m_0 = 7.0 \pm 0.3 - (0.7 \pm 0.2) \times q(\text{A.U.})$ with $r' = -0.23 \pm 0.08$ for the correlation coefficient. The negative correlation represents an observational selection effect--observers with small telescopes tend to see intrinsically fainter objects only when the perihelia are small. The n values do not show a significant q correlation.

From time-to-time, there are various suggestions for a solar modulation of comet brightness. Over the long time scale represented by the data available to us, there are only sunspot numbers available as indicators of solar activity. We have therefore calculated mean sunspot numbers for each period of comet observation. Since solar rotation would present the same <u>average</u> level of activity to the comet as it does to the earth.

We have searched for a statisticallysignificant solar modulation of the (m_0, n) with little success. A direct linear correlation with $\hat{R}$ for either m_0 or n has at most only a 20-30% chance of being non-zero. In addition, a logarithmic correlation for n (i.e. $\log n = \log n_0 + C_1\hat{R}$ for a regression equation) is absent. We conclude that the perihelion distance correlation along with remaining random errors and solution divergence problems obscure any real solar effect that might be present. We should point out that a higher degree of solar correlation is obtained if the raw Beyer values are used in the analysis. However, this can be entirely attributed to the fact that the average level of solar activity of the Beyer data ($\langle\hat{R}\rangle = 78 \pm 53$) is significantly higher than for the non-Beyer data ($\langle\hat{R}\rangle = 48 \pm 32$) and this couples with the Beyer systematic observational effect to produce an apparent solar correlation of n values.

The distribution of n values with the assigned solution weight agrees well with expectation of Poisson statistics except for sixteen solutions. Eleven of these (1861 I, 1862 III, 1913 IV, 1932 V, 1936 II, 1937 V, 1951 IV, 1959 VIII, 1960 III, 1961 II, and 1962 V) can readily be ascribed to the previously mentioned solution divergence problem. The remaining five (1927 IV, 1943 I, 1951 I, 1953 I, and 1968 I) cannot be assigned to this category and therefore must represent verified intrinsic cometary variations from the mean of the n value. These objects deserve a more detailed discussion than we can give here.

Summary and Recommendations

We have reviewed the power-law definition of comet brightness and discussed possible systematic influences that can affect the derivation of m_0 and n values from visual magnitude estimates. We have provided a rationale for the Bobrovnikoff aperture correction method and argue for its continued use. We have demonstrated that the Beyer extrafocal method leads to large systematic effects which if uncorrected by an instrumental (aperture or focal ratio) relationship, results in n values significantly higher than those derived according to the Bobrovnikoff guidelines.

We present a series of (m_0,n) parameter sets which have been reduced to essentially the same photometric system (Bobrovnikoff). In order that future observations are reduced to this same system we offer the following recommendations.

For observers

(a) Make extrafocal comparisons using the smallest possible aperture and magnification.

(b) Be sure to note instrument size, instrument type, focal ratio, and magnification.

(c) Use stars with spectral type G or earlier for comparison.

(d) Throw the images out-of-focus only by an amount needed to make the star and comet look identical. The more an image is out-of-focus, the greater is the required instrument correction. Beyer's and Sidgwick's methods are to be avoided if possible, since they can lead to serious problems even when used by skillful observers.

For users of visual magnitudes

(a) Do not attempt solutions for photometric parameters using observations for which aperture corrections have not or cannot be obtained as the values will be systematically affected.

(b) If possible, aperture corrections should be derived for each comet individually and for each type of instrument separately and for each method of extrafocal comparison (if necessary) separately. As a last resort, the mean aperture relationships derived by Bobrovnikoff (1941a) and Morris (1973a) can be used.

(c) Solutions obtained for comets with $q \to 1$ or $r \to 1$ should always be treated carefully. If necessary, a series expansion formula around $r = 1$ A.U. is to be preferred to the usual logarithmic formula.

(d) Most n values outside 3.6 ± 2.0 should always be suspect as possible cases of solution divergence.

(e) The probability of solution divergence is roughly proportional to $1/\sqrt{N}$ where N is the number of observations available.

(f) Since $\langle n \rangle = 3.6$, the use of $n = 4$ and $n = 6$ in making comet brightness predictions may be erroneous, particularly when attempting to use photographic observations (whose instrumental effects are related to focal ratio) combined with visual estimates (whose instrumental effects are functions of aperture).

(g) Solutions which are based on the Beyer system will on the average have an "apparent" n value that is 1.5 units too high compared to the Bobrovnikoff system. Insofar as the Beyer method represents the extreme of all magnitude estimates which have no aperture corrections, we could use $3.6 < n < 5.1$ for prediction of visual magnitudes and the standard $n = 4$ is a reasonable compromise.

(h) When combining individual observations, there are many sources of random error that produce poorly defined m_0,n values even when least-squares techniques are applied. Few of these are reported in the literature along with the raw observations, so considerable care must be exercised by the investigator to make sure that the following are recognized in each analysis:

1. Sky Background Effects - Moonlight (Meisel, 1970) and Twilight
2. Air mass effects (Meisel, 1970)
3. Observer inexperience - can be very large $\pm 0\overset{m}{.}5$
4. Comparison Star-Comet Color Mismatch - can be very large $\pm 0\overset{m}{.}3$ to $\pm 0\overset{m}{.}5$
5. Inconvenient location of comparison objects
6. Poor comparison star magnitudes
7. Drastic change in comet physical form and/or activity
8. Variations in observing site quality
9. Use of unreliable or unsuitable instrumentation.

Appendix. Conversion of Levin Parameters to an Equivalent Power-Law Set

Since the Levin (A,B) parameters appear from time-to-time in the literature, it is sometimes desired to convert to the equivalent (m_0,n) set without re-analyzing the original observations.

Two approaches are possible:

(a) If the (A,B) values were derived by least-squares, we can obtain an equivalent set of (m_0,n) values that would have been obtained by least-squares from the same observations. This conversion, though exact, is tedious. We list the necessary averages here for completeness.

$$n = \frac{B}{2.5 \times 0.43} \; \frac{\langle \ln r_i \rangle}{\langle \sqrt{r_i} \rangle} \; \frac{\langle r_i \rangle (1-B) - A\langle \sqrt{r_i} \rangle - \frac{1}{k}\langle \sqrt{r_i} \rangle^2}{\langle (\ln r)^2 \rangle - A\langle \ln r_i \rangle - B\langle \sqrt{r}\,\ln r_i \rangle - \frac{1}{k}\langle \ln r_i \rangle}$$

Explicitly taking time averages and converting

$$\langle \ln r_i \rangle = \frac{\int \ln r_i\,dt}{\int dt} = \frac{\int r^2 \ln r\,d\nu}{\int r^2 d\nu}$$

where ν is the true anomaly.

$$\langle (\ln r)^2 \rangle = \frac{\int r^2 (\ln r)^2 d\nu}{\int r^2 d\nu}$$

$$\langle r_i \rangle = \frac{\int r^3 d\nu}{\int r^2 d\nu}$$

$$\langle \sqrt{r_i} \rangle = \frac{\int r^{3/2} d\nu}{\int r^2 d\nu}$$

$$\langle \sqrt{r}\,\ln r \rangle = \frac{\int r^{3/2} \ln r\,d\nu}{\int r^2 d\nu}$$

(b) If it can be assumed that the least-squares or graphical methods are convergent to the correct A,B values, a more direct conversion can be performed.

$$m_0 = A + B$$

and
$$n = \frac{1}{2.172} B \langle\sqrt{r}\rangle$$

where
$$\langle\sqrt{r}\rangle = \frac{\int \sqrt{r}\, d\nu}{\int d\nu}$$

The assumption of a parabolic orbit was used in this study to compute the $\langle\sqrt{r}\rangle$ required above. The other means required in (a) above could also be computed under the parabolic assumption but we do not give these explicitly here because they are quite complicated. The evaluation of $\langle\sqrt{r}\rangle$ in the parabolic approximation is complicated but straightforward. We quote here the results for the time averaged $\sqrt{r}$. The average $\sqrt{r}$ obtained by integration over the true anomaly is considerably simpler. Since observations are not generally evenly distributed over the true anomaly, however, the longer expression is usually preferred.

$$\langle\sqrt{r}\rangle = \sqrt{q}\left[\frac{(B_2C_2 - B_1C_1) + \frac{3}{8}\ln\left\{\frac{A_2(1+B_2)}{A_1(1+B_1)}\right\}}{D_2 - D_1 + \frac{1}{3}(E_2 - E_1)}\right]$$

with $q < r_1 < r_2$,

$$U_i = r_i/q$$

$$A_i = \sqrt{U_i}$$

$$B_i = \sqrt{1 - U_i^{-1}}$$

$$C_i = (U_i^2/4 + \frac{3}{8} U_i)$$

$$D_i = \sqrt{\frac{r_i}{q} - 1}$$

$$E_i = \sqrt{\left(\frac{r_i}{q} - 1\right)^3}$$

where q is the perihelion distance, r_1 is the comet heliocentric distance of the first observation and r_2 is the heliocentric distance of the last observation. Equivalent expressions can be derived covering orbit segments which span the perihelion point by letting $\langle\sqrt{r}\rangle = \frac{1}{2}(\langle\sqrt{r}\rangle_{r_1 \to q} + \langle\sqrt{r}\rangle_{q \to r_2})$.

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THE EVOLUTION OF COMET ORBITS

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Abstract. This review states and defends seven conclusions on the origin of comets and the evolution of their orbits:

1. There is a $N^{-1/2}$ law of survival of comets against ejection on hyperbolic orbits, where N is the number of perihelion passages.

2. The short-period comets are not created by single close encounters of near-parabolic comets with Jupiter.

3. Observable long-period comets do not evolve into observable short-period comets.

4. Unobservable long-period comets with perihelia near Jupiter can evolve into observable short-period comets.

5. Long-period comets cannot have been formed or created within the planetary region of the solar system. (This conclusion is somewhat qualified because of possible effects of stellar perturbations.)

6. It is possible that some of ths short-period comets could have been formed inside the orbit of Neptune, but it is certain that others have the same distant source as the long-period comets.

7. The circularly-restricted 3-body problem, and its associated Jacobi integral, are not valid approximations to use in studying origin and evolution of comets.

The starting data are the orbits of known comets. We are indebted to the compilations and catalogs of Galle (1894), Porter (1961), and Marsden (1972). Models of comet origin and evolution must produce distributions of periods, inclinations, and other properties that fit these data, taking into account that the data include effects of observational selection.

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Analytic methods are often used to study orbit evolution. However, in my opinion treatments that are based on approximating the solar system by the restricted 3-body problem are not valid, and this is discussed in item 7 below. On the other hand, statistical methods, such as those of Shteins (1972) which treat diffusion of orbits, are informative and useful.

The most obvious approach is to start from the known orbits and calculate backwards or forwards in time. One would suppose that upon projecting the orbit back in time and allowing for planetary perturbations one could find the original orbit on which the comet first entered the solar system. This procedure works reasonably well for near-parabolic orbits. The most careful studies of these show no original hyperbolic orbits, but some comets enter the solar system on elliptical orbits so nearly parabolic that their original aphelia are at 25000 to 100000 AU. This latter set correspond to the long-period comets originating at these vast distances within a cloud of comets described by Oort (1950).

Starting with these near-parabolic comets and calculating forward we find that planetary perturbations during their first passage remove half of them so that they then leave the solar system forever on hyperbolic orbits. The other half leave on elliptical orbits and will return. Unfortunately, for those in elongated elliptical orbits all accuracy is lost between the first and second passages. An example: Suppose that a comet after interacting with the planets then moves well outside the orbit of Neptune on an elliptical orbit whose period is exactly 3600 years. When it returns it may pass some distance in front of Jupiter and lose energy such that its period after leaving the planetary region is now 23457 years, and so on. Now take the same comet and

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start again, altering just one of its elements by one part in 10^8. The elliptical orbit might now have a period of 36003 years, and when the comet returns the next time (three years or a quarter of a Jupiter period later than in the first case) it passes close behind Jupiter, gains energy and leaves the planetary region on a hyperbolic orbit never to return. The minute difference between the two cases has caused an entirely different evolution. Whether calculated forwards or backwards, the orbits of very-long-period comets are extraordinarily sensitive to the starting conditions.

The situation is better for the short-period comets, where the periods are more nearly comensurate with planetary periods. (in this paper a short-period comet is one whose period is less than 16 years) Here we recall the work of Kazimirchak-Polonskaya (1973) in projecting the orbits of known short-period comets into the past and into the future. These show the sort of behavior to be expected, but in this case again most of the accuracy is lost after a close approach to Jupiter because the impact parameter at Jupiter and the orbit afterwards is very sensitive to the starting elements.

Probably the most powerful and exact approach is that of numerical experiments with random starting conditions. This is the Monte Carlo method. If one wants to find how the solar system interacts with comets that approach it on parabolic orbits, he can throw a thousand hypothetical parabolic comets at a fairly realistic model of the solar system. No approximations need be made; all 9 planets can be included in their appropriate elliptical orbits. Each comet's orbit is calculated fairly exactly until planetary perturbations remove it on a hyperbolic orbit, even if it makes thousands of revolutions, as it does in some cases. There is the same extreme sensitivity to the starting elements, but the evolution of each orbit is a typical random result, and the distributions of properties are not dependent on the particular set of initial conditions. When the problem is repeated with an independent and new set of random initial conditions, this gives the same overall results within a certain statistical tolerance.

This Monte Carlo approach has already established seven conclusions or facts, and these are enumerated below. I believe they are established beyond reasonable doubt and am prepared to defend them.

1. The effect of planetary perturbations on a parabolic flux of comets is to remove some of these on hyperbolic orbits, the number surviving in elliptical orbits being proportional to $N^{-1/2}$, where N is the number of perihelion passages of each individual comet. The same $N^{-1/2}$ law is reached ultimately when the starting orbits are circular.

The $N^{-1/2}$ law is the result of numerical experiments, Everhart (1972b). The straight lines of slope -1/2 in Figure 1 illustrate the law for two cases. The upper line labeled B follows the survival of 5500 initially parabolic comets of small perihelia, and line A that of 600 such comets with perihelia near Jupiter's orbit.

One can think of this survival as the random walk of a population near the edge of a cliff, each member taking steps of a certain distribution of sizes randomly towards or away from the edge. Of course, for the comets the steps are steps in total energy. The elliptical orbits are back from the edge, the parabolic orbit is just at the edge, and the hyperbolic orbit, from which there is no return, corresponds to a step beyond the edge of the cliff. Surely this simple law found here empirically is also derivable from random walk theory.

In the case of initially circular orbits, the population of comets begins its random walk in energy fairly far from the edge of the cliff. There is a delay, and no members are lost for some time. Ultimately, however, some members are lost and the numerical experiments present-

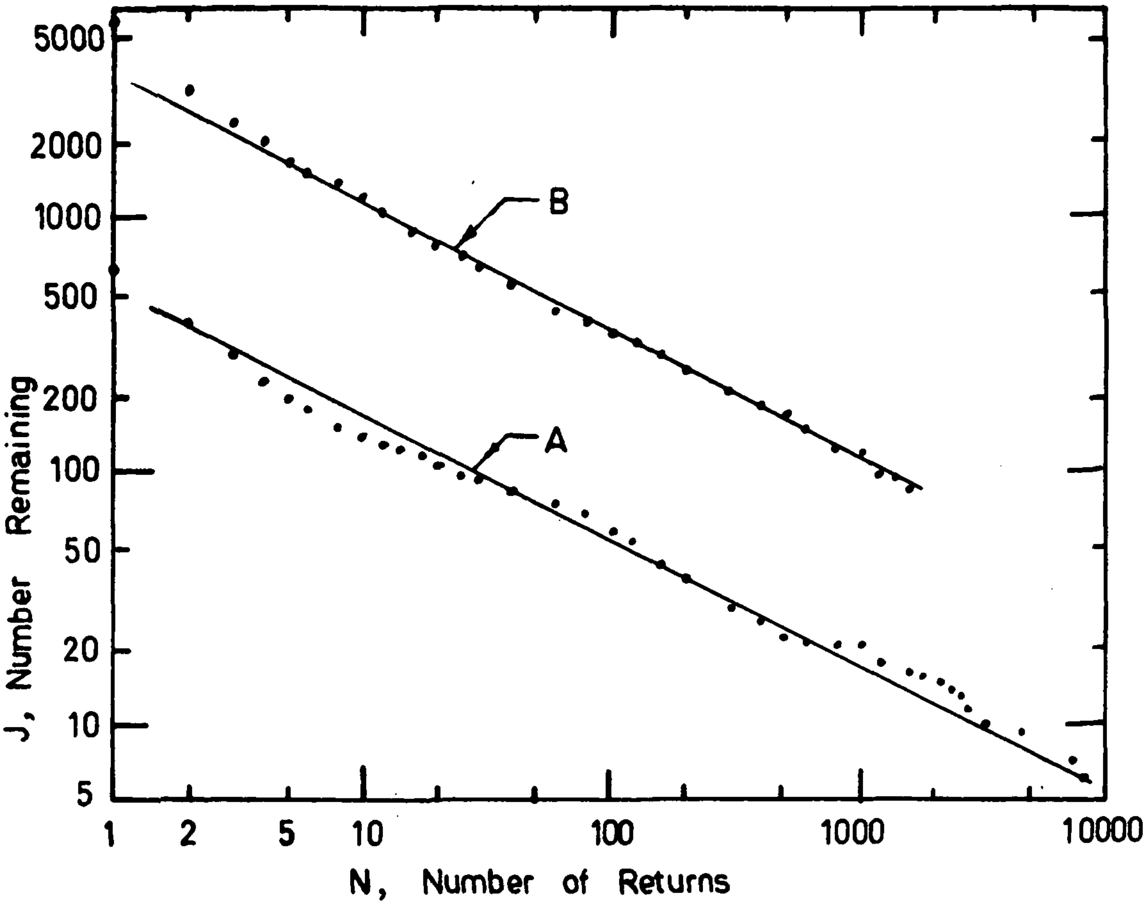

Fig. 1. This concerns survival of originally parabolic comets against being thrown out of the Sun-Jupiter system on hyperbolic orbits. The number remaining in elliptical orbits is plotted vs N, the number of returns. Line A is for hypothetical cases whose original parabolic elements were in the capture region, $i_o < 9^o$ and 4 AU$< q_o <$6 AU. Line B is for 5997 cases of all inclination and with $q_o <$4 AU. There were 6 left after 8000 returns in case A, and 80 left after 1600 returns in case B. Both lines show a $N^{-1/2}$ dependence.

ly approach the same $N^{-1/2}$ law. See the upper curve in Figure 2., which figure also appears in Everhart (1973b).

Note that this survival vs number of returns is not the same as survival as a function of time. For comets there is no thermal dissipation except when they are near the sun, so in a sense, their lifetime is measured in perihelion passages rather than in years. Lyttleton and Hammersley (1963) have studied the actual time dependence of survival, but this does not appear to have such a simple formula.

2. Although it is possible for an orbit of short period to be the result after a parabolic comet makes a single close encounter with Jupiter, this mechanism does not explain the existence of the short-period comets.

This was shown by H. A. Newton (1893). Not wanting to believe his results, and being a little dubious about Newton's procedures, I redid the problem as a numerical experiment and came to exactly the same conclusions, Everhart (1969). The convincing reason that short-period comets were not captured by Jupiter in a single encounter is that, if this were true, then one-fourth of all short-period comets would be retrograde, a result contrary to the data. The predicted distribution of periods also has the wrong shape. The detailed results may be found in Figures 6 and 7 the 1969 paper cited above.

3. There is no evolutionary path for long-period comets of small perihelia to evolve onto orbits of 5- to 13-year periods typical of short-period comets.

Such evolution simply does not happen in the numerical experiments. Some insight is offered by the lower curve, labeled B, in Figure 3. This shows the average period of those comets surviving in elliptical orbits after N returns. Comets that begin on parabolic orbits of small perihelia reach shorter periods very slowly. They cut across Jupiter's

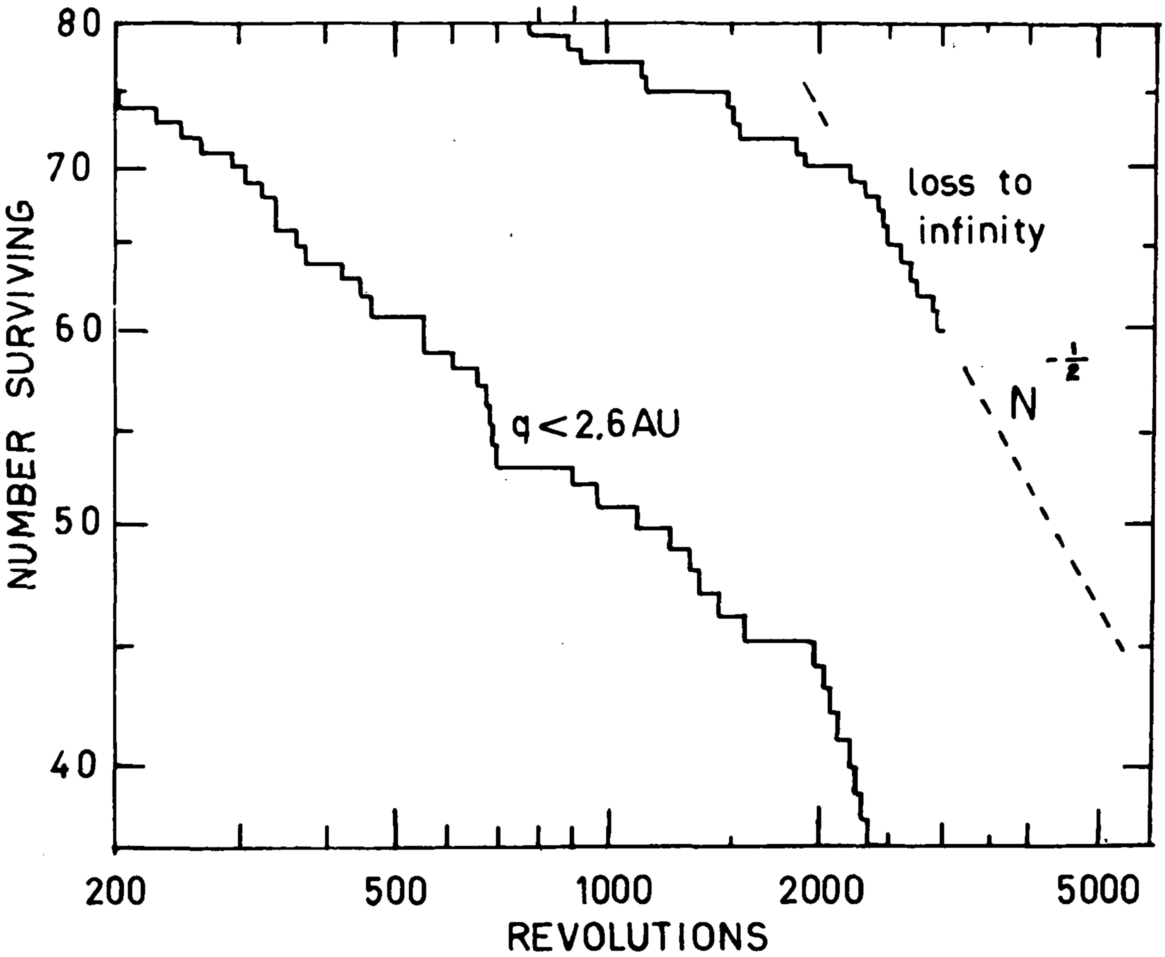

Fig. 2. This concerns the survival of hypothetical comets started in circular orbits in the Jupiter-Saturn region. The curve on the right plots vs revolution number the survival against loss infinity for 80 chaotic orbits. On the left is plotted vs revolution number N the number that have not yet achieved a perihelion value less than 2.6 AU at least once.

orbit at a large angle, the interaction is brief, and the energy perturbations are small. Those that survive the attrition of removal on hyperbolic orbits would not also survive the solar thermal dissipation of hundreds of thousands of returns at small perihelia. These results are from a study of the origins of short-period comets, Everhart (1972a, 1972b), but Figures 1 and 3 here have not previously been published.

4. There is a path for long-period comets of small inclination and with original perihelia near Jupiter's orbit to evolve into orbits typical of short-period comets. One phase of the evolution is a near-circular orbit just outside Jupiter's orbit.

This result from Everhart (1972a) may be understood by examining the upper curve of Figure 3. This class of orbits is brought to short periods rather rapidly because they interact strongly with Jupiter. Having their perihelia near Jupiter's orbit, they experience little solar dissipation during most of their evolution. At some stage in the evolution the orbit can become like that of a typical short-period comet. This happens after a rather sudden drop in the perihelion distance. The evolution shown in Figure 4 is accelerated in that each successive revolution as drawn might be the shape reached after integrating for another 100 revolutions. The circular phase of the orbit outside Jupiter's distance sometimes appears before and sometimes after the small-perihelia phase. It reminds one of the present orbit of Comet Schassmann-Wachmann I.

This evolutionary path is a qualitative result. A paper by Joss (1973) has found the above mechanism to be unable to account for the observed number of short-period comets, but a contrary result by Delsemme (1973) finds the model to be quantitatively acceptable. Joss assumes the existing numbers of long- and intermediate-period comets with perihelia near Jupiter to be random in

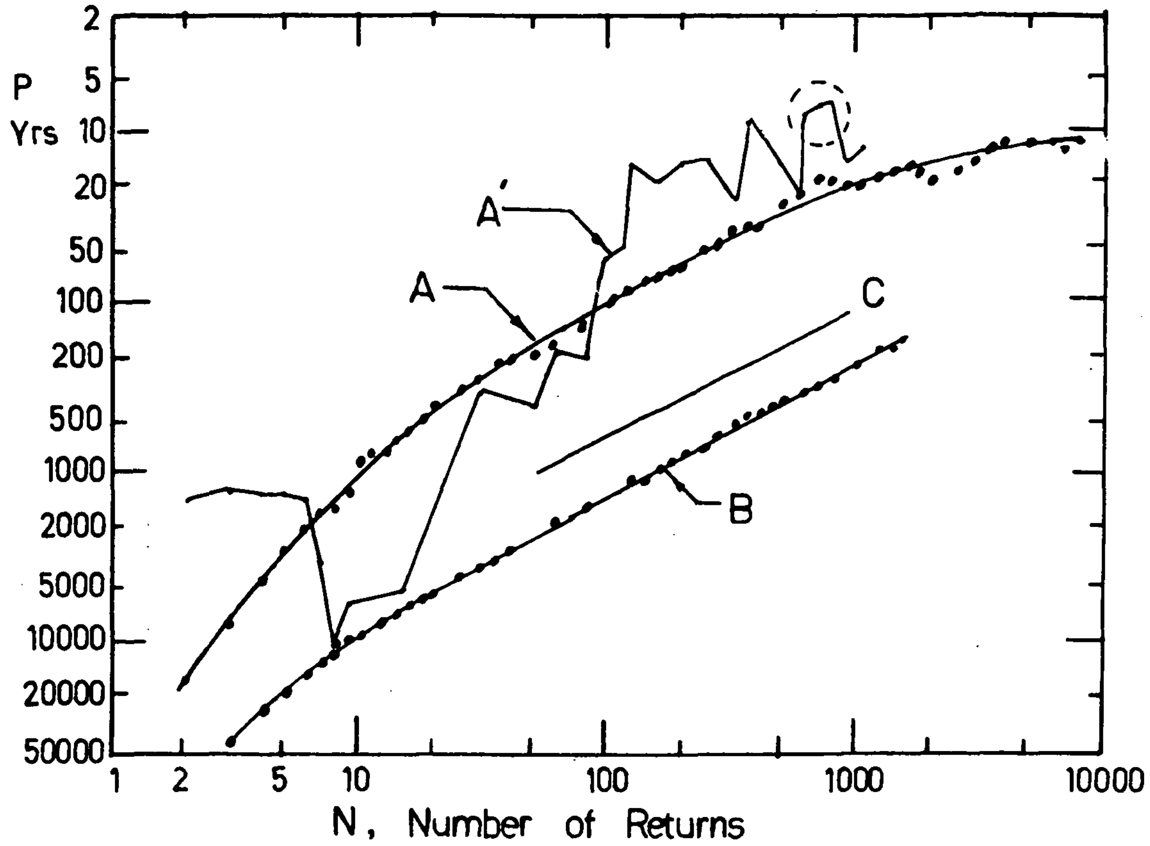

Fig. 3. The average period P is plotted vs the number of returns N. Curve A is for the comets from the capture region, followed up to 8000 returns. The broken line A' is for a particular one of these. It would have been visible as a short period comet of low perihelion distance only between its 784th and 848th return as indicated by the dashed circle. Curve B is for 5997 comets of original perihelion distance $q_o < 4$ AU, followed up to 1600 returns where there were 80 still remaining. The line C indicates the extent to which these curves show a (1/a) dependence on $N^{1/2}$, equivalent to P depending on $N^{-3/4}$.

their orbital parameters, and thus to have an inclination distribution as the sine of the inclination. Accordingly, there would be a very small number of comets with inclination near zero. Delsemme, however, looks at the number of such comets reaching perihelia per unit time, and he concludes, following work by Shteins (1972), that there is a tendency towards a concentration at small inclinations. This is one reason for the different conclusions of the two papers.

Evidently the problem needs more study. As pointed out by Kazimirchak-Polonskaya (1973), the outer planets may be effective in capturing comets of very large perihelia, to 30 AU. Her ideas are borne out by further numerical experiments of the writer (yet unpublished). Extending the capture region in perihelia to 30 AU would enlarge by a factor of 5 the number of long-period comets available for eventual capture to short periods by this mechanism.

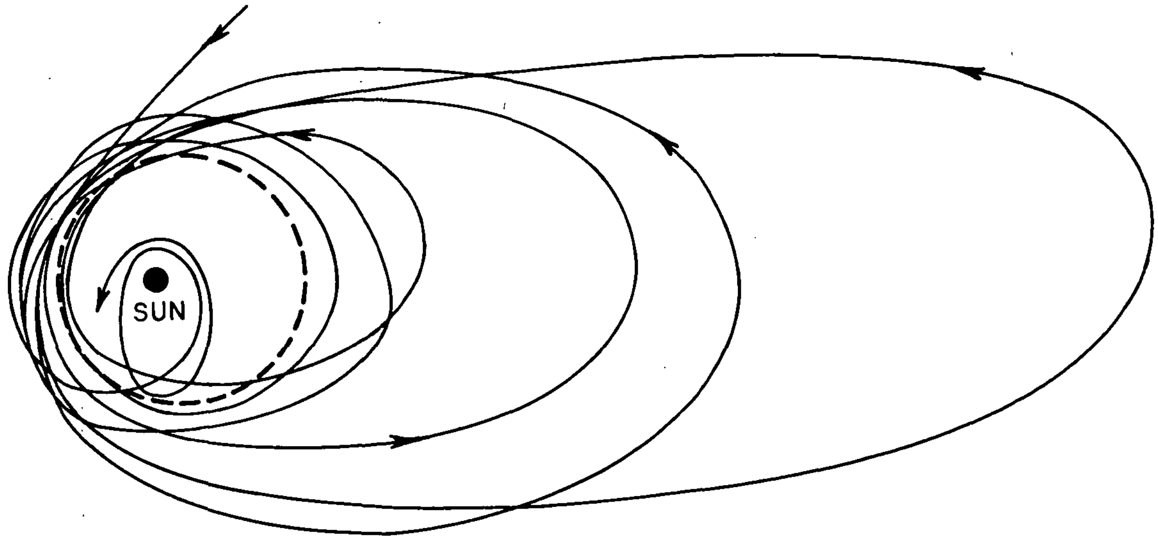

Fig. 4. The dashed line is Jupiter's orbit, and the solid line traces the path of a comet that entered originally on a parabolic path. The evolutionary path is simplified in that such changes would require hundreds of revolutions. The comet has a large perihelion distance except when it is in an orbit like those of the short-period comets.

5. Long-period comets do not originate within the planetary regions of the solar system.

The cloud of comets described by Oort (1950), which is the apparent source of the long-period comets, could not be composed of comets originally created within the orbit of Neptune, if the mechanism for removing them to large distances is that of planetary perturbations. In numerical experiments one can watch the diffusion of 1/a-values for hypothetical comets started within the planetary regions. (Here a is the semimajor axis and 1/a is a measure of the negative energy, positive for ellipses, negative for hyperbolas, and zero for parabolas). Figure 5, reproduced from Everhart (1973b), shows that the number of orbits vs 1/a goes linearly to zero at 1/a = 0. (Any one-dimensional diffusion or random walk problem, such as this one, where there is an absorbing edge, will show a concentration that goes linearly to zero at that edge.) However, this does not agree with the distribution observed for long-period comets, which shows a peak at 1/a = 0. In an experiment, Everhart (1973a, b), starting with circular orbits in the Jupiter-Saturn region, and following many examples for thousands of revolutions, not one orbit typical of an observable long-period comet was found.

It is possible, however, that stellar perturbations on comets very far from the sun would change this conclusion. A study of these effects is in progress by the present author.

6. It is possible that some short-period comets could have originated within the orbit of Neptune.

If one starts a number of hypothetical comets in circular orbits in the Jupiter-Saturn region, a fair number of these are seen to evolve into orbits like those of short-period comets, Everhart (1973b). Thus the distributions of their inclinations and periods are very much like those of the observed comets. However, one also gets the same reasonable-looking distributions if one starts with near-parabolic comets of small inclination with perihelia near Jupiter's orbit.

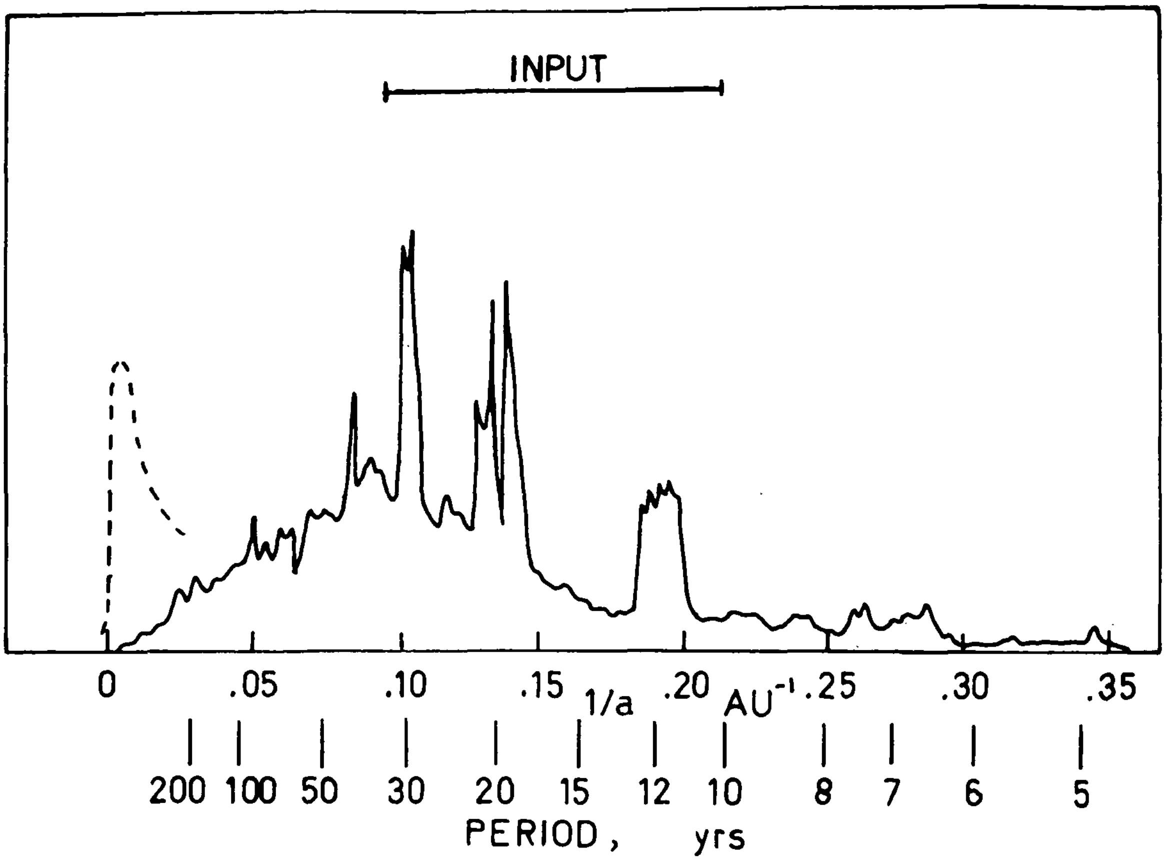

Fig. 5. The distribution of 1/a-values for 100 orbits, each followed for 3000 revolutions. Peaks are seen near Jupiter's period of 11.9 yr, near Saturn's period of 29.5 yr, and between these at the positions of the mid-range orbits. The dashed line near $1/a = 0$ is the distribution for known long-period comets.

Whether the fraction of short-period comets originating within the planetary regions is 0% or 99%, we cannot yet say on the basis of orbital evolution studies. We do know that some, if not all, must originate at large distances. Studies such as that of Joss and that Delsemme referred to already, should help decide whether it is necessary to postulate two sources of short-period comets, or whether a single source in a comet cloud at large distances is sufficient

Within the solar system there is a class of orbits that has been called "chaotic orbits", Everhart (1973a,b), as opposed to those in more regular patterns such as Trojans, horseshoes, or librating orbits. When chaotic orbits have small perihelia they resemble orbits of typical short-period comets. The pattern of the chaotic orbits appears to be independent of their previous history or origin.

7. The Jacobi integral (and its approximate forms, such as the Tisserand criterion and the "constant encounter velocity near Jupiter") should not be used in studies of evolution in the solar system.

For the purpose of studying small bodies such as comets, it has been customary to idealize and simplify the solar system retaining only the sun, Jupiter, and the comet in the form of the circularly-restricted problem of 3 bodies. If this were valid then the Jacobi integral could be used in analytic treatments on the origin and evolution of comets. Such papers are easy to write, and there have been dozens of them. Of course, the authors of these papers realize the approximation they are making, but they assume without any proof that it is relatively harmless, and with this approximation they derive simple and far-reaching conclusions. There is a particularly strong incentive to use the Jacobi integral because it is the only conservation equation, and without it an analytic development is difficult, if not impossible.

Unfortunately, numerical experiments with a fairly realistic model of the solar system shows the approximation to be downright wrong.

One example of this: According to the restricted problem there is an absolute barrier such that if the comet's Jacobi quantity is greater than 3.0, then the comet cannot penetrate from a perihelion outside Jupiter's orbit to one inside Jupiter's orbit. However, the exact orbital integrations show that in the course of many hundreds of revolutions a comet can at times have its perihelion well inside Jupiter's orbit and at other times its perihelion outside not only Jupiter's orbit but also outside Saturn's orbit. The corresponding values of the Jacobi quantity range from 2.8 to 3.6. It is just plain wrong to assume that a comet now in a short-period orbit originally entered the solar system with about the same Tisserand constant that it now has. Figure 6, reproduced from Everhart (1973b), shows the large and frequent changes in C_J, the Jacobi quantity referred to Jupiter, in the course of 3000 revolutions. (These changes are not due to inaccuracies in the numerical integration. When the mass of Saturn was set to zero, and Jupiter's orbit was made circular, then C_J was found to be constant to within one part in 10^5 in the course of 1000 revolutions.) Some of the variations in Figure 6 occur because Jupiter's orbit is not circular, but the major and sudden changes in this Jacobi quantity are caused by Saturn. In the paper cited above it is shown that there is an approximate relationship between the changes in C_J and the change in heliocentric energy caused by Saturn.

I hope I have persuaded readers not to write, and not to believe, simple discussions of the evolution of comets based on the restricted problem. Classification of comets according to their Tisserand constant cannot be valid, and developments based on a constant encounter velocity of comets at Jupiter's sphere of influence are not on a good foundation.

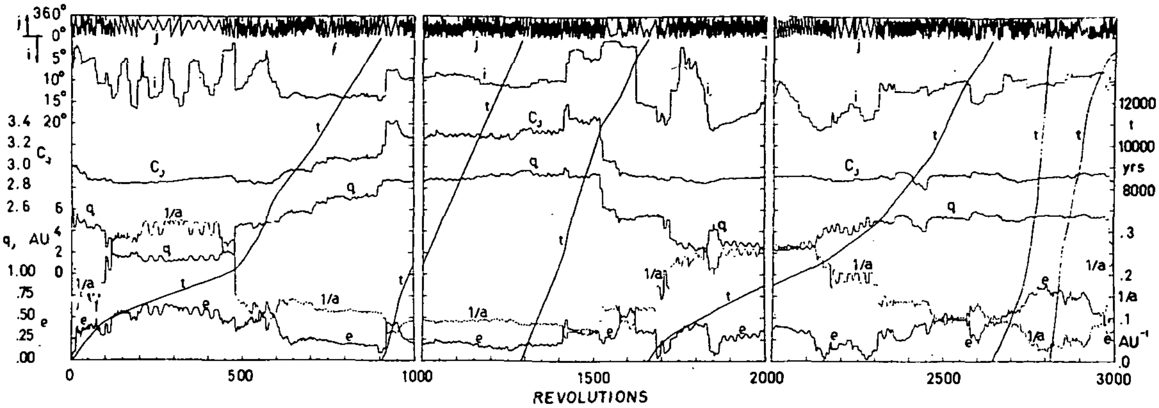

Fig. 6. A detailed history of the orbit of one hypothetical comet integrated for 3000 revolutions. The solar system model included Jupiter and Saturn, both in elliptical orbits. Here i is the inclination, C_J is the Jacobi quantity referred to Jupiter, q is the perihelion distance, e is the eccentricity, and 1/a measures the negative energy. The sloping line labeled t measures time, repeating its traverse every 15000 years. The line j is a comet-sun-planet angle discussed in the paper from which this figure is taken, Everhart (1973b).

Note that C_J varies between 2.8 and 3.6, and that q varies between 1.5 AU and 10 AU.

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DISCUSSION

B. G. Marsden: I am glad that you qualified your original point 5, for while your calculations represent a great step forward in our understanding of the way short-period comets evolve, I don't think we can use them to distinguish between the possibilities that comets originate at the extreme outskirts of the solar system or just beyond the orbit of Neptune. I must agree that the existence of the Oort cloud, particularly now that Sekanina and I have considerably refined the extent of the region from which "new" comets appear to have come, makes the idea of an origin at almost interstellar distances very attractive. But at the same time, when one considers that there are so many really spectacular comets of aphelion distance only a couple of hundred astronomical units—comets like Bennett, Donati, and the Kreutz sungrazers—one does rather wonder if some of them perhaps ejected near Neptune and were never out in the Oort cloud.

B. Lowrey: I feel that comments 2, 3, and 7 are overstated or require modification. While it is true that the Jacobi integral varies in the solar system, it is useful to study it as an evolutionary parameter. In particular, my use of the encounter velocity u (related to Tisserand's constant) in a recent paper (June 1973 A.J.) showed that the short period comets divided into two classes—those of high velocity and those of low velocity. The high velocity short period comets appeared to relate closely to the long period comets, and the low velocity ones did not. This use of the Jacobi integral therefore suggests a more detailed examination of orbit-element distributions to see if the high velocity short period comets compare with the long period comets.

D. Yeomanns: As you know, the aphelion distance of comet Encke is 4.1 A.U. The non-gravitational acceleration of Comet Encke's mean motion has been suggested as a possible mechanism for the evolution of Encke's aphelion distance within Jupiter's orbit. In your investigation of the evolution of parabolic orbits with high perihelia into short period comets of low perihelia, did you find any examples of short period comets whose aphelia were inside Jupiter's orbit?

E. Everhart: No, not at all; I found that did not happen. On the other hand, I am a little bit dubious about the non-gravitational effects having that effect on Comet Encke, because Marsden has calculated this thing for a number of apparitions backward in time, and I could detect no systematic change in its energy or its aphelia over a period of time. If I had to guess what caused Comet Encke, I would say it was an encounter with Earth or Venus, simply because that would and could bring it in closer.

B. G. Marsden: The smallest aphelion distance I know of produced by entirely gravitational means from a comet that was originally on the outside is 4.5 astronomical units, and this was in the case of Comet Oterma. That happened to be perturbed by Jupiter into a nice resonance orbit, at 3 to 2 resonance with Jupiter, although it's hard to see that the 3 to 2 resonance had anything to do with where the comet was thrown out. It was at least thrown into that 4.5 A. U. aphelion; I suppose this is rather close to the limits that one can do by gravitational means.

B. Jambor: Given a comet in a near parabolic orbit and releasing many small particles, all in hyperbolic orbits, is it possible that these hyperbolic orbits could be thrown into elliptical orbits by one encounter with Jupiter (or another planet)?

E. Everhart: I think it's possible, but it is very unlikely. The reason why we don't make comets in a single encounter is that the scale of influence around Jupiter that would do it is so small it has to be a cumulative group of small encounters.

D. A. Mendis: While it is clear that with the restricted 3-body problem one cannot get comets with initial low relative velocity thrown out of the solar system, repeated encounters with an elliptic, precessing and changing orbit could energize the comet towards equipartition (as in the Fermi process) and ultimately throw it out. This was first pointed out, I believe, by Opik, and the earliest numerical calculations in support were done in 1965 by Arnold.

E. Everhart: Yes, in fact, I find this without using the restricted problem at all, by simply doing an exact calculation. A particle which is well bound to the solar system with not nearly enough energy to leave, sooner or later will be thrown out by repeated encounters with Jupiter. That was the second figure, showing 80 objects in circular orbits, and by 3000 revolutions some 20 of them had already been thrown out of the solar system.

S. Vaghi: I understand that for your question concerning the Jacobi integral, your conclusions were derived from an experiment, a very special experiment, concerning only Jupiter and Saturn, which is very far from the approximation of the 3-body problem. You know, perhaps, that in '72 a paper was published by Kresak, concerning the use of the Jacobi integral as a classificational and evolutionary parameter for comets and asteroids. I would like to know where he was mistaken.

DISCUSSION (Continued)

E. Everhart: That's one of the papers I am objecting to. I didn't mention any names, but it's simply that, for something like an asteroid, which doesn't get very far away from its home base, this might be all right, but for something like a comet, I don't think so. The comet can range all over its classifications at various times in its orbital evolution. That's one of the papers I would say is not valid.

G. Wetherill: I think you overstated the case against the use of the Jacobi integral in discussions of orbital evolution. If you recall your own figure, in which the evolution of the various orbital parameters is shown, you will find that the fluctuation from the mean value of the Jacobi integral is only 10-20 percent, whereas other quantities, such as the semi-major axis and the eccentricity, change by large factors. It would be better if you were to say that the Jacobi integral should not be misused rather than saying that it should not be used. Actually it is quite useful to follow the random walk of the Jacobi integral as well as that of other quantities, such as 1/a and e.

One way in which this is useful in is distinguishing phenomena which are essentially dependent on the eccentricity and inclinations of the planetary orbits from those which still would occur to about the same extent in a more simple solar system and therefore are not critically dependent on assumptions concerning the constancy of the present values of the eccentricity and inclination of the planets. When this point of view is taken, it turns out most of your conclusions would also be valid in a much simpler solar system. In contrast, one phenomenon which is essentially dependent on failure of the restricted 3-body problem is that of the evolution of nearly circular orbits into hyperbolic escape orbits. This was understood and discussed by Arnold in his Monte Carlo work published in the Astrophysical Journal in 1965. For this reason, as well as others, a discussion of the possible evolution into the Oort cloud of a comet initially in a near-circular orbit in the Jupiter-Saturn region does not say very much about the equivalent problem in the region of Uranus and Neptune.

The other comment I would like to make concerns the previous work regarding Comet Encke. I have carried out Monte Carlo calculations for short period comets in which the perturbation of Earth and Venus as well as those of Jupiter are included. It turns out that it is very difficult to reduce the aphelion to that of Encke by Earth or Venus perturbations on a time scale of 10^3 years. Such changes are found on a time scale of 10^6 years but are very improbable for a comet young enough to still be active. It is much more likely that Encke's present orbit is a consequence of non-gravitational forces.

E. Everhart: A comment about the Jacobi integral, I was stating that if you regard it as a time-varying quantity whose instantaneous value tells you something about the current orbit, then I will agree it's properly used, but that's not the way many people have used it.

N76-21073

NONGRAVITATIONAL FORCES ON COMETS

B. G. Marsden

I. EARLIER INVESTIGATIONS OF NONGRAVITATIONAL EFFECTS

The study of the nongravitational effects on comets began slightly more than a century and a half ago. As is well known, Encke (1819) demonstrated that comet 1819 I had a revolution period of not more than a few years and that the same comet had also been observed in 1786, 1795 and 1805. The observations clearly required that the revolution period be about 3.3 years, and Encke went on to remark that, after approximate allowance had been made for the perturbations by the planets, the average revolution period seemed to be 1207.9 days between 1795 and 1805, but only 1207.3 days between 1805 and 1819. As a result of a more refined computation of the planetary perturbations, the following year he (Encke 1820) was able to confirm these figures and find in addition that the average period between 1786 and 1795 was as much as 1208.1 days. It seemed rather clear that for some unknown reason the period was decreasing at a rate of about 0.1 day per period, and further confirmation of this was provided by the observations of the comet—now known as P/Encke—at its first predicted return in 1822.

Utilizing the mean motion n rather than the revolution period, we have

$$n = n_o + \text{(planetary perturbations)} + n_1\,(t-t_o), \qquad (1)$$

where for P/Encke and an epoch t_o in the first part of the nineteenth century, $n_o \approx 1075''\ \text{day}^{-1}$ and $n_1 \approx 0\overset{''}{.}10\ \text{day}^{-1}\ \text{revolution}^{-1}$. In order to explain this secular acceleration term n_1, Encke (1823) postulated that the comet moved under the influence of a resisting medium, the impeding force being

$$-Bv = \mu U v^p r^{-q}, \qquad (2)$$

where r and v are the comet's heliocentric distance and velocity, μ is the product of the gravitational constant and the mass of the sun, and the coefficient U is to be determined from the observations; Encke also assumed that $p = q = 2$. The equations of motion of the comet in rectangular coordinates thus become

$$\ddot{x} + \mu x r^{-3} = \partial R/\partial x + B\dot{x}\,, \tag{3}$$

with $x \rightarrow y, z$, dots denoting differentiation with respect to the time, and R being the disturbing function for the planetary perturbations. On application of the method of variation of arbitrary constants (or orbital elements) it follows that

$$n_1 = 3n\, C_{pq}\, M_{pq}, \tag{4}$$

where

$$C_{pq} = U n^p a^{p-q+2} \tag{5}$$

(a being the semimajor axis of the orbit), and

$$M_{pq} = \int_{E_0}^{E} (1 + e \cos E)^{\frac{1}{2}(p+1)}\, (1 - e \cos E)^{-\frac{1}{2}(p+2q-1)} dE, \tag{6}$$

e being the orbital eccentricity and E(t) the eccentric anomaly.

Encke's actual calculations were made, not in terms of rectangular coordinates, but in terms of orbital elements. He determined n_1 empirically using Eq. (1) and found that it was essentially constant, at least until his own investigations terminated with the apparition of 1858 (Encke 1860).

Asten (1878) then established that the observations of P/Encke up to and including those in 1868 could be satisfied with the constant value $n_1 = 0''.1044$ day^{-1} revolution^{-1} (giving $U = 1/862$), and he also found that there appeared to be a secular variation in the eccentricity--or more specifically in $\phi = \arcsin e$. If we denote this secular variation by ϕ_1, defined by an expression analogous to Eq. (1):

$$\phi = \phi_0 + (\text{planetary perturbations}) + \phi_1\,(t-t_0), \tag{7}$$

it follows from the resisting-medium hypothesis that ϕ_1 is given by an expression analogous to Eq. (4), namely,

$$\phi_1 = -\cot\phi\ C_{pq}\ (M_{pq} - N_{pq}), \tag{8}$$

where

$$N_{pq} = \int_{E_0}^{E} (1 + e\cos E)^{\frac{1}{2}(p-1)}\ (1 - e\cos E)^{-\frac{1}{2}(p+2q-3)}\ dE. \tag{9}$$

Hence

$$\frac{\phi_1}{n_1} = -\frac{\cot\phi}{3\ n}\ (1 - \frac{N_{pq}}{M_{pq}}). \tag{10}$$

The integrals in the expressions for M_{pq} and N_{pq} may conveniently be worked out in terms of elliptic functions, and for $p = q = 2$, it can be shown that

$$M_{22} = \frac{1}{3}[32\mathrm{E}\ (1 + e^2)(1 - e^2)^{-2} - 4\mathrm{K}\ (5 + 3e^2)(1 - e^2)^{-1}], \tag{11}$$

$$N_{22} = 8\mathrm{E}\ (1 - e^2)^{-1} - 4\mathrm{K}, \tag{12}$$

where K and E (modulus e) are the complete elliptical integrals of the first and second kind, respectively. For P/Encke, with $e = 0.8463$, we have $\mathrm{K} = 2.100$, $\mathrm{E} = 1.232$, and with Asten's empirical value of n_1 it follows from Eq. (10) that $\phi_1 = -3''.68$ revolution^{-1}. Since this is in fact almost precisely equal to Asten's empirical value of ϕ_1, it seemed that the resisting-medium hypothesis had been amply demonstrated as the correct explanation for the nongravitational effect. Backlund (1884) showed that the observations were compatible with any resisting-medium law in which $p + q \geqslant 3$, and that as $p + q \rightarrow \infty$ the theoretical value of ϕ_1 tends toward $-3''.86$ revolution^{-1}.

Furthermore, although the resistive coefficient U determined by Möller (1861) in the case of P/Faye was some two orders of magnitude larger than that found for P/Encke, the ratio ϕ_1/n_1 again seemed to be consistent with the resisting-medium hypothesis. Möller (1865) withdrew his result, however, and he was subsequently unable to detect any significant nongravitational effects on P/Faye; but then Oppolzer (1880) established for P/Pons-Winnecke that although ϕ_1 could not be measured, the value of U was the same as for P/Encke.

Asten (1878) also found, however, that it was impossible to represent the 1871 observations of P/Encke in the framework of his study of the motion during 1819-1868, and after much deliberation he concluded that this was perhaps due to perturbations by the minor planet (78) Diana. Backlund (1884) showed that the observations of P/Encke during 1871-1881 were in fact compatible with the resisting-medium hypothesis, but that n_1 (or U) was substantially smaller than before. Later he claimed (Backlund 1910) that relatively sudden changes had taken place, with n_1 decreasing from $0\overset{''}{.}13$ to $0\overset{''}{.}08$ day^{-1} revolution^{-1} in 1858, to $0\overset{''}{.}06$ in 1871 and to $0\overset{''}{.}04$ in 1895; there was possibly another jump in 1904, and furthermore, there seemed to be evidence for a small periodic variation in n_1 during 1819-1858. While retaining the basic idea that the secular acceleration was due to a resisting medium, Backlund felt that the comet should be regarded as experiencing collisions of short duration, perhaps with a ring of meteoric material orbiting the sun. Backlund's investigations were continued by Matkevich (1935) and Idel'son (1935), and more recently Makover (1955) assumed that the nongravitational perturbation took the form of an impulse acting on the comet exactly at perihelion. The most recent calculations of this type (Bokhan and Chernetenko 1974) show that n_1 has now decreased to only $0\overset{''}{.}01$ day^{-1} revolution^{-1}.

Similar computations during the nineteenth century on other comets were not at all conclusive. The conflicting results for P/Faye have already been mentioned, and in a later study on P/Pons-Winnecke, Haerdtl (1889) suggested that there was no secular acceleration. Leveau (1877) did not seem to think it necessary to introduce any secular variations into the orbit of P/d'Arrest; and Rahts (1885) fitted the 1858, 1871 and 1885 observations of P/Tuttle, and Gautier (1887) the 1867, 1873 and 1879 observations of P/Tempel 1, by gravitational theory alone. Schulhof (1898) suspected a slight secular acceleration in the case of P/Tempel 2, but he later found his calculation of the perturbations to be erroneous (Schulhof 1899). After P/Encke, P/Biela seems to be the first comet for which a reasonably convincing secular acceleration was established (Hepperger 1898). Maubant (1914) found a secular acceleration for P/Tempel-Swift. Lamp (1892) confirmed the calculation by Schulze (1878) of the perturbations on P/Brorsen during 1873-1879 and was forced to conclude that the error of 0.6 day in the predicted perihelion time in 1879 implied that this comet had experienced a large secular deceleration (i.e., n_1 was negative); this could certainly not be explained on the basis of the resisting-medium hypothesis. The 3-day error in the predicted perihelion time of P/Halley in 1910 (Cowell and Crommelin 1910) was also suspected as being due to a nongravitational secular deceleration, in spite of Brady's (1972) conclusion that this comet was instead being perturbed by a planet having the mass of Jupiter and traveling in a highly inclined orbit at twice the distance of Neptune. (The existence of such a planet can be ruled out on several grounds: e.g., Klemola and Harlan 1972, Goldreich and Ward 1972, Seidelmann *et al*. 1972, Kiang 1973.)

One of the difficulties with the older calculations is that the investigators frequently made solutions for the planetary masses at the same time. In his investigations on P/Encke, Backlund used values of the sun : Mercury mass ratio ranging from less than 3 000 000 to almost 10 000 000; and Haerdtl's dicussion of P/Pons-Winnecke led to 1047.1752 ± 0.0136, rather than a value closer to 1047.35, for the sun : Jupiter mass ratio. More recently, Rasmusen (1967) found that one could eliminate the need for nongravitational effects on P/Olbers (and apparently also on P/Halley) by changing the latter mass ratio to 1051 (!). In any case, approximations were made in the old calculations, and there are obvious problems with the observations of diffuse comets; many astronomers have therefore been skeptical of the results (e.g., Roemer 1961). Nevertheless, modern calculations confirm the general correctness of the old results for P/Encke, P/Pons-Winnecke (Oppolzer's figures), P/Biela, P/Tempel-Swift, P/Brorsen and P/Halley, and they confirm that the nongravitational effects on P/Tempel 1 and P/Tempel 2 are very small. Nongravitational effects ought to have been detected in the nineteenth century for P/Faye and P/Tuttle, and particularly for P/d'Arrest, although examination of the motion of this last comet was rendered difficult by a close approach to Jupiter in 1861, by the missed returns of 1864 and 1884 and the severe discordances among the observations in 1877.

In more recent times Recht (1939) established that P/d'Arrest has a definite secular deceleration, and Kamieński (1933) found a slight deceleration in the case of P/Wolf--at least before a close approach to Jupiter in 1922 caused a substantial increase in the perihelion distance of this comet. Dubyago (1950) found a large secular acceleration in the case of P/Brooks 2, and Evdokimov (1963) a large secular deceleration for P/Giacobini-Zinner. Sitarski (1964) derived a slight acceleration for P/Grigg-Skjellerup and more recently (Sitarski 1970) a larger acceleration for P/Wolf-Harrington.

As for comets having somewhat longer periods, Schubart (1968) found it necessary to assume a secular deceleration in order to fit the prediscovery observations of P/Tempel-Tuttle in 1699 and 1366; and Herget and Carr (1972) confirmed that the error in the prediction for P/Pons-Brooks at its 1954 return (Herget and Musen 1953) must have been due to a nongravitational secular acceleration.

II. MODERN METHODS FOR THE STUDY OF NONGRAVITATIONAL EFFECTS

Although the equivalent of Eq. (3) was written down long ago (Encke 1831), all the studies mentioned in Sec. I were done essentially by considering Eq. (1), and in some cases by considering also Eq. (7) and possibly also even similar equations in other orbital elements: for a further discussion on this point see Sekanina (1968). Our own initial study (Marsden 1968) was made basically in the same manner and differed from the earlier investigations only in that it included a treatment of as many as 18 comets in as uniform and rigorous a manner as possible. The possibility of using Eq. (3) directly was briefly considered at that time, but before any computations were actually done we decided (Marsden 1969) to generalize it to

$$\ddot{x} + \mu x r^{-3} = \partial R/\partial x + F_1 x r^{-1} + F_2 (r\dot{x} - x\dot{r}) h^{-1} + F_3 (y\dot{z} - z\dot{y}) h^{-1}, \quad (13)$$

where $h^2 = (y\dot{z} - z\dot{y})^2 + (z\dot{x} - x\dot{z})^2 + (x\dot{y} - y\dot{x})^2$, and the F_i obviously represent three rectangular components of the additional nongravitational force, with F_1 directed along the radius vector, F_2 also in the orbit plane (along the velocity vector at perihelion or aphelion and if the orbit is circular), and F_3 normal to the orbit plane.

It is important to point out that it was not our desire to favor any particular theory concerning the true physical nature of either the nongravitational forces or of comets generally. We felt that Eq. (13) was of a sufficiently general form for deriving useful information about the nongravitational forces whatever their cause, and that even if the forces were entirely impulsive and discontinuous, this fact would become apparent from our studies.

Some experimentation was carried out as to the dependence of the F_i on r. It was quickly established that a simple r^{-2} or r^{-3} law was unsatisfactory, for beyond some 2 to 3 AU from the sun the nongravitational forces diminished very considerably. This was evident both from attempts to link successive apparitions of a number of comets and from the fact that the motions of the short-period comets of largest perihelion distance (notably P/Oterma and P/Schwassmann-Wachmann 1) seemed to be entirely unaffected by any nongravitational influence. Somewhat at random, we selected the form $r^{-3} \exp(-r^2/2)$, with r measured in AU, and the fact that solutions made using this law for various comets and over various timespans yielded results that were generally very regular and consistent (Marsden 1969, 1970; Yeomans 1971; Marsden and Sekanina 1971) gave us some confidence that the extraneous forces with which we were dealing were basically continuous, rather than impulsive, in nature.

Among the regularities was the fact that the radial component was generally directed outward from the sun and perhaps an order of magnitude larger than the transverse component, which was equally likely to be in either direction; the normal component was never significant. There were changes with time, but particularly in the case of the better-determined transverse components, it seemed that these changes were generally very smooth and uniform: contrary to Backlund, we concluded that a sudden change in the nongravitational influence on a comet was a relatively rare phenomenon.

Interaction with a resisting medium, or indeed any kind of collisional process, would therefore seem to be ruled out, at least as the basic cause of the nongravitational forces. The nonrandom form, and the absence of any nongravitational influence, not only on the orbits of comets of large perihelion distance, but also on those of some particularly stellar-looking comets of smaller perihelion distance (e.g., P/Arend-Rigaux and P/Neujmin 1), make it extremely difficult to argue in favor of any kind of "sandbank" model for comets. Of the cometary models that have ever been seriously proposed this leaves only the icy-conglomerate model (Whipple 1950) and the supposition that the nongravitational forces are reactive in nature (as in fact was first suggested by Bessel 1836). The general predominance of the radial component, and the fact that it usually acts outward from the sun, are definite points in favor of this model. This finding is actually an added bonus, for it implies that the angle by which the direction of maximum mass ejection from the comet lags behind the subsolar point would generally be very small, a point that is certainly not obvious when one considers the general problem of heat conduction through a rotating icy cometary nucleus (Whipple 1950).

Several other, completely different avenues of cometary research have led in recent years to the strong likelihood of the correctness of some kind of icy-conglomerate model. Delsemme and Miller (1971) have examined the problem of the variation of the rate of sublimation of possible ices in comets with heliocentric distance, and Delsemme and Delsemme (1971) were able to fit the function

$$g(r) = \alpha \left(\frac{r}{r_o}\right)^{-m} \left[1 + \left(\frac{r}{r_o}\right)^{n}\right]^{-k} \tag{14}$$

to their sublimation curve for water ice within ± 5 percent over the range of heliocentric distance 0.1 to 4.0 AU. This formula, and their numerical values ($m = 2.15$, $n = 5.093$, $k = 4.6142$, $r_o = 2.808$ AU, together with the normalizing coefficient $\alpha = 0.1113$), have been used in all the more recent calculations of cometary nongravitational parameters A_1 and A_2 (Marsden et al. 1973, Marsden and Sekanina 1974, Yeomans 1974), these parameters being defined by

$$A_i = F_i \, g(r) \qquad (i = 1, 2) \tag{15}$$

and determined from observations covering spans of time during which they can be treated as constant. Delsemme and Miller (1971) assumed that the visible absorptivity κ and the infrared emissivity ε of the water ice were each 0.9, and it can be shown that the results would be essentially the same whenever κ and ε have identical values. Changes in absorptivity and emissivity, as well as to other ices, can be handled, very simply but to a good degree of approximation, by retaining the above values of m, n and k and changing r_o to

$$r_o = 2.808 \, (\kappa/\varepsilon)^{\frac{1}{2}} \, (L_o/L)^2 \text{ AU}, \tag{16}$$

where L is the vaporization heat of the ice in question and L_o that of water ice. The significance of r_o is that beyond that distance from the sun most of the solar radiation incident on the comet is reradiated. Our fits to the observations of actual comets suggest that 1 AU $\lesssim r_o \lesssim$ 4 AU, and since for all other postulated cometary ices $L \ll L_o$, these other ices can be considered as dominant constituents only if $\kappa \ll 1$ (i.e., if the albedo is almost unity).

III. RESULTS FOR INDIVIDUAL SHORT-PERIOD COMETS

Fig. 1 shows the results of the computations of A_1 and A_2 for several comets, the units of these accelerations being AU per (10^4 days)^2. Converted to mass-loss rates these nongravitational parameters suggest that something like 0.2 to 0.3 percent is lost from each comet in one revolution (Sekanina 1969). For most of the comets several points are shown: they were derived from observations covering successive timespans, and the arrows indicate the direction of increasing time. The problem with this plot is that A_1 is usually very badly determined in relation to A_2, and even though the A_1 scale is only one-tenth the A_2 scale, there appear to be large discontinuities in the curves for several of the comets. Only the changes in A_2 with time are really significant, and it can be seen that whereas P/Brooks 2, P/Schwassmann-Wachmann 2, P/Encke and P/Forbes have values of A_2 that decrease (in absolute value), A_2 remains almost constant for P/d'Arrest, P/Tuttle and perhaps also P/Grigg-Skjellerup; in the cases of P/Pons-Winnecke and P/Kopff there are smooth transitions of A_2 through zero, whereas the A_2 values for P/Finlay, P/Comas Solá and P/Tuttle-Giacobini-Kresák show much greater irregularities. The rather anomalous result for P/Jackson-Neujmin is somewhat suspect because there are only two apparitions (in 1936 and 1970); nevertheless, it is certainly not possible to link these two apparitions by gravitational theory alone. The relatively large values of $|A_2|$ for P/Brooks 2 and P/Schwassmann-Wachmann 2 might be an artifact of the model (specifically the adoption of $r_0 = 2.808$ AU), for these comets have perihelion distances of 1.8-2.2 AU. On the other hand, the majority of the comets (those having $|A_2| \lesssim 0.1$) have perihelion distances ranging all the way from 0.3 to 1.8 AU; and it could be that in P/Brooks 2 and P/Schwassmann-Wachmann 2, which are "new" comets only recently perturbed in from much larger perihelion distances, we are seeing the result of the vaporization

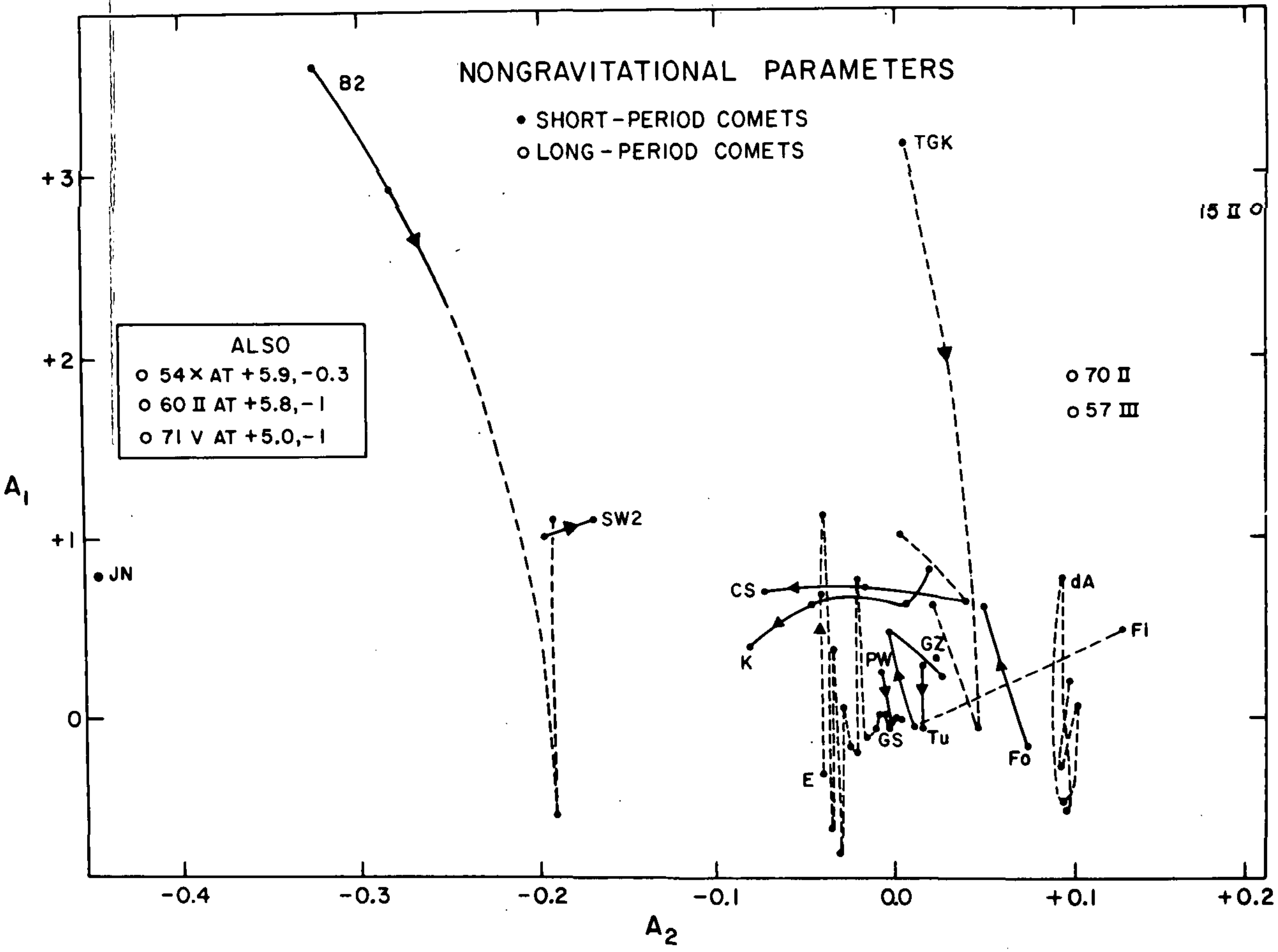

Fig. 1. Nongravitational parameters $\underline{A}_1$ and $\underline{A}_2$ for the short-period comets B2 (Brooks 2), SW2 (Schwassmann-Wachmann 2), JN (Jackson-Neujmin), CS (Comas Solá), K (Kopff), E (Encke), PW (Pons-Winnecke), GS (Grigg-Skjellerup), Tu (Tuttle), GZ (Giacobini-Zinner), TGK (Tuttle-Giacobini-Kresak), Fo (Forbes), dA (d'Arrest) and Fi (Finlay); and for the long-period comets 1915 II, 1954 X, 1957 III, 1960 II, 1970 II and 1971 V.

of a rather limited supply of free material that is much more volatile than water ice (Marsden et. al. 1973).

More useful for studying the variations of the nongravitational parameters with time is Fig. 2, which shows A_2 for P/Encke over the past two centuries (Marsden and Sekanina 1974). The decrease in $|A_2|$ (or in n_1) is seen to persist only since about 1820, before which time $|A_2|$ was increasing. We must leave it to our descendants to establish whether P/Encke acquires a secular deceleration during the twenty-first century, but there does seem to be a suspicion (first indicated, in fact, by Michielsen 1968) that the variation of A_2 can perhaps be represented by a damped sinewave. The sinewave could arise, for example, from slow changes in the direction of the axis of rotation of the comet (Marsden 1972, Sekanina 1972), whereas the damping could be a consequence of the core-mantle nuclear model (Sekanina 1969), in which the remaining icy content of the nuclear core is redistributed after each revolution without any shrinkage in the radius of the core. Eventually the comet could become inert [like (944) Hidalgo and perhaps some of the Apollo asteroids; P/Arend-Rigaux and P/Neujmin 1 appear to be comets that have almost reached this stage], although exact predictions of death date will be complicated by any continuing sinusoidal oscillations.

A few comets show large irregularities in their nongravitational parameters. To the ones already mentioned we can add P/Perrine-Mrkos, P/Schaumasse and P/Giacobini-Zinner, as well as the lost comets P/Biela, P/Brorsen, and perhaps also the other two lost comets (of more than one appearance) P/Tempel-Swift and P/Neujmin 2. (The last-named comet has been observed only twice, but a gravitational orbit solution is not completely satisfactory. To the list we could perhaps also add P/Westphal, the two

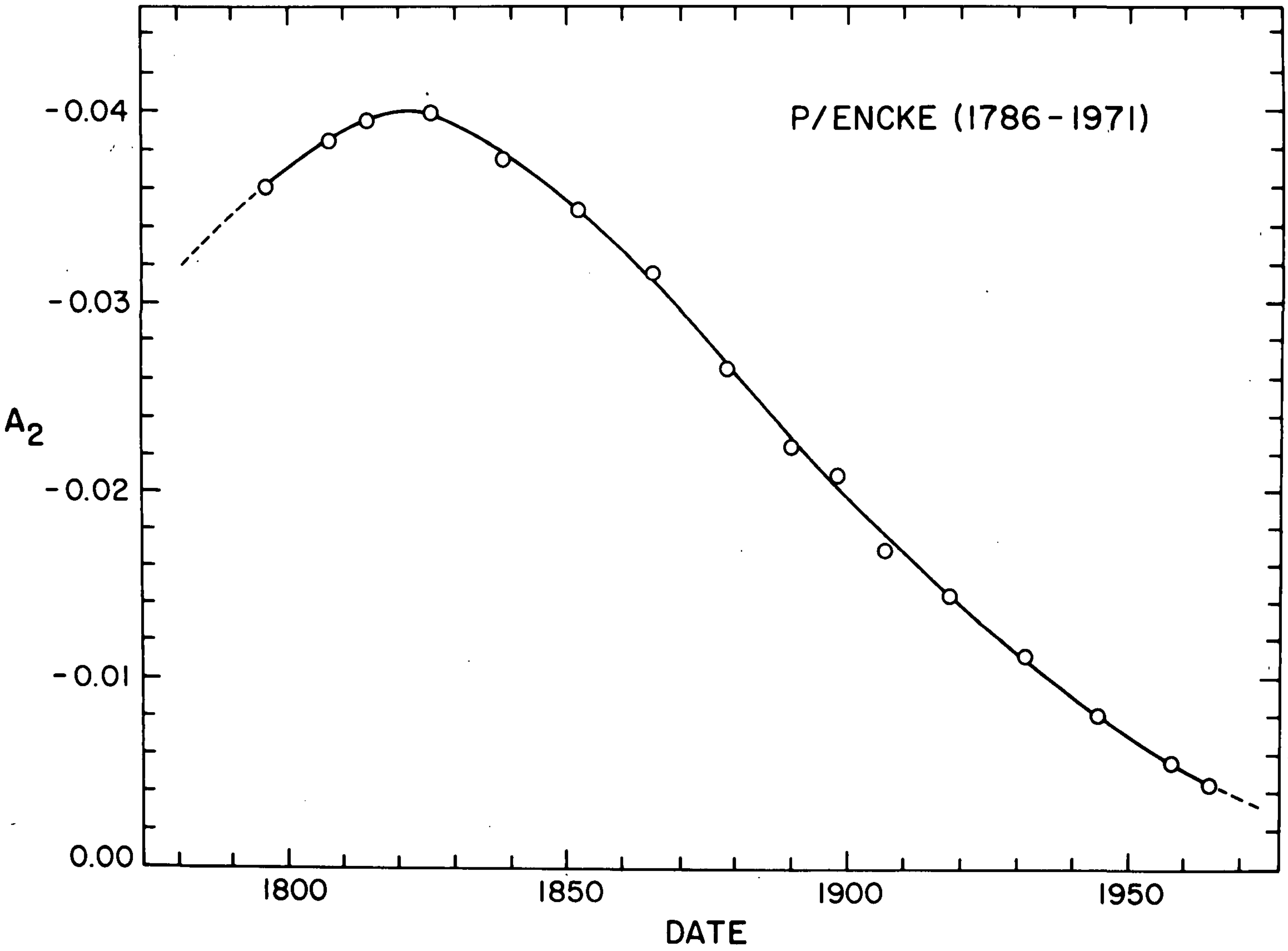

Fig. 2. The nongravitational parameter A_2 for P/Encke during 1786-1971.

apparitions of which cannot be linked at all well: this comet faded out before perihelion in 1913, and it is somewhat questionable whether it can be reobserved at its forthcoming return in 1975/76.) The possibility that these irregularities are due to collisions of the comets with small interplanetary boulders has been discussed in some detail (Marsden and Sekanina 1971), and it has been suggested that some comets are much more prone than others to collisional damage because their nuclei consist basically of low-density, high-albedo, snow-dust "mantle" material. On the other hand, it seems not at all out of the question that the irregularities in the nongravitational parameters are due to <u>sudden</u> changes in the directions of the axes of rotation of the comets (Marsden 1972), such changes arising when solar radiation has reduced the nucleus to an unstable shape. More theoretical and perhaps experimental (along the lines initiated by Kajmakov et al. 1972) work is needed on this problem.

IV. LONG-PERIOD COMETS

Fig. 1 also contains points for six long-period comets, each observed at a single perihelion passage. For a one-apparition comet A_1 is the better determined of the nongravitational parameters, although it is nonetheless very uncertain. It is encouraging, however, that positive values of A_1 have been obtained in each case (see also Marsden et al. 1973). As one might expect, there seem to be no cases of one-apparition comets of large perihelion distance that show the effects of nongravitational forces. On the other hand, these six comets are the only "nongravitational" cases encountered among several dozen suitable candidates for which new orbit determinations have been made.

Why should comet 1960 II, a comet strikingly lacking in dust, have a large A_1, detectable even though the observations cover less than six months, when the spectacular "dusty" comets 1957 III and 1970 II have only moderate A_1 values? And why don't well-observed comets like 1962 III and 1973f, which had particularly small perihelion distances, show any nongravitational effects at all? Little progress has been made toward answering these questions, and it is clear that more data on the possible detectability of nongravitational parameters for long-period comets are needed.

The unknown nongravitational forces acting on long-period comets must modify the derivation by Oort (1950) of the extent of the cloud of comets that is believed to surround the solar system: if only the comets of large perihelion distance are considered, it seems that the outer extreme of the cloud can scarcely be distant more than 50 000 AU, which is only about one-quarter of the result obtained by Oort (Marsden and Sekanina 1973).

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DISCUSSION

L. Biermann: I am just a little bit troubled by the absence or smallness of the non-gravitational normal forces in several well studied cases. For comet Humason the exceptional value of the surface to volume ratio might play an important role. The other cases seem to require or at least to support almost isotropic emission of the gases from the nucleus, such that no net reaction force remains. What are your ideas on this?

B. G. Marsden: I think that the gases that are being emitted from the comet Humason are not the principal constituent. Inside there you've got a lot of water-ice and not a great deal of it would vaporize in that case. The perihelion distance is only about 2.1 astronomical units. You get a bit of it, but even though it's a very active comet, really, in relation to the total mass of the comet, not very much was coming out.

The question as to whether it comes out in all directions, of course they would cancel out on the forces and this has been suggested in the case of comet Schwassmann-Wachmann 1. These outbursts of comet Schwassmann-Wachmann 1 may be isotropic but I think Dr. Roemer's observations of the outbursts of 1 show that they really aren't very isotropic.

D. J. Malaise: Did you ever try to estimate what is the amount of energy involved in the orbital change and how it would compare with the amount of energy in the rotational motion of the nucleus?

B. G. Marsden: No, we haven't actually done that. I should have. Dr. Sekanina determined the mass loss but that's about as far as we have gotten.

D. J. Malaise: I mean if the anisotropic evaporation gives you changing orbits and things like that, you might think that this is a process which is not directed. You might expect some equipartition of these effects on the translational motion of the orbit and on the rotational motion of the nucleus. So if you know what energy is involved in the translational motion of the orbit change, you can estimate how the rotation of the nucleus would change.

F. L. Whipple: I'll speak to that a bit.

Of course the total energy calculated in 1950 for the angular momentum about the sun with regard to rotation, these forces are fairly large. It wouldn't take very long if you could get all of the gas ejected on one side to give you a moment about the center to change the period very quickly.

I think that just a revolution or two would do for these comets. It's rather large. But of course you don't expect that.

The asymmetry comes from the sublimation of the material asymmetrically about the equator which then gives you a small component which can produce a procession effect in the axis. And I think that's what happens to Encke. It's a little tricky to work it out.

I think I may get back to it again with numerical integration.

E. Gerard: How could you explain that $A/\hat{2}$ could go from positive to negative values?

B. G. Marsden: This is just the axis of rotation going through the orbital plane. If the axis of rotation is in the orbital plane, you wouldn't get an $A/\hat{2}$ component.

Voice: Can you elaborate perhaps on the last point you made about the Oort cloud shrinking because of the non-gravitational forces, and also the possible evolutionary effects on a long-period orbit caused by the non-gravitational forces?

B. G. Marsden: We haven't been able to come up with any real theoretical reason as to why there is this shrinkage. All of the arguments that have been made by various people on this subject have some fallacy in them. They just are violating some factor in celestial mechanics.

This was entirely established numerically when you use that law, Delsemme's law. Then we found that 1/a was changed in a systematic manner for positive values of a/1, but we don't know why. I'm sorry.

The change in 1/a, yes. Well, we did try and study the contribution of the non-gravitational effects on that, but of course the problem here is really with the transverse components we don't know at all well in the case of the long-period comets and they could have quite a considerable change.

F. L. Whipple: I think your point was that there's a slight change in 1/a induced by the non-gravitational forces, which therefore affects the calculated outer dimension of the orbit.

B. G. Marsden: This was in Oort's own figures. With a large perihelion distance you don't have this problem, you see.

M. Dubin: On the rotation of the comets which you require to explain the over-all perturbations, have you had enough information to give a classification of the speeds of rotation and the directions of rotation?

DISCUSSION (Continued)

B. G. Marsden: It's not only rotation; it's the conductivity as well, which is tied in with this inextricably. One can't separate them.

M. Dubin: How can you possibly allow that the speed of rotation will not increase indefinitely and keep adding angular momentum by this process — a clear acceleration process? Wouldn't it be required that comets spin up to extremely high speeds, as with the Kopsky-Rajiski effect of meteorites?

B. G. Marsden: Since we sometimes observe the same value of the lag angle λ for a long period of time, I wouldn't have thought that there was any very obvious increase in rotation rate.

F. L. Whipple: We have yet to find the period of rotation of any comet. There is one case in which it looks as though there might be a 1.4-day period, but I question that one. This was for comet Bennett.

B. G. Marsden: It would be very nice if somebody would determine a good rotation period for a comet. There should be an opportunity to do this in 1978, when comet Arend-Rigaux returns. This comet will be no brighter than sixteenth magnitude, but it is very stellar, and with image tubes and modern techniques I think a good light curve and hence the rotation period could be determined.

G. H. Herbig: I would like to ask two questions — first about the significance of what I believe is the fact that the major axes and the inclinations of the long-period comet orbits indicate a rather isotropic distribution around the sun. This has been compared to the similar situation in the globular cluster orbits, high velocity star orbits around the center of the galaxy indicating a spherical halo around the galactic system which, in this case, is believed to reflect the shape of the pre-galactic cloud. Now my question is: in the case of the comets, perturbed as they must be by planets moving in the direct sense, what can you say about the analogy? What can you say about the cosmogonical significance of this isotropic distribution of cometary orbits about the sun?

B. G. Marsden: I don't know that one can say very much, except that there is a complex interplay of both planetary and stellar perturbations.

F. L. Whipple: Oort answered that, and I think Öpik probably did, too, back in 1932. With these large aphelion distances. I'm talking about 20,000 or more astronomical units, that order of magnitude, the passing stars very quickly disturb the inclination so that there is no expected orientation; even though there had been originally a plane, the passing stars destroy the evidence.

G. H. Herbig: So it could be then that these were all ejected from a flattened solar nebula disk, and the isotropy now just reflects stellar perturbations?

DISCUSSION (Continued)

F. L. Whipple: That's what Oort said.

G. H. Herbig: Is that true?

B. G. Marsden: We can't say. This goes back to our discussion yesterday afternoon. You can't say whether the comet originated out there at the great distances or just beyond the orbit of Neptune and were thrown out by Neptune, or maybe Neptune was made from comets and thrown out a little bit and then stars would start taking over.

All it takes, really, is one star coming along in an appropriate manner and you can do anything. There is a nice movie showing that sort of thing. Of course it applies to globular clusters.

G. H. Herbig: Well, my second question was those pictures of the eruption of the Schwasmann-Wachmann comet that we saw yesterday in which the expanding cloud had a corkscrew or a spiral form, this sort of looks like conservation of angular momentum in radially ejected material.

If you do interpret that structure in that way, is it consistent with cometary rotations and so forth that you infer from your theory?

B. G. Marsden: Well, we don't observe any non-gravitational effects on that comet. This is the trouble.

The spiral cloud you just mentioned, this was comet Bennett, wasn't it?

F. L. Whipple: No, it was another one, another one in the late '50's. I can't remember the name of it. It had a four-day period in oscillation and brightness. Malaise studied it.

B. G. Marsden: The wagging tail?

D. J. Malaise: Burnham, there were two of the others which were like that.

F. L. Whipple: Nobody can prove that that was rotation.

By the way, it takes a mass of micron size particles about the size of this room to produce the burst on Schwasmann-Wachmann. It's a very small amount of material.

DISCUSSION (Continued)

B. Donn: With regard to rotation, there is the phenomena of jets that have been occasionally observed coming out of comets in a rather narrow angle and persisting in the same direction for relatively long periods of time. If you talk about Schwassmann-Wachmann showing some sort of a spiral action, here you have a case where there is no indication of any change over periods, I think in some cases, of several days when these jets persist, which is very hard to explain, but that's what has been seen.

E. Roemer: In reference to the outbursts of P/S-W 1, the diffuse envelope gives the appearance of a filled shell of non-uniform surface brightness in which the orientation in position angle of structural features seems to be preserved during a radial expansion for time intervals of more then a month. I don't think that any information can be extracted from the surface brightness distribution as to the rotation of the nucleus on the basis of conservation of angular momentum of the ejected particles.

L. Biermann: Concerning these screw-type structures, I believe these are plasma structures. Of course the rather old explanation is that these are a consequence of almost force-free magnetic fields, and at least one needs magnetic fields anyway for different reasons. They are something which might be considered, and doesn't seem to be far-fetched.

H. U. Schmidt: May I come back to Professor Biermann's first question? I wonder whether you have answered the question really because as far as I understood the question, the big comets like Humason were excluded in that question and the question went to those smaller objects where one would really worry if there are no non-gravitational effects.

F. L. Whipple: Yes, that's the thing with the large comets, one revolution at a long period. Most of them are rather large bodies and it is difficult to get enough force to do very much while the small ones in large measure show it, except these that do not show any coma, the one or two cases.

B. G. Marsden: What about Kohoutek?

F. L. Whipple: Yes. But if it is not rotating, it is very difficult to pick up the change due to a radial force.

F. L. Whipple: (?): Would you be able to determine the radial component of the nongravitational force on comet Kohoutek?

DISCUSSION (Continued)

B. G. Marsden: If it were as large as that on comet Arend-Roland, I certainly think so. I don't know why some of the long-period comets show nongravitational forces and others don't.

F. L. Whipple: There is always the worry that the optical center of light that you measure may not reflect the center of the actual mass, namely, the nucleus, I don't know how to resolve that problem. It could upset these calculations on the single-apparition comets.

B. G. Marsden: I agree, although in some cases there are residuals of up to five or six seconds of arc, and for the long-focus observations I think it unlikely that the difference between center of light and center of mass could be so large. However, if the results from single-apparition comets were all the evidence we had on the existence of nongravitational forces on comets, I should be very skeptical.

D. A. Mendis: I would like to ask a question about the effect of the evaporating gases on the spin of a comet if the comet is not very regular. In that case, the axis of the expanding gas need not necessarily pass through the center of mass of the comet and this would give it a kick, not only in linear momentum but also in angular momentum, and this could probably either spin up or spin down the comet.

F. L. Whipple: Yes. I have spent quite a bit of time worrying about why comets split, particularly in the case of the new comets. The most rational explanation seems to be that they spin up.

It is almost impossible to find any other solution that will cause a comet to split except asymetric ejection of material that will cause a spin up. And you can very easily postulate shapes and conditions under which that effect would be very marked.

So it is quite possible, but how do you prove it?

W. Jackson: I thought Opik once wrote a paper saying that splitting of comets could occur through gravitational – breakup inside the Roche limit of the sun, I think is the word.

F. L. Whipple: That of course is in the sun-grazing comet families—the sun-grazing comets. There you do split off pieces. But the fact that the nucleus remains has been one of the strongest arguments for a discrete nucleus because if you had a gravel bank, nothing would remain.

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REVIEW OF INVESTIGATIONS PERFORMED IN THE U.S.S.R. ON CLOSE APPROACHES OF COMETS TO JUPITER AND THE EVOLUTION OF COMETARY ORBITS

E. I. Kazimirchak-Polonskaya

INTRODUCTION

The problem of the cosmogony of the solar system has long occupied a central position in astronomical research. The origin of comets plays a substantial role in the solution to this problem. It is therefore necessary to study in detail the "original" and "future" orbits of the comets with nearly parabolic orbits and to examine in particular the great orbital changes that take place when comets pass within the spheres of action of the giant planets.

In the U.S.S.R. -- especially at the Institute for Theoretical Astronomy (I.T.A.) in Leningrad -- considerable attention is paid to investigations of this type. In this respect it is useful to refer to IAU Symposium No. 45, organized in Leningrad in 1970, and in particular to the introductory report by Chebotarev (1972).

1. CALCULATION OF DEFINITIVE, ORIGINAL AND FUTURE ORBITS OF NEARLY PARABOLIC COMETS

Early work in this field was carried out by Mikhajlov (1924), Sakk and Kulikov (1951), Dirikis (1953, 1954), Galibina (1953), and Shmakova (1953).

Makover (1955a) developed a special method for calculating the original and future orbits of long-period comets; the method involves taking the true anomaly, rather than the time, as the independent variable. Several definitive, original and future orbits have been determined (Dirikis 1956; Barteneva 1955, 1965, 1970, 1971; Galibina 1958, 1963, 1964; Galibina and Barteneva 1965; Belous 1960, 1964, 1966, 1970). Galibina (1964) established that although the overwhelming majority of the original orbits were elliptical, about one half of the comets with definitive hyperbolic orbits continue to have hyperbolic orbits in the future and will therefore leave the solar system. Very similar results were obtained by Brady (1965). Reference should also be made to Sekanina's (1966) general catalogue of definitive, original and future orbits.

2. EARLY SOVIET INVESTIGATIONS OF THE GREAT TRANSFORMATIONS OF COMETARY ORBITS IN JUPITER'S SPHERE OF ACTION

The first work in the U.S.S.R. involving the investigation of large perturbations on cometary orbits and the successful prediction of the returns of short-period comets was carried out by Dubyago and Lexin (1923) and by Dubyago (1924, 1925).

Dubyago (1932a, 1932b, 1936, 1946, 1950, 1956a, 1956b) constructed a numerical theory for the motion of P/Brooks 2 from before the comet's discovery in 1889 to 1960, taking into account the perturbations by the planets Venus to Saturn and a variable secular acceleration. He also studied two passages of the comet through Jupiter's sphere of action, to minimum distances of Δ_{min} = 0.000964 AU from Jupiter in 1886 and Δ_{min} = 0.086 AU in 1922. In studying the first approach, he took into account the perturbations due to the Galilean satellites (although the effect proved to be negligible) and to Jupiter's oblateness. He also considered and dismissed the question, first raised by Poor (1894), of the possible collision of P/Brooks 2 with Jupiter's satellite V as the reason for the comet's disruption.

Subsequently, Dubyago (1955a, 1955b, 1956c) was engaged in research on the motion of P/Shajn-Schaldach and the great transformation of its orbit that took place during a close approach to Jupiter shortly before the comet's discovery in 1949. He also conducted theoretical investigations into the structure of comets and their possible disruption under the influence of Jupiter's destructive forces (Dubyago 1942) and into the nongravitational forces that affect the motions of comets (Dubyago 1948). Some of his ideas on the structure of the cometary nucleus are closely related to those of Whipple (1950, 1951); Dubyago (1948, 1956a) considered the dependence of the nongravitational forces on solar activity, on the perihelion distance of the comet and on the orientation of the comet's orbit.

An early work by the present author (Kazimirchak-Polonskaya 1950) included (1) a history of the studies of the motions of 32 short-period comets that approached Jupiter and other major planets; (2) a description of methods for considering the nongravitational effects on the motions of comets and a survey of the various hypotheses made between 1830 and 1950 on the causes of these effects; (3) the suggestion of a series of studies that might be made of orbital transformations for comets passing through and near Jupiter's sphere of action; and (4) the description of a new jovicentric method using special rectangular coordinates and taking into account the perturbations by the sun and planets, and the application of this method to a study of the motion of P/Wolf within Jupiter's sphere of action in 1922 (Δ_{min} = 0.125 AU). The comparison of these calculations on P/Wolf with the observations in 1925, as well as with the calculations (using a heliocentric method of variation of arbitrary constants) by Kamieński and Bielicki (1935), was very favourable.

Sochilina (1958) studied the changes in the orbit of P/du Toit-Neujmin-Delporte when that comet passed near Jupiter's sphere of action in 1954 (Δ_{min} = 0.656 AU) and noted that the mean motions of the comet and Jupiter would then be very close to 2:1 commensurability; Fokin (1958) studied the extended passage of P/Oterma through Jupiter's sphere of action (Δ_{min} = 0.168 AU) during 1936-1938, and Merzlyakova (1958) investigated that of P/Ashbrook-Jackson (Δ_{min} = 0.178 AU) in 1945.

A re-examination by Kastel' (1965) of the very close approach of P/Brooks 2 to Jupiter in 1886 gave Δ_{min} = 0.000985 AU, closely confirming the earlier result by Dubyago (1950).

3. DIFFERENCES AND DIFFICULTIES IN METHODS USED FOR THE CALCULATION OF LARGE PERTURBATIONS BY JUPITER

A statement of the problem and a review of research on the close approaches of short-period comets to Jupiter during 1770 - 1960 were given by Kazimirchak-Polonskaya (1961a, 1961b). The approaches of 33 short-period comets were discussed, and differences and difficulties in the methods used by the various authors were analyzed. The possibility of using these approaches to determine a more accurate value for the mass of Jupiter was demonstrated; such a determination has recently been made in the case of P/Wolf, for example (Kazimirchak-Polonskaya 1972a). A number of questions arise:

(1) What method -- variation of arbitrary constants, perturbations in rectangular coordinates, or whatever -- provides the most accurate results in calculations on the transformations of cometary orbits in the spheres of action of Jupiter and other planets? A number of investigators (e.g., Rasmusen 1935; Herget 1947; Dubyago 1956a; Marsden 1963, 1967; Marsden and Schubart 1965; Stumpff 1972; Klepczynski 1972) have applied Cowell's well-known method of perturbations in rectangular coordinates. On the other hand, Merton (1927), and especially

the Polish astronomers (Kamieński 1925, 1926, 1948a, 1948b, 1951, 1957, 1959; Kamienski and Bielicki 1935, 1936; Kepiński 1958) have utilized the method of variation of elements, defending it as being the most accurate method for calculating passages through Jupiter's sphere of action.

(2). What kind of method -- heliocentric or jovicentric -- should be preferred for very deep penetrations of comets into Jupiter's sphere of action? This is a very cogent question, for there are often severe discrepancies between the results of heliocentric and jovicentric methods applied to the same calculation.

(3) What differential formulae should be used in order to allow -- without repeated integration -- for small additional perturbations, such as those by Jupiter's satellites or by nongravitational forces?

(4) What criterion should be used in choosing the step-size for the integration?

4. THE CHOICE OF AN EXPERIMENTAL OBJECT FOR CHECKING THE VARIOUS METHODS

In order to overcome some of the difficulties mentioned in the previous Section it is useful to select a special experimental object. P/Wolf is an appropriate choice for three reasons: (1) the numerical theory for the motion of this comet was very skillfully constructed by Kamieński (1959) for the two isolated intervals of time 1884 - 1918 and 1925 - 1959; (2) P/Wolf passed close enough to Jupiter in 1922 that the correctness of the calculations can be verified by examining the pre-1922 and post-1922 observations/ and (3) the nongravitational forces on P/Wolf are practically insignificant.

The planetocentric method has been developed in special coordinates (Kazimirchak-Polonskaya 1962a). Taking P/Wolf as an example, the author demonstrated the practical equivalence of the method of variation of arbitrary constants and the method in special rectangular coordinates, both in difference and in quadrature forms. Question (1) of the previous Section was therefore answered.

Some advantages of the method in special coordinates, as opposed to Cowell's method, have been demonstrated (Kazimirchak-Polonskaya 1961c); the jovicentric form of the new method was worked out; and it has been demonstrated that the heliocentric and jovicentric methods give practically identical results in the case of P/Wolf. Table 74 of the cited paper contains the answer to Question (2).

Question (3) was solved by developing Encke's method in planetocentric form (Kazimirchak-Polonskaya 1962b) and by producing a series of differential formulae for taking into account various small perturbations. The procedure was applied to the calculation of the perturbations by Saturn on P/Wolf during the encounter with Jupiter in 1922.

As regards Question (4), the author has developed a new criterion that gives the integration step size as a function of the distance of the comet from sun and all perturbing planets.

5. CONSEQUENCES OF THE DEVELOPMENT OF ELECTRONIC COMPUTERS

The rapid growth of electronic computers has opened up many new areas of research on the motions of the minor bodies of the solar system (Kazimirchak-Polonskaya 1967a, 1967b, 1972b, 1972c; Kazimirchak-Polonskaya et al. 1968, 1972;

Kazimirchak-Polonskaya and Terent'eva 1973). Among these numerous problems we shall mention only two: (1) the construction of numerical theories of motion covering the whole period of observations of each comet, with full allowance for planetary perturbations and the effects of nongravitational forces; and (2) the investigation of the evolution of cometary orbits over the 400-year interval 1660 - 2060. The problems are closely related, and in practice the second one will be solved in conjunction with the first in the form of successive approximations.

The remainder of this review will be concerned mainly with the second problem, which can be subdivided as follows: (a) studying the orbital evolution of short-period comets of two or more apparitions; (b) redetermining the orbits of the short-period comets of only one apparition and then investigating the orbital evolution by a special method; (c) classifying the various approaches to the major planets and establishing the principal characteristics of the evolution of cometary orbits; (d) studying the transformations of the orbits of fictitious comets passing within the spheres of action of Uranus and Neptune and examining the mechanism whereby comets may be captured by these planets; (e) elucidating of the role of the giant planets in the evolution of cometary orbits; (f) specifying the successive stages in the evolution of cometary orbits, with consideration given to the stellar perturbations and the diffusion theory for long-period comets; and (g) analyzing all hypotheses on the origin of comets and developing the most probable hypothesis linking, as far as possible, all comets into a single complex.

6. INVESTIGATIONS ON THE EVOLUTION OF COMETARY ORBITS AND COMETARY CAPTURE

In an important series of papers, Everhart (1967, 1968, 1969, 1970, 1972a, 1972b, 1973) has applied and improved the statistical methods dating back to Newton (1878, 1893). Havnes (1972), using a simplified formulation, arrives at particular conclusions concerning the dominant influence of Jupiter on the evolution of cometary orbits. As a complement to these studies Kresák (1957, 1972a, 1972b, 1973) has made extensive investigations in which the Jacobi integral in the problem of three bodies is used for solving various cosmogonic questions, and somewhat similar approaches have been made by Vaghi (1973a, 1973b) and Lowrey (1973).

Marsden (1963, 1967, 1970) Marsden and Aksnes (1967), Stumpff (1972) and Klepczyncki (1972) have carried out exhaustive research on orbital transformations of different comets in Jupiter's sphere of action by Cowell's method, or more recently by using the numerical integration program of Schubart and Stumpff (1966).

The Soviet astronomers also invariably use numerical integration programs in their research. Full allowance is made for planetary perturbations, and the methods are continually being improved in order to make them suitable for more and more precise modelling of real cometary motion, even when comets penetrate very deeply into the spheres of action of the major planets.

7. METHODS AND COMPUTER PROGRAMS AT I.T.A.

The complex of computer programs at I.T.A. includes routines for numerical integration, reduction of observations, comparison of calculations with observations and improvement of orbits. At present there are in use three essentially different methods of integration and corresponding sets of programs for the BESM-4 computer; those by Belyaev (1972), Bokhan (1972) and Kazimirchak-Polonskaya (1967c, 1972b). They supplement and, if necessary, are used to check each other.

In the set of programs by Belyaev the integration is performed by Cowell's method in single precision. Perturbations by Venus to Pluto are considered, and the step size ranges from 40 days to some tens of minutes. The choice of the step size is made automatically according to the criterion by Kulikov (1960). Nongravitational effects are not taken into account.

In the Bokhan programs the method of variation of arbitrary constants by Herrick (1972) is used. Perturbations by Mercury to Pluto are included, and there is the possibility of allowing for nongravitational effects using the model by Makover (1955b). The integration step is selected according to the criterion by Kazimirchak-Polonskaya (1967c, Table XII). The programs by Bokhan are intended mainly for investigating the motions of objects with highly eccentric orbits, notably P/Encke and (1566) Icarus.

The programs by the present author are in double precision and take into account the perturbations by Mercury to Pluto and nongravitational effects. The choice of integration step ranges from 20 days to 5/64 day (1 hour 52.5 minutes). The author's set of programs, which includes some of the standard programs by Bokhan (1969, 1972), is especially suited for modelling the great transformations of cometary orbits in the sphere of action of any major planet.

8. THE USE OF METHODS AND SETS OF I.T.A. PROGRAMS FOR CONSTRUCTING NUMERICAL THEORIES OF COMETARY MOTION

The Belyaev set of programs is the one that is in most widespread use, both at I.T.A. and at scientific centers in Kazan, Kiev, Tomsk and elsewhere. Among the comets investigated using these programs are P/Faye (Belyaev and Khanina 1972), P/Giacobini-Zinner (Evdokimov 1972), P/Tempel-Tuttle (Kondrat'eva 1972), P/Stephan-Oterma (Shmakova 1972) and P/Ashbrook-Jackson (Merzlyakova 1974). The programs have also been applied to studies of the orbital stability of minor planets with "cometary" eccentricies (Chebotarev et al. 1970, 1972, 1974) and of the orbital evolution of meteor streams.

Using her own programs, the present author (Kazimirchak-Polonskaya 1972b) has eliminated the 1918 - 1925 discontinuity in Kamieński's (1959) theory of P/Wolf. Belous (1972, 1974a, 1974b) applied these same programs to P/Borrelly and to linking the two apparitions of P/Westphal and P/Brorsen-Metcalf (Belous 1974c, 1974d). The two apparitions of P/Stephan-Oterma have been linked (Kazimirchak-Polonskaya and Belous 1974). Bokhan and Chernetenko (1974) have investigated the motion of P/Encke during 1901 - 1970, and Kazimirchak-Polonskaya and Terent'eva (1973) have investigated the motion and evolution of the orbits of various meteor streams.

9. THE EVOLUTION OF COMETARY ORBITS DURING 1660-2060

The orbital evolution during 1660-2060 has been studied for a total of 52 short-period comets (although in a few cases, when an orbit was not sufficiently reliable, the interval was reduced to only 200 years). The more interesting results have been included in the following series of papers: Belyaev (1966, 1967, 1973a, 1973b); Belyaev and Khanina (1972); Belyaev and Reznikov (1973); Belyaev and Stal'bovskij (1974); Belyaev and Shaporev (1974); Belous (1974b); Kazimirchak-Polonskaya (1966, 1967a, 1967d, 1967e, 1967f, 1971, 1972c, 1973). In the case of P/Wolf the effects of nongravitational forces were included too (Kazimirchak-Polonskaya 1967d), the comet's variable secular deceleration having been changed after each approach to Jupiter according to the law established by Kamieński (1961). Although there were two close approaches to Jupiter going back from the discovery date of 1884 to 1660 (Δ_{min} = 0.12 and 0.25 AU), comparison with a computer run in which the nongravitational forces were excluded shows that their influence was negligible.

Belyaev (1973a) studied the orbital evolution of P/Neujmin 2, first on the basis of the system of orbital elements by Neujmin (1948), and then starting from elements he had determined himself. In spite of the 14 close approaches to Jupiter during the 400-year interval, the two results are very similar.

Of course, one cannot generalize this finding to all comets: there are some rather exceptional comets (e.g., P/Lexell and P/Kearns-Kwee) where the smallest changes in the initial elements alter the whole course of the calculated orbital evolution quite dramatically. Other single-apparition comets whose orbital evolution has been studied are P/Schwassmann-Wachmann 3 (Belyaev and Shaporev 1974), P/Churyumov-Gerasimenko (Belyaev 1973b), and P/Gunn and P/Kojima (Belyaev and Reznikov 1973).

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10. THE CLASSIFICATION OF THE APPROACHES OF SHORT-PERIOD COMETS TO THE MAJOR PLANETS

The study of the orbital evolution of 52 comets involved some 320 close approaches to Jupiter, more than 40 approaches to Saturn and a few approaches to Uranus. There were 86 passages through Jupiter's sphere of action and one passage through that of Saturn. Close approaches of short-period comets to Jupiter and Saturn are certainly not infrequent events, and they follow a complex regularity the study of which is of interest from many points of view.

On the basis of the available literature, Kazimirchak-Polonskaya (1967b) has classified 157 approaches of 63 short-period comets to Jupiter in terms of Δ_{min}.

11. THE PRINCIPAL CHARACTERISTICS OF THE EVOLUTION OF COMETARY ORBITS SUBJECTED TO GREAT PERTURBATIONS BY JUPITER

The typical transformations of cometary orbits that arise as the result of passages through or near Jupiter's sphere of action are illustrated in the following eight general examples:

(1). Comets that remain in Jupiter's family, but which are at first invisible from the earth, because their orbits have large perihelion distances and low eccentricities. After an approach to Jupiter, usually shortly before discovery, the perihelion distances are reduced, and the orbital eccentricities are increased. Examples are P/Churyumov-Gerasimenko (Fig. 1) and P/Gunn (Fig. 2).

(2). Comets that remain in Jupiter's family, but whose perihelion distances and orbital eccentricities pulsate in a generally irregular manner.

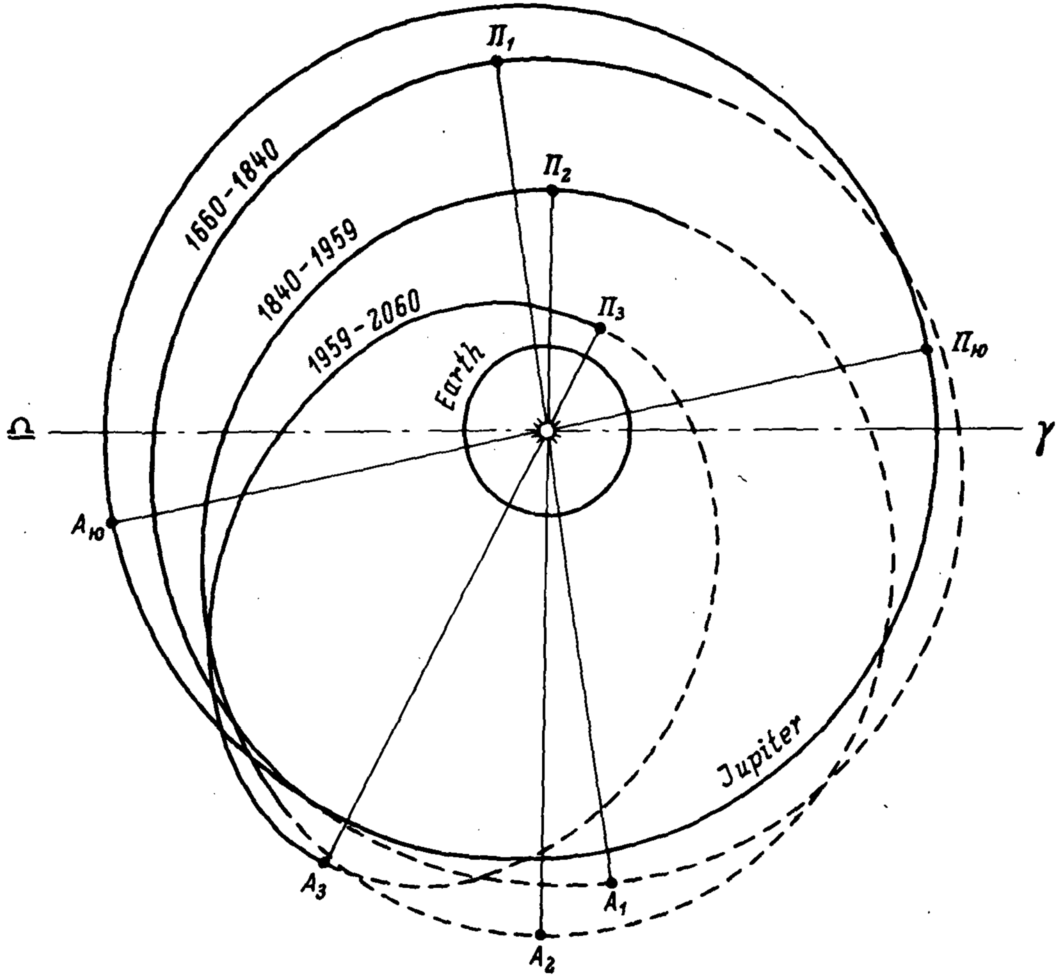

Figure 1. P/Churyumov-Gerasimenko (Belyaev 1973, p. 114). Π denotes perihelion, A aphelion, and the subscript 1-0 refers to Jupiter. The solid sections of the path of the comet are to the north of the ecliptic, the broken sections to the south.

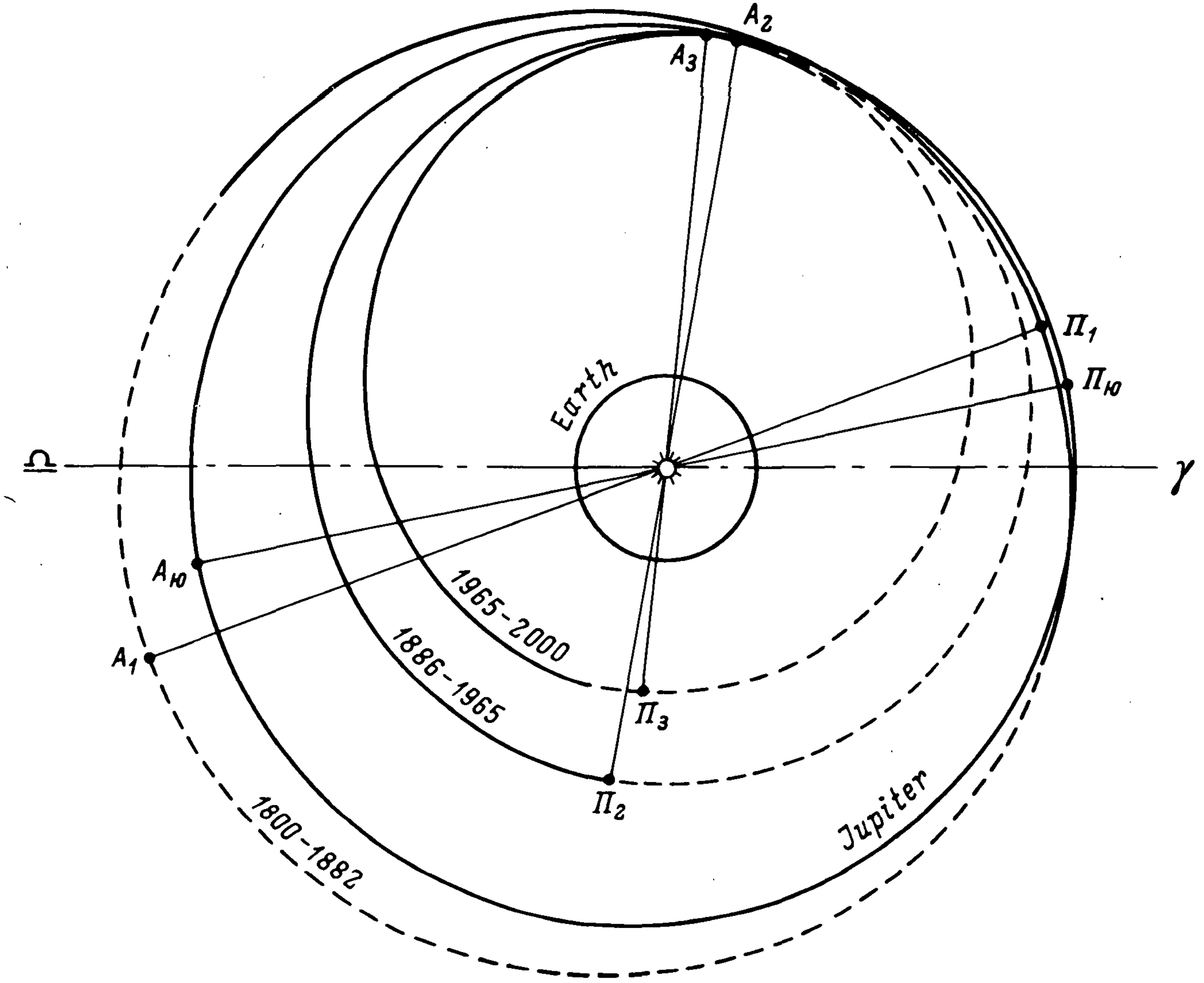

Figure 2. P/Gunn (Belyaev and Reznikov 1973, p. 112).

Examples are P/Wolf (Fig. 3), P/Wolf-Harrington (Fig. 4) and P/Schwassmann-Wachmann 2 (Fig. 5). This type of motion was first described by Kamienski (1954).

(3). Comets captured by Jupiter from Saturn's family.* These comets initially had large perihelion distances, but successive approaches to Jupiter cause them to decrease until the comets could be discovered. In the course of time the perihelion distances may increase again, and the comets will become lost from view. Examples are P/Whipple (Fig. 6) and P/Comas Solã (Fig. 7).

(4). P/Oterma (Fig. 8) has an exceptionally unstable orbit. Jupiter captured it during 1936-1938 from Saturn's family into an orbit near 3:2 commensurability. After an interval of some 20 years another approach to Jupiter caused it to be ejected back into Saturn's family.

(5). In contrast to P/Oterma, there must be comets that have stable orbits for extensive intervals of time. They are usually not observed and are located in the regions between neighbouring planetary families (Jupiter and Saturn, Saturn and Uranus, and especially Uranus and Neptune), as well as beyond the orbit of Neptune. The one observable example of such a comet is P/Schwassmann-Wachmann 1, which is located entirely between the orbits of Jupiter and Saturn.

(6). Comets from the region between Saturn and Uranus initially having perihelia on the orbit of Jupiter and captured into the Jupiter family. Examples are P/Brooks 2 (Fig. 9) and P/Schwassmann-Wachmann 3, for which $\Delta_{min} = 0.0056$ AU in 1882 (Fig. 10).

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* We shall continue to define comet "families" on the basis of aphelion distance. However, it would be useful to consider at some time in the future the alternative definition proposed by Bielicki (1972).

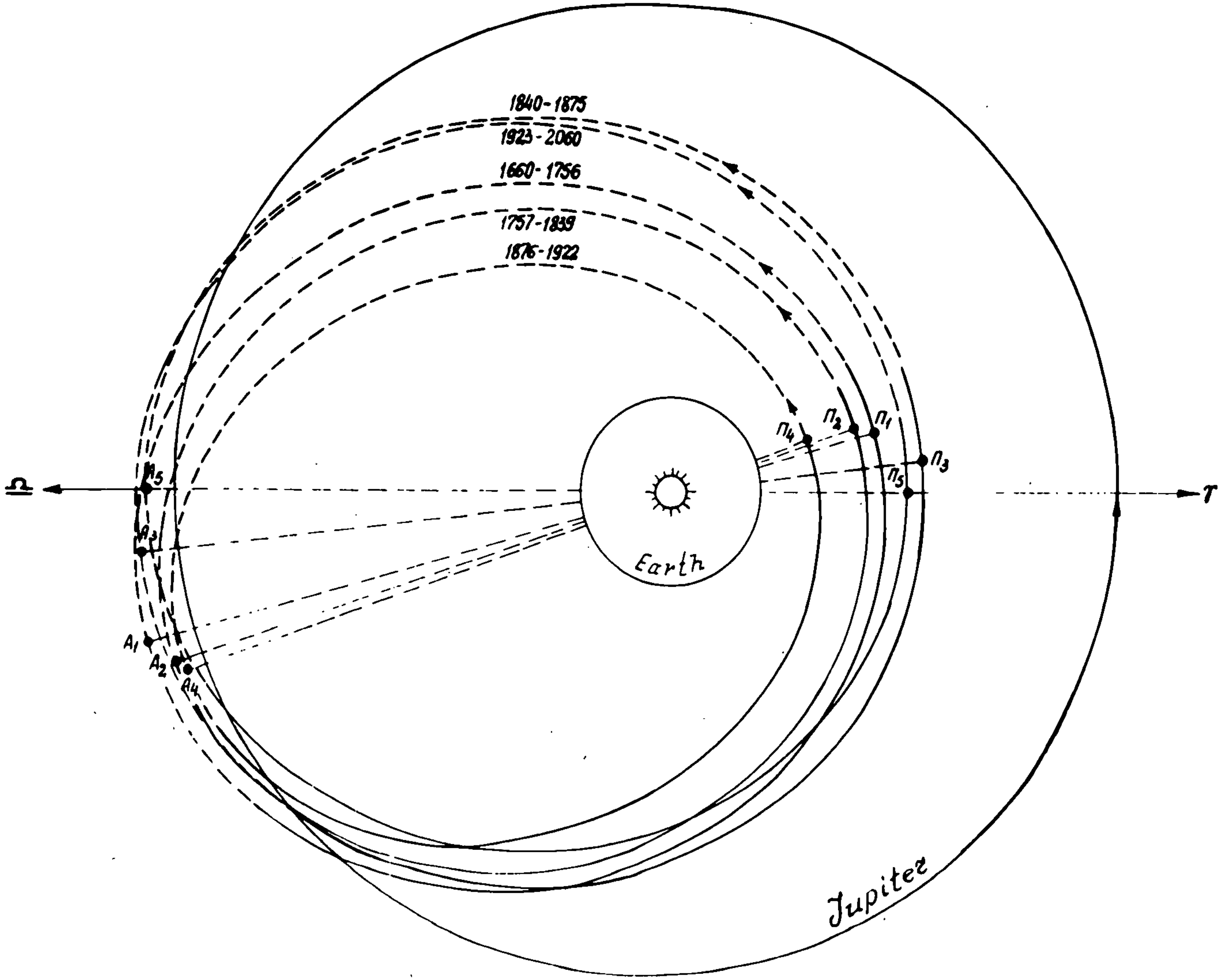

Figure 3. P/Wolf (Kazimirchak-Polonskaya 1967d, p. 63; 1972c, p. 376).

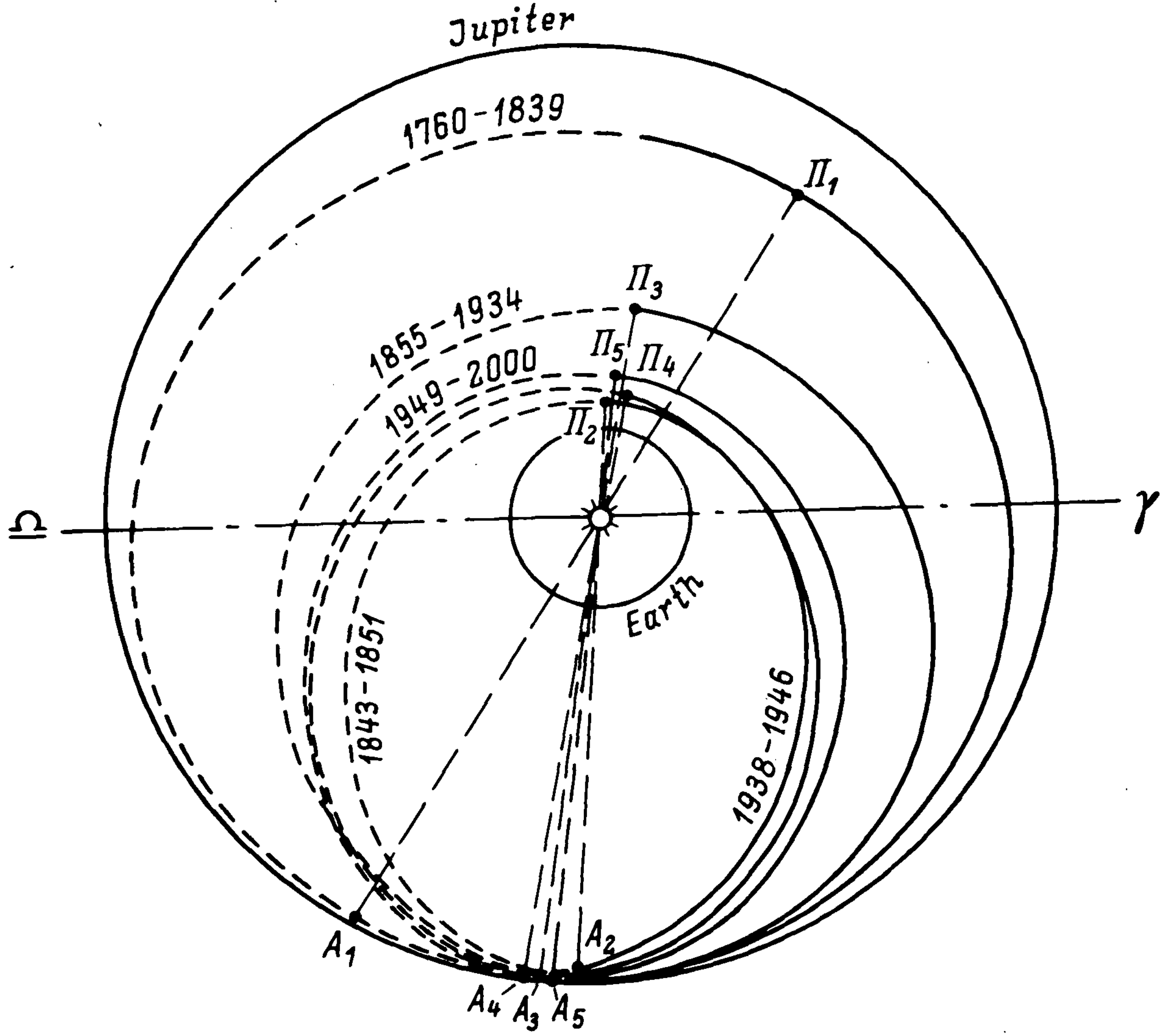

Figure 4. P/Wolf-Harrington (Kazimirchak-Polonskaya 1972c, p. 378).

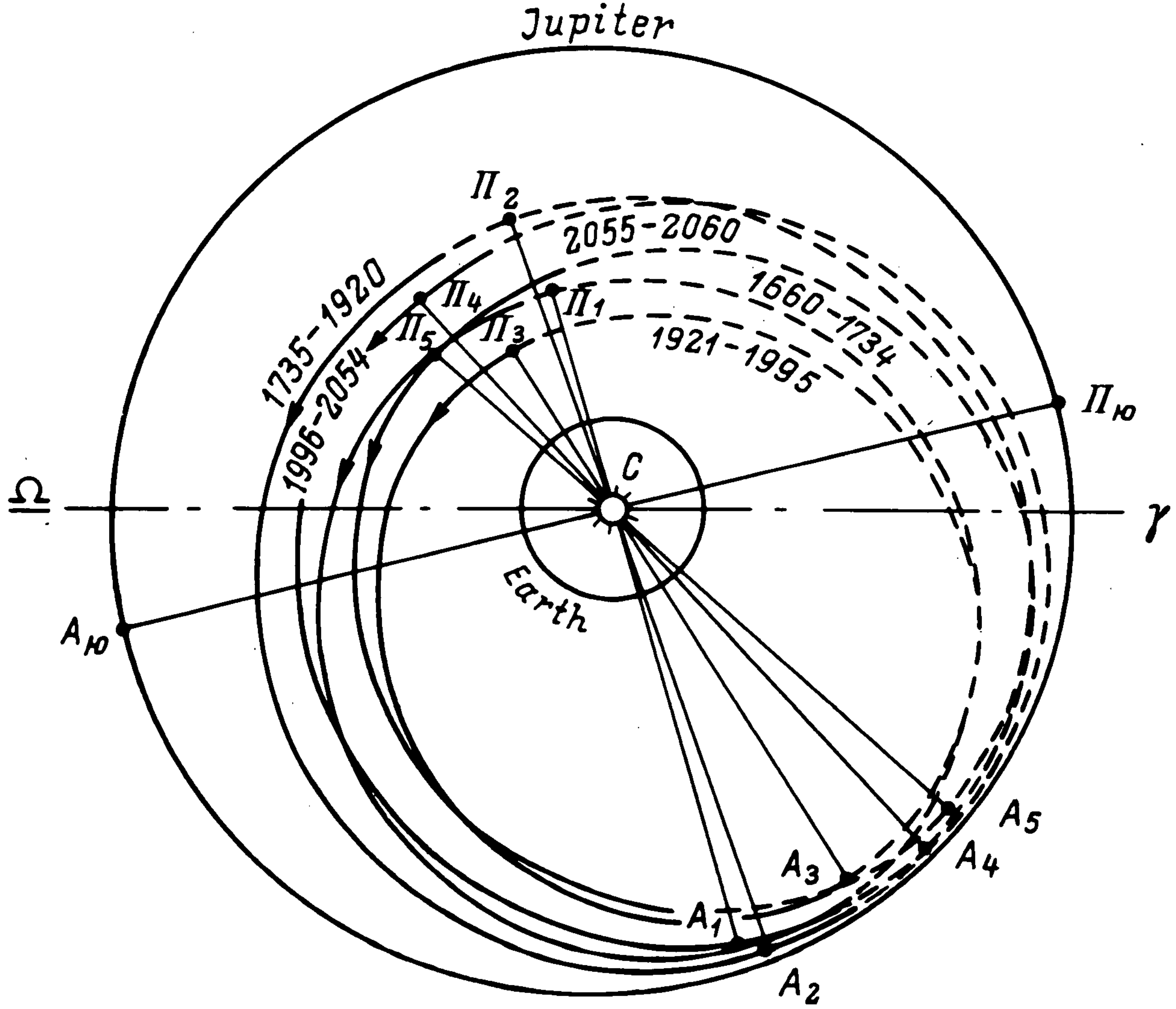

Figure 5. P/Schwassmann-Wachmann 2 (Belyaev 1967, p. 467).

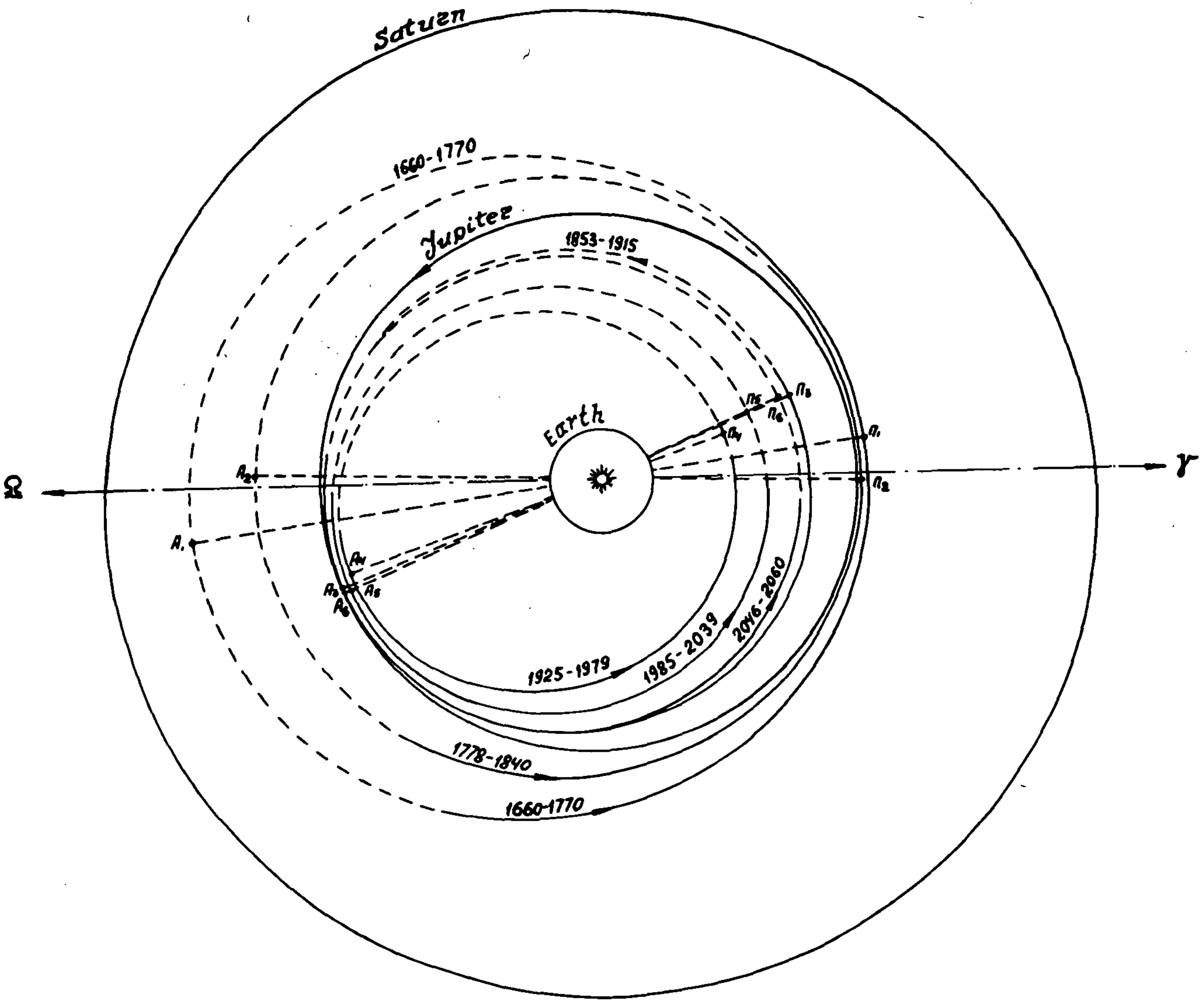

Figure 6. P/Whipple (Kazimirchak-Polonskaya 1967a, Table 6; 1972c, p. 379).

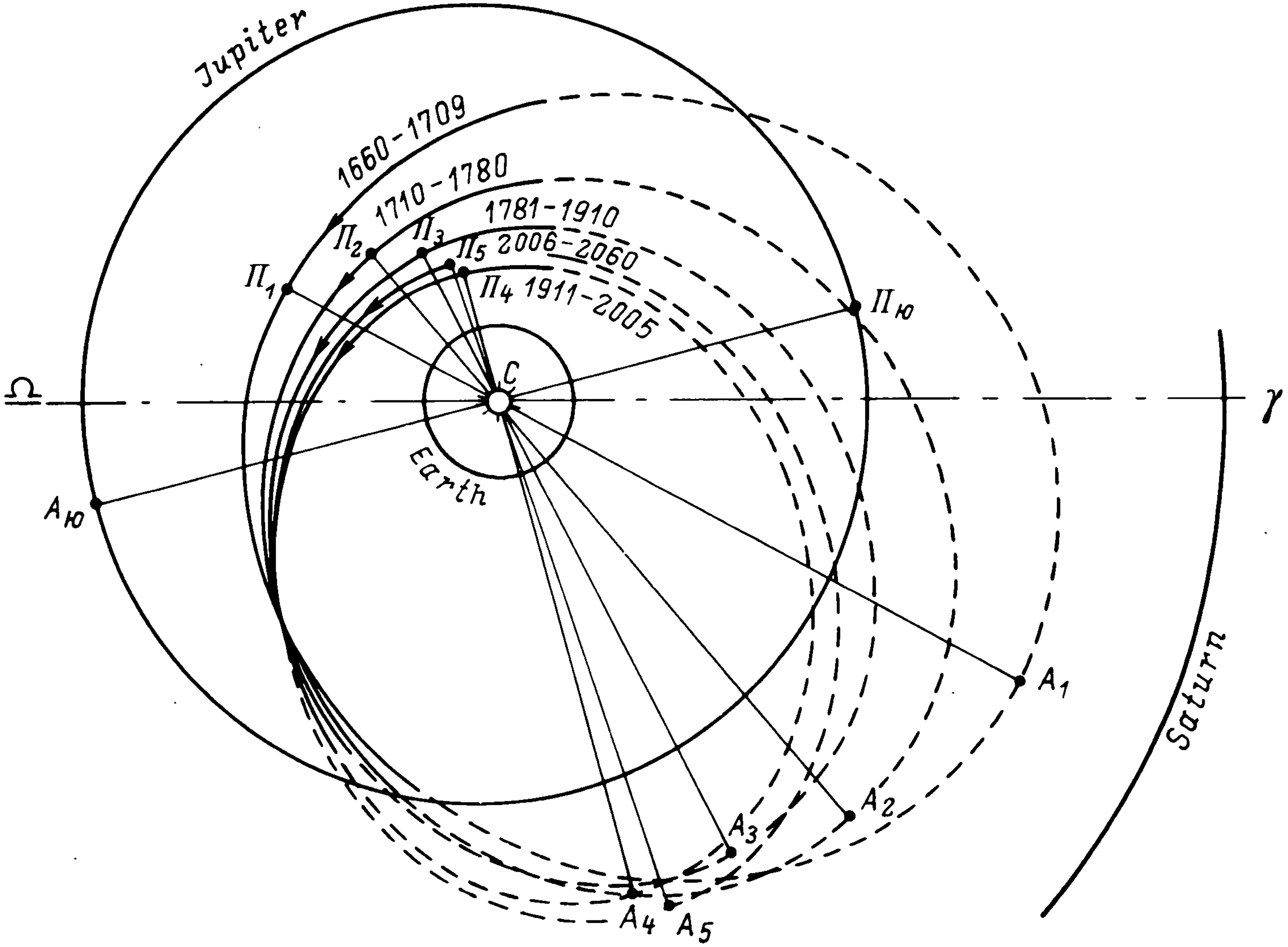

Figure 7. P/Comas Solá (Belyaev 1967, p. 468).

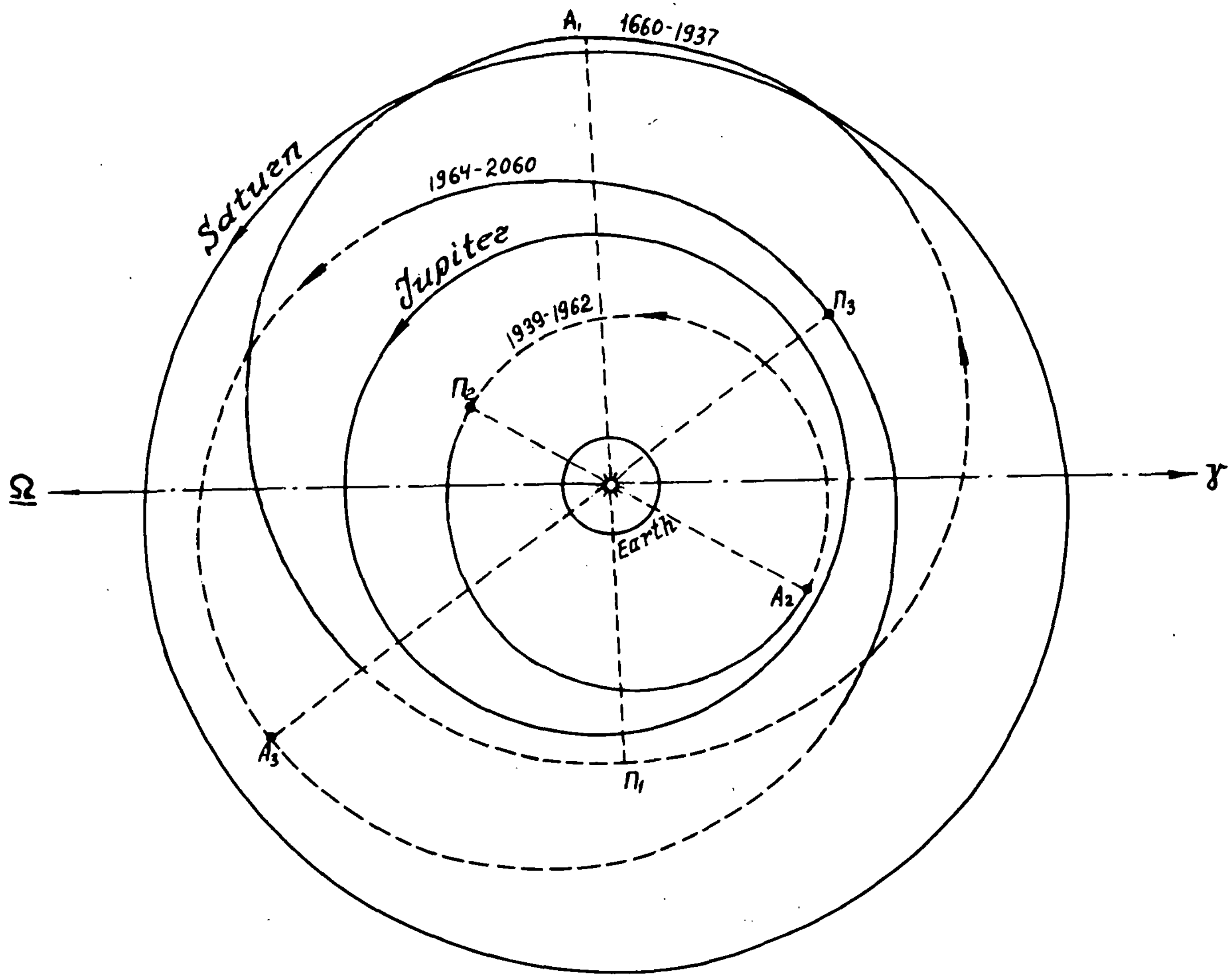

Figure 8. P/Oterma (Kazimirchak-Polonskaya 1967a, Table 17; 1972c, p. 380).

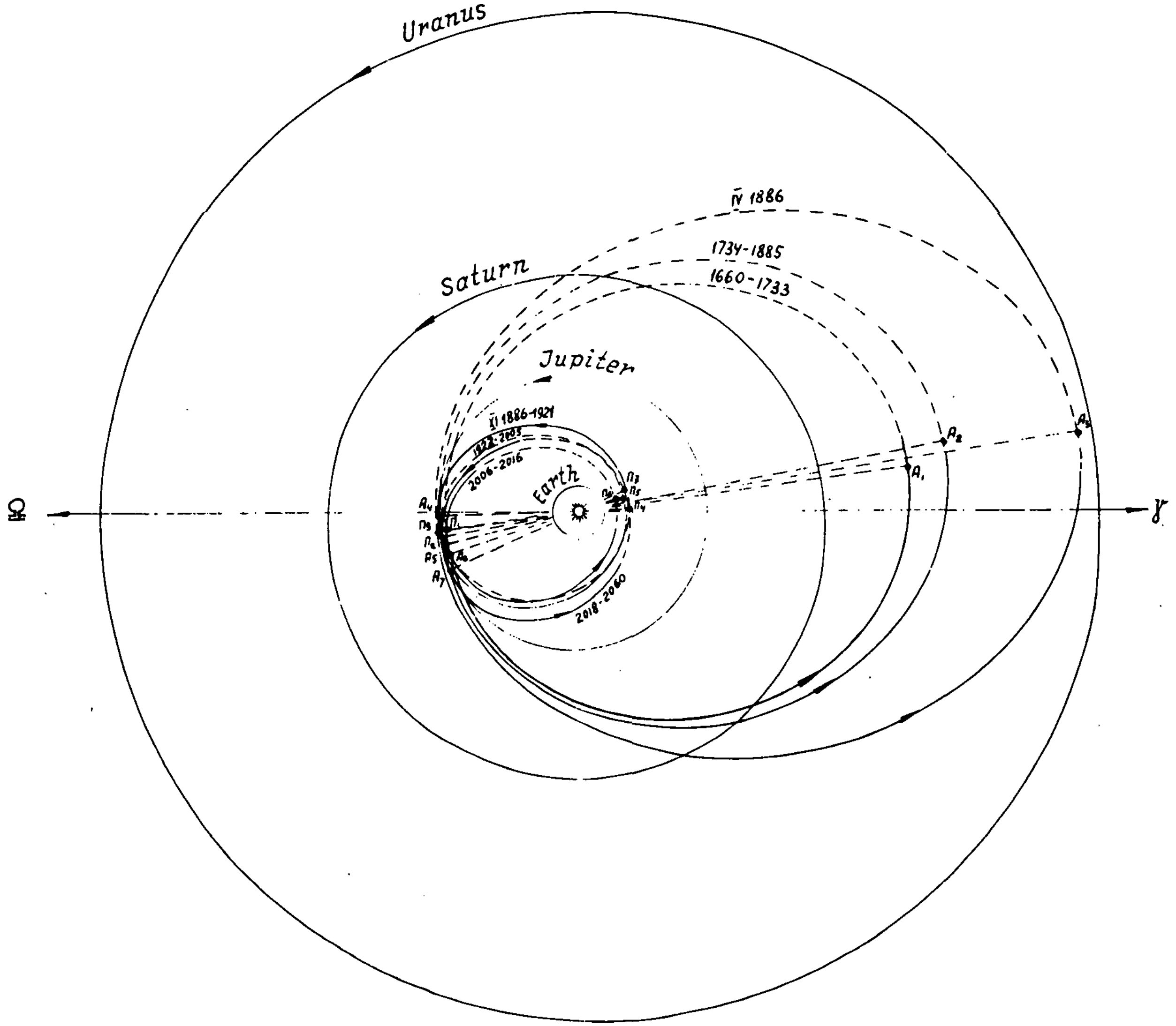

Figure 9. P/Brooks 2 (Kazimirchak-Polonskaya 1961b, p. 78; 1972c, p. 382).

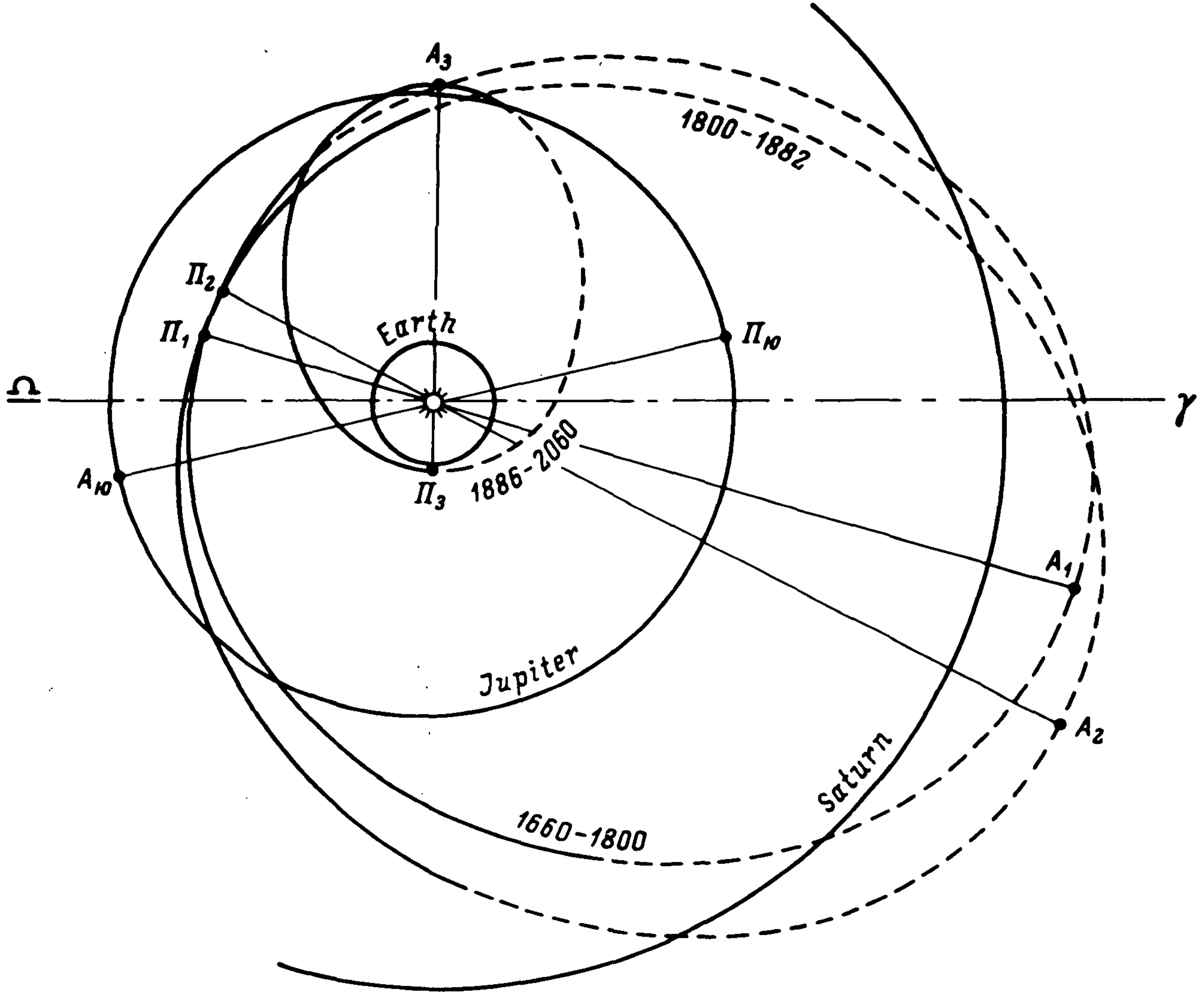

Figure 10. P/Schwassmann-Wachmann 3 (Belyaev and Shaporev 1974, p. 62).

(7). P/Lexell (Fig. 11) was captured by Jupiter in 1767 (Δ_{min} = 0.018 AU) from a nearly circular orbit (perihelion distance q = 3.3 AU, period P = 10 years) into an elongated elliptical orbit with its perihelion inside the orbit of Venus (q = 0.67 AU, P = 5.6 years). The comet was discovered in 1770 as a bright object, owing to its exceptionally close approach to the earth (within 0.016 AU). The comet encountered Jupiter again in 1779, and this time the approach was so close (Δ_{min} = 0.0015 AU) that the comet was ejected on an orbit having its aphelion far beyond the orbit of Pluto. The period of revolution increased to 260 years, and since the perihelion was removed to the orbit of Jupiter the comet will no longer be accessible to observation. As already noted, the future evolution of this comet is very sensitive to the initial conditions, and Fig. 12 shows the effect of changing the 1770 orbit slightly. It is not impossible that P/Lexell left the solar system on a strongly hyperbolic orbit.

(8). The orbital evolution of P/Kearns-Kwee (Fig. 13) was investigated by us on the basis of the provisional elements determined by Marsden (1964) from observations covering an interval of six months. It illustrates the possible two-stage capture of the comet by Jupiter: during the first very close approach (Δ_{min} = 0.042 AU) in 1855 Jupiter captured the comet from a hyperbolic orbit* into the Neptune family. After two revolutions around the sun, the comet passed deeply into Jupiter's sphere of action in 1961 (Δ_{min} = 0.032 AU) and was discovered two years later as a short-period comet of Jupiter's family.

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* It is necessary to stress that this is only a <u>possible</u> evolution and probably a mathematical fiction. A calculation by Marsden and Aksnes (1967), considering observations over an 18-month arc, indicates that the 1855 approach to Jupiter did not really occur.

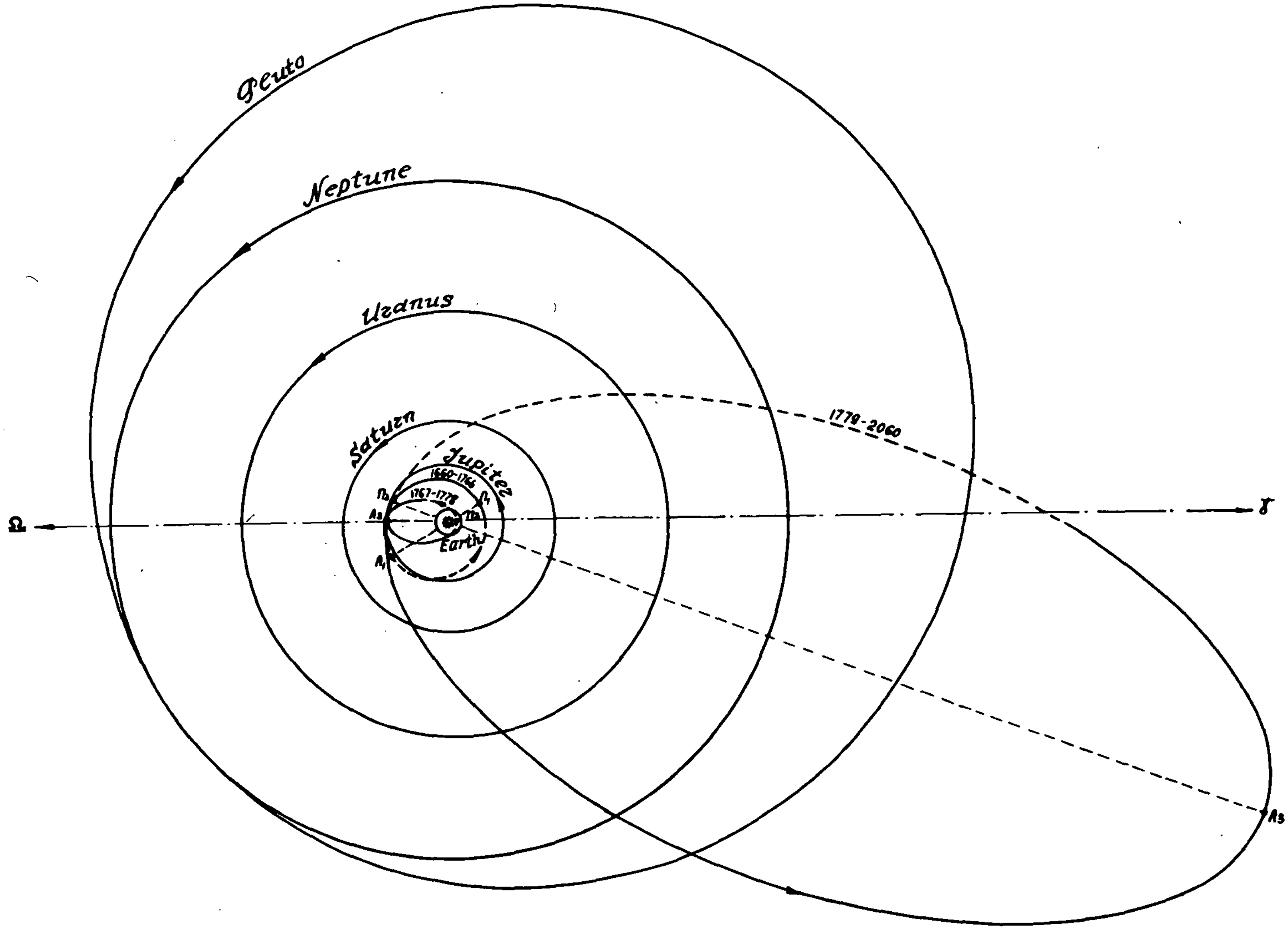

Figure 11. P/Lexell (Kazimirchak-Polonskaya 1967a, Table 18, 19; 1972c, p. 383).

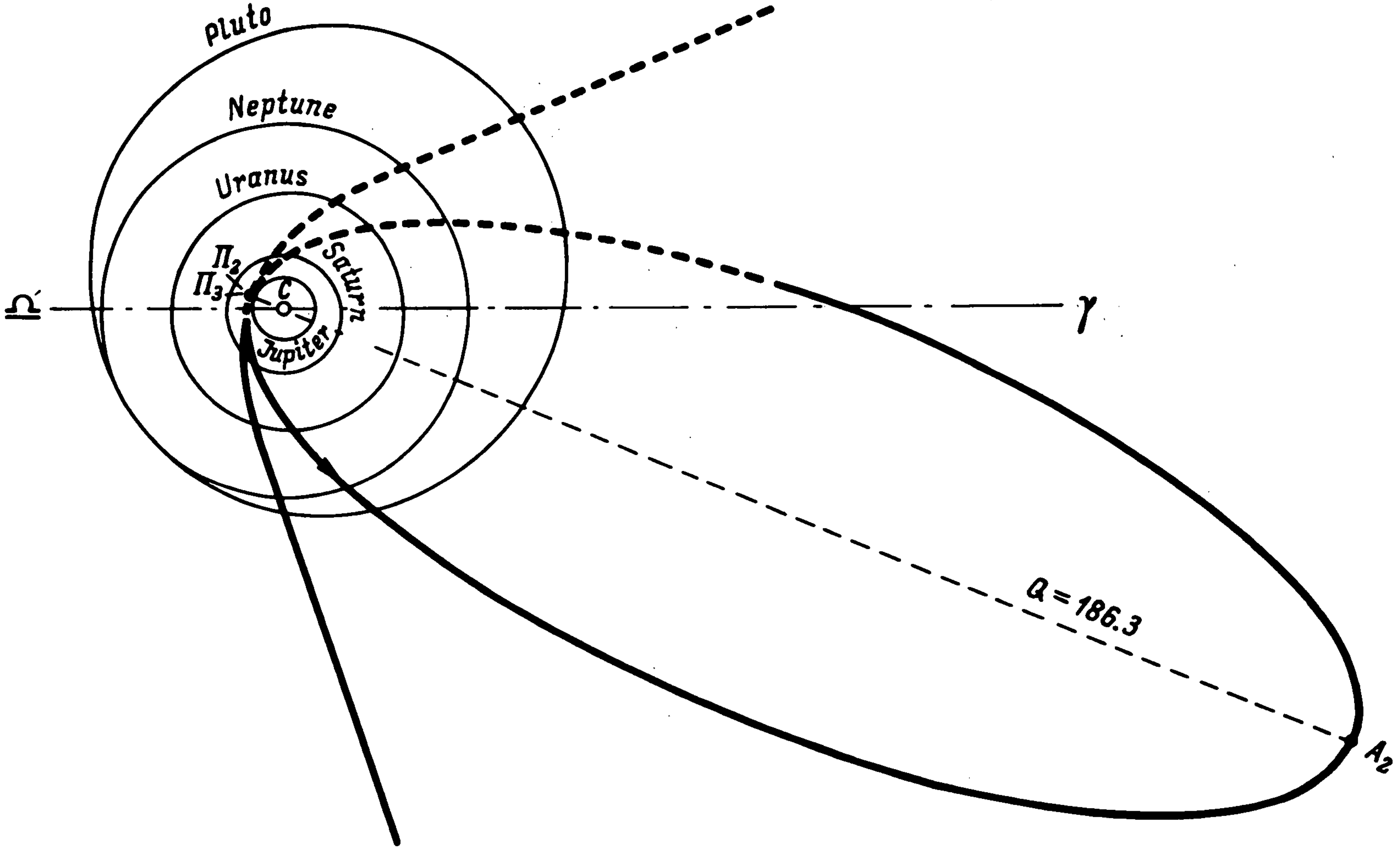

Figure 12. Variants of P/Lexell (Kazimirchak-Polonskaya 1972c, p. 384).

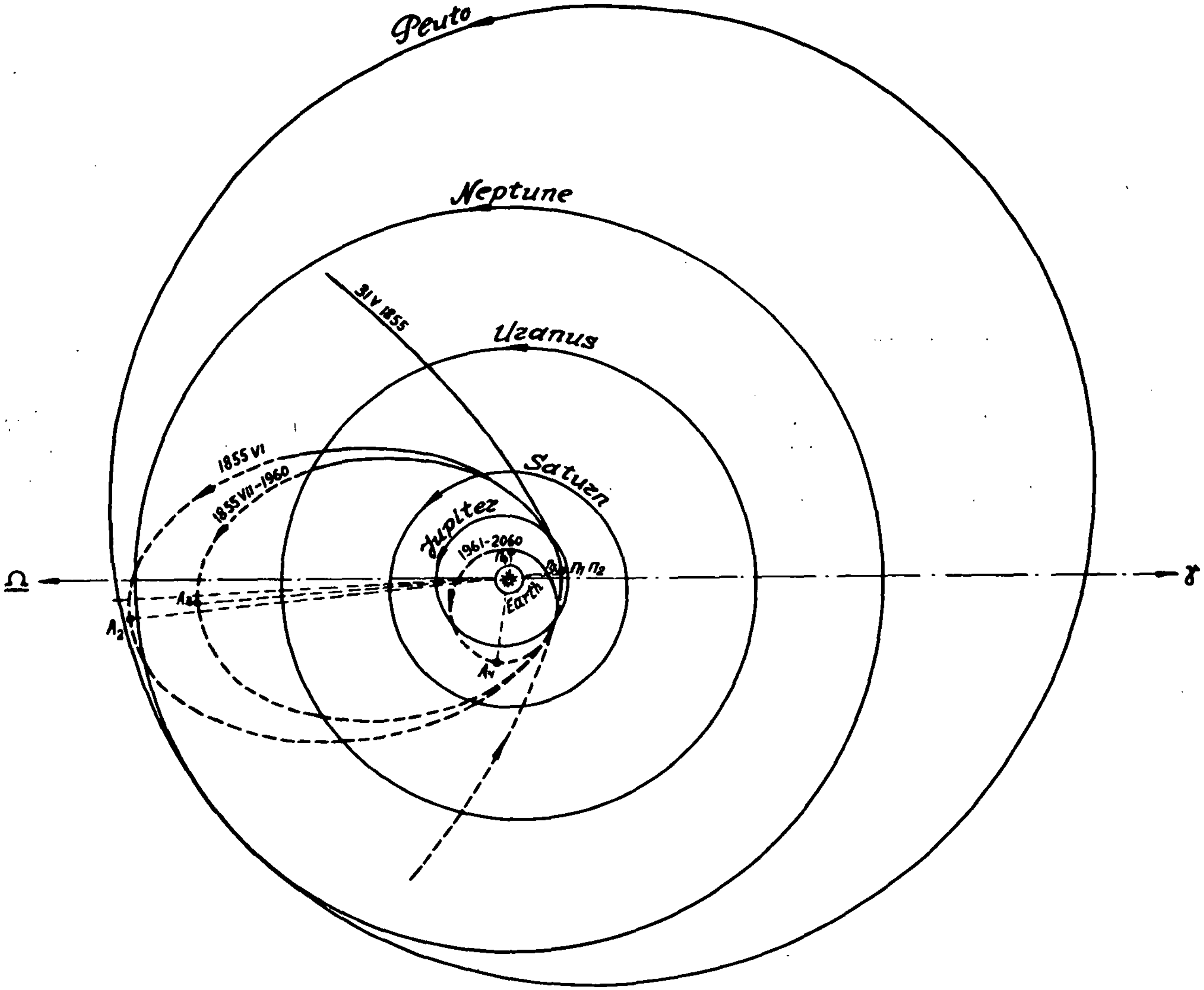

Figure 13. P/Kearns-Kwee (Kazimirchak-Polonskaya 1967a, Table 20, 21; 1972c, p. 385).

12. GREAT PERTURBATIONS OF COMETARY ORBITS BY SATURN

We have also studied the orbital evolution of some of the short-period comets belonging to Saturn's family, notably P/Neujmin 1, P/Neujmin 3 and P/Gale. In the course of a 200-year interval P/Neujmin 3, for instance, experienced six approaches to Saturn, and four of them had quite considerable effects, causing perturbations of more than 10° in ω and in Ω. After a very close approach of this comet to Jupiter in 1850 ($\Delta_{\min} = 0.12$ AU) Saturn ceased to be the dominant influence on its evolution. During 1660 - 2060 P/Neujmin 1 makes six approaches to Saturn and none to Jupiter, which shows that the secular evolution of the orbit of this comet is essentially determined by Saturn.

Perhaps the most interesting comet of Saturn's family is P/Gale. According to the initial system of elements obtained by Dinwoodie (1959) from the two apparitions, between 1660 and 2060 P/Gale made nine approaches to Jupiter and eight to Saturn. One of the latter approaches is the only known passage of a comet through Saturn's sphere of action ($\Delta_{\min} = 0.17$ AU in 1798). As is happened, this approach did not result in a particularly great transformation of the orbit of P/Gale. By varying Dinwoodie's elements slightly, we were able to decrease $\Delta_{\min}$ in 1798 to only 0.095 AU, and this caused a change of 173° in Ω.

It thus appears that although Jupiter must play the dominant role in the evolution of cometary orbits, Saturn can exert a strong temporary influence on the evolution of the orbits of some of the comets belonging to its family.

13. GREAT ORBITAL TRANSFORMATIONS OF FICTITIOUS COMETS IN THE SPHERES OF ACTION OF URANUS AND NEPTUNE

Although we have investigated the orbital evolution of several of the comets belonging to the families of Uranus and Neptune, (e.g., P/Stephan-Oterma, P/Pons-Brooks, P/Brorsen-Metcalf and P/Westphal), there were only two minor approaches of P/Stephan-Oterma to Uranus, and none of the comets made any close approaches to Uranus or Neptune. In order to study the effects of such close encounters it was necessary to produce some fictitious comets. In order that these comets might bear some resemblance to real comets it is essential to discuss the existence of the Oort cometary cloud and the theory of diffusion and to consider the distribution of some of the orbital elements of long-period comets.

Although the existence of the Oort cloud cannot be checked directly, some indication of its possible dimensions and structure may be determined by studying the "original" orbits of long-period comets for which fairly reliable definitive orbits have been calculated. The theory of diffusion, which dates back to van Woerkom (1948), has been elaborated by Oort (1950), Lyttleton (1953), Shtejns (1960, 1961, 1962, 1964, 1972), Shtejns and Kronkalne (1964, 1968), Shtejns and Riekstyn'sh (1960), Shtejns and Sture (1962), Kendall (1961) and Whipple (1962). We know that comets that formerly belonged to the cometary cloud gradually diffuse into the inner part of the solar system. Consequently, there must be a concentration of invisible comets having low-eccentricity, low-inclination orbits and perihelia far from the earth. Many of them could be around the orbit of Neptune.

The distribution of semimajor axes and perihelia of the orbits of long-period comets has been studied by many astronomers, notably Svedstrup (1883), Oppenheim (1924), Witkowski (1953, 1965, 1968, 1971, 1972) and Hurnik (1959, 1964). They arrived at the conclusion that there exists an incontestable connection between the distribution of the perihelia of these comets and the galactic equator, which fact testifies to the interstellar origin of comets.

Lyttleton (1948, 1953) suggested that the passage of the sun through a uniform interstellar dust cloud could lead to the formation of comets by accretion.

In view of the above, we have considered in our studies comets having initial orbits of two types:

(1). Comets with nearly circular, low-inclination orbits that formerly belonged to the cometary cloud on the periphery of the solar system, but which have already approached the orbit of Neptune as the result of diffusion. These may also be the comets which belonged, according to a hypothesis by Whipple (1972) to an extensive belt of comets beyond Neptune's orbit.

(2). Comets of cosmic origin arriving directly from interstellar space on hyperbolic orbits. These orbits are both direct and retrograde and penetrate Neptune's sphere of action.

We shall designate the fictitious comets passing through the sphere of action of Uranus by U-1 and U-2 and those penetrating the sphere of action of Neptune by N-1, N-2, ..., N-8. In an earlier paper (Kazimirchak-Polonskaya 1972c) we have treated the characteristic features of the orbital evolution of the fictitious comets U-1, U-2, N-1, N-2 and N-3.

14. ORBITAL EVOLUTION OF COMETS N-4 TO N-8

Comet N-5 has a nearly circular transplutonian orbit of small inclination ($i = 8\overset{\circ}{.}7$); its perihelion is located near the orbit of Neptune, and its revolution period is 210 years. Having penetrated deeply into Neptune's sphere of action in 1715, ($\Delta_{min} = 0.0004$ AU), this comet leaves along a direct orbit ($i = 22\overset{\circ}{.}1$) having its perihelion between the orbits of Uranus and Saturn, its aphelion not far beyond the orbit of Neptune and a revolution period of 103 years (Fig. 14).

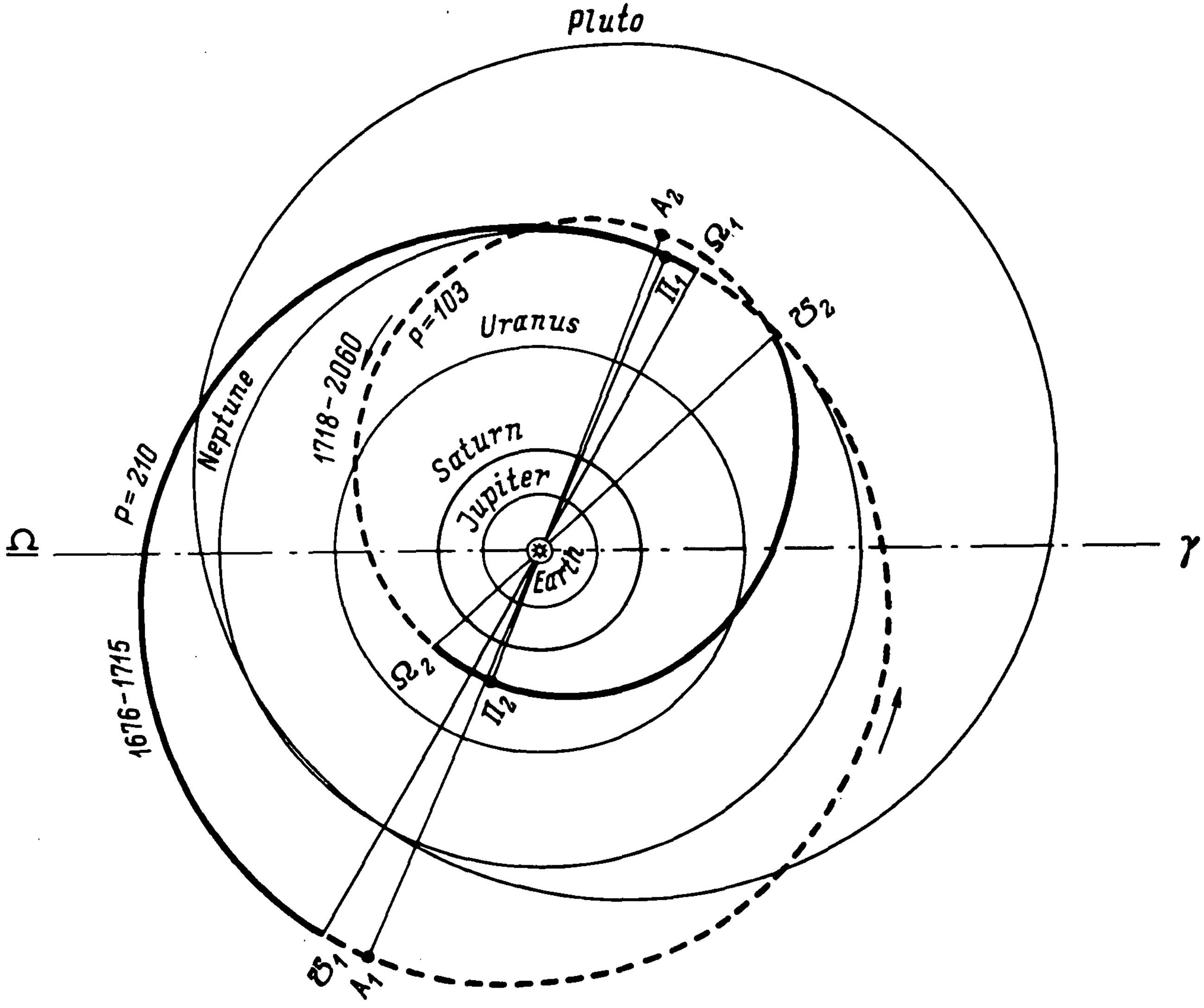

Figure 14. Comet N-5.

Comet N-6 is of interstellar type; it has a retrograde hyperbolic orbit ($i = 135\overset{\circ}{.}2$), and its perihelion is located between the orbits of Neptune and Uranus. Its encounter with Neptune occurs in 1710 ($\Delta_{min} = 0.0005$ AU), before perihelion passage. The comet is ejected along a nearly circular, direct, transplutonian orbit ($i = 16\overset{\circ}{.}0$) having its perihelion near the orbit of Neptune, its aphelion beyond the orbit of Pluto, and a revolution period of 220 years (Fig. 15).

Comet N-7 is another retrograde interstellar comet ($i = 159\overset{\circ}{.}0$), but its perihelion is located between the orbits of Uranus and Saturn. It encounters Neptune after perihelion, passes twice within a very small distance of the planet (Δ_{min} = 0.00035 and 0.00065 AU). Afterwards it retains its retrograde orbit ($i = 136\overset{\circ}{.}6$), but with a perihelion distance of only 1.2 AU; its aphelion is located near Neptune's orbit, and the revolution period is 61 years (Fig. 16). The final orbital inclination of comet N-7 is very similar to that of P/Pons-Gambart, while the size and shape of its orbit are practically identical with those of P/Westphal.

Comet N-8 also has a hyperbolic retrograde orbit, but after penetrating Neptune's sphere of action, it leaves on an orbit that is even more hyperbolic than initially.

Finally, we briefly mention Comet N-4, discussed in detail elsewhere (Kazimirchak-Polonskaya 1975). It is captured as a stable satellite of Neptune having an orbit intermediate between those of Triton and Nereid (Fig. 17).

We conclude that the planets Jupiter to Neptune, with their great masses and extensive spheres of action, have a substantial effect on the evolution of the orbits of comets. These planets can transfer comets from one planetary

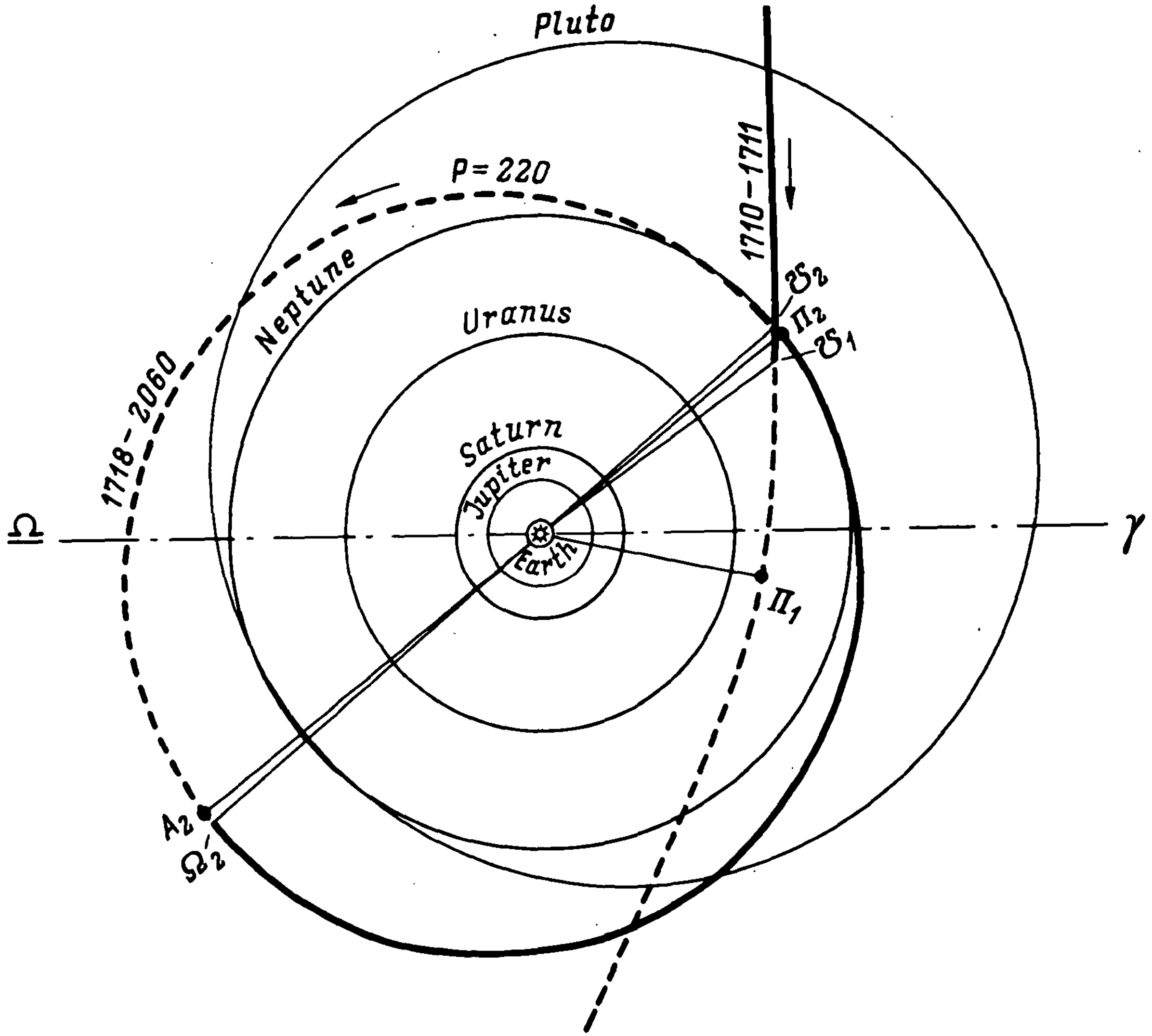

Figure 15. Comet N-6.

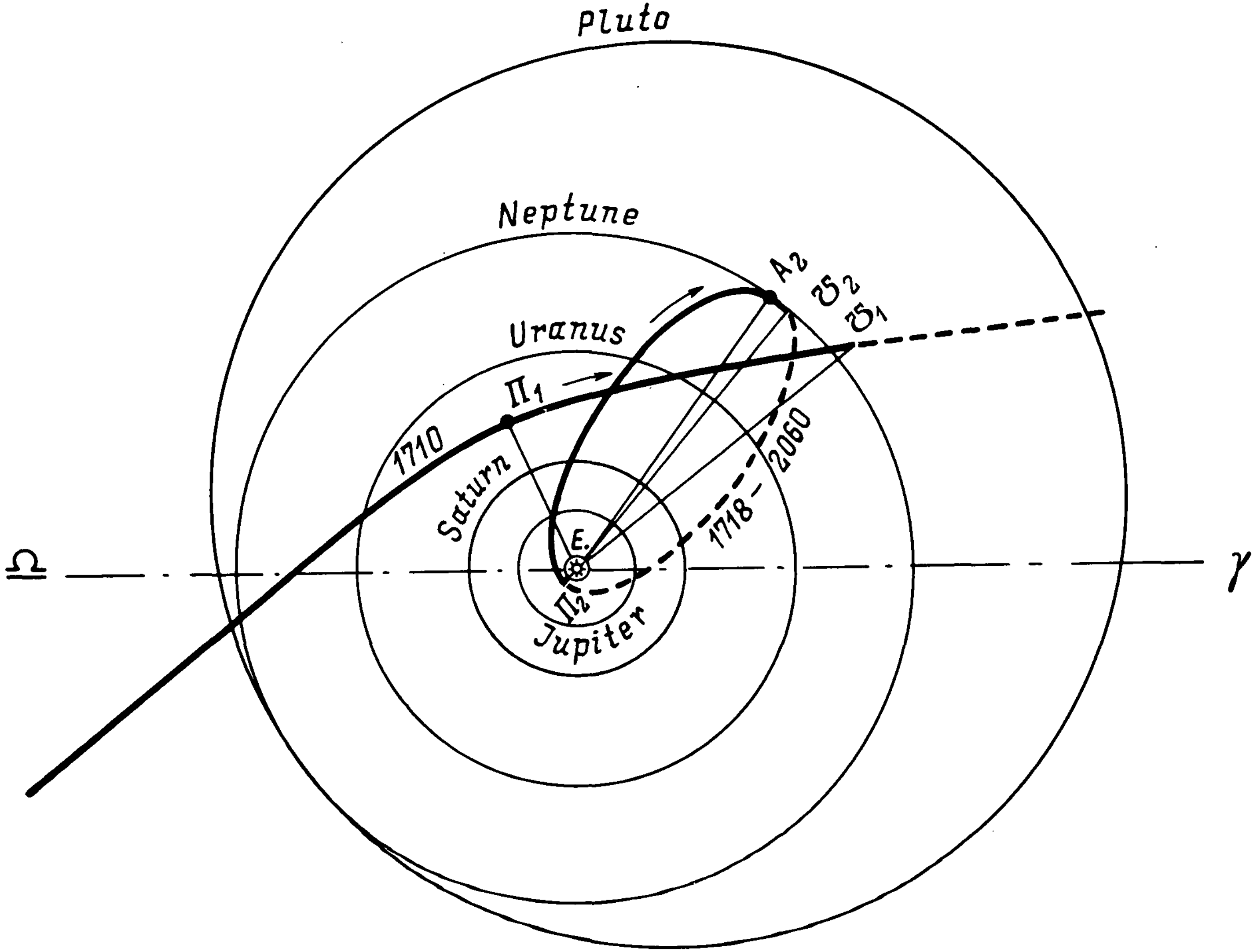

Figure 16. Comet N-7.

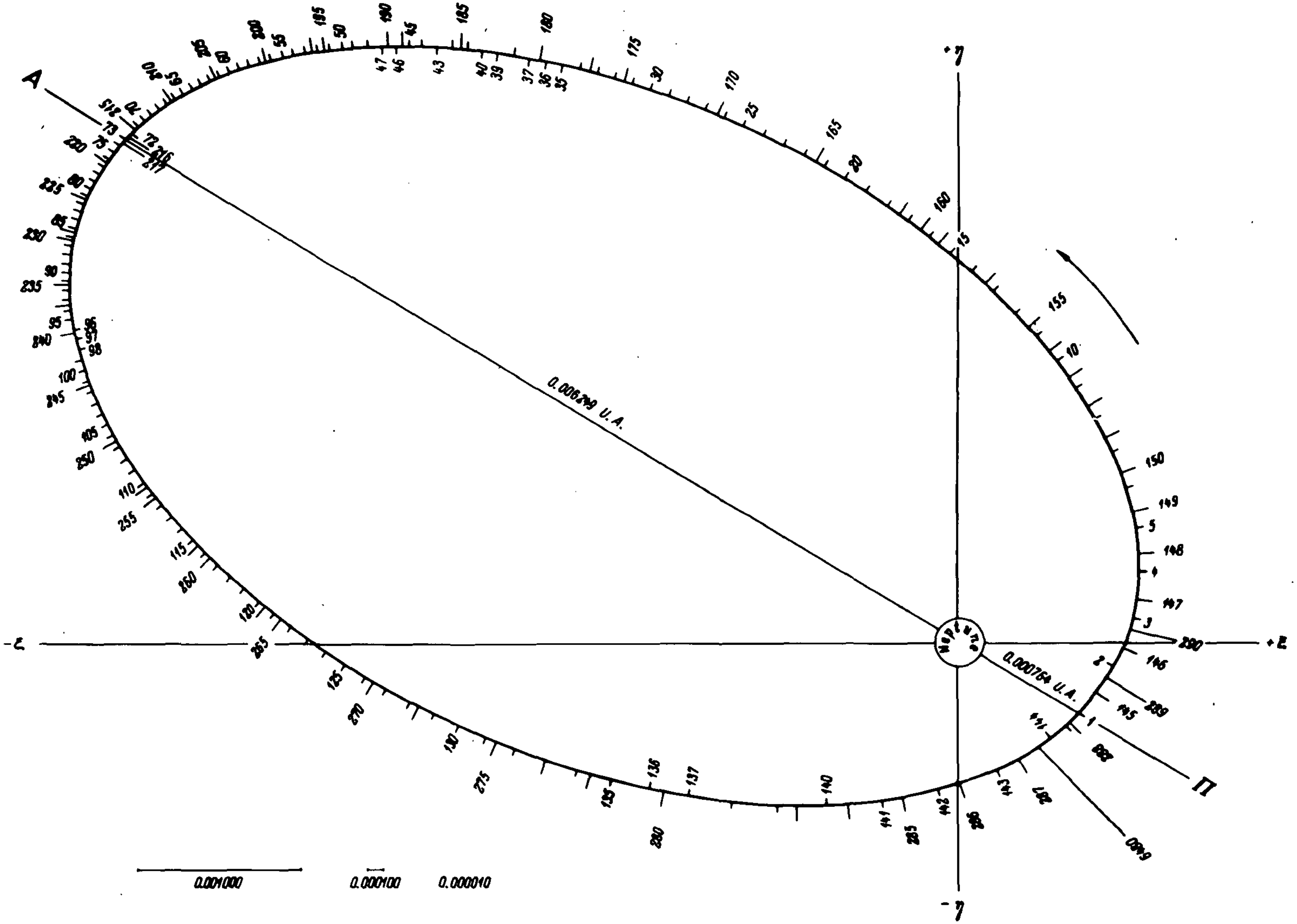

Figure 17. Comet-Satellite N-4 (Kazimirchak-Polonskaya 1974).

family to another and in exceptional cases can remove them beyond the limits of the solar system; conversely, they can also capture comets from transplutonian and even from hyperbolic orbits.

15. COMETARY ORIGIN

In a number of papers (Kazimirchak-Polonskaya 1967a, 1967f, 1972c) the author has criticized the classical theory of cometary capture and demonstrated that the various simplifications made -- though perhaps fully justified at the time -- were the cause of contradictions that arose between theoretical deductions (Callandreau 1892; Newton 1893) and the observations.

Using electronic computers and the modern methods of celestial mechanics, we reconsidered the numerical theory of capture and presented the successive stages of cometary orbital evolution, taking into account stellar perturbations and the theory of diffusion. This enabled us to eliminate the discrepancies that formerly existed. Our more recent investigations confirm our view that cometary capture undoubtedly takes place, but it is a very complex process, extending in some cases for perhaps millions of years.

The process begins either with the sun capturing interstellar matter into its own very extended sphere of action, or with the formation, in some way, of a cometary cloud at the periphery of the solar system. The problems of the stability of cometary motion in the outer regions of the solar system and the shape of the cometary cloud have been studied by Chebotarev (1963, 1964, 1966, 1970), Nezhinskij (1972), and Antonov and Latyshev (1972).

Cometary perihelia are thrown into the inner part of the solar system, either as a result of the sun's capturing an interstellar comet or on account of stellar perturbations on comets belonging to the cometary cloud. When such comets penetrate deeply into the sphere of action of one of the outer planets (particularly Jupiter or Neptune) they may be converted -- immediately or in successive stages -- into short-period comets. An interesting example of Jupiter's capture of a fictitious comet on a parabolic orbit has been discussed by Sitarski (1968).

The great majority of the comets in the cometary cloud will diffuse into the inner solar system in the course of 10^5 or 10^6 years and, according to the diffusion laws, they acquire nearly circular orbits of small inclination, with their perihelia concentrated at the distances of the outermost planets. Transplutonian orbits of small inclination and perihelia near the orbit of Neptune may be formed as the result of diffusion (e.g., comet N-5) or by Neptune's capture of a comet from interstellar space (e.g., comet N-6).

At this stage further captures can be made by the giant planets. These captures may develop by a slow evolution or catastrophically. Evolutionary capture consists of a series of successive steps, with capture first by Neptune, then by Uranus, by Saturn, and finally by Jupiter. Catastrophic capture may involve transformation from an interstellar orbit directly into the inner part of the solar system (e.g., comet N-7) or the capture by Jupiter of a comet directly from the families of Uranus or Neptune (e.g., P/Kearns-Kwee).

This concept of capture permits us to suppose that all comets (whether interstellar or on nearly parabolic orbits, or of long or short period) represent a unified cometary system, the development of which is determined in the spheres of action of the sun and the planets Jupiter to Neptune. Nevertheless, it is desirable that there should be further critical analysis of our numerical capture theory, as well as of other hypotheses of cometary origin (e.g., Lagrange 1812; Vsekhsvyatskij 1930, 1933, 1955, 1967, 1969, 1972a, 1972b; Lyttleton 1953; Whipple 1972, Fesenkov 1972; Safronov 1972).

Table 1

Short-period Comets of Neptune's Family

Name and Designation of Comet		q(A.U.)	e	P(yr)	i
P/N-7	1750	1.23	0.92	61.6	136°
P/Pons-Gambart	1827 II	0.81	0.95	63.8	136
P/Westphal	1852 IV	1.25	0.92	61.2	41
P/Dubyago	1921 I	1.12	0.93	67.0	22

Table 2

Characteristic of Orbits of Neptune Satellites: Triton, Nereid and N-4

Satellite	Mean distance from Neptune (10^3 km)	Δ_{min} (10^3 km)	Δ_{max} (10^3 km)	Sidereal period of revolution	e of mean orbit	i relative to ecliptic
Triton	354	354	354	$5^{d}21^{hr}02^{min}39^{sec}$	0.00	132°.79
N-4	524	91	957	11 05 31 12	0.73	60.87
Nereid	5570	1337	9803	359 09 36	0.76	4.97

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