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Charge-Coupled Device Photometry of Comet P/Halley

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Comet P/Halley has been observed during its approach to perihelion at heliocentric distances $R = 11.0$ AU and $R = 8.2$ AU. No extended coma is seen and limits can be placed on the fraction of the total light contributed by coma. The brightness of the comet varies on a short time scale. The variations may be due to transient activity or to rotation of the irregular nucleus. © 1984 Academic Press, Inc.

1. INTRODUCTION

Comet P/Halley is well known as an object of considerable popular interest and attention. The comet is scientifically interesting for its accurate ephemeris provides a rare opportunity to plan detailed physical observations far ahead of their execution. In particular, there is much to be learned from observations of the comet at large heliocentric distances, $R > 5$ AU, where outgassing from the nucleus may be minimal and where the nucleus might be observed directly. Insight into the development and growth of the coma and tail may also be obtained from systematic observations at large R.

For these and other reasons, Comet P/Halley has been the recent subject of numerous telescopic searches and sightings. A short summary of the early searches is given by Yeomans (1981). Following the recovery by Jewitt *et al.* (1982b) at $R = 11.0$ AU, confirmations were announced by Belton and Butcher (1982), Baudrand *et al.* (1982), and Sicardy *et al.* (1983). The first observations showed that the comet was close to the location predicted by Yeomans (1981) and had a brightness consistent with a nucleus of a few kilometers in radius. The comet was of stellar appearance, with neither coma nor tail. Later observations by West and Pedersen (1983), at $R = 10.5$ AU, revealed a possible brightness fluctuation of 1.0 ± 0.4 mag. The fluctuation was interpreted as evidence of early coma production. More recent mention of variability has been made by Lecacheux *et al.* (1984).

The present paper has two functions: we present the recovery observations of 1982 October in more detail than was possible in Jewitt *et al.* (1982b) and we compare and contrast these observations with extensive photometry obtained 1984 January. The observations at $R = 11.0$ and $R = 8.2$ AU are used to constrain the properties of Comet P/Halley.

2. OBSERVATIONS

The observations were taken with a cooled 800 × 800 pixel charge-coupled device (CCD) manufactured by Texas Instruments. This device is especially suited to photometric observations of faint comets

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since it has high quantum efficiency (about 0.7 at 0.65 μm wavelength), has very low read noise (about 10 electrons per pixel per read out), and has a linear response (deviations from linearity are $\lesssim$ 0.1% in the brightness range of interest). The CCD was used with the PFUEI camera (Gunn and Westphal, 1981) at the prime focus of the Palomar 5-m telescope. The image scale was 0.42 arcsec/15-μm pixel. Images were obtained through the g, r, and i filters described by Thuan and Gunn (1976) and Wade *et al.* (1979). These filters have central wavelengths 0.50, 0.65, and 0.80 μm, respectively, and have FWHM ≈ 0.1 μm. Flat field exposures were taken at the beginning and end of each night by exposing on a tungsten-illuminated patch on the inside of the observatory dome. The bias level of the CCD was measured for each recorded frame.

Data collection with PFUEI was controlled via a PDP-11 computer. The latter enabled real-time flattening of the CCD images and permitted early judgment of the quality of the data. At the times of the observations, Comet P/Halley appeared projected close to the galactic plane, leading to several problems with bright stars in the comet field. The detrimental effects of the bright stars were reduced by two methods: First, a set of opaque masks was used to block the brightest stars in the 5.6-arcmin-wide field. Second, the exposures were accumulated in segments of sufficiently short duration as to prevent saturation of field star images near the comet. Despite these precautions, about one third of the attempted observations were affected by bright field stars. These observations have been omitted from the present analysis.

The comet was identified primarily by its motion relative to field stars. In 1982 October, the telescope was tracked at sidereal rate, and the motion of the comet (at about 3 arcsec/hr) was removed by subsequent image processing. In 1984 January, the telescope was tracked on the comet (the rate was about 23 arcsec/hr relative to the sidereal). The success of the tracking was judged by the absence of movement of the comet image between successive CCD frames and by the uniformity of the trailed star images. The mean tracking errors were measured to be $< 4 \times 10^{-4}$ arcsec/sec.

A journal of observations is presented in Table I. The columns in the table have the following meanings: the first four columns list the observation number, the UT date and time of the middle of the exposure, and the airmass of the observation. Columns 5–7 list the filter through which the exposure was obtained, the duration of the exposure in seconds (e.g., 4 × 300 signifies a 1200-sec duration exposure accumulated in four segments of 300-sec each), and the FWHM of the seeing, in arcseconds. Photometric calibration for the observations listed in Table I was obtained through observations of the standard stars HD 19445, HD 84937, BD + 26° 2606, Ross 34, and Feige 34.

The first observation listed in Tables I and II is a 1σ upper limit to the r filter brightness on UT 1981 December (Jewitt *et al.*, 1982a). Representative g and r images from UT 1982 October (observations 2 and 3 of Table I) are shown in Fig. 1. Images through all three filters are shown in Fig. 2, from UT 1984 January (observations 15–17 of Table I). The comet image is not obviously extended relative to adjacent field stars.

3. PHOTOMETRY

Photometric measurements of comet P/Halley were made according to a standard procedure. Particular attention was given to the possible presence of very faint background objects near the comet image, and to the effects of the extended wings of bright stars some distance from the comet. The results of the measurements are presented in Table II. The first three columns of the table have been transferred from Table I, for ease of use. Remaining columns list the *g*, *r*, and *i* magnitudes, together with the associated uncertainties; the heliocentric distance, *R* (AU); the geocentric dis-

TABLE I

JOURNAL OF OBSERVATIONS

No.	Date	UT	Airmass	Filter	Exposure (sec)	Seeing (arcsec)	Note
1	1981 Dec 18	~08:00	~1.2	r	4 × 300	1.3	[a]
2	1982 Oct 16	~11:50	~1.2	g	20 × 120	1.0	[b]
3	1982 Oct 16	~12:38	~1.1	r	8 × 120	1.0	[c]
4	1984 Jan 04	06:28:56	1.11	g	1 × 300	1.9	
5	1984 Jan 04	06:37:26	1.11	g	1 × 300	2.2	
6	1984 Jan 04	06:50:46	1.10	g	1 × 1000	2.0	
7	1984 Jan 04	07:09:15	1.09	g	1 × 1000	2.1	
8	1984 Jan 04	07:23:32	1.09	g	1 × 300	1.8	
9	1984 Jan 04	07:40:08	1.09	g	1 × 600	2.3	
10	1984 Jan 04	07:53:58	1.09	g	1 × 600	2.2	
11	1984 Jan 07	06:07:39	1.13	g	4 × 75	1.6	
12	1984 Jan 07	06:18:45	1.12	r	4 × 100	2.0	
13	1984 Jan 07	09:49:13	1.36	g	8 × 40	1.9	
14	1984 Jan 07	10:01:26	1.41	r	8 × 40	1.8	
15	1984 Jan 08	06:24:40	1.11	g	4 × 75	1.5	
16	1984 Jan 08	06:35:09	1.10	r	4 × 75	1.7	
17	1984 Jan 08	06:45:20	1.09	i	4 × 75	1.5	
18	1984 Jan 08	10:28:05	1.58	i	4 × 75	1.6	

[a] Upper limit reported by Jewitt *et al.* (1982a) using the same observing system.

[b] Recovery observations.

[c] This r filter observation was not discussed by Jewitt *et al.* (1982b).

TABLE II

PALOMAR PHOTOMETRY OF COMET P/HALLEY

No.	Date	UT	*g*	*r*	*i*	R (AU)	Δ (AU)	*α* (degrees)
1	1981 Dec 18	~08:00		≥25.0		12.73	11.83	1.9
2	1982 Oct 16	~11:50	24.3 ± 0.2			11.04	10.93	5.2
3	1982 Oct 16	~12:38		24.4 ± 0.2		11.04	10.93	5.2
4	1984 Jan 04	06:28:56	23.27 ± 0.10			8.18	7.23	1.7
5	1984 Jan 04	06:37:26	22.9 ± 0.15			8.18	7.23	1.7
6	1984 Jan 04	06:50:46	22.95 ± 0.10			8.18	7.23	1.7
7	1984 Jan 04	07:09:15	22.98 ± 0.07			8.18	7.23	1.7
8	1984 Jan 04	07:23:32	22.93 ± 0.10			8.18	7.23	1.7
9	1984 Jan 04	07:40:08	23.15 ± 0.10			8.18	7.23	1.7
10	1984 Jan 04	07:53:58	23.3 ± 0.30			8.18	7.23	1.7
11	1984 Jan 07	06:07:39	22.2 ± 0.20			8.16	7.21	1.9
12	1984 Jan 07	06:18:45		22.4 ± 0.20		8.16	7.21	1.9
13	1984 Jan 07	09:49:13	22.27 ± 0.10			8.16	7.21	1.9
14	1984 Jan 07	10:01:26		21.89 ± 0.10		8.16	7.21	1.9
15	1984 Jan 08	06:24:40	23.20 ± 0.10			8.16	7.21	2.0
16	1984 Jan 08	06:35:09		23.18 ± 0.10		8.16	7.21	2.0
17	1984 Jan 08	06:45:20			23.15 ± 0.10	8.16	7.21	2.0
18	1984 Jan 08	10:28:05			23.11 ± 0.10	8.16	7.21	2.0

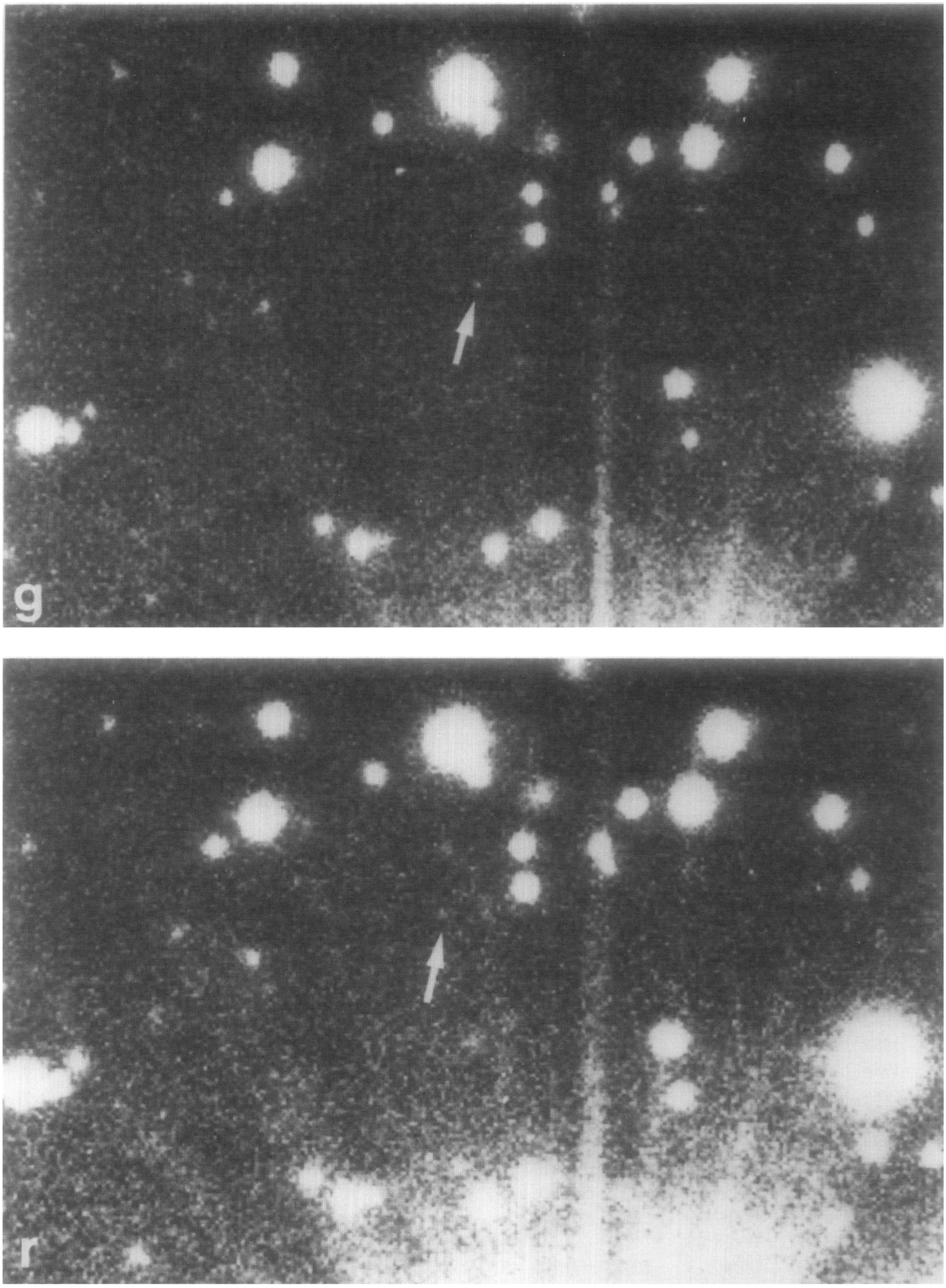

FIG. 1. Two of the images obtained 1982 October from which comet Halley was first identified. These are observations 2 (upper) and 3 (lower) of Tables I and II, from which the picture parameters may be read. Comet Halley is indicated by arrows of 7 arcsec in length. North is toward the right of the figure, east to the bottom.

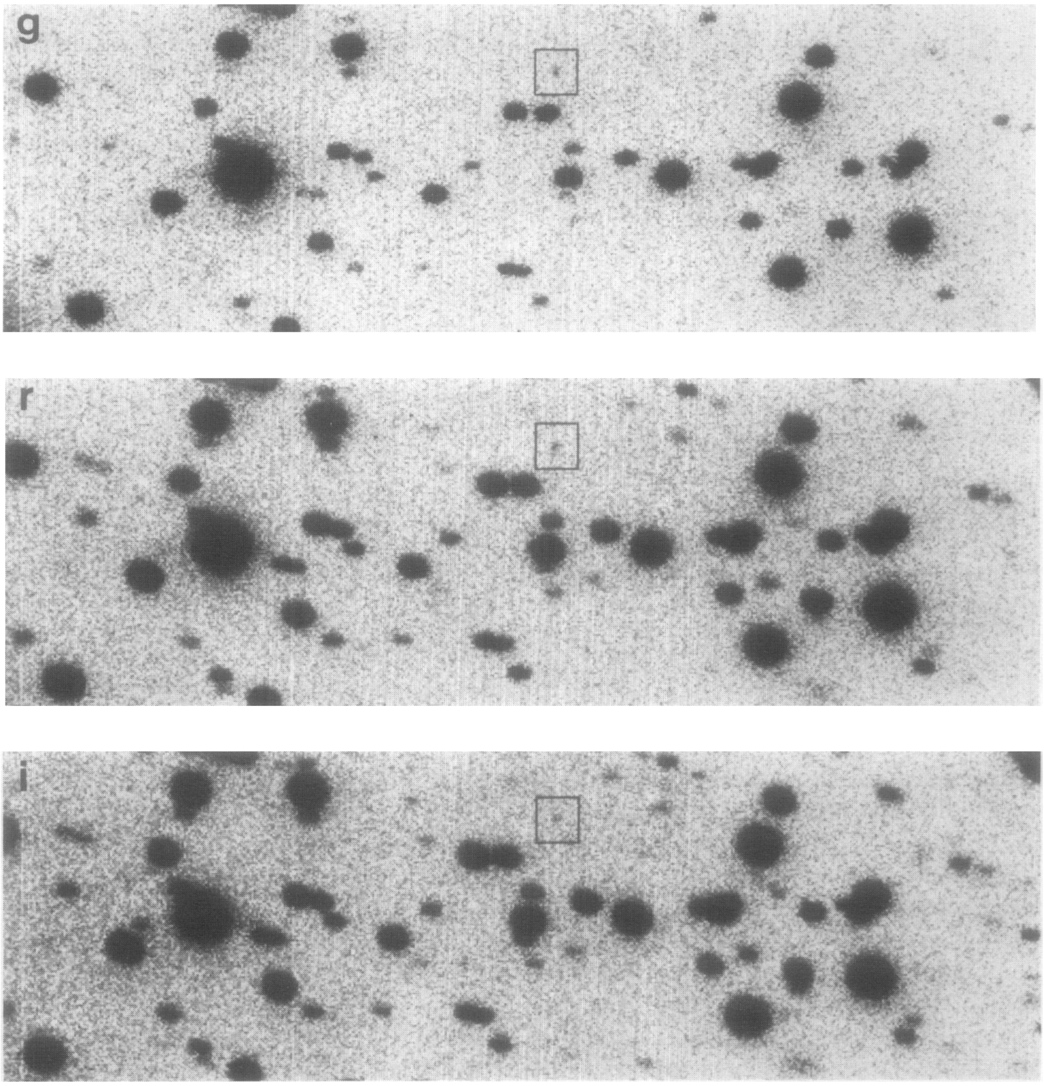

FIG. 2. Images taken 1984 January through the g, r, and i filters. These are observations 15–17 of Tables I and II. Comet Halley is enclosed by a box of 8 arcsec width. North is toward the bottom of the figure, east to the left.

tance, Δ (AU); and the phase angle, α (degrees), of the comet. The magnitudes were generally determined within circles of 6- to 10-arcsec radius about the comet. The magnitudes were found to be constant within circles having radii $\gtrsim$ 4 arcsec, consistent with the absence of extended emission from coma or tail. Measurements of the standard stars demonstrate that each night was photometrically stable to better than 0.03 mag or about 3%. The uncertainties on the tabulated *g*, *r*, and *i* magnitudes exceed this value and reflect the uncertainties of the sky brightness around the comet in each image.

The *g* magnitudes from Table II are plotted as a function of the date in Fig. 3. The solid line in the figure represents "inert nucleus" behavior in which the brightness is assumed to be proportional to $R^{-2}\Delta^{-2}$. A

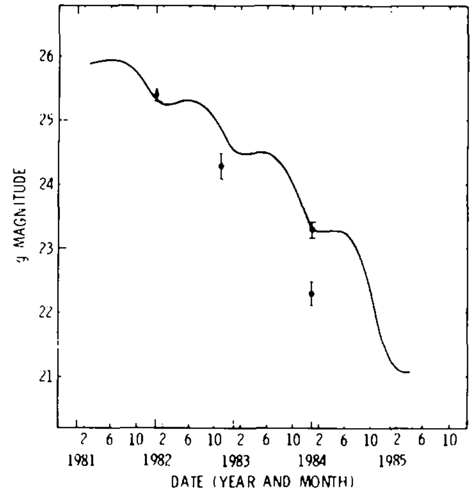

FIG. 3. Graph of the g mag of Comet Halley versus the UT date of observation. The observations and their uncertainties are indicated by dots. The solid line shows the lightcurve of an inert nucleus having zero phase coefficient. The line has been forced to pass through the mean of the g filter observations of UT 1984 January 04.

flat phase function and a spherical, uniform nucleus have been assumed. The model has been arbitrarily normalized to the mean of the observations of UT 1984 January 04.

Figure 3 shows that the general brightness increase of Comet Halley between 1982 October and 1984 January is similar to the brightness increase of the inert nucleus model. However, it is apparent that the brightness was subject to significant variation in the latter observing period. (The time base of the 1982 observations was too short to reveal variations of the type observed in 1984.) An examination of Table II reveals that the g filter brightness of Comet P/Halley varied by about 1 mag on a time scale of 1 day. The brightness was effectively constant for a 90-min period beginning UT 1984 January 04d 06h 29m but had increased by 0.8 ± 0.2 mag (a factor of 2.0 ± 0.5) by UT 1984 January 07d 06h 08m. Between UT 1984 January 07d 09h 49m and UT 1984 January 08d 06h 25m the brightness declined to its January 04 value. A similar variation is suggested by the less numerous r magnitudes. The observed short-term brightness fluctuation is reminiscent of the variation reported by West and Pedersen (1983) and by Lecacheux *et al.* (1984).

The colors of Comet Halley may be obtained from Table II:

$$(g - r) = 0.38 \pm 0.10$$
$$(r - i) = 0.03 \pm 0.20.$$

These are to be compared with the corresponding solar colors $(g - r)_0 = 0.18$ and $(r - i)_0 = -0.03$. Evidently, the colors are consistent with the solar colors within the uncertainties of measurement. At optical wavelengths there is no evidence for blue color which might be indicative of Rayleigh scattering from submicron grains.

4. IMAGE SHAPE

The CCD images can be used to constrain the brightness of the coma at projected distances from the nucleus of a few arcseconds (corresponding to a few times 5×10^6 m at the comet). For this purpose, an image of 2000-sec effective exposure was formed by adding two g-filter images of 1000 sec each (images 6 and 7 of Tables I and II). The azimuthally averaged surface brightness was computed within concentric annuli centered on the comet image. Figure 4 contains a plot of the average surface brightness versus the annulus radius. The peak of the profile has been normalized to 100 surface brightness units, corresponding to 25.5 g mag/arcsec^2. A similarly constructed surface brightness profile of a field star is shown for comparison. The star was selected from an adjacent short exposure (untrailed) image and has been normalized to 100 surface brightness units at the peak.

Within the uncertainties imposed by the variable seeing, the star and comet profiles appear similar. Only small differences between the profiles of the star and of the comet are evident. They may be attributed to a slight change in the atmospheric seeing between the two images (see column 7 of Table I). The differences cannot be due to short-term trailing of the comet image since

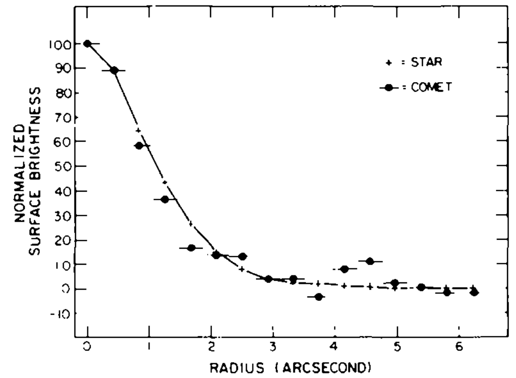

FIG. 4. Azimuthally averaged g filter surface brightness profiles of Comet Halley (dots) and a field star (crosses joined by continuous lines). The star and comet profiles have been normalized to a surface brightness of 100 units at their peaks. One hundred units of Comet Halley's surface brightness correspond to 25.5 g mag/arcsec^2. The radial distance (in arcseconds) from the center of each image is plotted horizontally.

the comet profile is actually more condensed than the star profile.

The placing of formal limits to the presence of coma is model dependent: it is necessary to assume the spatial form of the coma. In many comets the surface brightness is observed to decrease in proportion to the reciprocal of the projected distance from the nucleus. This distribution is expected of a refractory grain coma produced by an isotropic source of fixed strength. The total magnitude of such a coma may be estimated from

$$g_{\mathrm{TOTAL}} = -2.5 \log(2\pi r^2) + g(r)$$

where $g(r)$ (magnitudes per square arcsecond) is the surface brightness at projected distance r (arcseconds) and g_{TOTAL} is the magnitude of the coma within a circle of projected radius r. From Fig. 4, an approximate upper limit to the coma surface brightness at $r = 4$ arcsec may be set equal to 10% of the peak of the surface brightness profile, corresponding to $g(4) > 28.0$ mag/arcsec^2. Hence, the coma within 4 arcsec of the nucleus is fainter than $g_{\mathrm{TOTAL}} = 23.0$, a limit which may be compared with the observed magnitude of the comet, $g = 23.0 \pm 0.1$. It may be concluded that a large fraction of the light from Comet Halley could be scattered from a refractory grain coma without changing the stellar appearance of the comet.

5. DISCUSSION

An important question concerns whether the observed brightness variations of Comet Halley are caused by variable coma production or by the rotation of an irregular or spotted nucleus. The argument of the previous section demonstrates that the comet might possess a considerable isotropic coma of refractory grains even though the image appears stellar. Other types of comae are also permitted by the star-like surface brightness profile shown in Fig. 4. In particular, comae which are more centrally condensed than the isotropic refractory grain coma could be present around the nucleus of Comet Halley. Steep surface brightness profiles are expected of sublimating grain halos, for instance. It is also possible that the nucleus has a trapped coma of grains following suborbital trajectories. These and other speculations are not presently susceptible to observational constraint.

The only substantial clue as to the origin of the brightness variations of Comet Halley is provided by the time scale of the variations. If ejected grains were the cause, then the time scale for the decline of the excess brightness would equal the time needed for the grains to cross the radius of the projected effective diaphragm within which photometry was performed. The diaphragm crossing time may be estimated from

$$t_{\mathrm{D}} \simeq 1.4 \times 10^3 \ \phi\Delta R^{0.5}$$

where t_{D} is measured in seconds, ϕ (arcseconds) is the projected diaphragm radius, and Δ (AU) and R (AU) are the geocentric and heliocentric distances, respectively. The Bobrovnikoff/Delsemme velocity relation (Delsemme, 1982) has been assumed for the ejected grains. Inserting $\phi = 10$ arcsec, $\Delta = 7.21$ AU, and $R = 8.16$ AU gives $t_D \approx 3 \times 10^5$ sec. This may be compared with the time interval in which the brightness halved, namely, $t_0 < 7 \times 10^4$ sec (i.e., between 1984 January 07 and 08). Since $t_D/t_0 > 1$, it appears that transient ejection of refractory grains was not the cause of the brightness variation. This conclusion does not extend to volatile grains or to grains moving in the gravitational influence of the nucleus: such grains may sublimate or fall back to the nucleus on time scales less than t_D. In short, it is not possible to discriminate between nucleus activity and nucleus rotation as the cause of the brightness variations, although refractory grains would seem to have little effect on the appearance of the comet.

Regardless of the specific interpretation placed on the brightness variations, the observed g magnitudes may be used to estimate upper limits to the cross section of the nucleus and to the rate of mass loss from it. For these purposes we use

$$p\beta^2 = 2.25 \times 10^{22} R^2\Delta^2 10^{0.4(g_\odot - g)}$$

where p is the geometric albedo at 0.5 μm wavelength, $\pi\beta^2(\mathrm{m}^2)$ is the total cross section, and $g_\odot = -26.64$ is the g magnitude of the Sun. The phase angle dependence of the scattered light has been neglected. Taking R, Δ, and g from Table II, we compute $p\beta^2 = 1.4 \pm 0.3 \times 10^6$ m^2 (1982 October 16), $p\beta^2 = 1.1 \pm 0.1 \times 10^6$ m^2 (1984 January 04), and $p\beta^2 = 2.2 \pm 0.2 \times 10^6$ m^2 (January 07).

If the observations are taken to refer to the bare nucleus, then the $p\beta^2$ values may be used to estimate its dimensions. The geometric albedo of the comet nucleus, p, is unknown, but the adoption of $p = 0.1$ is unlikely to be wrong by as much as a factor of 10. To order of magnitude the nucleus would present cross sections of 3.5×10^7 m^2 on January 04 and 6.9×10^7 m^2 on January 07, the change being due to rotation of the nonuniform nucleus. It is possible that p varies with position on the nucleus. The equivalent-circle radii of the nucleus would be about 3×10^3 and 5×10^3 m, respectively, again assuming $p = 0.1$. In view of the uncertain contribution from coma, the above values of $p\beta^2$ must be regarded as upper limits to the true value of the nucleus.

The present observations are too sparse to permit the determination of the rotation period of the nucleus, even assuming there is no coma. However, from the constancy of the g magnitude on January 04, and of the i magnitude on January 08, the period would seem to be $\lesssim 4$ hr. In the present interpretation, the decrease from January 07 to January 08 suggests significant rotation of the nucleus in 20 hr: the period cannot be longer than a few days. It may be noted that several asteroids show brightness modulation by a factor of 2 or more. Mostly, these bodies have diameters less than about 10^4 m (e.g., Harris and Burns, 1979).

If the brightness variations are instead caused by the coma then it is possible to estimate the amount of material involved. The sum of the cross sections of the grains ejected between 1984 January 04 and January 07 is approximately $\pi\beta^2 = \pi \times (2.2\text{–}1.1) \times 10^6/p = 3.5 \pm 0.5 \times 10^6/p$ (m^2). The mass of the grains may be estimated from $m = 4\pi\rho a\beta^2/3$, where ρ (kg m^{-3}) is the grain density, and a (m) is the mean grain radius. Adopting $\rho = 10^3$ kg m^{-3}, $a = 10^{-6}$ m, and $p = 0.1$, we find $m = 5 \times 10^4$ kg. Consequently, the mean mass loss rate between January 04 and January 07 amounts to $\dot{m} = 0.2$ kg sec^{-1}. This is about 10^4 times smaller than the mass loss rate from a typical active comet near $r = 1$ AU, but is still large in comparison with the sublimation rate of a water-ice nucleus at the distance of Comet Halley (Washburn, 1928). For example, a slowly rotating, perfectly absorbing spherical water-ice nucleus of 10^3-m radius would sublimate at a rate $\dot{m} = 3 \times 10^{-7}$ kg sec^{-1}. A flat water surface of the same cross section and oriented normal to the Sun would give $\dot{m} = 6 \times 10^{-4}$ kg sec^{-1}. Even allowing that the nucleus of Comet Halley may exceed 10^3-m radius, it appears implausible that water ice could provide a probable source of coma at such large R. In particular, the brightness variations of Comet Halley are not caused by variable sublimation of water ice on the nucleus.

6. CONCLUSIONS

1. Comet Halley has been observed at $R = 11.0$ and $R = 8.2$ AU with a single observing system. At these heliocentric distances, the comet has a star-like surface brightness profile and Sun-like broadband optical colors.

2. The general brightness increase between $R = 11.0$ and $R = 8.2$ AU is similar to the increase expected of an inert nucleus. However, the brightness of Comet Halley varies by about 1 mag on a time scale $\lesssim 1$ day. The variations are not due to the ejection of refractory grains from the nucleus, but other forms of activity may be responsible. Alternatively, the brightness variations may result from rotation of an irregular and/or spotted nucleus.

3. The product of the geometric albedo of the nucleus with the square of its radius does not exceed about $2.2 \pm 0.2 \times 10^6$ m^2. Between 1984 January 04 and January 07, the mean mass loss rate from Comet Halley was $< 10^{-4}$ times the mass loss rate from a typical active comet at $R = 1$ AU.

APPENDIX

The g, r, and i filters used in the present investigation have several advantages over the usual V, R, I, "Johnson" filters. However, since many observers use the latter system we present approximate transformations between the two systems as given by Hoessel and Mould (1982):

$$V = g - 0.03 - 0.37\,(g - r)$$
$$I = i + 0.55\,(r - i) - 0.55$$
$$R - I = 1.31\,(r - i) + 0.33.$$

We adopt $(g - r) = 0.38 \pm 0.10$ and $(r - i) = 0.03 \pm 0.20$, giving for Comet Halley:

$$V = g - 0.17 \pm 0.04$$
$$I = i - 0.53 \pm 0.11$$
$$R = I + 0.37 \pm 0.28$$

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