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AURORA

BY
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AURORA

a review by

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1. Introductory Description

Descriptions of aurora of great antiquity are known. Some of the most famous are those by Aristotle (Meterologica, Book I, Chap. 5 (ca 340 B.C.)), Pliny (Historia Naturalis, Book II, Chaps 27 and 33 (ca. 77 A.D.)), and Seneca (Quaestiones Naturales, Book I, Chaps. 14 and 15 (Ca. 63 A.D.)). In central Europe the rare auroras were considered as warnings for coming calamities and the descriptions from the Middle Ages, especially, are characterized by superstitions and fears. In northern Europe where auroras are more common such superstitions did not influence the objective observation to the same extent. A remarkably good description can be found in the Norwegian chronicle The King's Mirror of about 1250. It is partly quoted by Störmer (1955) and he also quotes some good descriptions of auroral events of more recent time.

The name aurora borealis, or northern dawn, seems to have been first used by the French philosopher Gassendi in 1621, (Jacka and Paton, 1963) and is an appropriate description of the usual appearance of the northern lights when they are observed in medium latitudes. In analogy with aurora borealis the southern lights have been called aurora australis. "The northern dawn seen from middle latitudes is mostly the upper portion of a display which is overhead at higher latitudes. It is only when aurora moves equatorwards on the rare occasions of the great events that middle latitude observers can see those parts of the display which, being below the horizon, are so frequently concealed from them. Aurora then belies its title, since it is no longer an unspectacular glow on the horizon, like the dawn, and it is more aptly called "The Merry Dancers," the name by which it is known in the northern isles of the Britain" (after Jacka and Paton, 1963). In the last years aurora has been made by man with the use of high-altitude nuclear explosions. The first artificial aurora was observed in 1958 (Cullington, 1958, Fowler and Waddington, 1958).

This review will concentrate on auroral characteristics which are influenced by the geomagnetic field and on results obtained in the last few years. Excellent extensive reviews of auroral phenomena have appeared, (Harang, 1951; Störmer, 1955; Chamberlain, 1961) some fairly recently, and the reader is referred to them for details on, e.g., the auroral spectrum, older morphological studies, correlations with other phenomena, etc. The emphasis here will be on the morphology, which is largely determined by the geomagnetic field. Rocket and satellite studies of primary auroral particles will also be treated in some detail, since they are not contained in the extensive treatises mentioned above. Finally, proposed theoretical models for various auroral phenomena will be briefly discussed in relation to the observations.

In this first subsection a short description of some auroral characteristics will be given.

1. Intensity and Energy Considerations

Aurora is one of the most intense luminous phenomena in the sky, as is illustrated in Table 1 (after Friedman, 1960, except for the aurora value). The very strongest auroras are even more intense than the value given in Table 1. They are fully comparable to the full moon. The majority of auroras are, however, weaker and the whole scale down to the intensity of the airglow exists.

For estimation of brightness of aurora by visual observers, the following four classes of an International Brightness Coefficient (IBC) are used: I, the brightness of the aurora is equal to that of the Milky Way; II, brightness equal to that of thin moonlit cirrus clouds; III, brightness equal to that of moonlit cumulus clouds; and IV, the aurora provides a total illumination at the ground equivalent to full moonlight. These definitions are extremely crude. Seaton (1954) made a first effort to place the IBC scale on an absolute basis. His results have been slightly modified by Hunten (1955), who proposed the following definitions in terms of number of photons of λ 5577 Å (generally the most important emission in aurora) per cm^2 (column) and sec.

IBC I	10^9	= 1 kR
II	10^{10}	= 10 kR
III	10^{11}	= 100 kR
IV	10^{12}	= 1000 kR

Table 1

Source	Flux (ergs cm^{-2} sec^{-1})
Sun	$1.4 \cdot 10^{6}$
Full moon	$3000 \cdot 10^{-3}$
Strong aurora	$1000 \cdot 10^{-3}$
Total starlight	$1.8 \cdot 10^{-3}$
Airglow (visible)	$16 \cdot 10^{-3}$
OH (infrared)	$19 \cdot 10^{-3}$
Lyman-α	$10 \cdot 10^{-3}$
Celestial sources (1230-1350Å)	$0.1 \cdot 10^{-3}$
Cosmic rays	$3.8 \cdot 10^{-3}$

10^6 photons/cm^2 (column) sec is called 1 Rayleigh (1R) in accordance with the proposal of Hunten et al. (1956). (For a discussion of the Rayleigh unit see also Chamberlain, 1961, Appendix II). The Rayleigh unit is not limited to a special wave length as is the IBC.

The energy influx required to produce visible aurora has been measured (McIlwain, 1960; O'Brien and Taylor, 1964) and has also been computed from optical emissions (Omholt, 1959; Chamberlain, 1961). The results show reasonable agreement. 0.2 – 1% of the input energy seems to be converted to visible light. The input energy required to produce an IBC I aurora is of the order of a few ergs/cm^2 sec (see e.g. Hultqvist, 1964c). Measurements by means of the Injun 3 satellite show that the average energy input rate required to sustain auroras around the world is of the order of 10^{18} ergs/sec (10^{11} watts) (O'Brien and Taylor, 1964). The average energy flux of the solar wind within a cylinder of radius 10 earth radii is of the order of 10^{20} ergs/sec. Thus in the average about 1% of the solar wind energy has to be transformed into particle precipitation. However, during very strong auroras an appreciable fraction of the relevant solar-plasma energy flux must be converted into kinetic energy of precipitated particles, and the energy density of the solar beam may even be unsufficient on some occasions (Mogilevskiy, 1963). Large auroral events thus contribute much energy to the upper atmosphere. Most of this is probably radiated away (only some 15% transformed to heat according to Chamberlain, 1961). It seems quite possible that the temperature of the upper atmosphere in the auroral zones is primarily determined by the particle influx (Bates, 1960b; Chamberlain, 1961; Maeda, 1963).

Recent observations of tne drag on Injun 3 indicate that the upper atmosphere temperature in the auroral zone is essentially the same as at the equator on geomagnetically disturbed days (Jacchia and Slowley, 1964). The heating accompanying geomagnetic perturbations in the auroral zones seems to be 4 or 5 times greater than the heating experienced during these perturbations in low latitudes.

2. Definition and Classification of Aurora

In connection with intensity the definition of aurora has to be considered. It has been fairly common to mean by aurora sporadic emissions of intensity at least a few times the airglow intensity but not to include emissions weaker than that. From a physical point of view this is not a good definition. Airglow and aurora, the production mechanisms of which are different, may well be thought of as being of similar brightness.

A definition based on the mechanism of excitation and emission would certainly be preferred. Along this line aurora is often defined as emissions in which the intensity ratio between the 3914 Å nitrogen band - which is produced by collision excitation - and the oxygen atom line at 5577 Å is of the order of unity. In airglow it is usually much less than unity. Unfortunately, however, the excitation mechanisms are complex and are not well-known, which makes it impractical to use them in definitions. One parameter seems to be of widely different importance for airglow and for aurora: the geomagnetic field. Roach and Roach (1963) have defined aurora as emissions, the geographical location of which is determined by the geomagnetic field. The auroral phenomena then also include the stable red arcs, which are mostly subvisual and located in middle latitudes (see the review by Roach and Roach, 1963). We will in this review consider as aurora all emissions which are produced in one way or the other by particles of energy well above thermal and we will also include the above mentioned medium-latitude red arcs (m arcs), for which it is not known whether they are produced by particles (of very low energy) or not.

The aurora is an extremely complex phenomenon. The various types that occur can be grouped in the following six classes, for instance (due to Elvey, 1964)

1. Polar glow
2. Discrete polar cap auroras
3. High red aurora (Störmer's type III)
4. Intermediate red arcs (Störmer's type II)
5. M-arcs
6. Ordinary displays (Störmer's type I)

The polar glow aurora was discovered by Sandford (1961b). It is produced by the same solar protons in the energy range from some 10 Mev to several 100 Mev, which give rise to polar cap absorption. This type of aurora is thus fairly rare and has a pronounced maximum of occurrence frequency at solar activity maximum. The glow is distributed over the whole polar caps and is often subvisual.

The discrete polar cap auroras have several characteristics which are quite different from ordinary auroral-zone aurora (Störmer's type I).

Their occurrence frequency is higher at low solar activity then at high and they also show a negative correlation with magnetic activity. The spectrum is, however, similar to that of ordinary auroral displays.

Class No. 3 – high red aurora – is the most common type in low latitudes but it also occurs in the auroral zone sometimes.

The intermediate arcs are very rare. They often look grey due to faintness. The average lower height limit is 196 km (which is between the values for ordinary auroral displays and high red aurora; therefrom their name). The red 6300 Å line is the most prominent spectroscopic feature. For more details see Störmer (1955).

The so-called ordinary auroral displays are, by far, the most common type of aurora and the rest of this review will deal mainly with them. Not only visual light is emitted by the aurora but emission also takes place in the ultraviolet (see for instance Chamberlain, 1961) and at radio-frequencies (cf e.g. Hartz, 1958, Murcray and Pope, 1960, Egan and Peterson 1961, and Martin and Helliwell, 1960).

In this review we will include among the auroral phenomena not only emissions of electromagnetic radiation but also the so-called radio aurora. The term radio-aurora refers to the effect on the propagation of radio waves, especially in the VHF and UHF frequency ranges, by the ionization in the atmosphere produced simultaneously with the excitation. Such ionization gives rise to radio echoes of a special type.

3. The Development of an Auroral Display

The auroral displays show an enormous variety in their temporal development. One can, however, talk about typical sequences of events (see e.g. Heppner, 1954, Akasofu, 1963d). Equatorward of the auroral zones the display may begin with a glow along the poleward horizon. The glow then rises from the horizon and forms one or more quiet and mostly homogeneous bows of light (arc), oriented approximately east-west. An "arc" may remain relatively quiescent for hours, drifting slowly towards north or south. Suddenly it may brighten here and there and "rays" begin to appear across the arc. The arc is then likely to fold and so to lose its regular bow shape and to form an irregular "band." If the rays are very long, the band assumes the appearance of a great "drapery," waving like a curtain in the sky. Rapidly moving and fading irregular forms may appear and disappear all over the sky.

As the display dies down, waves of light may surge upwards from the horizon in quick succession causing existing auroral forms to brighten as the waves pass over them (flaming aurora). A continuous glow (veil) may extend over a large part of the sky, serving sometimes as a background to the active forms. At other times, diffuse patches of light, closely resembling clouds, appear here and there in the sky. These may come and go,often with regular pulsations, until twilight sets in. There is a tendency for reformation into arcs after the diffuse surface phase. The development pattern is closely correlated with the details of the coincident magnetic disturbance. The described sequence is typical equatorward of the auroral zone, as mentioned. On the poleward side, and especially over the central polar caps the development is quite different. This will be discussed in section 3. For some good descriptions of individual auroral events, see for instance Störmer (1955).

4. Auroral Forms

In the last few decades the auroral forms have mostly been classified in accordance with the recommendations of 1930 of the International Union of Geodesy and Geophysics. These recommendations were worked out by Störmer (1930a, b) and are described in detail also in his book (Störmer, 1955).

The Committee for the "International Quiet Sun Year" (IQSY), 1964-1965, of the "Comité International de Géophysique" (CIG) has adopted a new scheme of nomenclature for describing auroras. It will be briefly reviewed below, following Jacka and Paton (1963).

An aurora is described in terms of 4 parameters (6 if brightness and color also are to be included).

1. Auroral forms are divided into three groups

1.1. Band-like forms: These are characterized by a continuous lower border.

(i) When the form appears as a simple, slightly curving arch (Fig. 1.1) or part of an arch, with a regular lower border it is called an arc (A).

(ii) When the lower border is irregular and contains kinks or folds (Fig. 1.2) the form is called a band (B).

1.2. Diffuse forms: These may take the form of a patch (P) or a veil (V).

(i) The patch is simply a blob of illumination with an ill-defined boundary; it often resembles an isolated cloud.

(ii) The veil refers to the uniform luminosity that may cover a large part of the sky. It may occur alone or as a background to other forms.

1.3. Rays (R): These are shafts of light aligned in the direction of the earth's magnetic field (cf. Fig. 1.3). There may be a single ray, a bundle of rays close together or many scattered rays (subscripts 1, 2, 3 may be added to R to indicate short, medium, and long rays respectively).

2. Structure is described by the following three adjectives

2.1. Homogeneous (H): This term implies an apparent lack of internal structure in the form. The brightness is uniform or it changes only gradually across the form. A homogeneous arc (HA), and horseshoe-shaped bands are shown in Fig. 1.4.

2.2. Striated (S): The form contains rather irregular striations or filaments aligned roughly parallel with the lower border (Fig. 1.5). Striation is usually recognizable only when the form is nearly overhead.

2.3. Rayed (R): Rayed forms are characterized by the appearance within them of rays which are aligned along the lines of force of the geomagnetic field (Fig. 1.6).

3. Qualifying parameters: One of three qualifying parameters may, when relevant, be added to the description.

3.1. Multiple (m): This term is used when there occur two or more associated and roughly parallel forms of the same kind. (A subscript numeral indicates the actual number of forms, e.g. m_2HB signifies two closely situated homogeneous bands).

3.2. Fragmentary (f): This term is used when only a portion of an arc or band is present.

3.3. Coronal (c): When any rayed form is viewed in the direction of the lines of magnetic force the rays appear to converge. Homogeneous forms may also present a similar coronal appearance where they pass over the magnetic zenith.

4. Condition describes the behavior of a form or of the whole display.

4.1. Quiet (q): The form undergoes only very slow changes in position or shape.

4.2. Active (a): is a form which moves or changes its shape rapidly. Such forms are frequently bright.

(i) a_1 – refers to the movement of folds or irregularities along the boundary of a band.

(ii) a_2 – refers to the rapid change of shape of the lower border of a form while the form itself may also move rapidly across the sky.

(iii) a_3 – indicates the occurrence of a rapid movement of rays horizontally along a form.

(iv) a_4 – refers to a display as a whole in which forms fade rather quickly, while new, similar or different forms appear in other parts of the sky. A photograph of such an event is seen in Fig. 1.7.

4.3. Pulsing (p): this describes a condition of fairly rapid and often rythmic fluctuation in brightness. The period of the fluctuation may range from a fraction of a second to the order of minutes.

(i) p_1 – pulsating forms: The affected form or forms display a variation in brightness, the phase of which is uniform throughout the forms.

(ii) p_2 – flaming aurora. This kind of pulsing extends over a large area of the sky which appears lit by surges of light sweeping upwards over it.

(iii) p_3 – flickering: A large part of the display undergoes very rapid and more or less irregular changes in brightness as if lit up by flickering flames. This occurs only rarely.

(iv) p_4 – streaming: An irregular variation of brightness that progresses rapidly along the horizontal extent of homogenous forms.

Most auroras can thus be fairly well described by four symbols–or sometimes five–with subindices. For instance a_3 cfR_2Bsignifies a fragment (f) of a rayed band (R_2B) whose rays are of medium length (R_2), are moving rapidly in a horizontal direction along the form (a_3) and form a corona in the magnetic zenith. Symbols indicating the brightness and color may be added after the symbol for the form (for details see Jacka and Paton, 1963).

The auroral arcs and bands at the auroral zones are characterized by very long extension in east-west direction and a remarkable thinness in north-south direction. From the photographic recordings of aurora made during IGY continuous auroral arcs of lengths 4000-5000 km have been reported (Feldstein et al., 1962, Akasofu, 1963). The values mentioned were limited by the coverage of the net of recording cameras, so arcs may be still longer. Recent measurements of the thickness of 40 zenithal arcs have given values varying between 3.5 and 18.2 km with an average value of 9.1 km (Kim and Volkman, 1963). The thickness was found to increase with increasing magnetic activity. On the other hand, for an active auroral curtain the thickness has been measured to be as narrow as 150-350 m (Akasofu, 1961). No significant diurnal or seasonal variation was found. The vertical extension of the arcs and bands is generally a few ten km. It has been found to vary with solar activity, the extension being smaller and the atmospheric depth greater at the end of a solar cycle (Elvey, 1957). When the sunspot acitivity starts to increase again, the auroras often appear less deep in the atmosphere and have extension to great heights–the red auroras of type A.

The stable midlatitude red arcs, discovered by Barbier (1958), differ completely from ordinary auroral arcs. They cover some hundreds of kilometers in latitude and in height. Present evidence suggests that they may occur in complete rings around the world (cf. Roach and Roach, 1963).

The rays are characterized by great length and thinness. The length has been extensively studied by Störmer (1955). It may amount to several hundred km, but a more common value is between 100 and 150 km. Especially the sunlit rays can be very long and have been found to extend up to 1100 km sometimes. The diameter of the rays is of the order of 1 km (see e.g. the recent study of Akasofu, 1963b).

Wilcke (1777) first noticed that the auroral rays are aligned approximately along the earth's magnetic field lines. Vegard and Krogness (1920) found that the elevation of the "radiant point," i.e. the point towards which the rays in a corona appear to converge, is systematically one degree or so lower than the magnetic zenith. This difference is too great to be due to the curvature of the field lines. (The rays would have to be at about 1000 km to show a one degree displacement). Störmer (1938) found the auroral zenith to wander around a little in the sky. Abbott (1958) measured a rate of motion for the radiant point of at least 1° in 5 minutes of time. The radiant point was found on either side of the normal (undisturbed) magnetic zenith, but measurements of the disturbed field showed that the instantaneous magnetic zenith was 7 or 8° lower than the radiant point. No relationship between the motions of the magnetic zenith and the auroral zenith was found. Cole (1963) has studied in detail the geometry of the radiant point and found that it commonly differs by 0.5° from the "local auroral zenith," defined by him as the direction of a (hypothetical) ray, regarded as a segment of a straight line, passing through the observer. The difference may amount to as much as several degrees. Observations of the local auroral zenith have not yet been reported. Presuming the rays are oriented along the field lines such observations would give valuable information about the detailed direction of the geomagnetic field lines at auroral heights, which is difficult to obtain with comparable accuracy in other ways.

Detailed studies have shown that fine structures exist not only in auroral forms seen rayed to the eye or the camera but also in what is normally called homogeneous forms (Nadubovich and Starkov, 1961). Dark filaments of a minimum width of 150 m and an average length of about 20 km have been found. They have been observed most often in the morning hours. The duration is several minutes.

There is a fine structure in aurora not only in space but often also in time. Rapid variations in auroral emission rate have recently been observed and studied by Campbell (1960a,b), Campbell and Rees (1961, Campbell and Leinbach (1961), Iyengar and Shepherd (1961), Omholt (1962), Skrynnikov (1962), Berger (1963), and Gustafsson (1964).

For a more detailed review of older investigations of the characteristics of various auroral forms, see e.g. Störmer (1955) and Chamberlain (1961).

5. Emission Spectrum

But for a very brief introductory survey, the auroral spectrum will not be dealt with in this review. For a detailed review see e.g. Bates (1960) and Chamberlain (1961).

The aurora seen in high latitudes is usually green to the eye. The colour is due to a forbidden transitition ($^1S \rightarrow {}^1D$) in the oxygen atom. The wavelength is 5577Å, which is close to the maximum sensitivity of the eye. The transition probability is very low corresponding to a life-time of the excited level of about 3/4 sec (Omholt and Harang, 1955).

In lower latitudes the aurora is often seen to be red (high red aurora in the nomenclature used). The spectral characteristic is then the 6300, 6364, 6391 Å triplett of O, which is produced in cascade ($^1D \rightarrow {}^3P$) after the 5577Å line. The 6300 line is also forbidden with a lifetime of the excited level of about 110 sec (Omholt, 1960). Due to the long lifetime, deactivation is important for this line and it is therefore mostly seen in auroras at high altitudes. The long lives of the metastable levels from which the λ 5577Å and λ 6300Å lines are emitted give rise to colour variations in active auroras as these lines are emitted for some time after the excitation has ceased.

There exist auroras even in high latitudes with anomalously increased 6300Å emission. One famous example of this was the one on 11 Feb. 1958. Most other auroral spectra belong to one of three types, between which the boundaries are, however, not very sharp (Krasovskii, 1961). The first type is the low-latitude spectrum mentioned above, in which the ratio of the intensities of the 6300Å and 5577 Å lines is high, and where these two emissions strongly dominate over e.g. the nitrogen molecule bands. In the next type, lines of neutral and ionized atoms dominate but in addition emissions of ionized and neutral nitrogen molecules are seen. This type of spectrum is observed in both high and low latitudes. Finally, the third type is characterized by numerous intense molecular bands. It is remarkable that in such spectra the green line of atomic oxygen and the first and second positive and negative band systems of N_2 are correlated in great detail. This third type of spectrum most frequently appears in high latitudes. The difference between the spectra are apparently accounted for by the depth of penetration of the exciting agent into the atmosphere, the depth increasing from the first to the third type.

Auroras located at great atmospheric depths usually have a red lower border (red aurora of type B). This is due mainly to the first positive bandsystem of the neutral nitrogen molecule. The reason for the domination of the N_2 emissions at great depths is probably that the 'S level of OI is deactivated by collisions to an appreciable amount.

The sunlit auroras have a spectrum different from that of the auroras located in the dark atmosphere. They have a bluish-white color which is produced by resonance emission of primarily the first negative band-system of the positively charged nitrogen molecule (N_2^+).

Of special interest are the hydrogen line emissions. They were first found by Vegard (1939). Analysis of their line contour showed that protons are entering the upper atmosphere with velocities up to 4000 km/sec (Meinel, 1951). They are seen mostly in homogeneous forms. More recently, weak hydrogen glow has been observed preceding the appearance of bright auroras (Romick and Elvey, 1958, and others). Auroras have been observed in which the $H\alpha$ line was so strong compared to other spectral emissions that this aurora might have been produced by proton impact alone (Omholt et al. 1962). In any case it appears certain that in those auroras the protons supplied, relatively, at least one order of magnitude more energy than in other types of aurora, for which electrons are certainly the main energy contributors. The hydrogen glow is barely visible or even invisible to the eye. It occurs before the electron aurora and, when this has started, on the equatorside of it before midnight. After midnight no hydrogen emission is observed south of auroral forms but rather north of these. A distinct dark region is often seen between the proton aurora and the main forms (Stoffregen and Derblom, 1962). For more details see the reviews of Chamberlain (1961), Krasovskii (1961) and Galperin (1963).

In the midlatitude stable red arcs, mentioned earlier, no other spectroscopic feature than the 6300 Å line has been clearly identified. The location of these arcs is definitely controlled by the geomagnetic field. They are namely lined up along projections of circles from the geomagnetic equatorial plane to the earth's surface along the geomagnetic field lines. It is not clear how they can be produced by collision excitation without any other spectroscopic features being excited. According to Dalgarno (1964), the excitation may be a heating effect caused by low energy particles. On the other hand, if the excitation is chemical it is difficult to understand how the magnetic field control comes in. Megill and Carleton (1964) have proposed that local electric fields may be responsible for the excitation. A number of other proposals for excitation mechanisms are reviewed by Roach and Roach (1963).

6. Methods of Recording Visual Aurora for Morphological Studies

Almost all data concerning the morphology of aurora was taken by visual observers up to IGY. During IGY a large net of so called all-sky-cameras, photographing the whole sky automatically every minute, was in operation. Various allsky-cameras have been constructed and used by Gartlein (1947), Lebedinskii (1955), Stoffregen (1955), Park (1957) and Davis and Elvey (see Elvey and Stoffregen, 1957, for a detailed description). A set of allsky-camera pictures are shown in Fig. 1.8. Most allsky films taken hitherto have been 16mm black and white film. The Soviet and Canadian cameras used, however, 35mm film. In the last few years color film has begun to be used (Sandford and Heiser, 1959; Gadsden, 1960; Sandford, 1961). The committee for the "International Quiet Sun Year," 1964-65, of CIG has recommended the use of 35 mm film, which provides more details of the aurora. For detailed synoptic studies over large areas it is highly desirable that the net of cameras will be denser in the future than it was during IGY. Experience has shown that for most part of the polar regions the possibilities of obtaining large scale synoptic patterns from the IGY records are very limited. A most important contribution to the solution of the morphology problem may be given by very high altitude satellites, taking photographs showing most of the polar caps and auroral regions. Automatic devices for analyzing allsky-camera films have been constructed (Elvey and Belon, 1957; Nagata and Kaneda, 1961).

Davis, Deehr, and Leinbach (1960) have made an evaluation of all-sky-camera observations by comparing them with simultaneous visual and photometric observations. They arrived at the following conclusions, among others.

(a) The US model allsky-camera operated during IGY (and probably most other types as well) was slightly less sensitive than an experienced visual observer in detection of very weak diffused forms and is about equal in detecting very weak but well defined forms.

(b) The allsky-camera is much superior to the visual observer in accurately locating and recording the shape of most auroral forms.

(c) The eye is more able to see the details of very bright or fast-moving forms. If the observer were to watch only a small part of the sky, his observations would, in general, be superior to those of the allsky-camera in that small region. However, if the entire sky is to be observed, the allsky-camera is superior in the sense of (b) above.

(d) A greater degree of continuity in auroral forms is often indicated in the compressed image of the sky on all-sky photographs than is apparent to the visual observer.

(e) During the times when visual observers report pulsating aurora, the over-all appearance of the display seems to be quite distinctive and often readily identified on the allsky film.

The exposure time of the ordinary allsky-cameras is generally around 20 sec. By means of image intensifier and TV camera it is possible to take auroral pictures 24 times a second. Such films allow studies of two to three orders of magnitude more rapid time variations than has earlier been possible. An instrument for rapid filming of aurora was used successfully for the first time in the autumn of 1963 (Davis and Hicks, 1963).

It has recently become possible to observe visual aurora in daytime (Noxon, 1963).

Figure Captions

Fig. 1.1–Auroral arc

Fig. 1.2–A band

Fig. 1.3–Auroral rays photographed with an exposure time of 1/60 sec, 24 pictures per sec. (Courtesy T. N. Davis and G. T. Hicks).

Fig. 1.4–Homogeneous auroral arc and bands

Fig. 1.5–Striated auroral arc

Fig. 1.6–Rayed bands

Fig. 1.7–Photograph of an active aurora. The forms move and fade rapidly and new forms appear continuously in other parts of the sky.

Fig. 1.8–Allsky camera pictures taken at Kiruna on 29 Jan. 1957 (Courtesy W. Stoffregen)

Comment: Alternatives to Figs. 1-2 and 4-7 can be taken from either "Photographic Atlas of Auroral Forms," published by the International Geodetic and Geophysical Union, Oslo 1957 or the "Auroral Atlas," prepared by the Committee for the International Quiet Sun Year of the "Comité International de Géophysique," Edinburgh 1963. or – concerning Figs. 2, 4, and 6 – from Chamberlain's book "Physics of aurora and airglow."

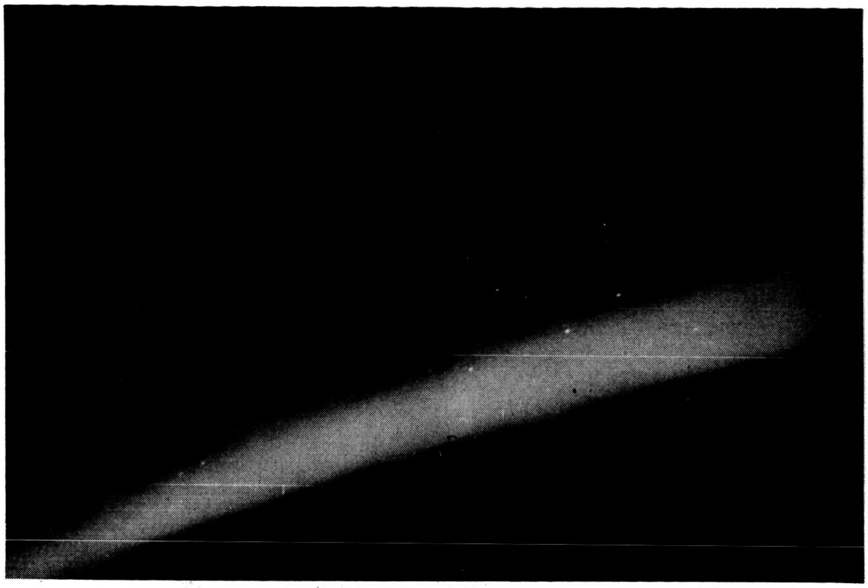


Fig. 1.1-Auroral arc

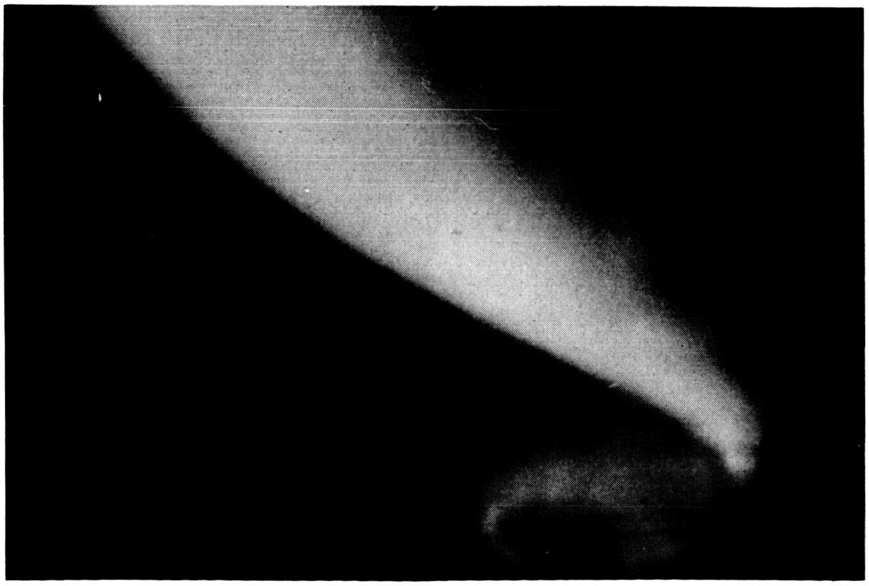


Fig. 1.2-A band

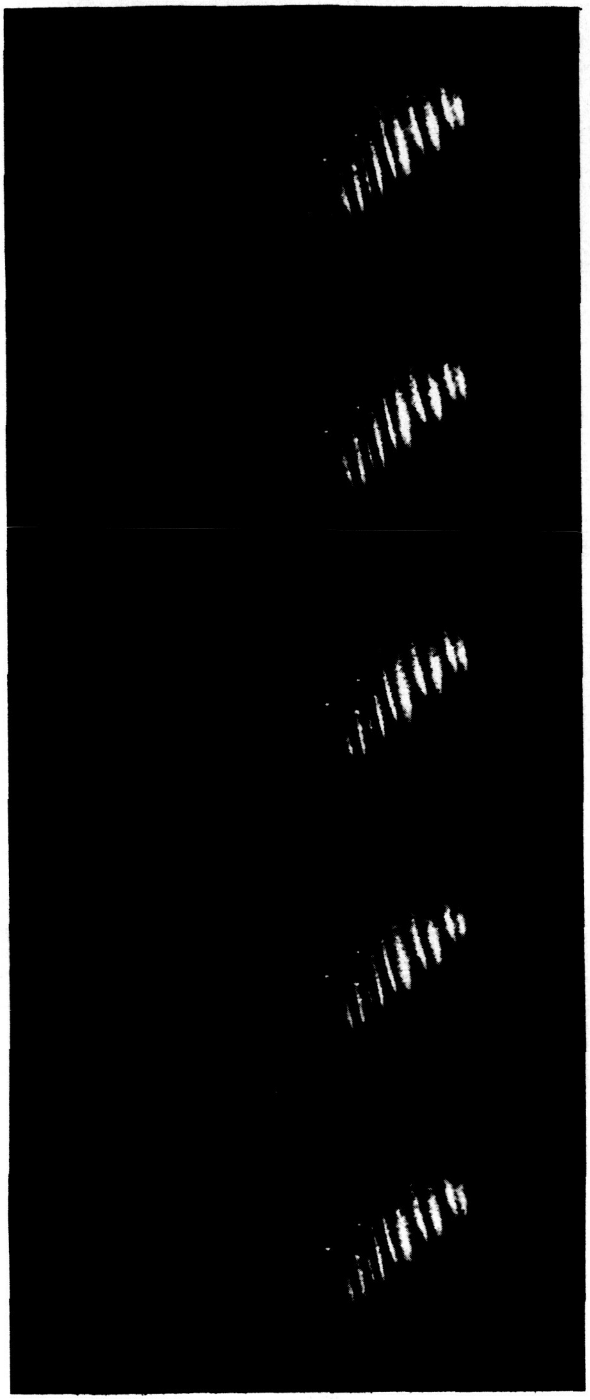


Fig. 1.3–Auroral rays photographed with an exposure time of 1/60 sec, 24 pictures per sec. (Courtesy T. N. Davis and G. T. Hicks).

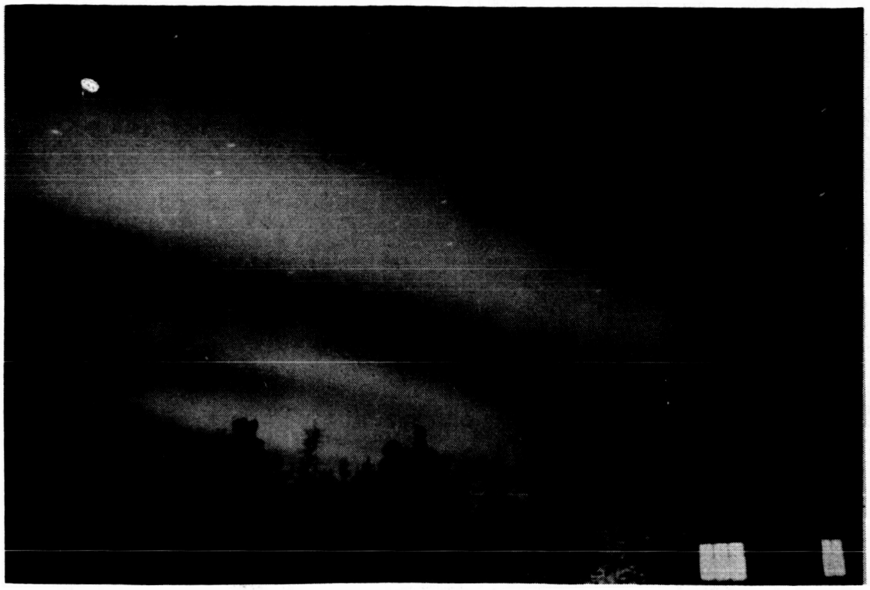


Fig. 1.4–Homogeneous auroral arc and bands

Fig. 1.5–Striated auroral arc

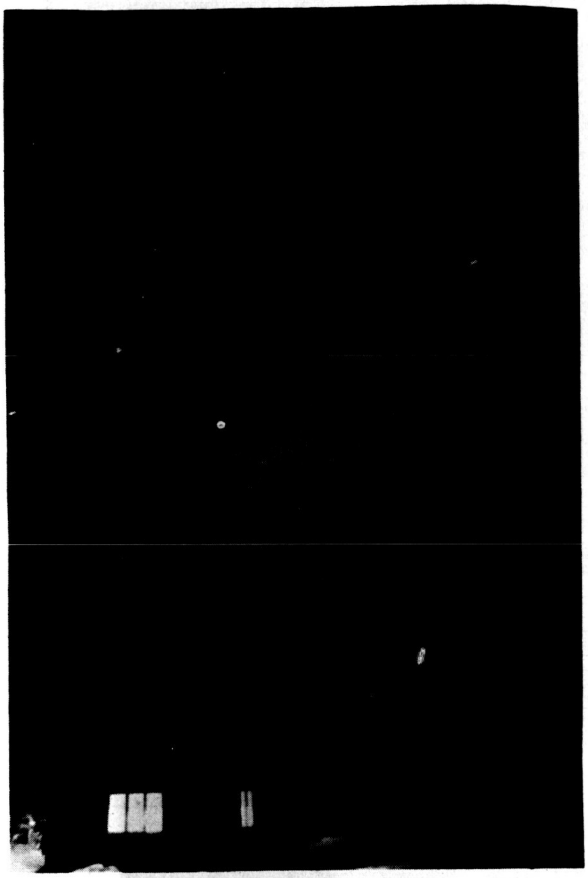


Fig. 1.6–Rayed bands

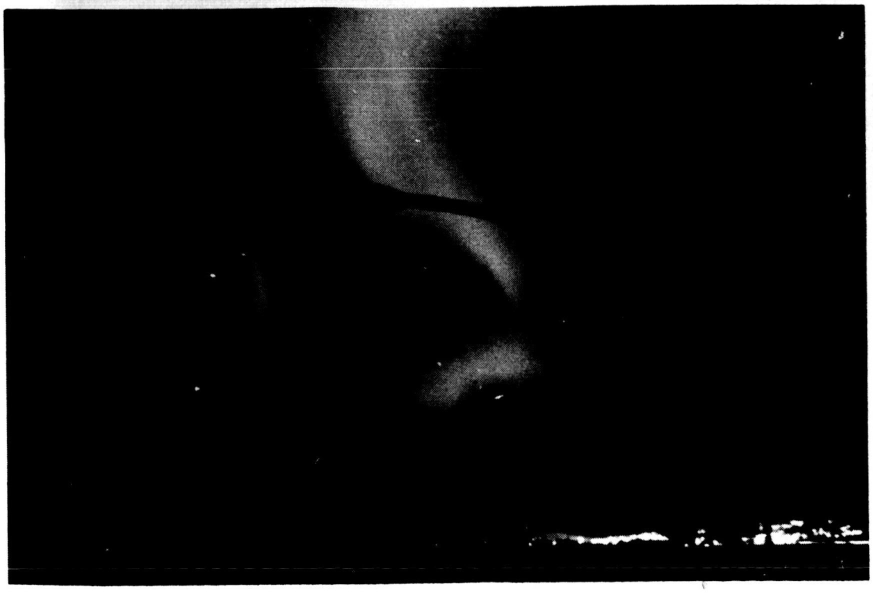


Fig. 1.7–Photograph of an active aurora. The forms move and fade rapidly and new forms appear continuously in other parts of the sky.

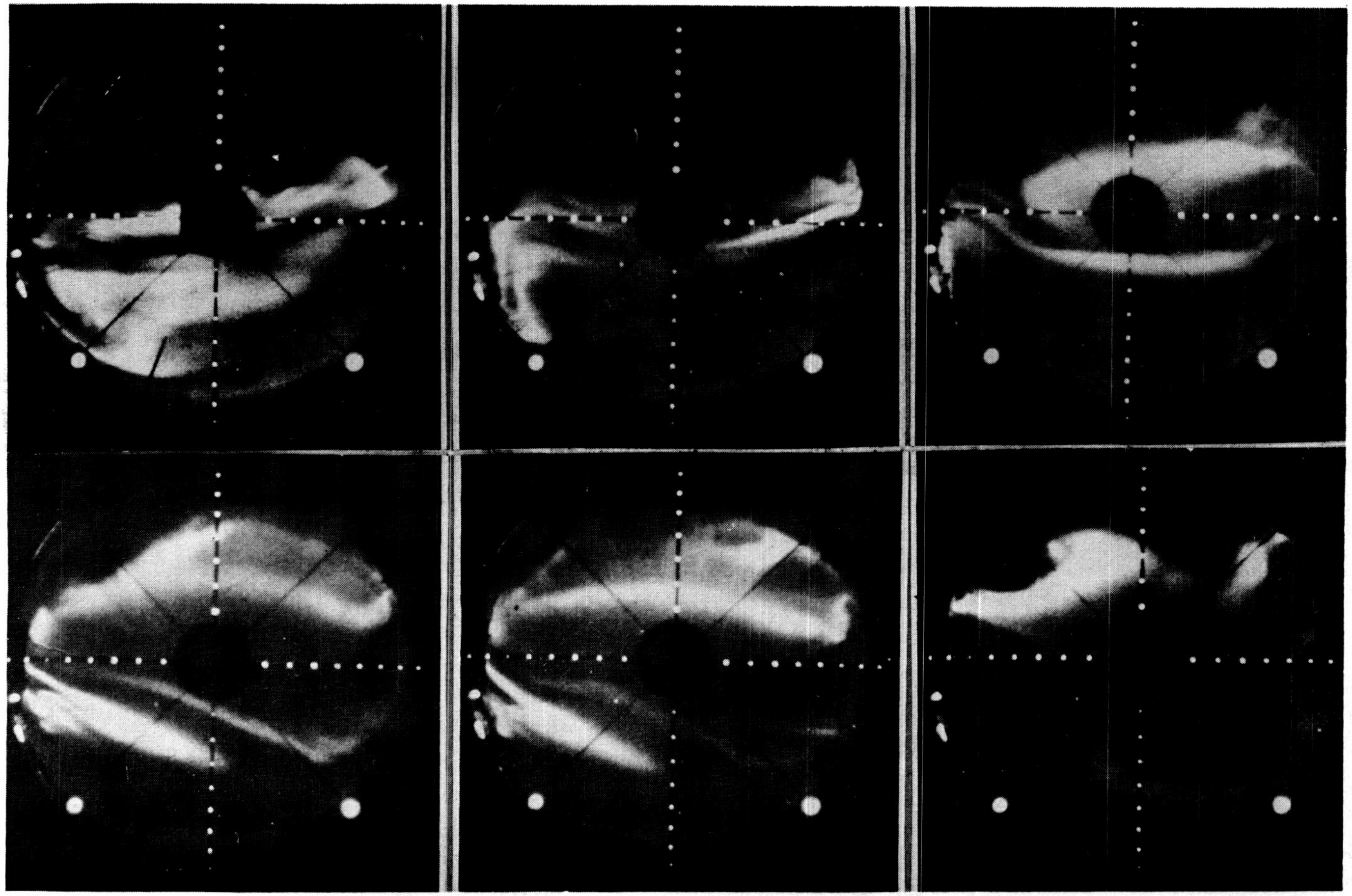


Fig. 1.8—Allsky camera pictures taken at Kiruna on 29 Jan. 1957
(Courtesy W. Stoffregen)

2. Morphology of Visual Aurora

1. Geographical Distribution of Auroral Activity

(a) Introduction

That the auroral activity does not increase continuously towards the poles seems to have been noted in print first by Muncke (1837). The dependence of auroral occurrence frequency on latitude was studied by Loomis (1860, 1868) in USA and by Fritz (1868, 1873, 1874, 1881) in Germany. Fritz (1881) made a detailed analysis of a large amount of data on aurora originating from very old times up to about 1878, from which he could delineate the first detailed map of the location of the northern auroral zone.

Fritz's auroral zone was defined as the locus of points where the probability of seeing an aurora in any part of the sky during any part of the night was maximal. It is thus a line, having no width. The curve connecting points with equal probability of seeing aurora in any part of sky at any time of night is called an isochasm. The auroral zone is thus the maximum isochasm. It has been recommended by Chapman (1953) and others to use the probability of seeing aurora overhead in evaluating geographical statistical distribution curves. Lines connecting points of equal probability of auroral occurrence in the zenith are called isoauroral lines or isoaurores.

It has become customary in recent years to think of the auroral zone as having a finite, but generally unspecified and variable, width. In this review, we will use the definition by which the width of the auroral zone is equaled to the distance between the points of half-maximum amplitude of a particular measure of auroral activity. The position of the peak of the auroral zone will be taken as that position at which there is maximum occurrence of overhead auroras, as determined by observations taken over a period of several months. With this definition we cannot talk about variation of the location of the auroral zone through one night or from one night to another, as is often done in the literature. One is then using the notation auroral zone for the area in which aurora exists at a given moment of time. Below, "auroral precipitation area" or "zone" or "momentaneous auroral occurrence zone" will be used for this unique-time distribution of visual auroral activity.

Both the width and the location of the center of the auroral zone is highly dependent on the type of activity-measure employed. The most commonly used measure is the occurrence frequency of auroral activity, generally defined as the ratio of the number of half-hour (or full-hour) intervals in which aurora could be seen overhead to the total number of half-(or full-) hour intervals. The intensity of the aurora is not taken into account in this measure. Davis (1962 a, b) also employed auroral incidence, defined by the total number of auroral lower borders appearing each hour—as determined by counting the lower borders at 5-minute intervals—in a 1° latitude band passing through the station. It gives similar but somewhat sharper distributions.

The following terminology on auroral geography, suggested by Chapman, is widely used. The auroral regions (north and south) extend from geomagnetic latitudes (ϕ_m) 60° to the poles; the subauroral belts between 45° and 60° magnetic latitude; and the minauroral belt between 45° N and 45° S. The auroral regions include the auroral zones and the auroral caps (the polar regions within the auroral zones). Alternatively, the regions on the equatorial side of the auroral zones are named cis-auroral regions, while those on the polar side which cover the polar cap, are called the transauroral regions (Jacka and Paton, 1963).

(b) Observed locations of the auroral zones and latitudinal distribution of visual auroral activity

The northern auroral zone delineation of Fritz (1881) and Vestine's (1944) modification of it are shown in Fig. 2.1 together with a zone determined by Feldstein (1960) on the basis of photographic recordings taken at 39 Arctic stations and visual observations made at three sites during the IGY, 1957-58.

While Fritz's auroral zone was based almost entirely on unsystematic auroral observations from several hundred years B. C. up to about 1878, Vestine had at his disposal more systematic observations, particularly those from the two polar years 1882-3 and 1932-3. Both delineations, however, are based on material obtained over very long periods of time with secularly changing geomagnetic field, varying solar activity, partly unknown meteorological conditions, etc. In contrast, Feldstein's curve is based on observations made within a few years with the use of a fairly uniform technique at all stations. The auroral indices employed in his determination are more accurate than those previously used, as only the aurora in the zenith has been utilized.

The greatest difference between Vestine's and Feldstein's northern auroral zones is in the region of Hudson Bay, in North America, where Feldstein's curve reaches about 4° farther south than Vestine's.

The first attempt to investigate the auroral statistics in the southern hemisphere was made by Boller (1898). White and Geddes (1939) estimated the location of the zone on the basis of scattered visual observations of aurora australis, and Vestine and Snyder (1945) defined a zone based on geomagnetic observations in the Antarctic. These two zones are shown in Fig. 2.2 together with Bond's and Jacka's (1960) and Feldstein's (1960) zones. The IGY material used by Feldstein was taken at 20 stations on the Antarctic continent and at two stations on islands situated south of Australia. The technique employed in the evaluation was similar to that used in the Arctic.

A recent study of the detailed latitudinal variation of auroral occurrence frequency is that of Davis (1962 b), shown in Fig. 2.3. It refers in time to the solar activity maximum in 1957-58. The "incidence" of auroral forms, as defined above, was deduced from allsky-camera records taken in Alaska (for the geomagnetic latitude, ϕ_m, less than 69°) and in northern Canada (for $\phi_m > 69°$). The indicated spread for the points representing incidence at high latitude is due to the uncertainty involved in connecting the Alaskan data with those of the high-latitude Canadian stations.

The curve has its maximum between 66° and 67° geomagnetic latitude in Alaska. The width of the zone, as defined above, is about 6° in latitude. The scale for the "incidence" in Fig. 2.3 is a relative one. The hourly occurrence frequency was found by Davis (1962 a) to be between 60 and 70% at about 66° geomagnetic latitude at solar activity maximum. Already at $\phi_m = 60°$ it was down to 10%, while on the inner side of the auroral zone, the decrease was slower (c.f. Fig. 2.3). Feldstein and Solomatina (1963) found that the frequency of auroral occurrence in the zenith during IGY was about 55% on magnetically quiet days and about 90% on disturbed days in the auroral zones. The index of activity used was the ratio of the number of half-hour intervals with auroras in the zenith to the total number of half-hour intervals of observation, as recorded in the form of ascaplots. The last mentioned investigators also found that the probability of auroral occurrence in the boreal and austral auroral zones are very closely the same.

Nothing was known before IGY about the detailed relations between auroral phenomena in the two hemispheres, but in the last few years some results on this have appeared. They are, however, not consistant. While Jacka (1961) did not find any correlation between the occurrence of aurora at College and MacQuaire Island, which are nearly conjugate points (off by 600-700 km), and Fillius (1960) reported correlation between the general auroral activity at Ellsworth Antarctic station and the conjugate area in USA, but very small correlation (if at all significant) between the detailed pictures in the two areas, DeWitt (1962) observed good detailed correlation of form and motion and of variation of luminosity between auroral events observed at Campbell Island and MacQuaire Island in the southern hemisphere and at Farewell and Kozebue in the northern one. Breakup of the auroras was found to be simultaneous in the conjugate areas. The conjugacy of the observation points employed by DeWitt was certainly better than for any of the other two investigations quoted above. It seems therefore most probable that auroras usually occur as conjugate pairs at either end of geomagnetic field lines, as has long been suspected. More observational data would be of great value.

The occurrence of aurora in very low latitudes (subtropical and tropical) is extremely rare. Even in central Europe and southern USA the probability of seeing aurora is only a few thousandths of that at the center of the auroral zone. Instead, these medium and low latitude auroras are generally very spectacular and have often been noted and recorded also in ancient times. Recent summaries of older observations of auroras extending into the minauroral region have been made by Schove (1955), Matsushita (1956) and Chapman (1957 a, b). Several auroras occurring at very low latitudes have been described rather fully by Chapman (1953, 1957 c), Abbott (1951), and Abbott and Chapman (1959 a). A type of red auroral arcs occurring rather regularly in subauroral latitudes will be discussed later in this chapter.

(c) Comparison of observational auroral zones with various theoretical curves

There are good reasons for postulating circular symmetry in the geomagnetic equatorial plane outside the earth's surface of distance parameters representing statistical averages for corresponding variables of those processes, in and near the equatorial plane, which are associated with the occurrence of auroral phenomena in or near the two auroral zones. Only the dipole field affords a measurable contribution in the equatorial plane at a distance of several earth radii from the earth's surface, and the dipole field is circularly symmetric. Thus the configuration in the geomagnetic equatorial plane will not be influenced by the earth's rotation, provided minor effects of the different directions of the geomagnetic and the rotation axes are disregarded. The equatorial plane process will therefore be seen in the same average distance range at a given geomagnetic time from all geomagnetic meridians on the earth. It follows that–if the processes in the equatorial plane and in the auroral zones are connected by the real magnetic field lines, as seems physically plausible–the only longitudinal dependence of e.g. the averages of a great many auroral locations, observed at fixed points on the earth and equally distributed with regard to geomagnetic time, will be that introduced by the deviation of the earth's magnetic field from a dipole field. This deviation is appreciable at and near the earth's surface.

What has been said here should be true, even if the geomagnetic field is heavily distorted in its outer regions. If that is so, the distance at which the process in the equatorial plane takes place may be quite different from that of the intersection with the equatorial plane of that dipole line which intersects the earth's surface at the same place as the real field line connecting the auroral processes in the earth's atmosphere and in the equatorial plane.

According to this view the configuration in one hemisphere will correspond to the projection of the corresponding one in the other hemisphere along the geomagnetic field lines.

The only assumption made in the foregoing is that an electron or an ion moves from the equatorial plane to one of the auroral zones along a geomagnetic field line or on some surface defined by field lines. Such an assumption seems to be well founded. No other details of the actual physical processes are involved.

The projections of circles in the equatorial plane to the earth's surface along the real field lines, were calculated by Hultqvist (1958) for purposes of comparison with experimental isochasms. The projections are practically identical with the L curves of McIlwain (1961). Hultqvist used a perturbation method consisting of integration along the dipole line of the deflection from a dipole field line of the higher approximation line due to the effect of the second to the fifth terms in the spherical harmonic development of the earth's magnetic field. The calculations yielded deflection vectors for a large number of dipole lines. These gave the deflection for the point of intersection of the higher approximation field line—coinciding with the pertinent dipole line in the equatorial plane well outside the earth's surface—and the earth's surface from the corresponding point of intersection of the dipole line itself.

The calculations were carried out for 36 equidistant longitudes for each of 15 geomagnetic colatitudes, most of them less than 30 degrees. The results of Vestine's et al. harmonic analysis of the earth's magnetic field for epoch 1945, the most recent epoch for which data were then available, were used in the computation.

The projections of equatorial plane circles are ovals with the longest diameter approximately in the plane containing the 170° and 350° geomagnetic meridians. Two circle projections are shown in Fig. 2.4 (northern hemisphere) and Fig. 2.5 (southern hemisphere). They correspond to the two circles in the geomagnetic equatorial plane having radii of 7.13 and 5.60 earth radii, for which the projections along the dipole lines are the geomagnetic colatitude circles 22° and 25° respectively.

Hultqvist pointed out that the experimental northern auroral zone of Vestine accorded well with the circle projections except over the North American continent, where the calculated curve extended about 4° farther south than the observational one. The IGY data as presented by Feldstein and illustrated in Fig. 4 show that the configurational agreement between the IGY northern auroral zone and the projections of circles is good. The maximal difference in latitude between Feldstein's zone and that projection which conforms best to it amounts to about one degree.

Since the network of observation stations in and near the northern auroral zone was quite dense during the IGY, it seems probable that the error in location of the experimentally determined auroral zone is only of the order of 1° in latitude. The geomagnetic data used in the calculations are for epoch 1945, which may account for minor inconsistencies with the observations of 1957-58. It is probable, however, that this error also is less than one degree of latitude. It is thus evident that the IGY northern auroral zone is, within the limits of probable error, in full configurational accord with the calculated projections of circles in the equatorial plane.

Feldstein's auroral zone in the southern hemisphere is shown in Fig. 2.5 together with the projections of the circles of radii 5.60 and 7.13 earth radii. The experimental curve differs quite significantly from the computed ones. While it follows the course of the latter in the geomagnetic longitude range of 320° E–90° E, it is much nearer to the Antarctic continent for the rest of the longitude circle where it is located over the sea. In fact, Vestine's and Snyder's (1945) auroral zone agrees better with the computed one than Feldstein's does.

A question of interest is whether the discrepancy between the IGY southern auroral zone and the projections of circles is a real one or attributable merely to inaccuracy of the observational data and/or of the computed curves. The errors of the geomagnetic data, used in the computations, are certainly greater for the Antarctic than for the Arctic. As mentioned earlier, the computations were based on Vestine's et al. harmonic analysis of the geomagnetic field for epoch 1945, when the southern hemisphere data were very sparse. Although this fact may partially account for the discrepancy, it seems likely that only a minor part of the 6 latitude degrees difference over the sea is primarily attributable to errors in the harmonic analysis of the geomagnetic field, especially as a comparison with recent numerical computations by Dudziak et al.(1963) on the basis of the spherical harmonic coefficients for epoch 1960 by Jensen and Cain (1962) show only minor deviations.

All observational stations in the discrepant region were situated on or close to the coast of the Antarctic continent far inside the auroral zone. This means in effect that the auroras occurring in the auroral zone were visible from these stations at low elevation, a circumstance which implies considerable error in the observational results.

Indeed, since publication of Feldstein's paper, Bond and Jacka (1960) have communicated a report in which they note that the latitude of the auroral zone in the region of MacQuarie Island, south of Australia (point 15 on Fig. 2.5), is only one or two degrees more than that of the station. A small part of their auroral zone–the one near MacQuarie Island–is shown in Fig. 2.5 as curve No. 2. Taking this and the above mentioned considerations into account, it would appear that the auroral zone is fairly consistent with the computed curves, with which it shows agreement over the Antarctic continent. This seems so much the more plausible in view of the close accord between observed auroral zone and circle projections for the northern hemisphere. Indeed, it would be surprising if the two hemispheres showed entirely different degrees of agreement between the two types of curves.

Although, as mentioned above, there are good reasons for postulating circular symmetry in the geomagnetic equatorial plane for the processes producing aurora in the earth's atmosphere, it is certainly not the only possible approach. If e. g. the drift around the earth of the primary auroral particles in accordance with the adiabatic invariants is the determining process for the configuration of auroral occurrence curves, it is perhaps reasonable to expect that the isoaurores should be identical with the lines of constant second adiabatic invariant. Vestine and Sibley (1960) computed such curves. They are very nearly identical with the projected equatorial-plane circles and it is therefore not possible to judge between the two approaches on that basis. Vestine and Sibley also calculated, using the spherical harmonic analysis of Finch and Leaton (1957), the mirror height of electrons for which the second adiabatic invariant, $J = \int_{||} d\ell / v$, has the value 15.7. Their heights range from 57 km to 420 km in the northern hemisphere and from -15 km to 633 km in the southern hemisphere.

Figure 4 and 5 include, for purposes of comparison, curves showing two other types of more or less theoretical auroral zones: the zones suggested by Gartlein and Sprague (1960), which are almost identical with the isoclines 76°, and Quenby's and Webber's (1959) curves, which are based on calculations of vertical cut-off rigidities for cosmic ray particles in the earth's magnetic field, and take into account both the dipole and non-dipole parts of the internal field. Neither of these two curves conforms as closely to observed data as do the circle projections.

What conclusions can be drawn from the similarity between observed isoaurores and projections of circles in the earth's geomagnetic equatorial plane into the earth's atmosphere along the geomagnetic field lines? Not too many, in fact, since no details of the actual physical processes are involved. The geomagnetic field can be strongly distorted and we still expect to find the circular symmetry for the statistical data.

However, it can be concluded from the data presented above that local conditions close to the earth probably play a negligible role for the average auroral distribution over the earth's surface. The adiabatic drift of the primary particles around the earth seems not to be important for the shape of the isoaurores. If this process were important, one would expect the mirroring height to have a profound influence on the precipitation rate of particles and therefore on the frequence of occurrence of aurora. Since the mirror height varies very much with longitude for one J = const shell, important variations in intensity and auroral occurrence frequency for various points along such a curve would be expected. This is not observed. That the drift motion is not important in this respect is also expected because of the fact that most primary auroral electrons need a time very much longer than the time scale of auroras in order to drift around the earth.

There are other statistical parameters than the isoaurores that may be expected to show circular symmetry in the equatorial plane. One is the average southern extent of the aurora at a definite degree of magnetic disturbance. Such curves have been evaluated by e.g. Gartlein et al. (1960) and Feldstein (1963). A comparison of the curves in Fig. 2.6 with the circle projections in Fig. 2.4 shows a good agreement. The southern extent increase with increasing Kp.

(d) Dependence of auroral zone location on the solar cycle

The pole distance of the auroral zone has been found to be dependent on the phase of the solar activity cycle. Sheret and Thomas (1961) made a detailed analysis of the auroral observations made at Halley Bay, Antarctica, in the years 1956-59. The position of the auroral zone, obtained from observations of quiet arcs, was the following in the four years.

Table 1

Year	1956	1957	1958	1959
median south geomagn. lat	70.8	71.8	71.9	71.0

The auroral zone was thus closer to the pole at the solar-activity maximum in 1957 than before and after. This result is opposite to that of Feldstein (1962), who compared the location of the auroral zone in the Asian Arctic at solar activity maximum (1957-58) and at solar minimum (1954-55). He found the auroral zone to be 2.5 -3° closer to the geomagnetic pole at the minimum of the solar cycle than at maximum. These variations in the location are discussed also in subsection 6 on motions.

(e) Auroral type effects

The distribution of auroral activity described above refers to all types and forms of aurora. Most of the basic data are obtained from black and white allsky-camera films of fairly long exposure times, which makes it impossible to distinguish between various spectroscopic characteristics as well as between quiet and rapidly varying auroral forms.

It is, however, of great theoretical interest to know whether there are significant differences in location between different types of aurora, especially between auroras caused by positive and negative primary particles. This is because relations–at least qualitative–between the locations of proton and electron precipitation areas is contained in several theoretical models. For instance, it seems difficult to think of electromagnetic acceleration processes if positive and negative particles are precipitated together along the geomagnetic field lines.

In fact, it has been found that hydrogen line emitting aurora (see p. 13) usually is located on the equator side of the electron produced aurora before midnight (cf. the reviews of Omholt, 1963, and Galperin, 1963). (After midnight no hydrogen emission is observed south of auroral forms, but rather north of these; Stoffregen and Derblom, 1962). There is often a distinct dark region (up to 1° wide in latitude) between the "proton aurora" and the main forms. One would therefore expect the isoaurores and the auroral zone for "proton aurora" alone to be located one or a few degrees farther from the poles than the ordinary auroral zones (which certainly are the electron precipitation zones).

As mentioned in section one, there are several different types of auroral phenomena. The latitudinal distribution of the occurrence probability for high red arcs, for instance, certainly has its maximum in the subauroral regions. No detailed statistical studies of their geographical distribution exist as yet. Stoffregen (1962) has investigated the occurrence of different auroral forms in the geomagnetic latitude band 58-76° N (at the longitude of Scandinavia). His results, which he considered as a rough approximation, are shown in Fig. 2.7. As can be seen in the figure, the pulsating auroras occur most frequently some 5 degrees south of the auroral zone. This was also found by Heppner et al. (1952).

The low latitude aurora mentioned above is different from the stable subauroral red arcs described on p. 10. The red arcs populate subauroral mid-latitude regions with shape very similar to the projections of circles along the field lines from the equatorial plane, described above (see Roach and Roach, 1963). The regions have their centers somewhere between the circle projections corresponding to equatorial plane circles of radii 2.5 and 3 earth radii (i.e. L = 2.5 and 3 respectively). These red arcs seem not to exist in the auroral zones.

There certainly exist still other differences in the latitudinal distribution of the occurrence frequency for different types of aurora. The aurora inside the auroral zone has several characteristics that distinguish it from the aurora seen at and outside the auroral zone. In general, the high-latitude forms are relatively weak in intensity and more fleeting than those seen at the auroral zone. The forms consist, in part, of weak diffuse arcs and of bands that frequently show ray structure. Ray bundles are common, and these are usually arranged so as to appear as part of arcs, bands or draperies with variable intensity (cf. Davis, 1962 b).

(f) Inner auroral zones

Alfvén (1955) proposed on theoretical grounds that there should exist secondary auroral zones inside the ordinary ones, at geomagnetic colatitudes between 5 and 10 degrees. Since this proposal was made, a large number of attempts have been made to determine from observations if the inner auroral zones exist or not. At this time, it does not seem possible to draw firm conclusions. It is clear that the zone, if it exists, is much less pronounced than the main zones (which is not unexpected from Alfvén's theoretical point of view).

Observations in favor of and against the existence of the inner zones will be briefly reviewed.

Nikolskiy (1963) has discussed the Soviet data relevant to the existence of inner auroral zones. Most data is geomagnetic. What is generally found is a morning maximum in magnetic activity between 75 and 80° N geomagnetic latitude, most pronounced in the summer. The shape of the zone, found by Nikolskiy, is a spiral in a circular latitude-time coordinate system, unwinding in a clockwise direction. Meek (1957) found that the maxima of ionospheric disturbances are concentrated along a similar spiral.

On the other hand Lassen (1959), observing at Godhaven (about 80° geomagnetic latitude), could not find any magnetic evidence for an inner zone of high activity but instead he observed a type of zenithal aurora occurring around 6 h. local time, which seemed not to come up from south (i. e. from the main auroral zone) but to be produced sporadically at great elevation in the sky seen from Godhavn. The elevation did not change significantly in the course of the morning. Lassen found that the morning-type of aurora is uncorrelated not only with the local magnetic activity but with the planetary state of disturbance too. Analysing data obtained in other parts of Greenland and in the northernmost Canada, Lassen concluded that morning aurora of the described kind is observed in the zenith only along a curve coinciding with the projection of the circle with radius 20 earth radii in the geomagnetic equatorial plane ($L = 20$) on the earth's surface.

Witham et al (1960), for instance, investigated the magnetic disturbance characteristics. They, and many other investigators of various parameters, could not reach any definite conclusion about the existence of an inner zone of high disturbance.

Davis (1962 b) analyzed allsky-camera films taken at Thule ($\phi_m = 88°$), Alert ($\phi_m = 86°$), Resolute Ray ($\phi_m = 83°$), Baker Lake ($\phi_m = 74°$) and Churchill ($\phi_m = 69°$). The scaling was made by counting the number of auroral forms within zenith distance 80° on each fifteenth frame of the film from each station. The total number of forms was recorded. The result can be seen in Fig. 2.3. There is no indication from this diagram of an inner auroral zone. However, the lack of stations in the critical region between 74° and 82° prevents the making of a strong statement of the absence of a zone there. It appears that if there is an inner auroral zone, it must lie between 76° and 81° latitude over northern Canada, and that the enhancement of the number of auroral forms within this zone must not be great.

2. Diurnal Variation of Visual Auroral Activity

As does the geographical distribution of aurora, the diurnal variation of auroral activity varies considerably with the measure of the activity used. In addition, it depends on the type of auroral display and perhaps on season and phase of the sunspot cycle. Very much still remains to be done before our knowledge of the diurnal variation of auroral activity is consistent and complete.

The most widely used measures of auroral activity are "occurrence frequency" and "incidence," defined in the previous subsection. Fig. 2.8 (after Davis, 1962 a) shows the occurrence frequency of visual aurora in a latitude belt of width 1° centered over each of the Alaskan stations Barrow (68-69°), College (64-65°), and Farewell (61-62°). Geomagnetic midnight occurs 1 to 2 hours after local midnight, the displacement from local midnight being largest for Barrow and smallest for Farewell. These curves demonstrate a shift of the auroral occurrence toward earlier local time with increasing latitude. In Fig. 2.8 there is also a curve marked 3914. It is drawn from data by Murcray (1959) and represents relative allsky 3914 Å intensity over College during 1955 and 1956. As can be seen in the figure, this curve has its point of gravity located several hours later than the others. This is due to an important difference between the auroral intensity distribution in premidnight and postmidnight hours. Before midnight the auroral forms stand out sharply above the low intensity of the background, but after midnight the intensity of the background is enhanced so that individual auroral forms are not easily distinguished.

Davis and DeWitt (1963) have evaluated the per cent of hours in which aurora was observed at Byrd, Antarctica, close to the southern auroral zone, for every hour of day and night in a two-months period of southern winter. Their result is shown in Fig. 9. The auroral occurrence frequency has a maximum around geomagnetic midnight (at about 2200 local time) and a deep minimum around geomagnetic noon.

Reports on diurnal variation of aurora have also been given by Tromholt, 1882; Carlheim-Gyllenskiöld, 1886; Paulsen, 1893; Vegard, 1912; Chrée, 1927; Sverdrup, 1927; Lee, 1930; Fuller, 1933, 1935; Currie and Edwards, 1934; Davies, 1935 a, 1950; Stagg, 1937; Stetson and Brooks, 1942; Jacka, 1953; Elvey et al., 1955; Murcray, 1959; Hale, 1959; Lassen, 1959, 1961; Malville, 1959; Chamberlain and Thorson, 1960; Feldstein, 1960; Feldstein and Solomatina, 1961; Loginov, et al., 1962 and others. A large number of these investigators have found diurnal variation curves similar to the occurrence curves in Fig. 2.8 and 2.9 with maximum fairly close to geomagnetic midnight.

There have been many suggestions of a less pronounced, secondary maximum in the early morning hours but it has not been possible to find at some stations (Hulbert, 1931). Studies of ascaplots for IGY by Feldstein (1960) and Feldstein and Solomatina (1963) have resulted in the curves of Fig. 2.10 showing the geomagnetic time of maximum auroral occurrence frequency as function of the distance of the observation place from the observed auroral zone (curve 3 in Fig. 2.1), which distance is an approximately linear function of the geomagnetic latitude, corrected for the higher terms in the spherical harmonic expansion. There are two spiral-shaped curves in Fig. 2.10 unwinding in opposite directions. At the auroral zone, Feldstein found only one maximum (around geomagnetic midnight). Also, at geomagnetic latitudes around 78° only one maximum occurred (on the dayside) and at latitudes in between there were two maxima. The same result has been presented by Malville (1964). Similar functions of latitude have been found for the time of maxima of various other disturbance measures:

e.g. for geomagnetic disturbances by Meek (1955), Burdo (1957) and Nikolskiy (1957), for sporadic-E ionization by Hagg et al. (1959), for redio aurora by Forsyth et al. (1960) and Egeland et al. (1962) and for radio wave absorption by Thomas and Piggot (1960).

On the basis of their observational results, Feldstein and Solomatina (1961) and Khorosheva (1961, 1962) (see also Feldstein, 1964) have proposed that the precipitation curve for aurora at a given time has the shape of the two combined spirals in Fig. 2.10. An instantenous auroral zone of a similar shape has been proposed by Akasofu, (1963 d). Support for this shape are among other observations those of Khorosheva (1961), who mapped 17 cases of momentary auroral distribution over the eastern hemisphere and found parts of oval-shaped curves similar to that in Fig. 2.10. However, the simple regularity of Fig. 2.10 was not found by Davis (1962 b) and the results of the case studies of some strong auroral events made by Akasofu (1960, 1962, 1963) and Akasofu and Chapman (1962) gave instantaneous configurations of the aurora, which were very closely similar to the projections of equatorial-plane circles on the earth's surface along the geomagnetic field lines (see previous subsection). The extensive auroral studies by Morozumi (1963) at the South Pole (geomagnetic latitude 78° S) did not show one, but two peaks in the diurnal variation curve for auroral occurrence. Instead for a maximum at magnetic noon there was a minimum.

A theoretical motivation for an oval auroral zone, being at higher latitude at noon than at midnight, is obtained when one considers the drift motion of particles around the earth in a magnetosphere, which is compressed by the solar wind on the dayside. The mirror points are at lower latitudes in the night than in the day. On this theoretical basis oval instantaneous auroral zones have been proposed by Rees and Reid (1959) and by Liemohn (1960). Detailed calculations by Malville (1960) show, however, that the expected effect is much less than the observed (less than 2° as compared with 8° observed). O'Brien (1963) therefore, concludes that if the diurnal variations are related at all, it is only in the sense that they are effects of a common and as yet unknown cause. More observational data are evidently needed before a conclusion about the existence or nonexistence of the oval instantaneous auroral zone can be reached.

That the main maximum in the diurnal distribution of auroral activity occurs close to geomagnetic noon at geomagnetic latitudes of about 78°, as Feldstein found, need not necessarily mean that the corresponding processes in, or close to, the equatorial plane take place on the dayside, namely if the topology of the geomagnetic field is the one proposed by Johnson (1960) and others. A fairly evident hypothesis is that the neutral points or lines of that model are responsible for the daytime maximum in auroral occurrence.

Two spiral arcs of a kind described above are incorporated in the qualitative model for magnetic disturbances and associated phenomena proposed by Axford and Hines (1961).

That the diurnal variation differs for different auroral forms has been found by e. g. Fuller (1935) at College, Alaska, which is close to the auroral zone (cf. Fig. 2. 11). Strong and brilliant forms have some predominance during the evening hours, and the faint and quiet forms in the morning. The hydrogen glow generally precedes the appearance of bright auroras, as first found by Romick and Elvey (1958) near the auroral zone, and the diurnal variation curve for this type of aurora therefore has its maximum well before midnight. Pulsating aurora occurs most often in the morning hours (Heppner, 1954).

3. Other Time Variations of Visual Auroral Activity

(a) 27 day recurrence tendency

Auroras tend to repeat with a period of about 27 days, which is the synodic rotation period of the sun. As the moon considerably influences the possibilities of observing aurora, the apparent repetition tendency of auroral activity is enforced by the synodic lunar period (29. 5 days), which is fairly close to the solar one. When the analysis is corrected for the lunar effect, a small but definite indication of a recurrence maximum around 26 and 27 days remains, which evidently is due to the rotation of the sun (Meinel et al., 1954). By the second and third solar rotations, no recurrence tendency remains.

(b) Seasonal variation

In the subauroral regions the annual curve of auroral occurence frequency has two maxima at the equinoxes. Fig. 2.12 shows the monthly aurora occurrence frequency distribution found by Meinel et al., (1954) at Yerkes Observatory. The existence of spring and fall maxima were known already to Mairan (1733). It was proposed by Cortie (1912) that the similar maxima in geomagnetic disturbances are due to the earth being at highest heliographic latitudes in March and September.

If this is true, the angular diameters of the solar plasma beams do usually not exceed about 5° as seen from the sun. This is certainly not so for the very largest solar events, however.

The dependence of the seasonal variation on latitude is obscured by the change with latitude of the ratio of the lengths of day and night. If this change is ignored, as it usually is, then the summer minimum becomes progressively deeper with increasing latitude, while the winter minimum becomes progressively shallower, disappears and is replaced by a maximum, which is then the only one in the distribution (cf. e.g. Chree, 1911). Gartlein and Moore (1953) found that the ratio of the mean of the numbers of overhead auroras in North America occurring in June and December to that for auroras in March and September is a steadily increasing function of geomagnetic latitude. Between about 58 and 60° N the level of activity appears to be constant throughout the year. Feldstein and Shevnina (1961) investigated the seasonal variation in auroral occurrence frequency in two hours centered on local midnight–thereby eliminating the influence of the diurnal variation–for six stations between 63 and 83° geomagnetic latitude in the northern hemisphere and for five stations between 66° and 90° geomagnetic latitude in the southern one. They found the same seasonal variation as described above at and close to the auroral zones, but no perceptible seasonal variation in auroral frequency on the central auroral caps.

(c) Sunspot cycle variation

Fig. 2.13, after Tromholt (1902), shows the correlation between the number of days with aurora per year, observed in Norway between 1761 and 1877 and the sunspot number. The correlation is good and the maxima seem to coincide. Meinel et al., (1954) found a similar correlation when analyzing auroral observations made at Yerkes Observatory between 1897 and 1951. The maximum auroral activity occurred, however, during those 5 eleven year sunspot cycles some 2 years after the sunspot maximum. Egedal (1937) too, found a time delay of the maximum occurrence frequency of aurora in relation to the solar activity in Denmark during the 3 solar cycles from 1897 to 1929, but the delay was only 1 year.

4. Orientation of Auroral Arcs

Hitherto various characteristics or auroral "activity," i.e. of statistical parameters describing the probability of occurrence of aurora, have been described. Now we will go somewhat more into detail. In this section the orientation of auroral arcs, which can be readily measured from photographic recordings, will be discussed.

(a) Average orientation

There exist fairly much data on the average orientation of auroral arcs. Even the very early studies of aurora showed that quiet auroral arcs tend to be oriented in a preferred direction, approximately perpendicular to the horizontal component of the geomagnetic field. A number of these early investigations were discussed by Fritz (1881). Vegard and Krogness (1920) referred the directions to the geomagnetic meridian and the Norwegian school made a large number of accurate direction determinations in northern Scandinavia.

In the majority of the pre-IGY investigations average values of all observed quiet arcs and bands were estimated. The fact that the observations were often made only during a certain period of the night–and in different periods for different investigations–was not considered.

A fairly extensive collection of such data is contained in Fig. 2.14 (after Hultqvist, 1962 b). Also included are a number of computed projections of circles in the equatorial plane on the earth's surface along the geomagnetic field lines (Hultqvist, 1958).

Despite the above-mentioned reservations concerning the observational material, it is evident from Fig. 2.14 that, in general, the alignment of the arcs conforms to the direction of the relevant circle projection quite closely, and that the agreement with the circle projections is better than with the geomagnetic latitude circles. The observed arc azimuth is in most cases, greater than 90° in those quadrants where the azimuth of the circle projections exceeds 90°, and less than 90° in quadrants where this is under 90°. Thus, it has been verified experimentally that on the eastern and western coasts of Greenland the observed average azimuths deviate in opposite directions from 90°, as do the azimuths of the circle projections.

Starkov and Feldstein (1960) and Evans and Thomas (1959) investigated the alignment of arcs at two places where the isoclines and the geomagnetic latitude circles differ greatly (Dixon near the northern auroral zone and Halley Bay near the southern one). They found that the prefered direction of alignment is far more consistent with geomagnetic latitude circles, and therefore with the higher approximation circle projections, than with the isoclines.

The available observational results for the southern hemisphere are relatively exiguous. A collection of IGY and subsequent data is contained in Fig. 2.15. The arrows indicate results of observations of directions, as sighted to the auroral point of highest elevation. Two arrows for any single station represent the results of observations during each of the two years 1957 and 1958. The differences in direction of the arrows for the two years demonstrate the uncertainty of the results.

As will be seen from Fig. 2.15, the agreement between observed directions with those of the projected equator plane circles is fairly good for all places except Byrd (No. 9), and the agreement is certainly better than for the geomagnetic latitude circles.

Because of the existence of a diurnal variation in the orientation of the auroral arcs, increased accord between the directions of the arcs and of the circle projections is to be expected if values for a short period (e.g. 1 hr) of the night are compared. The results of such a comparison for local midnight at twelve stations, most of them in or near the northern auroral zone, are presented in Table 2 and Fig. 2.16. A comparison with Fig. 2.14 clearly shows that the concordance of the arc directions with the circle projections is better for the selected material of Fig. 2.16 than for the unselected values of Fig. 2.14.

Table 2 contains azimuths of quiet auroral arcs at local midnight in the northern hemisphere (measured from northern geomagnetic meridian towards the east). The observed azimuths for stations 1-7 are after Davis (1961), those for stations 8-13 are after Feldstein (1960), and that for Tromsö is after Harang (1945).

(b) Diurnal variation in the orientation in and near the auroral zones

Although it was evident from the observations of Bravais at Bossekop in northern Norway as early as 1838-40 that the directions of the arcs and bands show a diurnal variation, very little attention was paid to this phenomenon until the ninteen-thirties, and even now only few studies exist.

From allsky-camera recordings taken at Kiruna ($\phi_m = 65.3°$ N) in the period December 1958 to end of 1962, the directions of 559 quiet auroral arcs were estimated. Only arcs reaching from horizon to horizon or, in the case of the most distant ones, covering an azimuth angle of view of about 100° were used in the analysis. The error in the measured direction of an arc probably does not exceed 4°.

Table 2

No.	Station	Geomagn. Coord.		Observed azimuth (degr.)	Approx. measure of deviation	Azimuth of circle projection ("theor. azimuth")	Diff. obs. azimuth and "theor. azimuth"
		°N	°E				
1	Baker Lake	73.8	314.8	94	Diff. max-min ~60°	93	1
2	Churchill	68.8	322.5	99	Diff. max-min ~60°	95	4
3	Barrow	68.6	241.2	92	Diff. max-min ~60°	84	8
4	Fort Yukon	66.6	256.8	90	Diff. max-min ~80°	87	3
5	College	64.6	256.5	86	Diff. max-min ~60°	87	-1
6	Farewell	61.4	253.2	83	Diff. max-min ~60°	86	-3
7	Choteau	55.5	306.0	88	Diff. max-min ~70°	95	-7
8	Schmidt	62.6	226.6	80	Diff. max-min ~30°	80	0
9	Dixon	63	162	98	Stand. deviat. <±10° for magn. quiet periods	98	0
10	Vise	69	176	103	~±15°	100	3
11	Pyramid			111	~±15°	113	-2
12	SP-7 1957-58			96		96	0
13	SP-7 1958-59			0		0	0
14	Tromsö	67	117	98	Diff. max-min ~27°	106	-8
15	Kiruna	65.3	115.6	106	Stand. deviat. ±5°	105	1

The result of the alignment investigations is shown in Fig. 2.17.

For each hour of Mean European Time (MET) the average direction and the standard deviation were computed, for which procedure the direction value of each arc was weighted with the arc's duration. The durations vary over a wide range–from less than a minute to about an hour.

The total average azimuth for the whole material is 109°. A typical standard deviation for a 1 hr. period is 5°.

At the top of Fig. 2.17 is shown the number of arcs used for each hour. The number is maximal around geomagnetic midnight. In the morning hours the aurora is usually unsuitable for direction determination–as a rule, it is diffuse and situated far to the north. That is the reason why the observational material is smallest for that part of the night.

The azimuth change in the morning is so rapid as to resemble a discontinuity of the type predicted by the Alfvén theory (see e.g. Alfvén, 1950).

In fact, the "discontinuity" can probably be observed only in longitudes where geomagnetic time runs ahead of local time, since daylight will preclude auroral observations in or close to the auroral zones until 8 or 10 o'clock geomagnetic time in other longitudes.

A number of similarly obtained diurnal variation curves for auroral arc orientation, based on observations in or fairly near the northern auroral zone (up to a geomagnetic latitude of 80°), are shown in Fig. 2.18.

The wide dispersion of the location and form of the different diurnal variation curves is striking. The amplitude of the diurnal variation also varies greatly. Here a regularity emerges, the amplitude increasing rapidly with latitude. Thus, the auroral arc direction varies at Baker Lake (geomagnetic latitude 74°) over a range of 70°, while at Choteau (geomagnetic latitude 56°) the range is only 20° (and at Kiruna, 65° N, 15°, if the final rapid increase in azimuth is ignored).

A "discontinuity" in the morning hours has been observed only at Godhavn and at Kiruna. As mentioned above, observation is likely to be possible only in the eastern geomagnetic hemisphere, where the geomagnetic time is running ahead of the local time. The difference between geomagnetic and local times is greatest in the region of northern Scandinavia (about 2 hours), where it is possible to observe aurora up to 1000 hrs geomagnetic time. The reason why such "discontinuity" has not been observed at the Siberian stations could be that the geomagnetic time differs less from local time at those sites than it does at Godhavn and Kiruna.

For the southern hemisphere there is still a paucity of published observational data concerning the diurnal variation of arcs in and near the auroral zone. One such diurnal variation curve, of Evans and Thomas (1959) for Halley Bay, is shown in Fig. 2.19. From this curve it can be seen that at the southern auroral zone the azimuth–measured east from geomagnetic north–increases with time instead of diminishing as in the northern hemisphere. The range of variation (about 15°) is similar to that for the stations of lowest latitude in Fig. 2.18. This lends support to the assumption that the northern and southern momentaneous auroral occurrence curves are geomagnetically conjugated.

Comparison of the curve for Halley Bay in Fig. 2.19 (No. 1) with that for Oasis (No. 2 in Fig. 2.19) of geomagnetic latitude 78° shows that the range of variation increases with latitude in the southern hemisphere also.

(c) Discussion of the diurnal variation near the auroral zones

In order to ascertain the degree to which the differences between the curves in Fig. 2.18 could be attributed to referral of the direction to the geomagnetic meridian, i.e. to overlooking of the effect of the non-dipole part of the geomagnetic field, Hultqvist (1962 b) made a correction for this factor in respect of several stations near the northern auroral zone. The direction, instead of being referred to the geomagnetic meridian, was referred to the perpendicular to the projection of circles in the geomagnetic equatorial plane on to the earth's surface along higher approximation geomagnetic field lines. The azimuths of these circles at a number of stations are given in Table 2. By changing the time scale to the geomagnetic one, the curves of Fig. 2.20 were obtained.

A comparison of Figs. 2.18 and 2.20 shows that the agreement between the North American stations on the one hand and Cape Schmidt and Kiruna on the other, was much improved by this modification.

Fig. 2.20 also includes the theoretical curve of Alfvén (1939, 1940, 1950). A comparison shows that the time derivative sign is the same, but that all the experimental azimuths are higher than the theoretical ones before midnight and that the amplitude of the diurnal variation for most stations is greater than theoretically expected.

The "discontinuity" observed at Kiruna has the same amplitude as that on the theoretical curve but is displaced about 1½ hour in the positive time direction.

From the observed diurnal variation curves of Fig. 2.20, a third type of auroral precipitation curve can be evaluated by integration according to formula (1)

$$\theta = \theta_o \exp\left(-\int_{\lambda_o}^{\lambda} \cot \alpha \, d\lambda\right) \tag{1}$$

where θ is the geomagnetic colatitude,
λ is the geomagnetic time angle,
α is the azimuth of the auroral arcs measured from geomagnetic north towards east,
λ_o is the geomagnetic time angle at the start of the observational curve, and
θ_o is an integration constant that determines the polar distance of the curve.

This curve is Alfvén's theoretical I curve. It is defined by the orientation of the auroral arcs around the auroral zone, considered to be fixed in relation to the sun.

From the Kiruna diurnal variation curve of Fig. 2.20 the I curve of Fig. 2.21 has been derived. The whole curve is situated outside the circle with which it coincides at 1800 hours, in contrast to Alfvén's theoretical curve, which is inside the circle. The difference is due to the fact that the observation curve in Fig. 2.20 is situated almost completely above azimuth 90°. The difference between the experimental and theoretical curves varies between 7 and 9°, which means that the theoretical curve is situated outside the standard deviation "region" of the observational material.

The very high amplitudes of the diurnal variations found for high latitude stations are not contained in Alfvén's model, according to which the greatest deviation of the arc azimuth from 90° should be at 0600 hours geomagnetic time, where the I curve has a singular point and the azimuth changes from 105° to 75° in the auroral zone.

Even for L = 70 earth radii, corresponding to a geomagnetic auroral latitude of above 80°, the azimuth is only 76° at 0600 hours.

Khorosheva (1961, 1962) investigated recordings of aurora made simultaneously at widely different longitudes in the arctic of the eastern hemisphere and found that the auroras form a single, physically related band which changes synchronously in brightness, width and latitude over its entire extension. On the basis of these observations, Khorosheva and Feldstein proposed that the momentaneous auroral precipitation zone forms an oval-shaped curve around the geomagnetic axis pole, at the normal distance of the auroral zone (about 23°) on the night side but only 10-12° from the pole on the day side, i.e. the zone is similar in shape to the combination of two spiral arcs shown in Fig. 2.10. The proposal (Feldstein, 1964) also implies that the auroral arcs are lined up along the momentaneous precipitation zone of the described shape. This would explain the existence of two maxima in the diurnal variation curve for auroral occurrence at latitudes inside the ordinary auroral zones. It would, however, mean that the aximuth of the auroral arcs, measured from the perpendicular to the auroral zone (curve 3 in Fig. 1), would be smaller than 90 after midnight, with the most rapid change in direction around midnight. That is usually not observed.

(d) Diurnal variation on the central auroral caps

On the central auroral caps (inside about 80° geomagnetic latitude) the diurnal variation of the orientation of quiet auroral arcs has been reported to be entirely different from the one described above. Observed (smoothed) diurnal variation curves are shown in Fig. 2.22 for both the northern and southern central caps. Curve 2 in Fig. 2.19 also belongs to this category.

If the azimuth in Fig. 2.22 is taken from geographic north, the diurnal variation curves imply that the arcs are continuously pointing to the sun while the earth rotates below the auroral pattern. The first to report such a 360° diurnal variation of the auroral arc direction seems to have been Mawson (1914), but it was forgotten and rediscovered by Weill (1958). In the last few years it has also been reported by Davis (1960, 1961, 1962 b), Feldstein (1960), and Denholm and Bond (1961).

Consistent data showing this 360 degrees rotation of the arcs during the 24 hours of day and night have thus been presented by several investigators and there seems to be no doubt that the effect is real. There are, however, a number of inconsistencies between observational results found by different observers (see Hultqvist, 1962 b) and there is, therefore a need for more observations.

It has been suggested by Cole (1959, 1960) and Davis (1960, 1961, 1962 b) that the geometric pattern of aurora over the polar caps is the same as the pattern of the ionospheric current system which is equivalent to the local-time-dependent component of the geomagnetic disturbance-the DS current system (see Fig. 2.23). These views were incorporated as important constituents of the qualitative model of geomagnetic storms and associated phenomena by Axford and Hines (1961). According to this model the DS currents and the auroral arcs should have the same direction over the auroral caps.

The angle between auroral arcs and the direction of the horizontal currents, corresponding to the observed magnetic disturbance, has been evaluated by Sobouti (1961), Davis and Kimball (1962), Pudovkin and Yevlashin (1962), Feldstein (1964) and others for auroral and trans-auroral latitudes. Near the auroral zone, all investigators found the directions being identical within measuring accuracy. While Feldstein's results in the near polar regions were that the directions mentioned form an angle of, in the average, about 50°, Sobouti (1961) did not see any difference at Resolute Bay (geomagnetic latitude 83.2° N). A disagreement between directions of auroral arcs and the ionospheric current lines has also been found in the Antarctic (see Cole, 1963). A difference between the two directions introduces difficulties for theoretical models which require that the geographical pattern of auroral arcs and of the DS current system should be identical (like the model of Axford and Hines, 1961). It is, however, to be remembered that the horizontal geomagnetic disturbance component shows the direction of the ionospheric current only for simple current patterns.

(e) Other variations in arc orientation

Jensen and Currie (1953) found a pronounced seasonal variation in the auroral arc orientation in the years 1949-51 at Saskatoon (lat. 52.1° N) and Chesterfield (lat. 63.3° N) Canada. The peak to peak variation in azimuth over a year amounted to about 30°, with a maximum azimuth of 115° in February at Saskatoon and minima in October-November and April-May. The seasonal-variation investigation of Jensen and Currie (1953) seem to be the only one made.

Those authors also studied the dependence of the arc direction on the activity of the auroral display. No significant difference between quiet and active dispalys could be found. When grouping their observational material for auroral arc orientation with regard to magnetic disturbance level, Jensen and Currie obtained for Saskatoon an average azimuth of 93° ± 1° (standard deviation) for the highest degree of activity, 100° ± 1° for median disturbance and 100° ± 2° for the lowest degree of disturbance. More investigations of the kinds undertaken by Jensen and Currie, made for different geomagnetic longitudes, would be of great value.

No theoretical models of aurora contain any seasonal variations in the auroral activity at all. The difference in direction between the earth's rotation axis and the dipole axis has been neglected so far.

5. The Height and Vertical Extent of Visual Aurora

The height of auroras was studied extensively especially in the first two to three decades of this century by the Norwegian school of auroral physics, with Störmer as the originator. Detailed reports of the methods used and the results obtained can be found in the books by Harang (1951) and Störmer (1955). Observations in Canada and Alaska have been reported by McLennan et al. (1931), Currie (1934, 1955), Fuller and Bramhall, (1937), and McEwen and Montalbetti (1958). Southern hemisphere observations have been published by Geddes (1939). Only a very short review will be given here.

The height can be measured only if the auroral form contains some well defined features which can be identified on photographs taken from two places at a distance from each other comparable to the height of the aurora (paralactic photography).

In most auroras the lower border is well defined and the height given in most reports is the height of the lower limit of the aurora, as seen on photographic pictures. Fig. 2.24 shows the height distribution of lower limits for different auroral forms (after Vegard and Krogness, 1920). The differences between the various types represented in the figure are fairly small.

The dependence of the heights of the lower borders of auroral arcs on their intensity is shown in Fig. 2.25 (after Harang, 1951). As can be seen from Fig. 2.25, there is a difference of 20 km in height between weak and very strong arcs. Harang found a similar but less strong dependence on intensity also for other forms.

The results described above were obtained in or close to the northern auroral zone. The height of subauroral zone aurora has been extensively studied by Störmer (cf. Störmer, 1955) over southern Scandinavia. Compared with the auroral heights determined in the vicinity of the auroral zones the height diagram for southern Norway shows a far greater extension towards increasing heights. The lower limits are, however, the same in both cases. According to Barbier (1963) the majority of auroras seen over central Europe have lower limits situated above 250 km altitude.

In addition to the type effects shown in Fig. 2.24, there are a number of others. Störmer (see Störmer 1955) determined the height of the lower limit of sunlit auroras and found a height distribution completely different from those in Fig. 2.24. The distribution was very extended in height, with its maximum of probability at about 300 km.

Aurora of type B, i.e. aurora with the lowest part red due to emissions from the first positive band system of N_2 and first negative system of O_2^+, usually occurs at altitudes for the lower border of between 80 and 100 km. The lowest height of aurora reported was found by Harang and Bauer (1932) for a type B display. Numerous measurements were made on an intense arc and they obtained some points extending down as low as 65 km with an average height of 70 km.

On the other hand, red aurora of type A (with the 6300 Å O line dominating) is observed mostly at heights greater than those shown in Fig. 2.24. The medium latitude aurora mentioned above, which has a lower limit greater than 250 km, is mostly of this kind.

Störmer has reported a type of homogeneous arc, lying in the dark atmosphere near 200 km, which may be of a different kind from the aurora observed at 100 km level (Barbier, 1963; see also p. 6).

Finally, the quiet mid-latitude red arcs have been found to occur at heights between 390 and 560 km, but most often in the interval 400-450 km (see the review by Roach and Roach, 1963).

The extent along the field lines of an auroral form is quite different for different forms. Fig. 2.26 (after Vegard; cf. Harang, 1951, p. 35) shows the mean variation of light intensity in vertical direction for different auroral forms. An ° indicates the upper limit of photographic impression. Some average numerical parameters have been collected in Table 3 (after Vegard and Krogness, 1920).

Table 3

Type	l_1	l_2	l_3
arcs	6.4 km	14.0 km	14.0 km
arcs with ray-structure	5.8 km	13.6 km	46.7 km
draperies	9.1 km	16.3 km	63.4 km
rays	-	-	137.0 km

Here l_1, l_2 and l_3 are the distances from the lower limit to the height of maximum luminosity, the upper limit of strong luminosity, and the upper limit of faint luminosity, respectively. It is evident from Fig. 2.26 and Table 3 that the rays differ entirely from the other auroral forms in respect of luminosity distribution with height.

There is a solar-cycle variation in the height of the lower boundary of aurora as well as in vertical extent (Elvey, 1957). Both height and vertical extension are lower in years with solar-activity-minimum than at high solar activity.

6. Motions

There are many different types of motions associated with the auroral activity and individual auroral forms. Some of the motions for which observational data are available will be discussed here. From the point of view of the theoretical models of aurora, we are interested in how the auroral precipitation zones change location with time under various conditions as well as in how individual complete forms, or irregularities in the forms, move. These types of motion will be discussed in this subsection, where we will deal with the statistical properties. In subsection 7 examples of motion in connection with changes of momentaneous auroral geographical distributions will be discussed.

(a) Changes in the geographical pattern of auroral activity

It has been mentioned already before in this review that the location of the auroral zone shifts towards lower latitudes when the solar activity increases (although inconsistency exists in the available data). The first one who deduced this motion from observational data seems to have been Tromholt (1882). Davies (1950) evaluated a change of about 3 degrees of latitude between solar maximum and solar minimum.

Tromholt (1882) and Davies (1950) also arrived at a seasonal variation in the polar distance of the auroral zones. This is large around the equinoxes and small at solstizes. This is supported also by the recent study by Feldstein and Shevnina (1961), but the opposite result was found by Sheret and Thomas (1961).

With the statistical definition of the auroral zone adopted earlier in this section, seasonal variation in its location are the shortest that can exist. We will, however, now consider briefly the average behavior of the momentaneous auroral precipitation zone as a function of geomagnetic disturbance level (this momentaneous region of auroral activity is often called the auroral zone in the literature). There exist two types of data of relevance in this respect: those which concern the equatorward boundary of the region where auroras occur, and those referring to the region of maximum occurrence frequency for the aurora at a given moment of time.

Gartlein et al. (1960) found the southern boundary of aurora in the northern hemisphere to be at almost 10° lower latitude for $K_p = 5$ than for $K_p = 1$, the $K_p = 5$ boundary passing through Stockholm, southernmost Alaska and the Great Lakes in North America (see Fig. 6). Akasofu and Chapman (1963) found the southern limit of latitude of northern quiet auroral arcs to be approximately a linear function of Dst(H), i.e. of the ring current field, for 16 magnetic storms studied. The latitude variation with the ring current amounted to more than 10°, the southern limit reaching 49° geomagnetic latitude for the strongest storms investigated.

The southern border of auroral activity in Alaska, taken to be the lowest latitude position at which defined auroral forms appear, was found by Davis and Kimball (1960) to move regularly in the course of the night in the manner shown in Fig. 2.27. The extreme southern extent of the smoothed curves occurs, as can be seen in Fig. 2.27, around geomagnetic midnight (which is 1-2 hours after local midnight in Alaska). Davis (1962 b) states that the decrease in the number of discrete forms in low latitudes in the morning must be due to the actual disappearance of the forms in place—either because of a decrease of auroral luminosity or to a tendency for the forms to diffuse—and not to withdrawing to the north.

Jacka (1953) studied the location of the region of maximum auroral occurrence around MacQuarie Island in the southern hemisphere. He found that the southern auroral precipitation zone moves towards the equator with increasing K_p as $\Delta\phi = 2.95 - 0.605\ K_p$, where $\Delta\phi$ is the latitude departure of the homogeneous arcs from MacQuarie Island. From Jacka's relation, it can be seen that the latitude of the auroral precipitation zone can vary with as much as 5-6°. This is the same amount as found by Feldstein and Solomatina (1961).

A question of interest is the following: is the detailed shape of the distribution of auroral activity within the auroral precipitation zone changed when its center or southern boundary moves in latitude. Studies of this have been reported in the last few years. Some investigations of individual events will be reviewed in subsection 7, below. Here the average behavior will first be discussed.

Feldstein and Solomatina (1961) reported that at the same time as the auroral precipitation zone withdraws from the pole, there is an expansion of the zone, also towards higher latitudes, but they did not present quantitative results. Davis and Kimball (1960) and Davis (1962 b) give some details. Fig. 2.28, after Davis (1962 b) shows several measures of auroral activity vs. geomagnetic latitude for weak and strong displays. For curve A the maximum K index at College during the display has been the criterion for classing. Davis points out that the small difference between strong and weak events at high latitudes, shown in Fig. 2.28, does not mean that there is no connection between magnetic and auroral activity in those latitudes, but only that the highest K index achieved during a display at an auroral-zone station is a poor indicator of the auroral activity at the auroral zone. In Fig. 2.28 B, C, and D the division of the displays into strong and weak was made on the basis of the total number of forms observed in Alaska between geomagnetic latitudes 60° and 70° during each display. In Fig. 2.28 D the total number of auroral forms moving north or south through the zenith of the station has been taken as measure of auroral activity.

Fig. 2.28 clearly indicates that the position of the maximum activity is at essentially the same geomagnetic latitude (66° to 67°) for both small and large displays, but at the lower latitude positions the relative increase of activity for the large displays is considerably greater than at higher latitudes.

(b) Motion of individual auroral forms

A drift of distinct luminous auroral features must be due either to a drift or change of the source of the impact particles or to a change in the electric and magnetic fields experienced by the particles on their way to the atmosphere. The studies of the drift motion of auroral forms is therefore, of course, of considerable interest.

The available observational data in general give the motion in N-S and E-W direction. Considering the deviation from the E-W direction of both geomagnetic isolatitude lines and the average orientation of the auroral forms, it would be preferable in the future to have the motions measured parallel and perpendicularly to the observed auroral zone or to the individual auroral arcs. In this review the motion will, however, have to be divided into N-S and E-W direction.

With regard to the motions of individual auroral forms there are two cardinal observations, which are valid irrespective of direction. First, all parts of rays, which can be several hundred km long, appear to move at the same velocity, aligned with the geomagnetic field in the first approximation, and secondly, auroral forms and inhomogeneities have not been reported to overtake one another.

(i) Meridional motion

The motion of individual auroral forms varies with latitude and local time.

Davis and Kimball (1960) found, when scaling allsky-camera films from Alaska to determine the meridional motions, that the direction of first motions observed each evening at the various latitude positions followed definite trends. On many nights, there existed a geomagnetic latitude between 60° and 70°, north of which the first motions were to the north, and south of which the first motions were to the south. This latitude they referred to as the "latitude position of origin." According to Davis (1962 b), the auroral forms do not necessarily form at this latitude. Rather, they seem to develop within a few degrees of the "latitude position of origin" and have a direction of first motion determined by whether the forms develop on the poleward or equatorward side of the "latitude position of origin." Davis and Kimball found the "latitude position of origin" to be between 60° and 70° on 86 of the 180 nights when aurora was observed over Alaska during the 1957-1958 season. On 58 other nights the aurora first moved south across the whole latitude band 60°-70°. Approximately 10 nights were found on which either the first motions were without pattern or there were more than one latitude of origin.

The regularity mentioned was for the first direction of motion seen in the evening. Later on in the night both northward and southward moving forms are observed. In fact, Davis and Kimball (1960) and Davis (1962 b) found that during IGY the number of auroral forms moving southward within the geomagnetic latitude band 60° to 70° over Alaska was greater than the number of north-moving forms at any time in the night. Bhattacharyya (1961) observed near Ottawa, well to the south of the auroral zone, that the number of equatorward moving forms outnumbered those in the reverse direction only up to 0200 hours (75th meridian time). Fillius, Gartlein and Sprague found a similar result at the southern auroral zone (according to Cole, 1963). The data presented by Davis (1962 b) differs from those of Bhattacharyya and Fillius et al. in that Davis gave the number of forms within a 10° latitude range, whereas the others presented observations from one place.

Older observational results of local time dependence of meridional motion in subauroral latitudes have been reviewed by Harang (1951) and Störmer (1955). They can be roughly summarized in the following way: the motion is on the average equatorwards before midnight and polewards after. The apparent discrepancy between the results of Davis and Kimball (1960) and most older results may be due to the difficulty to distinguish, without the use of allsky films, between motion of the equatorward boundary of auroral activity and actual meridional movement of individual forms.

Kim and Currie (1958) analyzed the N-S motion south of the northern auroral zone with regard to velocity. They found the volocity to be greatest (about 160 m/sec) at the latitude of the auroral zone. The number of occasions of equatorward movement exceeded those polewards in every 50 m/sec speed range up to 670 m/sec except in the range 0-50 m/sec.

(ii) Longitudinal motion

At the auroral zones and in subauroral latitudes both east and west longitudinal motions of auroral forms occur during the night, westerly predominating early in the night and easterly in the morning. (Meinel and Schulte, 1953; Meek, 1954; Bless et al., 1955; Malville, 1959; Evans, 1959, 1960; Kim and Currie, 1960; Bond, 1960; Stoffregen, 1961; Davis and DeWitt, 1963). Most investigators are agreed that east-west motions are in general much faster—by at least a factor of 3—than north-south motions, amounting to several hundred m/sec for average disturbance levels. Kim and Currie (1960) observed a general increase of speed with proximity to the auroral zone and also with increasing geomagnetic disturbance level.

Davis (1962 b) and several before him found that during the simplest type of auroral display, one accompanied by positive disturbance of the horizontal magnetic field in the evening and negative disturbance in the morning, the auroral motion is westward during the positive disturbance and eastward during the negative. The reversal from westward to eastward auroral motion is abrupt to within 30 minutes and occurs at the time of, or some minutes after, the change of sign of the horizontal magnetic disturbance.

Mawson (1914) and Stoffregen (1961 b) observed inside the southern and northern auroral zones, respectively, that the longitudinal motion in auroras was, in general, from the daylight to the dark side of the earth, i.e. opposite the general trend outside the zone.

According to Davis (1961, 1962 b), the moderate evening aurora at the auroral zone is typified by the existence of a partial or complete array of west-opening loop structures along which clockwise (as seen from above) motions of irregularities occur. These motions are superimposed on the general westward drift of the auroral forms. Following the change from positive to negative horizontal disturbance, broken forms are prevalent, but now counter clockwise motions occasionally can be seen. Auroral displays accompanied by magnetic disturbance of variable sign have correspondingly complicated auroral motion.

The motion pattern observed by Davis agrees with Mawson's and Stoffregen's observations inside the auroral zones and it also fits well to the theoretical model of Axford and Hines (1961).

Recently, Omholt (1962) has reported east-west speeds of rays in a very active auroral curtain as high as 30 km/sec. These observations were made with a new technique. The data reported are only preliminary and more measurements of this kind will certainly add much to our knowledge about the auroral mechanisms. Still higher velocities of irregularities along auroral forms (up to 124 km/sec) have been observed by Davis and Hicks (1963) with the use of image amplifier technique, permitting 30 exposures/sec or more.

7. Dynamic Morphology of Individual Auroral Displays

A few synoptic studies of auroral displays have been published since IGY (but much fewer than would be desirable). This type of investigation is certainly one of the most important that can be made at the present stage of our knowledge about aurora. Those published have revealed several previously unknown characteristics of the auroral morphology. A brief review will be given here.

Khorosheva (1963) found that auroras observed simultaneously at different longitudes in the eastern hemisphere form a single, physically related band, which changes synchronously in brightness, width, and latitude over its entire extension.

Davis (1962 b) and Davis and Kimball (1962) analyzed synoptic auroral maps for Alaska and evaluated the results reviewed earlier concerning auroral motion and auroral configurations. Good evidence for the configuration pattern of aurora being similar to that of the DS current system was found.

Synoptic maps covering still larger areas than those of Davis (1962 b), namely eastern Siberia, Alaska, and western and central Canada, have been prepared and analyzed by Akasofu (1960, 1962, 1963) and Akasofu and Chapman (1962). The disturbance periods studied are the very great ones. (Sept. 22-23, 1957, Feb. 11, 1958, Feb. 13, 1958; March 24, 1958).

A short report of the time history for the Feb. 13, 1958 aurora, given by Akasofu (1963), will be included here, because it illustrates better than has been done before the development of a large aurora on a world-wide scale. Fig. 2.29, a-e, shows snapshots of the situation at five different moments of time.

Three arcs extended across Alaska at 0830 UT but only one to the north of eastern Siberia (Fig. 2.29 a). Five minutes after the breakup, the auroras over Alaska were completely disrupted. A few arcs rapidly moved northward and one of them went to the north of Barrow (Fig. 2.29 b). To the west of Alaska a remarkable loop formation can be seen in Fig. 2.29 b. It seemed to be produced at the time of the breakup over Bering Strait. There is a great difference in the latitude range of the aurora between Alaska and Canada in Fig. 2.29 b. This is because the zone with aurora did not expand simultaneously over the longitude range shown. It started over Alaska. There was, however, a strong increase in brightness also over Canada when the breakup began in Alaska.

At 0900 UT the expansion had spread to central Canada (Fig. 2.29 c). A new breakup started at 0907 UT in Alaska and the broken bands became much brighter also in central Canada. At 1030 UT the auroral forms in Alaska and the Siberian Arctic Sea were quiet again and there were several faint arcs. The aurora was, however, still irregular in Canada and did not recover to this quiet phase, although it became fainter. The auroral precipitation zone was still expanding to the north there.

Some of the observations made by Akasofu in analyzing synoptic sequences similar to the one in Fig. 2.29 are summarized here.

(1) The auroral precipitation zone starts to move away from the pole when the ring current starts to build up. It may reach latitudes 10° (or more) less than that of the auroral zone. The width of the precipitation zone in quiet periods (between polar magnetic (DP) substorms) is not increased (5° wide or less).

(2) The breakup occurs when a DP substorm starts. It is characterized by a sudden increase of the brightness and rapid and complicated folding or wavy motions of all arcs and bands over a large area on the morning side, together with a rapid expansion polewards of the precipitation zone. The northward expansion often starts around midnight or in the early morning and propagates into the morning side. It may amount to more than 10°.

(3) Breakup with poleward expansion has been observed in the auroral zone already 4 minutes after the sudden commencement.

(4) At the breakup, westward traveling folds are often formed. They propagate with velocities of 300-600 m/sec and have characteristic lengths of a few hundred km. Akasofu thinks it is possible the folds are identical with those observed and studied by Davis (1962 b).

(5) Some of the auroral forms in the auroral caps move up there from auroral zone latitudes during and after the breakups.

(6) Complete breakup of the quiet auroral forms are not so common on the auroral caps as in the auroral zones or on their equatorward side.

(7) An arc extending at least 5000 km in E-W direction was seen on March 24, 1958.

It is evident that a large number of the characteristics found by Akasofu do not fit into any theoretical model, in most cases because the existing models are not detailed enough. Some of the results presented above seem to disagree with some proposed models. The disrupted auroral forms shown in Fig. 2.29 are not similar to the DS-current pattern to be expected on the basis of Axford's and Hines' (1961) model for magnetic storms and aurora, just to mention one of the most recent ones. Also, the observation of large scale activation of aurora, with breakup and northward expansion of the auroral precipitation zone already 4 minutes after a sudden commencement, seems not fit their model.

Akasofu (1963 d) has worked out a model of simultaneous auroral activity over the entire polar region in terms of the auroral substorm, which corresponds to the polar geomagnetic substorm (DP).

Figure Captions

Fig. 2.1–Northern auroral zones determined from observations (on a map with geomagnetic co-ordinate system). Curve 1 is that of Fritz (1881), Curve 2 is Vestine's (1944) and Curve 3 Feldstein's (1960).

Fig. 2.2–Southern auroral zones determined from observations (on a map with geomagnetic co-ordinate system). Zone 1 is according to White and Geddes (1939), Zone 2 to Vestine and Snyder (1945), Zone 3 to Bond and Jacka (1960) and Zone 4 to Feldstein (1960).

Fig. 2.3–(After Davis, 1962b) The incidence of auroral forms at geomagnetic latitudes 60-88°.

Fig. 2.4–Comparison of Feldstein's (1960) northern observational zone (Curve 1) with a number of "theoretical" auroral zones: 2 is according to Gartlein and Sprague (1960), 3 to Quenby and Webber (1959) and 4a and b are projections of two circles in the geomagnetic equatorial plane (corresponding to colatitudes 22 and 25 degrees respectively; Hultqvist, (1958).

Fig. 2.5–Comparison of Feldstein's (1960) southern observational zone (Curve 1) and that of Bond and Jacka (1960) (Curve 2) with different "theoretical" auroral zones: 3 is according to Gartlein and Sprague (1960), 4 to Quenby and Webber (1959) and 5a and b are projections of two circles in the geomagnetic equatorial plane (corresponding to colatitudes 22 and 25 degrees, respectively; Hultqvist, 1958). The numbered points show the approximate locations of the stations at which the IGY observational material – the basis of Feldstein's auroral zone – was collected. The numbering is that of Feldstein (1960).

Fig. 2.6–Southern extent of aurora borealis for two different levels of geomagnetic activity (after Gartlein, Gartlein and Sprague, 1960).

Fig. 2.7– (After Stoffregen, 1962) Approximate latitude distribution for different auroral types.

Fig. 2.8– (After Davis, 1962a) Percentage hourly occurrence in a latitude belt of width 1° centered over each of the stations: Barrow (68°-69°), College (64°-65°), and Farewell (61°-62°). The curve (3914) is drawn from data by Murcray (1959) and represents relative all-sky 3914Å intensity over College during 1955 and 1956.

Fig. 2.9– (After Davis and DeWitt, 1963) Diurnal variations of hourly occurrence of visual aurora within 150 km of Byrd Station for all clear, dark hours in May and June 1960.

Fig. 2.10–(After Feldstein and Solomatina, 1963) Geomagnetic times of maximum frequency of auroral occurrence in the zenith as function of geomagnetic latitude corrected for the non-dipole part of the geomagnetic field.

Fig. 2.11–(After Fuller, 1935) Diurnal variation of different auroral forms and of auroras of different intensities at College, Alaska.

Fig. 2.12–(After Meinel et al., 1954) (a) Fraction of all auroras observed in each calendar month at Yerkes Observatory; (b) monthly frequency distribution corrected for cloudiness and number of dark hours in each month.

Fig. 2.13–(After Tromholt, 1902) Variation of the number of auroral days, N, in each year, observed in Norway, and the sunspot number between 1761 and 1877.

Fig. 2.14–Directions of quiet auroral arcs in the northern hemisphere. 1. Haldde and Bossekop; 2. Cap Thordsen; 3. Jan Mayen; 4. Nain; 5. Kingua Fjord; 6. Fort Rae; 7. Sagastyr (the data for points 1-7 are after Vegard and Krogness, 1920); 8. Chesterfield; 9. Coppermine; 10. Cape Hope's Advance; 11. Saskatoon; 12. Coral Rapids; 13. Aroostook; 14. Gjöahavn (the data for points 8-14 are taken from Currie and Jones, 1941; the dotted lines at Chesterfield and Coppermine refer to all types of aurora); 15. Baker Lake; 16. Churchill; 17. Barrow; 18. Fort Yukon; 19. College; 20. Farewell; 21. Choteau (the data

for points 15-21 are after Davis, 1961; the values are averages for the hour around geomagnetic midnight); 22. Godhavn (the data are after Lassen, 1959, and refer to the early morning hours); 23. the region of Micardbu (approximate data after Störmer, 1944); 24. Tromsö (the data are after Harang, 1945, and refer to geomagnetic midnight); 25. Wiese; 26. Dixon; 27. Cape Schmidt (data for points 25-27 are after Feldstein, 1960, and refer to local midnight); 28. Thule (data of Harang, taken from Störmer, 1955); 29. Kiruna (refers to geomagnetic midnight). The map has a geomagnetic coordinate system.

Fig. 2.15—Directions of quiet auroral arcs and sighting directions to the highest points of quiet arcs and bands (arrows) in the southern hemisphere. 1. Macquarie Island; 2. Mawson (data taken from Bond and Jacka, 1960); 3. Vastok; 4. Oasis (the data, after Feldstein, 1960, refer to local midnight); 5. Halley Bay; 6. Shackleton (data from Evans and Thomas, 1959); 7. Ellsworth; 8. South Pole; 9. Byrd; 10. Little America; 11. Scott Base (the long arrows at points 11 and 12 are after Hatherton and Thomas, 1959); 12. Hallett (short arrow); 13. Wilkes (the data for points 7-13 are from Gartlein et al., 1960, the two arrows at points 9 and 13 show the average directions for the two years 1957 and 1958, the 1957 arrow being the one nearest the meridian at both points); the map has a geomagnetic coordinate system.

Fig. 2.16—Directions of quiet auroral arcs and bands at local midnight in the northern hemisphere. 1. Baker Lake; 2. Churchill; 3. Barrow; 4. Fort Yukon; 5. College; 6. Farewell; 7. Choteau (data for points 1-7 taken from Davis, 1961); 8. Cape Schmidt; 9. Dixon; 10. Wiese (data taken from Feldstein, 1960); 11. Tromsö (after Harang, 1945); 12. Kiruna. The map has a geomagnetic coordinate system.

Fig. 2.17—Observed directions of quiet auroral arcs at Kiruna as function of MET and of approximate geomagnetic time. For each hour the average direction and the standard deviation are given. The lower, dashed curve is Alfvén's theoretical diurnal variation curve (see Alfvén, 1950).

Fig. 2.18–Observed (smoothed) diurnal variation curves for the orientation of quiet auroral arcs and bands in and near the northern auroral zone. 1. Baker Lake (geom. lat. 74°); 2. Churchill (geom. lat. 69°); 3. Barrow (geom. lat. 69°); 4. Fort Yukon (geom. lat. 67°); 5. College (geom. lat. 65°); 6. Farewell (geom. lat. 61°); 7. Choteau (geom. lat. 56°) (curves 1-7 are after Davis, 1962b); 8. Dixon (geom. lat. 63°) (after Starkov and Feldstein, 1960); 12. Godhavn (geom. lat. 80°) (after Lassen, 1959); 13. Tromsö (geom. lat. 67°) (after Harang, 1945); 14. Kiruna (geom. lat. 65°).

Fig. 2.19–Observed (smoothed) diurnal variation curves for the orientation of quiet auroral arcs in the southern hemisphere. 1. Halley Bay (geom. lat. 66° S; outside the auroral zone) (after Evans and Thomas, 1959); 2. Oasis (geom. lat. 78°S; far inside the auroral zone) (after Feldstein, 1960).

Fig. 2.20–Observed diurnal variation curves (smoothed) for the direction of quiet arcs, corrected for the non-dipole part of the geomagnetic field, given as a function of geomagnetic time for a number of stations situated in or near the northern auroral zone. 1. Barrow (geom. lat 69°); 2. Fort Yukon (geom. lat. 67°); 3. College (geom. lat. 65°); 4. Farewell (geom. lat. 61°) (curves 1-4 are based on data taken from Davis, 1961); 5. Cape Schmidt (geom. lat. 63°) (based on a curve presented by Feldstein, 1960); 6. Kiruna (geom. lat. 65°); 7. Alfvén's theoretical diurnal variation curve (cf. e.g. Alfvén, 1950).

Fig. 2.21–Curve 1 is the auroral zone corresponding to Alfvén's I curve, evaluated from the Kiruna curve of Fig. 17 for diurnal variation in the orientation of quiet auroral arcs. It is corrected for the non-dipole part of the geomagnetic field. Curve 2 is Alfvén's theoretical I curve (see Alfvén, 1950).

Fig. 2.22–Observed diurnal variation curves (smoothed) for the direction of quiet arcs at stations deep inside the auroral zones. The azimuth is measured towards the east from geographic north for curves 1-5 and from geomagnetic north for curves 6-8. 1. Dumon d'Urville (geom. lat. 76° S) (after Weill, 1958); 2. Wilkes (geom. lat. 77° S); 3. Dumont d'Urville; 4. Scott Base (geom. lat. 79° S); Hallet (geom. lat. 74 °S) (the curves for points 2-5 are after Denholm and Bond, 1961)

6. Thule (geom. lat. 88°N); 7. Alert (geom. lat. 86°N); 8. Resolute Bay (geom. lat. 83°N) (the curves for points 6-8 are after Davis, 1961)

Fig. 2.23-(After Davis, 1962b) The alignment of auroral forms in a polar coordinate system with geomagnetic colatitude and approximate geomagnetic time as polar and azimuthal coordinates. The dashed lines represent the discontinuous post break-up aurora.

Fig. 2.24-(After Vegard and Krogness, 1920) Distribution of lower limits for different auroral forms.

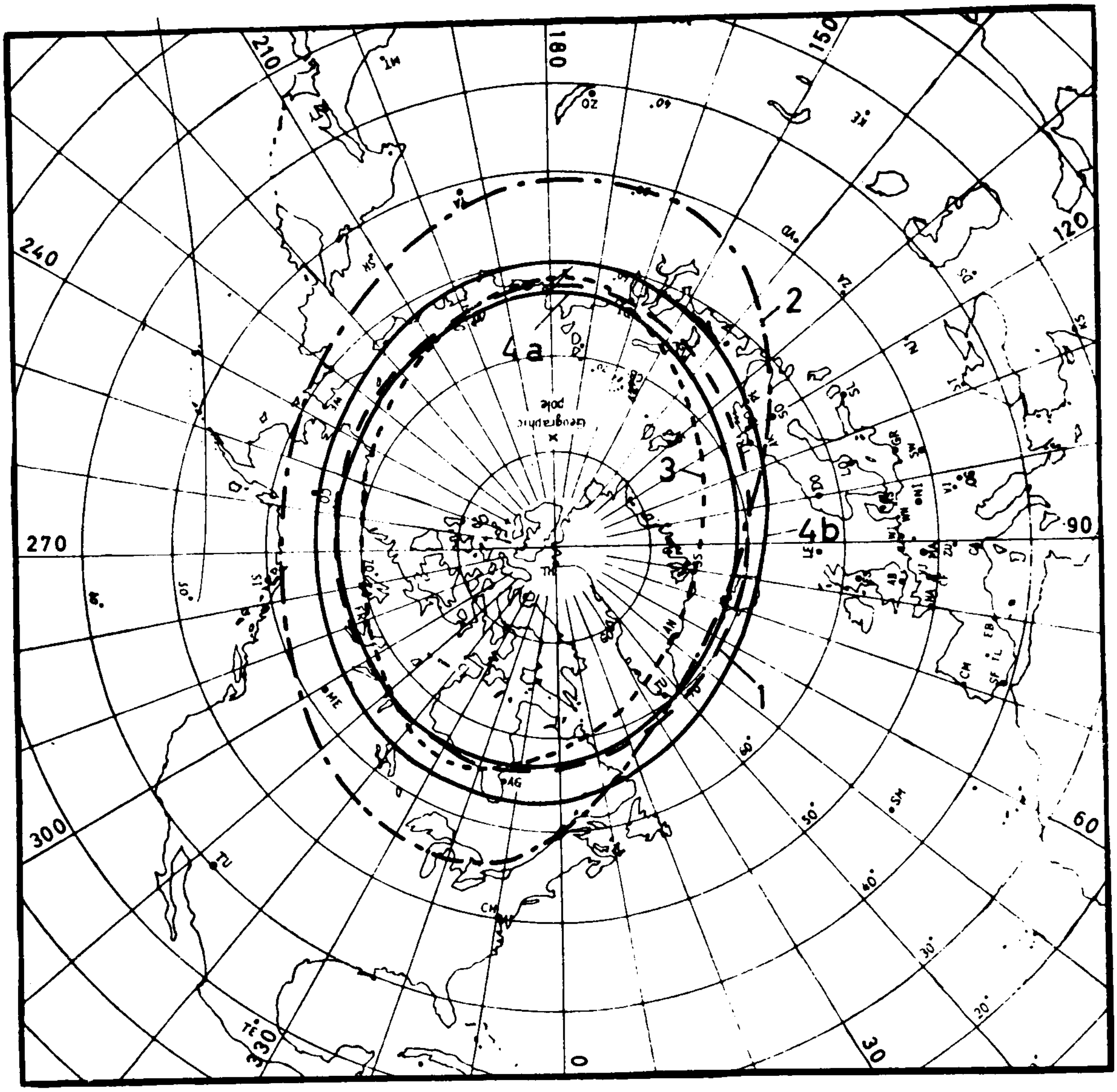
Fig. 2.25-(After Harang, 1944) Lowering of the heights of arcs with increasing intensities, as observed from Tromsö 1929-38.

Fig. 2.26-(After Harang, 1951) Distribution of light intensity along different auroral forms.

Fig. 2.27-(After Davis, 1962a) Diurnal variation of average southern extent for each of three groups of displays extending to geomagnetic latitudes 65°, 64° and beyond 64°. The number beside each point gives the number of displays contributing to that particular mean position.

Fig. 2.28-(After Davis, 1962b) Several measures of auroral activity versus latitude for weak and strong displays observed in Alaska in the season 1957-58. (A) Curves of total incidence for 25 displays during which the maximum K-index for College did not exceed 5 (dashed line) and for 25 displays for which it exceeded 5 (solid line). (B) Average percentage hourly occurrence of overhead auroras (local time interval $19\text{-}05^h$) during 24 strong and weak displays. (C) Total incidence of forms during the 24 strong and 24 weak displays used to draw curves B. (C) Total south and north moving forms observed throughout 31 strong and 30 weak displays.

Fig. 2.29-(After Akasofu, 1963) The distribution of the auroras on February 13, 1958. The field of view of each allsky camera station is indicated by a circle of radius 500 km. The dark dot on the top of each map shows the direction of the sun. L-curves 4,6 and 8 are also shown.



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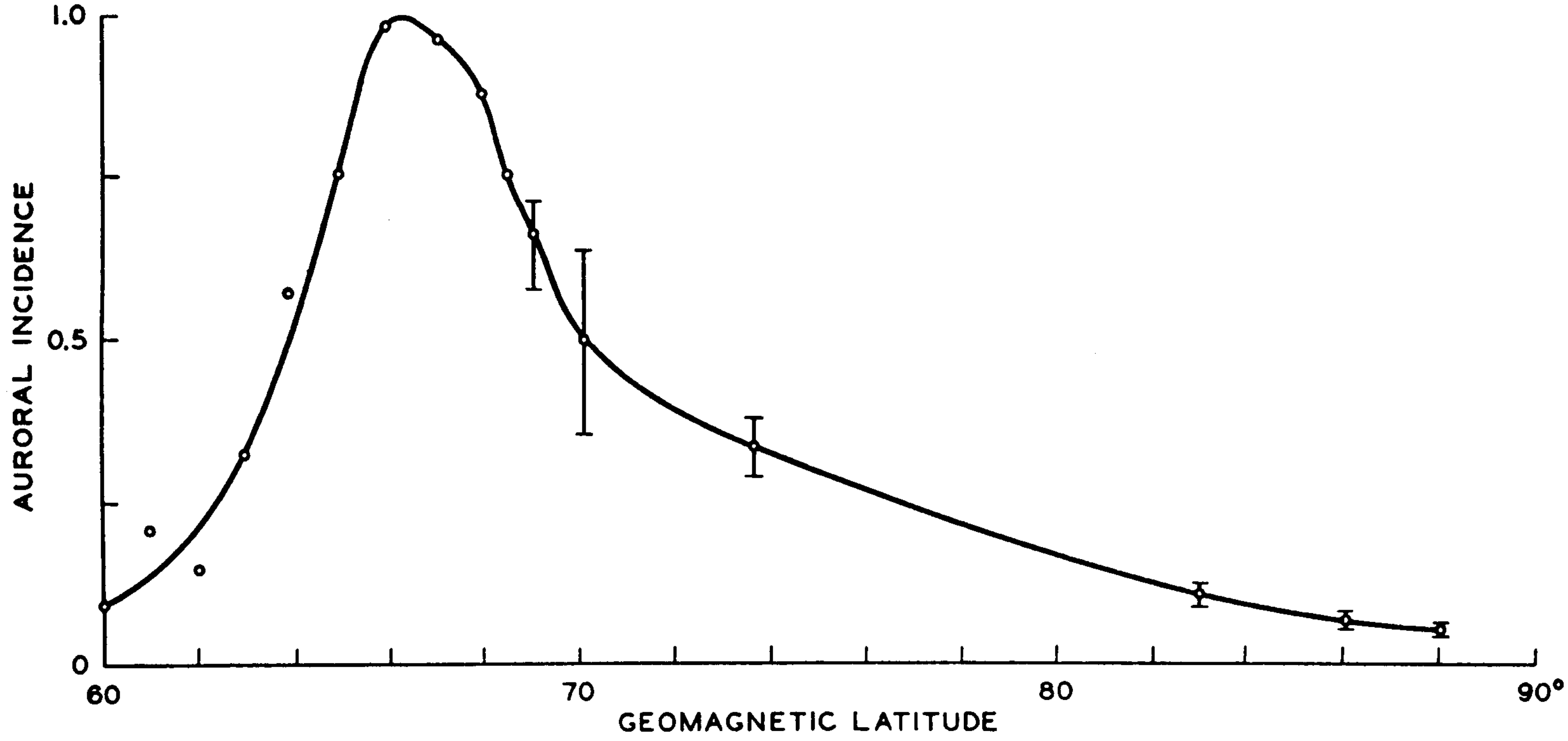


Fig. 2.3-(After Davis, 1962b). The incidence of auroral forms at geomagnetic latitudes 60-88°.

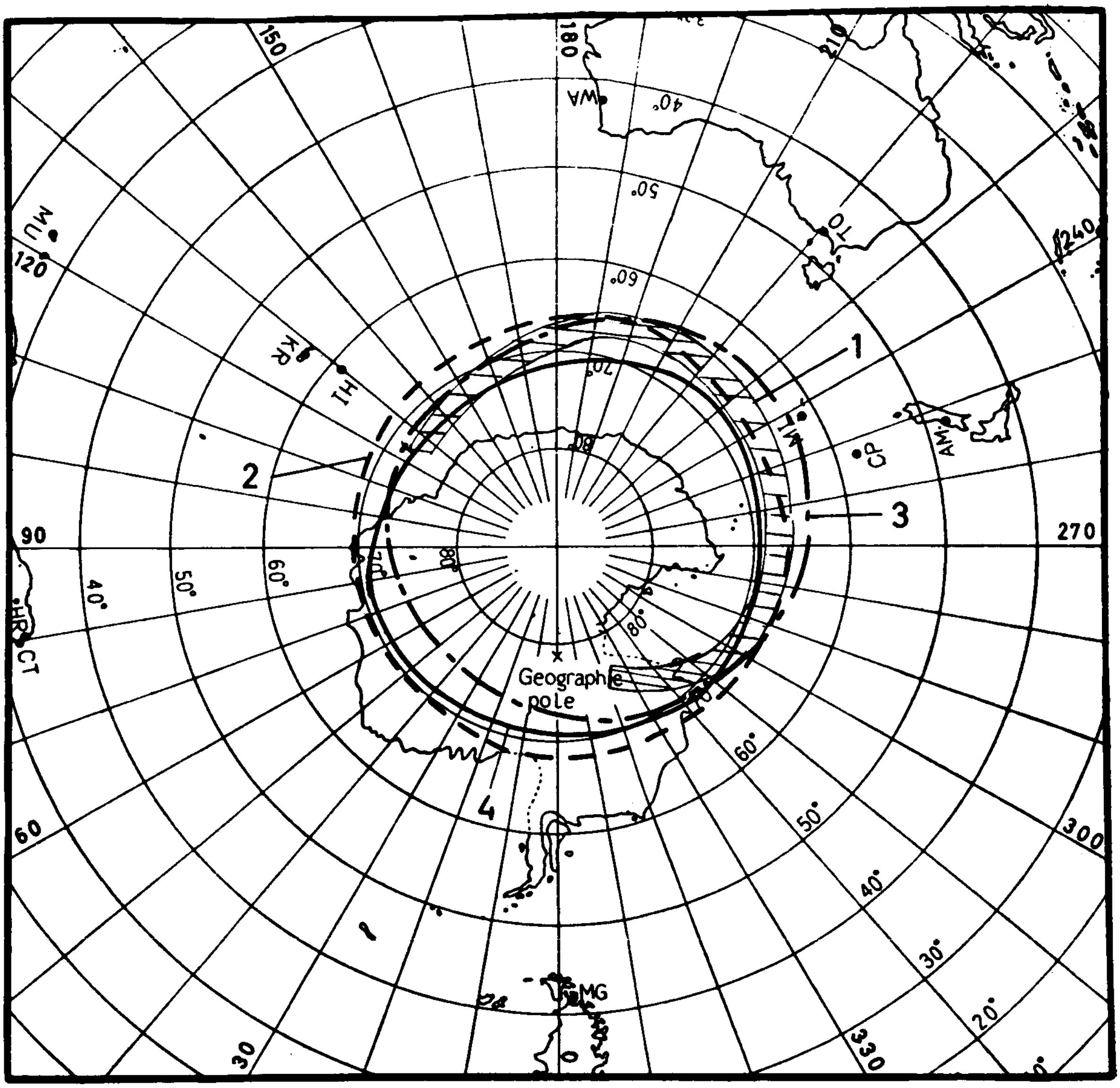
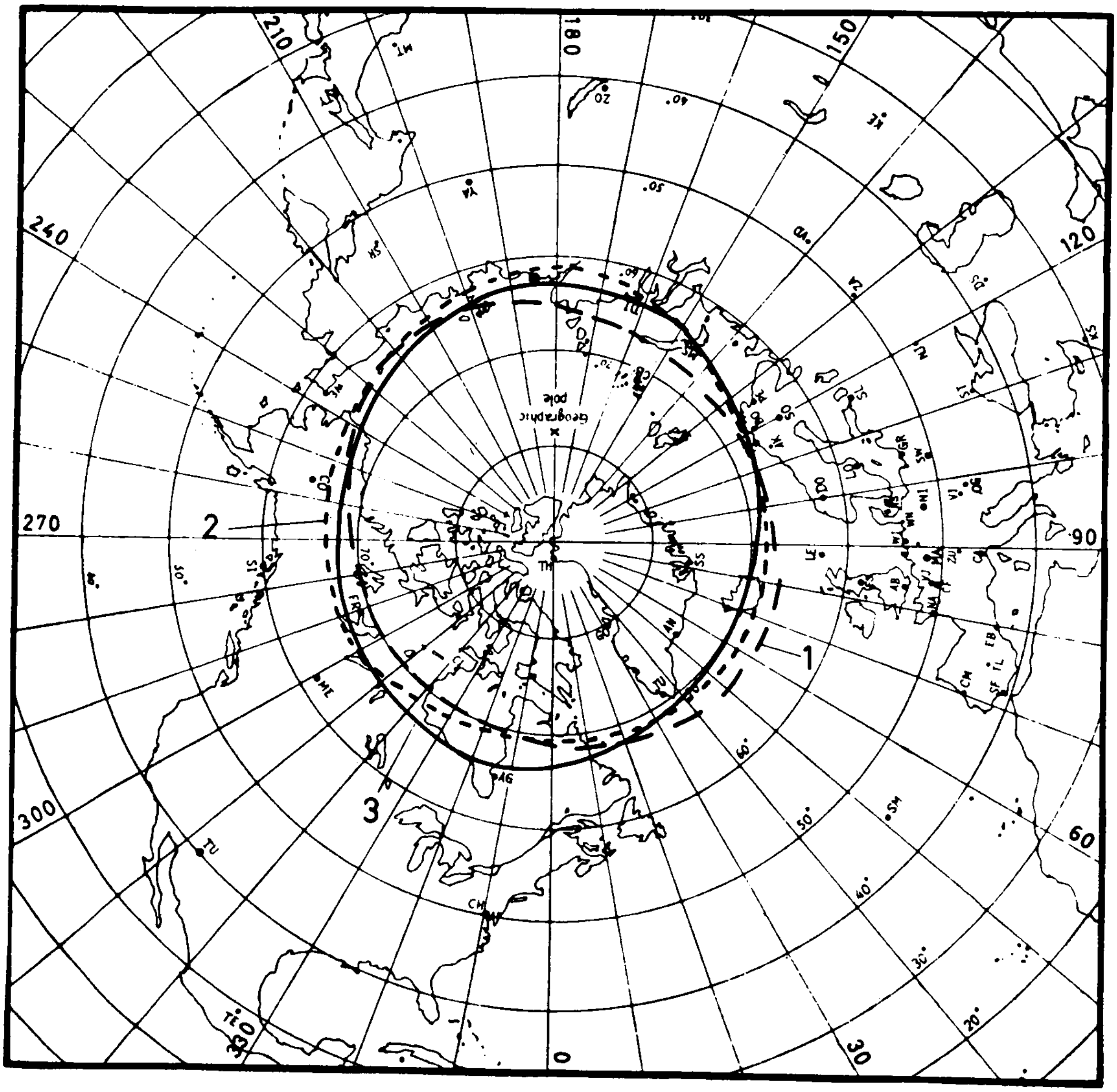


Fig. 2.2–Southern auroral zones determined from observations (on a map with geomagnetic co-ordinate system). Zone 1 is according to White and Geddes (1939), Zone 2 to Vestine and Snyder (1945), Zone 3 to Bond and Jacka (1960) and Zone 4 to Feldstein (1960).



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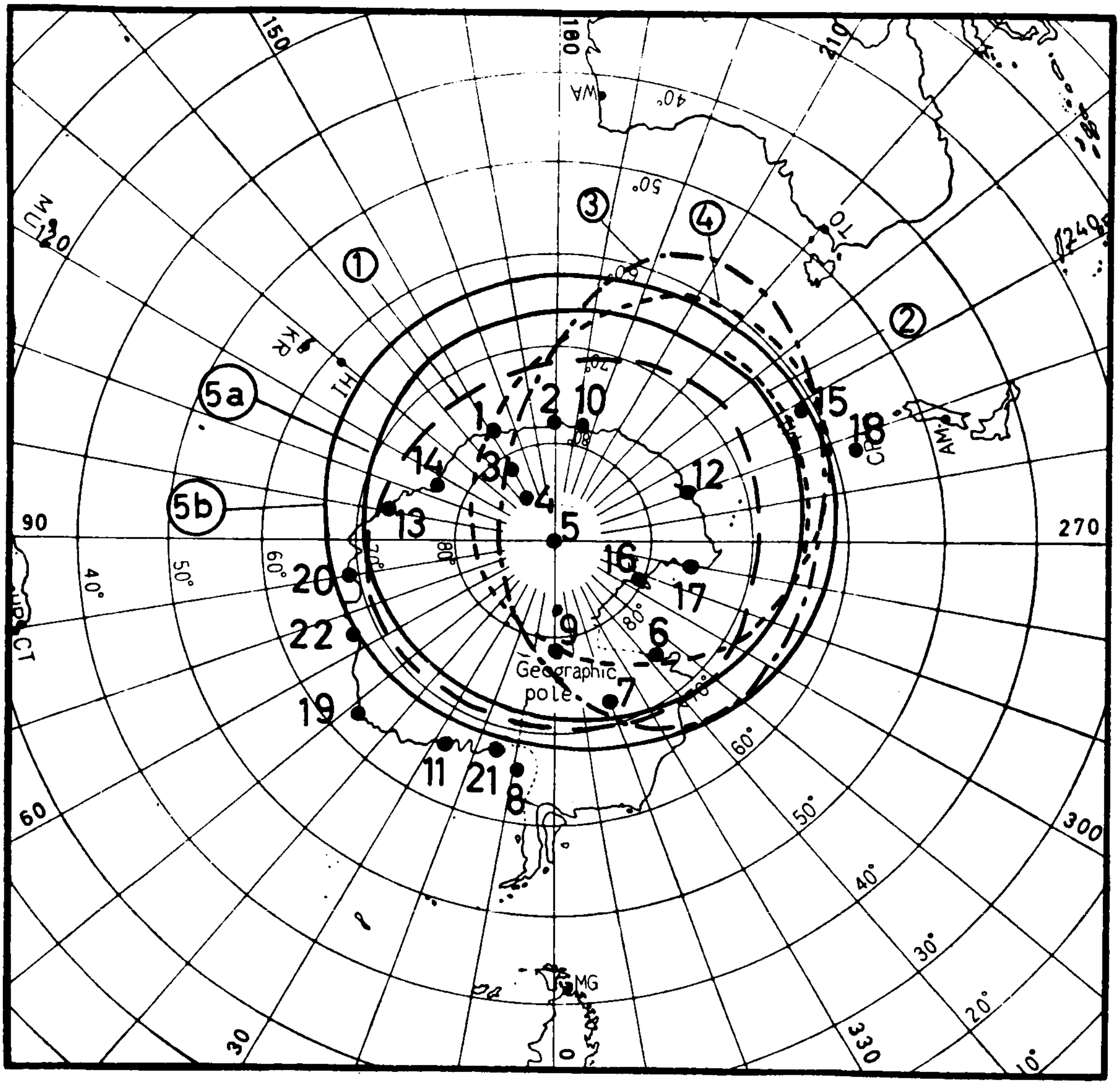

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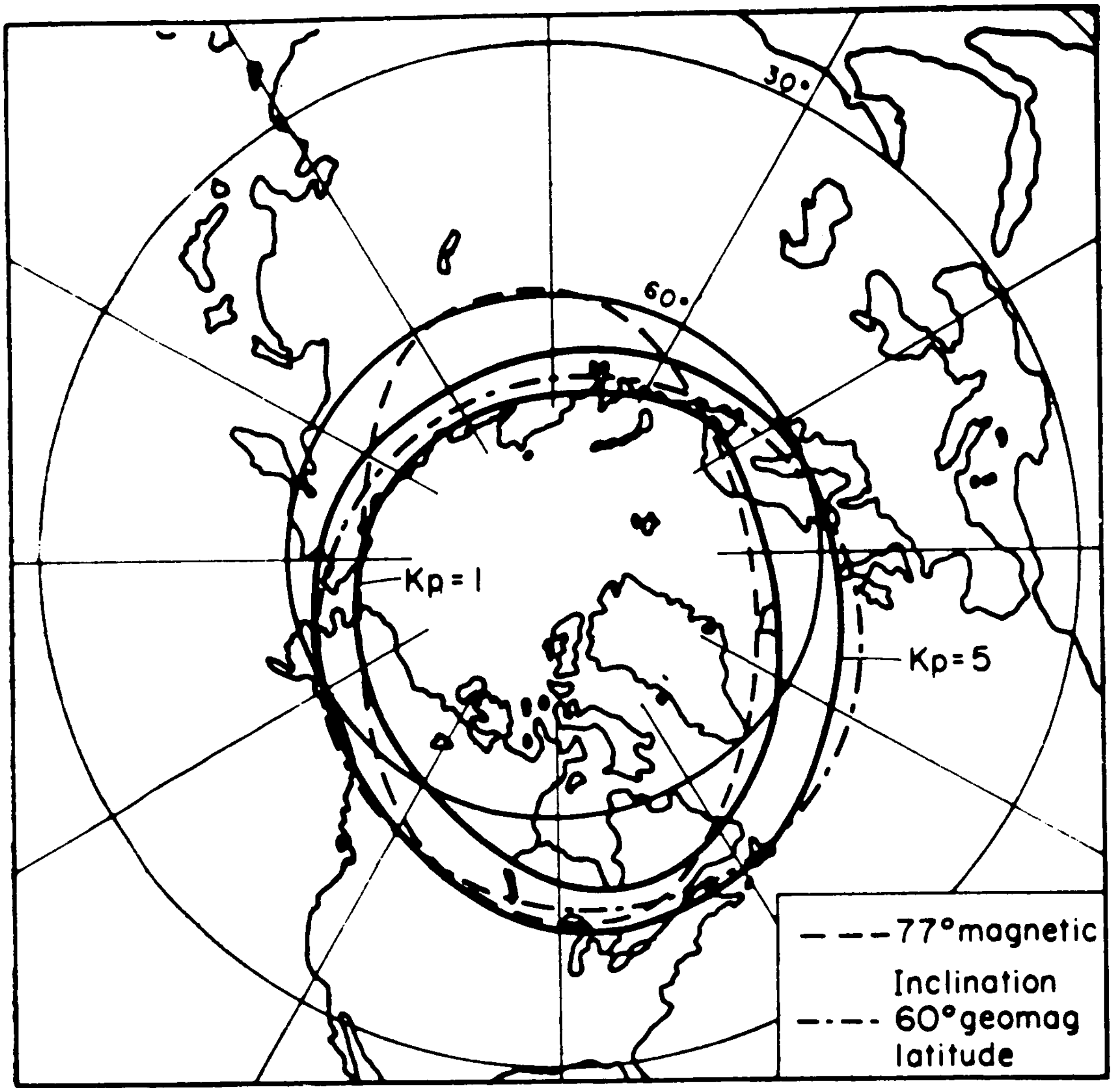


Fig. 2.6–Southern extent of aurora borealis for two different levels of geomagnetic activity (after Gartlein, Gartlein and Sprague, 1960).

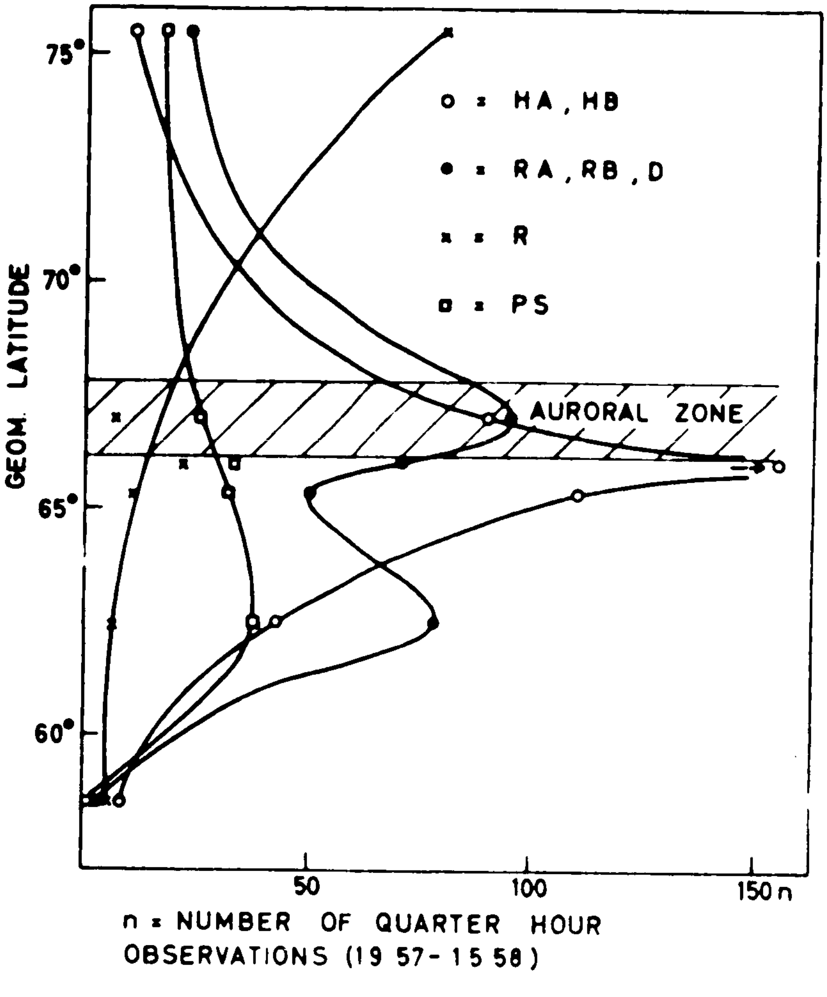
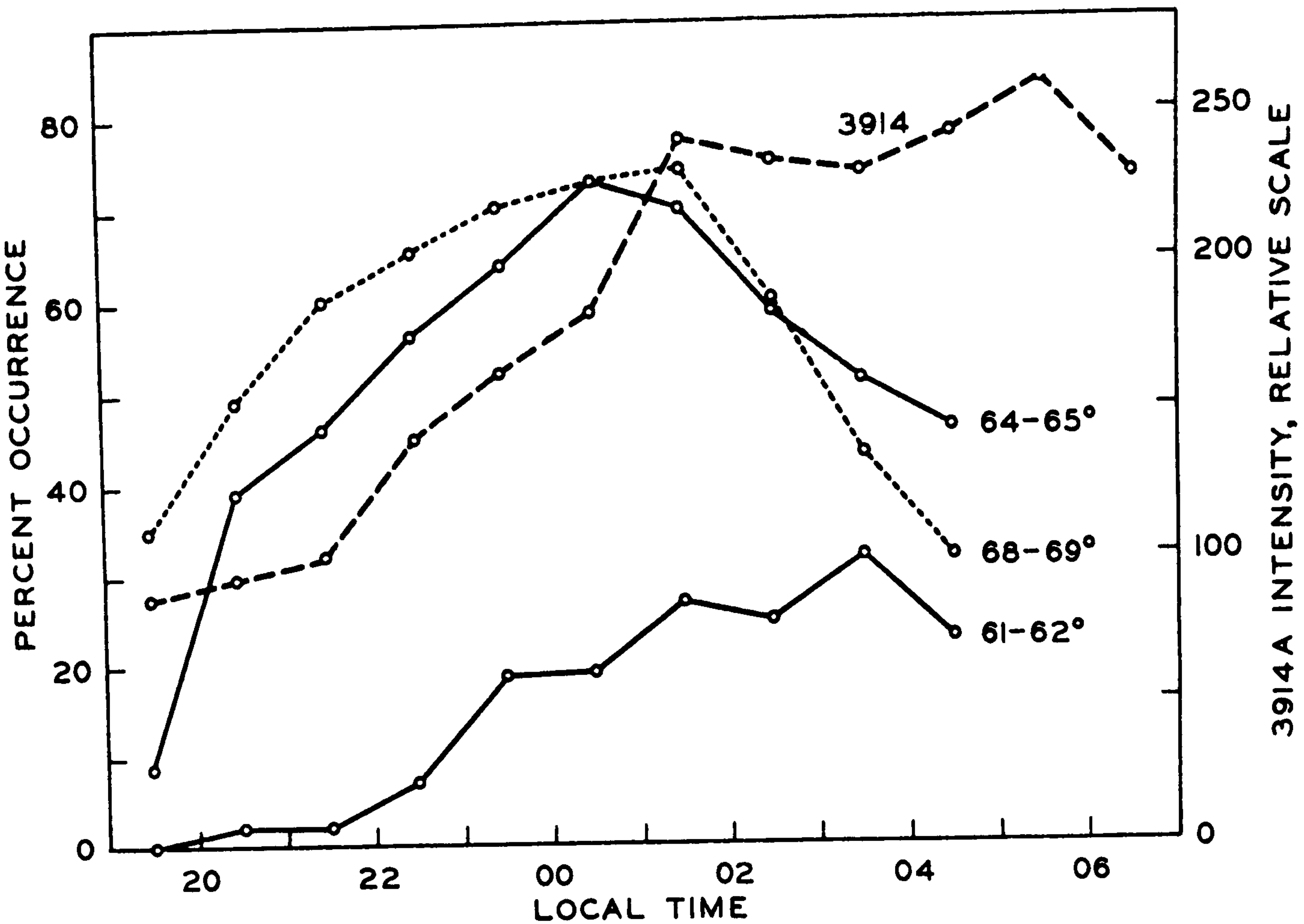


Fig. 2.7–(After Stoffregen, 1962) Approximate latitude distribution for different auroral types.



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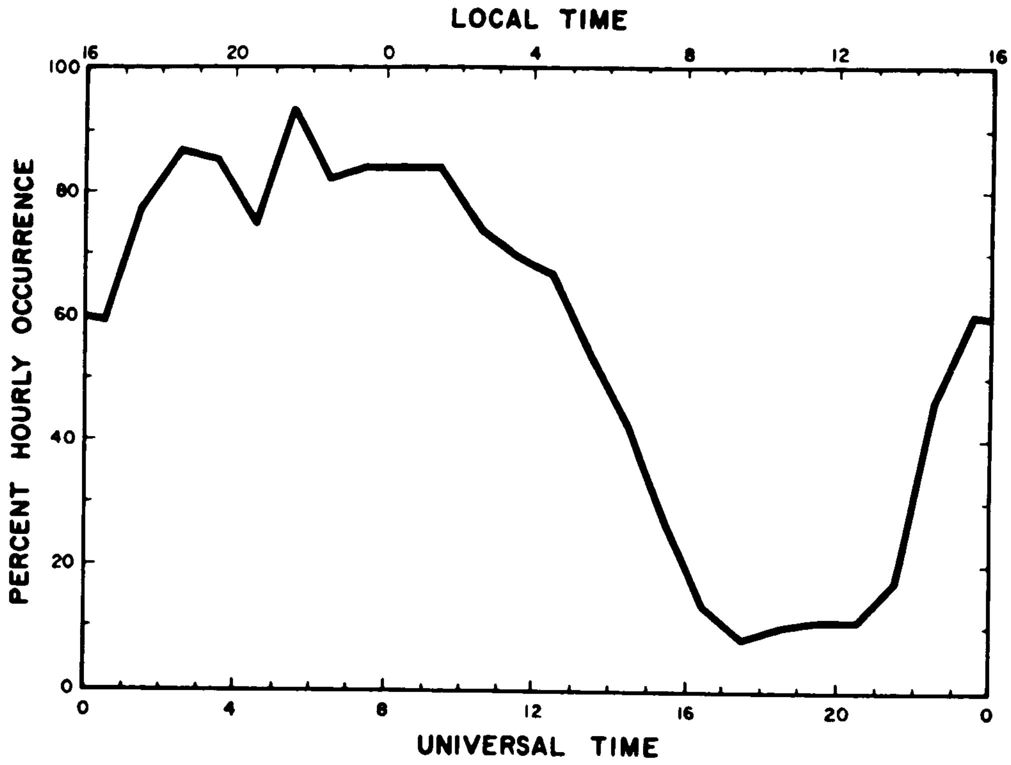


Fig. 2.9–(After Davis and DeWitt, 1963) Diurnal variations of hourly occurrence of visual aurora within 150 km of Byrd Station for all clear, dark hours in May and June 1960.

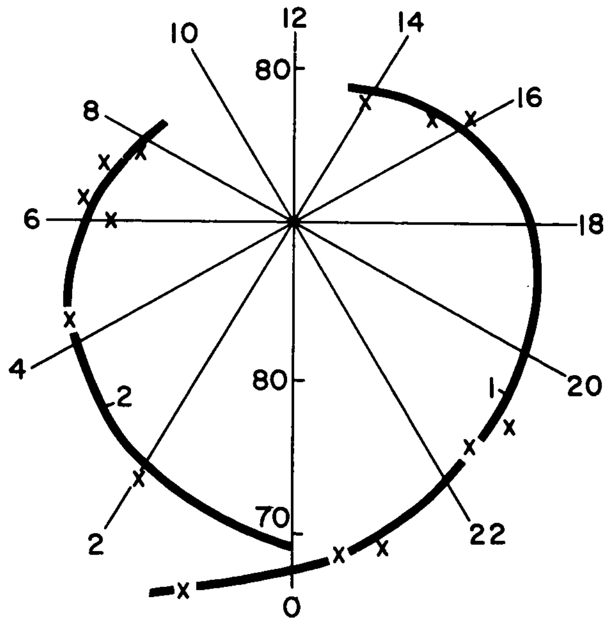


Fig. 2.10—(After Feldstein and Solomatina, 1963) Geomagnetic times of maximum frequency of auroral occurrence in the zenith as function of geomagnetic latitude corrected for the non-dipole part of the geomagnetic field.

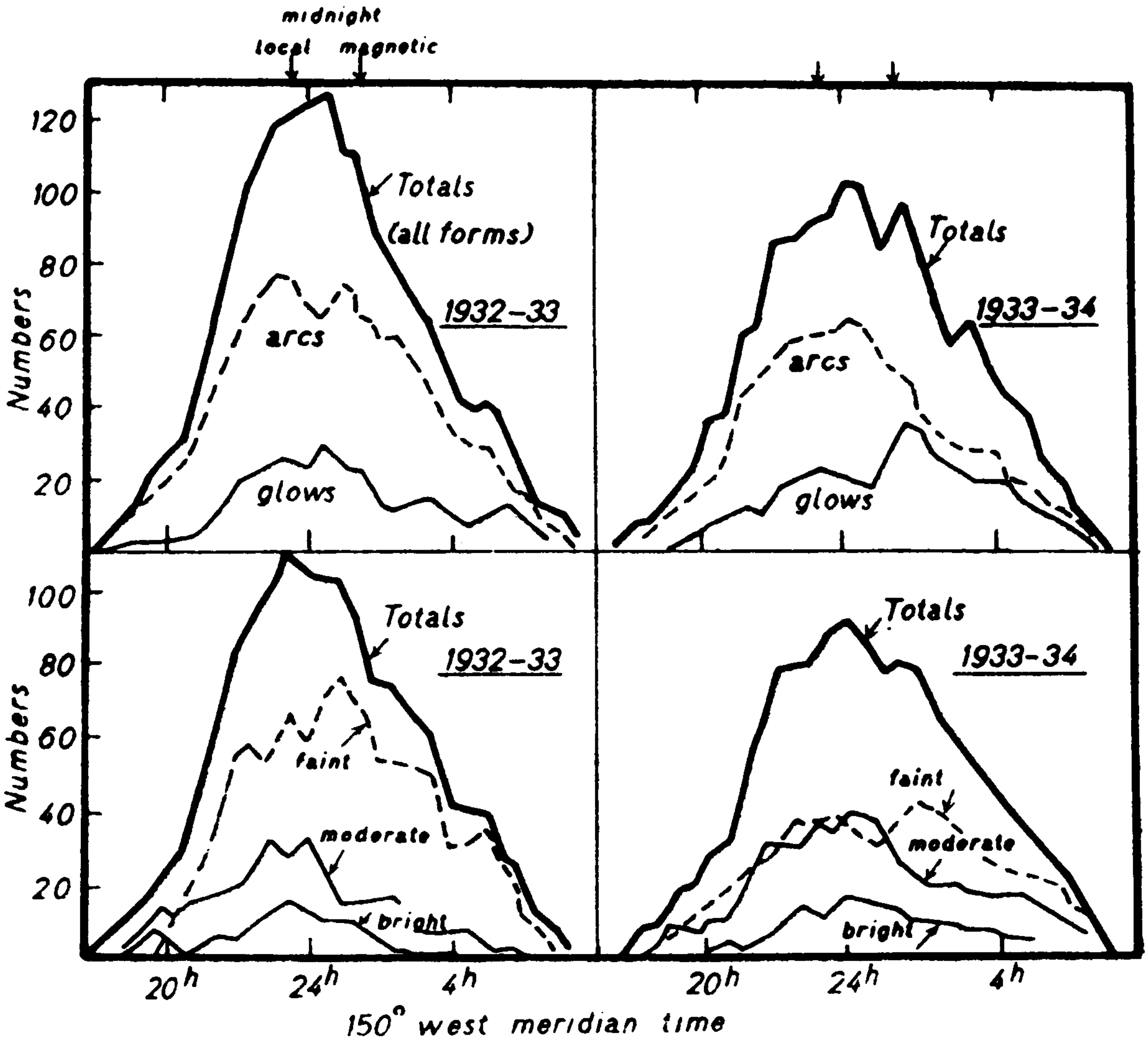


Fig. 2.11-(After Fuller, 1935) Diurnal variation of different auroral forms and of auroras of different intensities at College, Alaska.

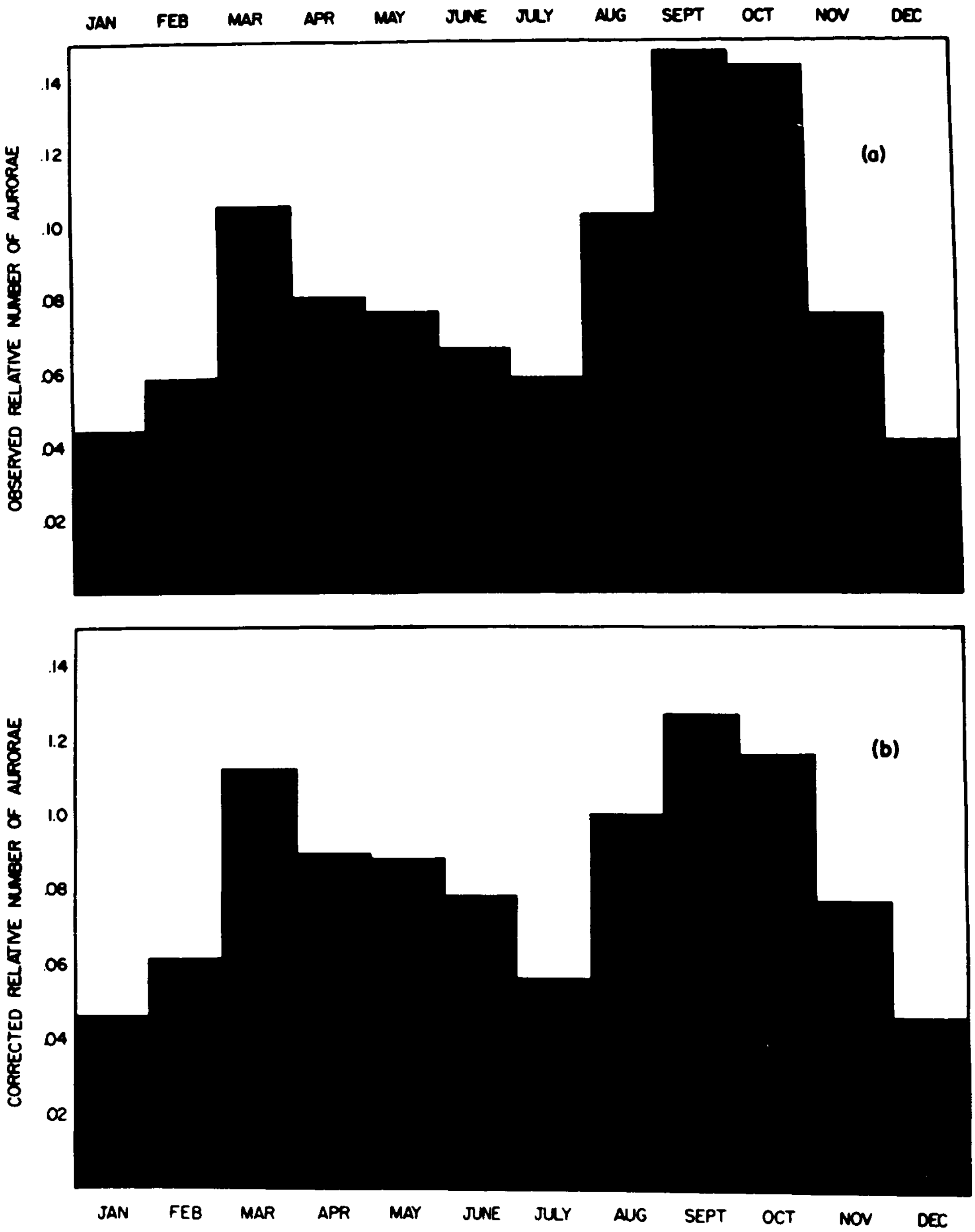


Fig. 2.12–(After Meinel et al., 1954) (a) Fraction of all auroras observed in each calendar month at Yerkes Observatory; (b) monthly frequency distribution corrected for cloudiness and number of dark hours in each month.

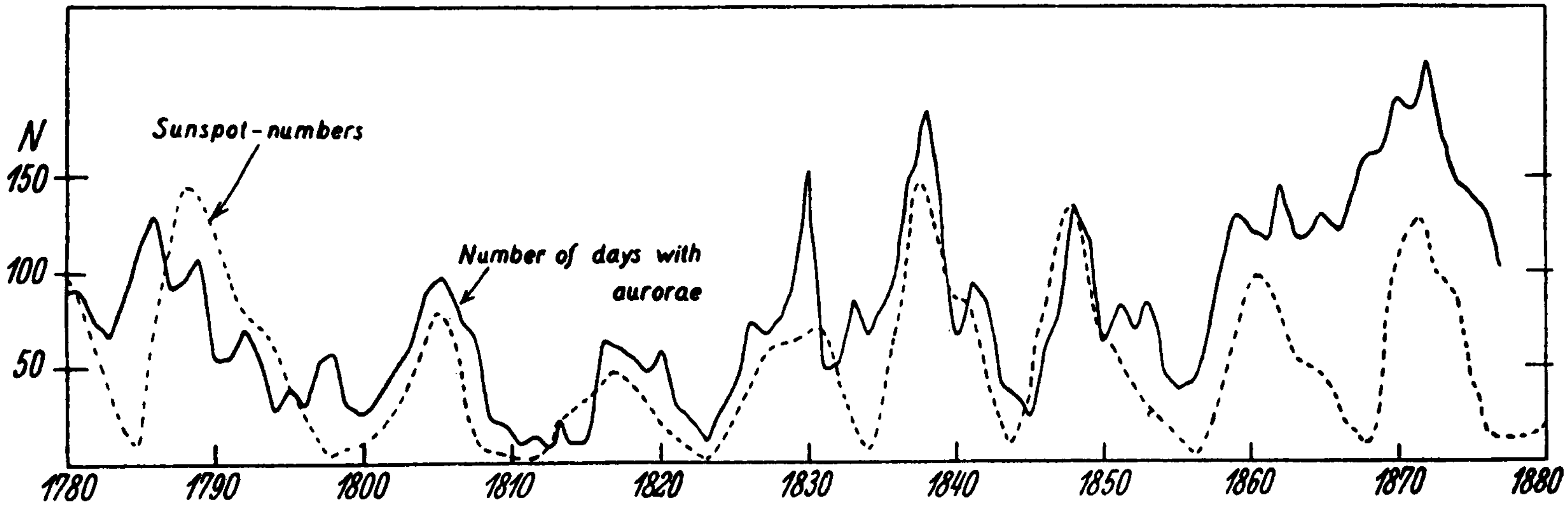


Fig. 2.13-(After Tromholt, 1902) Variation of the number of auroral days, N, in each year, observed in Norway, and the sun-spot number between 1761 and 1877.

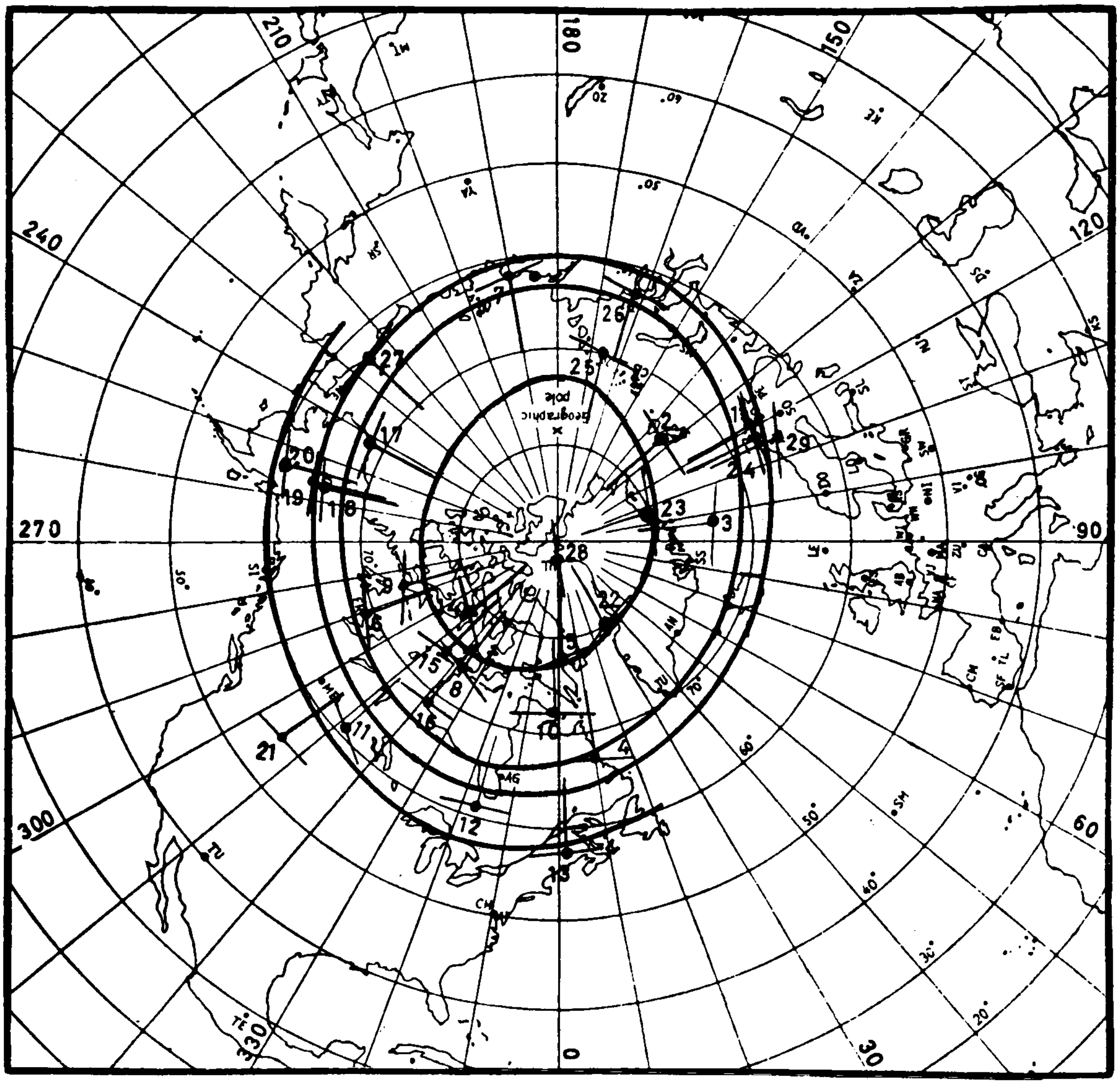


Fig. 2.14—Directions of quiet auroral arcs in the northern hemisphere. 1. Haldde and Bossekop; 2. Cap Thordsen; 3. Jan Mayen; 4. Nain; 5. Kingua Fjord; 6. Fort Rae; 7. Sagastyr (the data for points 1-7 are after Vegard and Krogness, 1920); 8. Chesterfield; 9. Coppermine; 10. Cape Hope's Advance; 11. Saskatoon; 12. Coral Rapids; 13. Aroostook; 14. Gjöahavn (the data for points 8-14 are taken from Currie and Jones, 1941; the dotted lines at Chesterfield and Coppermine refer to all types of aurora); 15. Baker Lake; 16. Churchill; 17. Barrow; 18. Fort Yukon; 19. College; 20. Farewell; 21. Choteau (the data for points 15-21 are after Davis, 1961; the values are averages for the hour around geomagnetic midnight); 22. Godhavn (the data are after Lassen, 1959, and refer to the early morning hours); 23. the region of Micardbu (approximate data after Störmer, 1944); 24. Tromsö (the data are after Harang, 1945, and refer to geomagnetic midnight); 25. Wiese; 26. Dixon; 27. Cape Schmidt (data for points 25-27 are after Feldstein, 1960, and refer to local midnight); 28. Thule (data of Harang, taken from Störmer, 1955); 29. Kiruna (refers to geomagnetic midnight). The map has a geomagnetic coordinate system.

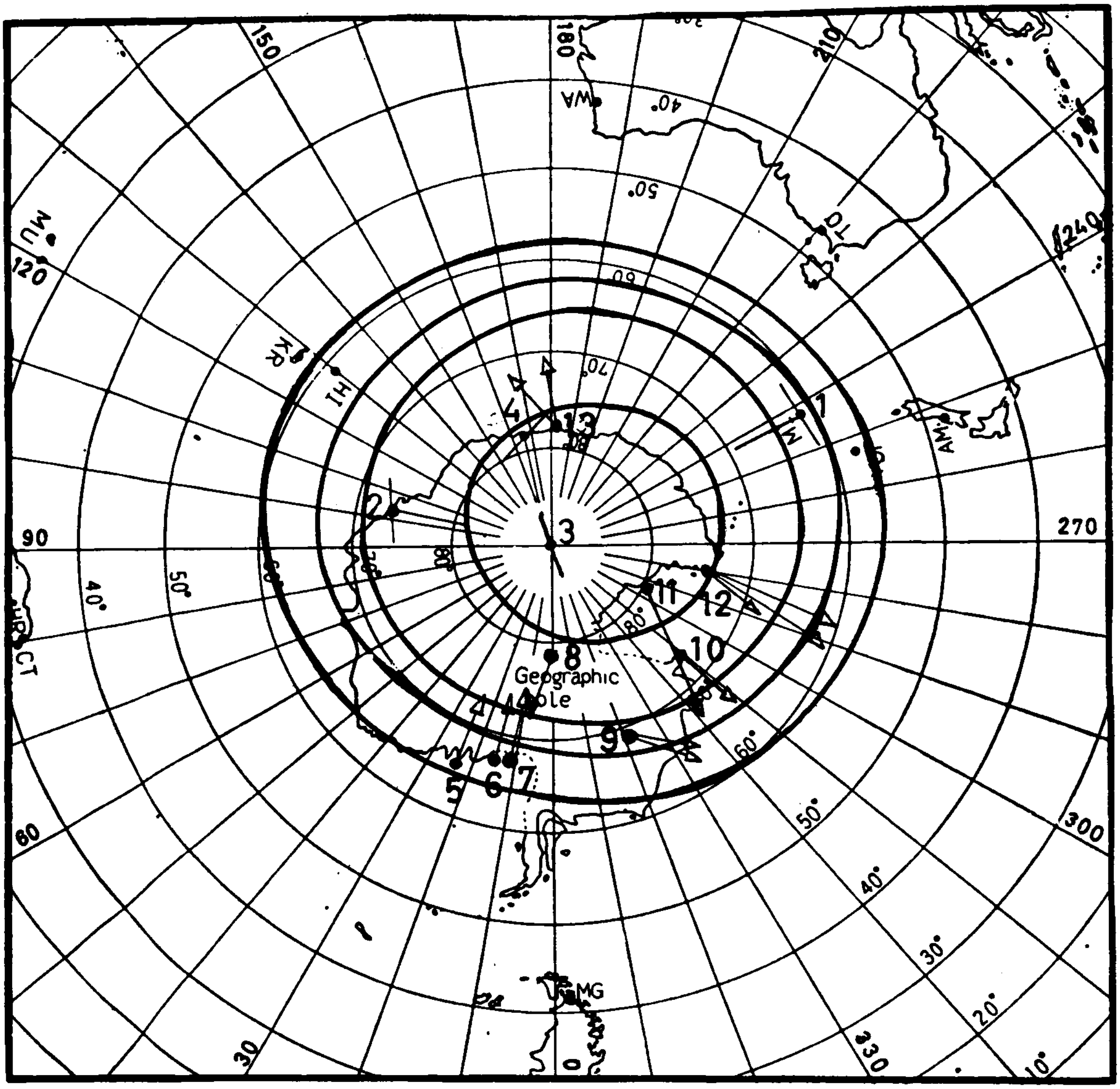


Fig. 2.15-Directions of quiet auroral arcs and sighting directions to the highest points of quiet arcs and bands (arrows) in the southern hemisphere. 1. Macquarie Island; 2. Mawson (data taken from Bond and Jacka, 1960); 3. Vastok; 4. Oasis (the data, after Feldstein, 1960, refer to local midnight); 5. Halley Bay; 6. Shackleton (data from Evans and Thomas, 1959); 7. Ellsworth; 8. South Pole; 9. Byrd; 10. Little America; 11. Scott Base (the long arrows at points 11 and 12 are after Hatherton and Thomas, 1959); 12. Hallett (short arrow); 13. Wilkes (the data for points 7-13 are from Gartlein et al., 1960, the two arrows at points 9 and 13 show the average directions for the two years 1957 and 1958, the 1957 arrow being the one nearest the meridian at both points); the map has a geomagnetic coordinate system.

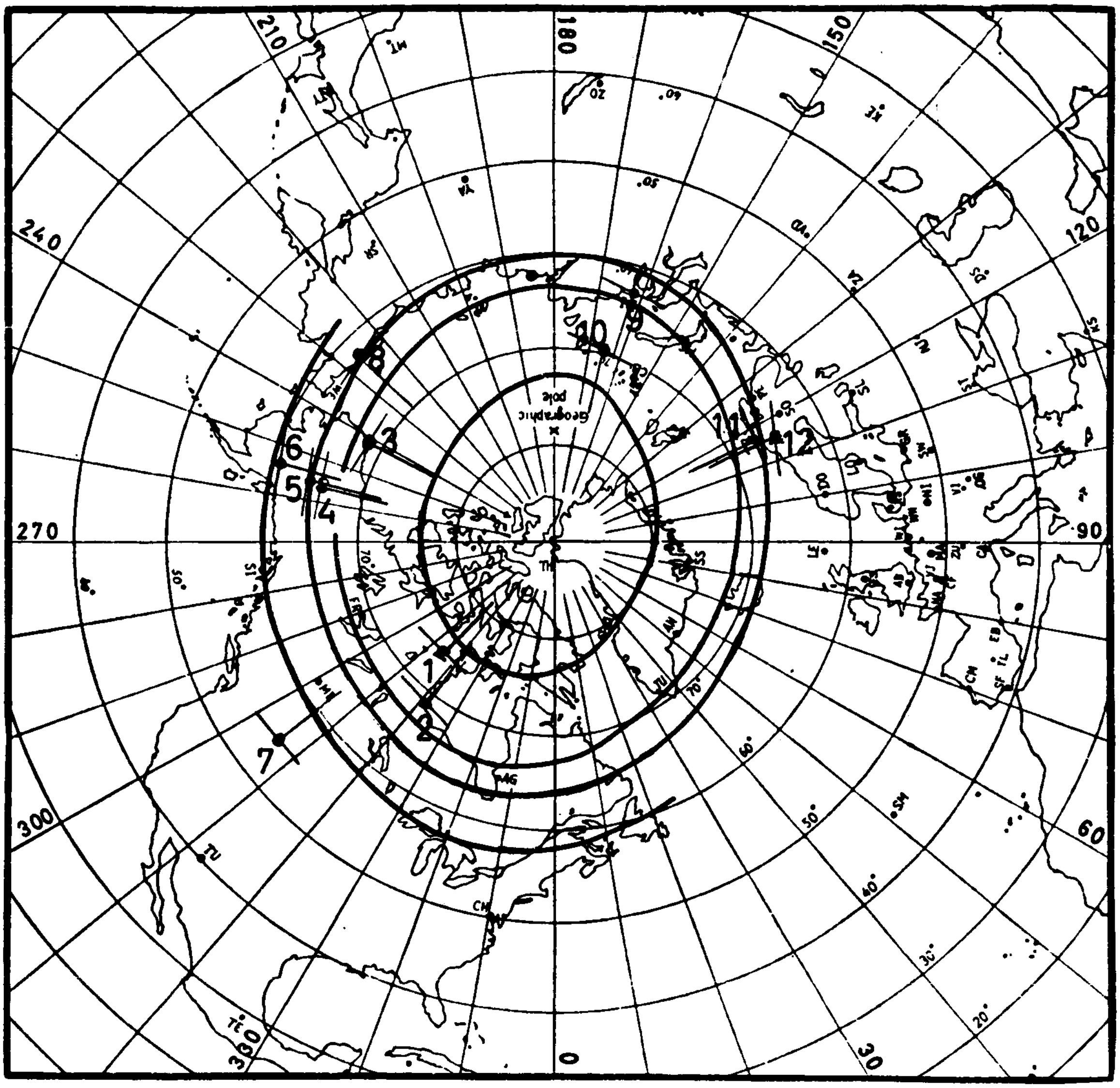


Fig. 2.16—Directions of quiet auroral arcs and bands at local midnight in the northern hemisphere. 1. Baker Lake; 2. Churchill; 3. Barrow; 4. Fort Yukon; 5. College; 6. Farewell; 7. Choteau (data for points 1-7 taken from Davis, 1961); 8. Cape Schmidt; 9. Dixon; 10. Wiese (data taken from Feldstein, 1960); 11. Tromsö (after Harang, 1945); 12. Kiruna. The map has a geomagnetic coordinate system.

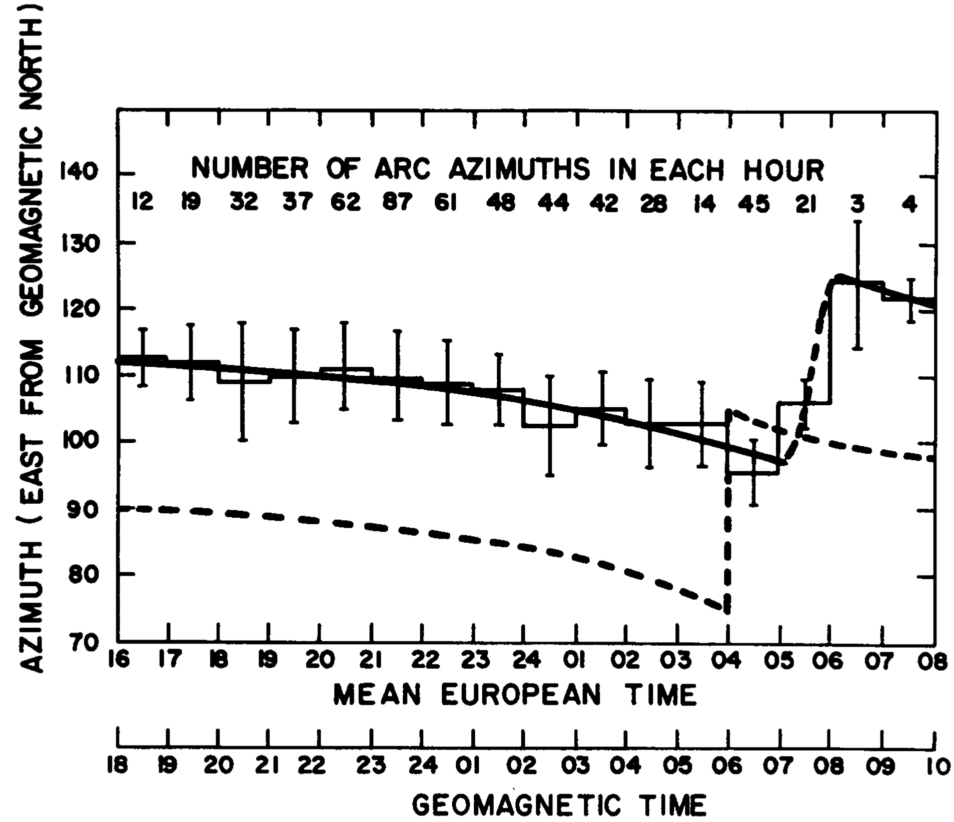


Fig. 2.17–Observed directions of quiet auroral arcs at Kiruna as function of MET and of approximate geomagnetic time. For each hour the average direction and the standard deviation are given. The lower, dashed curve is Alfvén's theoretical diurnal variation curve (see Alfvén, 1950).

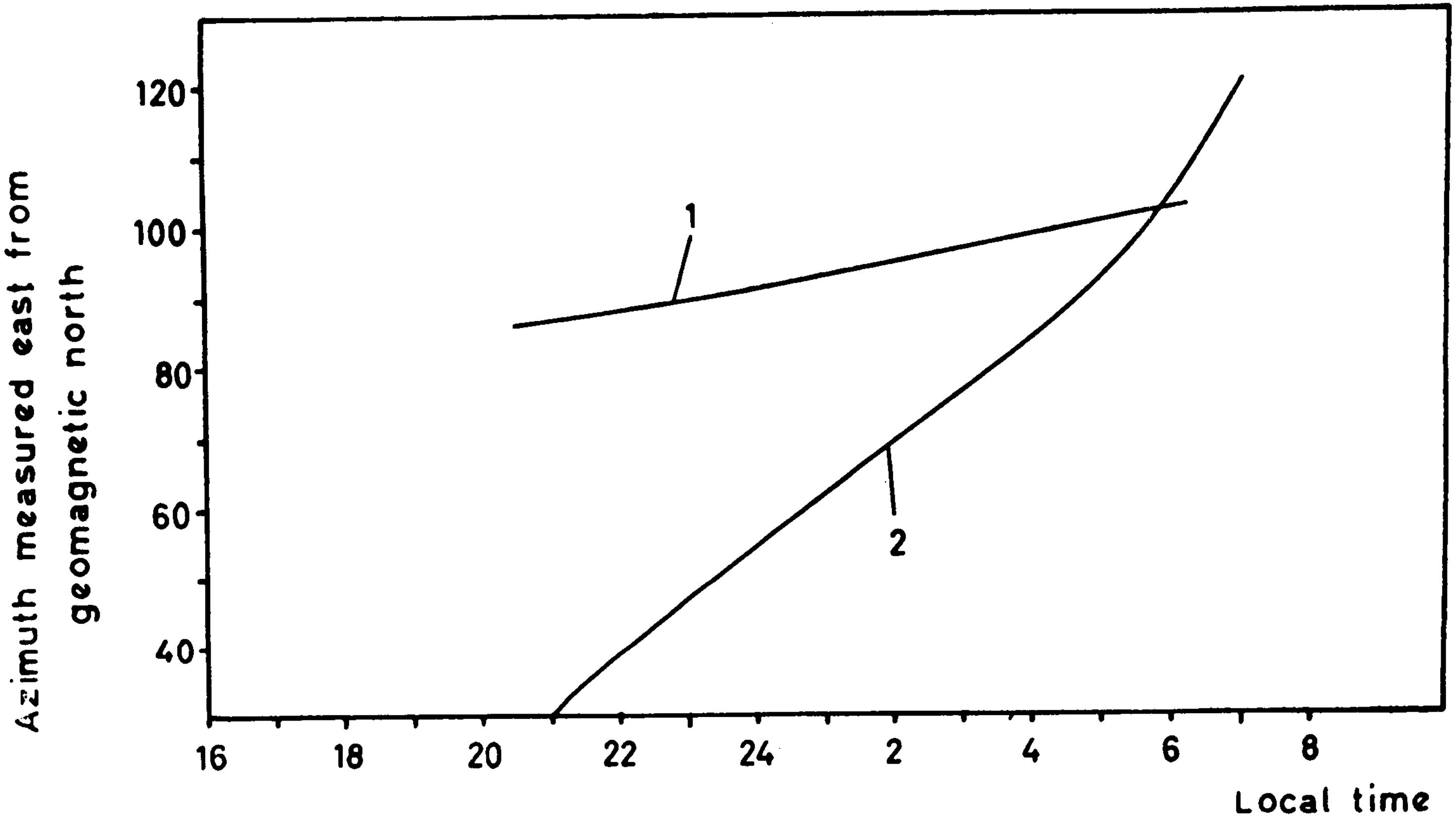


Fig. 2.19–Observed (smoothed) diurnal variation curves for the orientation of quiet auroral arcs in the southern hemisphere. 1. Halley Bay (geom. lat. 66°S; outside the auroral zone) (after Evans and Thomas, 1959); 2. Oasis (geom. lat. 78°S; far inside the auroral zone) (after Feldstein, 1960).

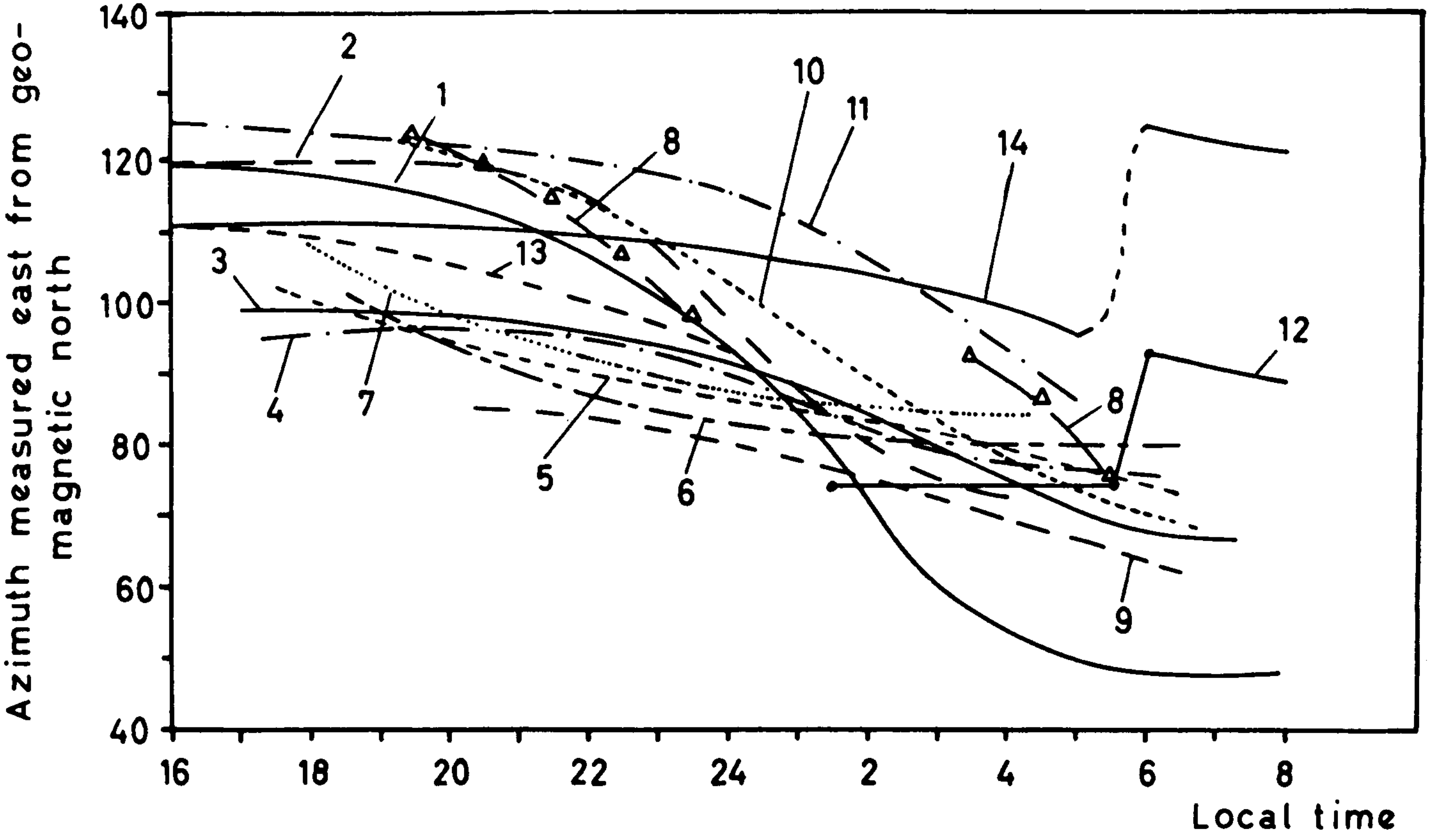


Fig. 2.18–Observed (smoothed) diurnal variation curves for the orientation of quiet auroral arcs and bands in and near the northern auroral zone. 1. Baker Lake (geom. lat. 74°); 2. Churchill (geom. lat. 69°); 3. Barrow (geom. lat. 69°); 4. Fort Yukon (geom. lat. 67°); 5. College (geom. lat. 65°); 6. Farewell (geom. lat. 61°); 7. Choteau (geom. lat. 56°) (curves 1-7 are after Davis, 1962b); 8. Dixon (geom. lat. 63°) (after Starkow and Feldstein, 1960); 12. Godhavn (geom. lat. 80°) (after Lassen, 1959); 13. Tromsö (geom. lat. 67°) (after Harang, 1945); 14. Kiruna (geom. lat. 65°).

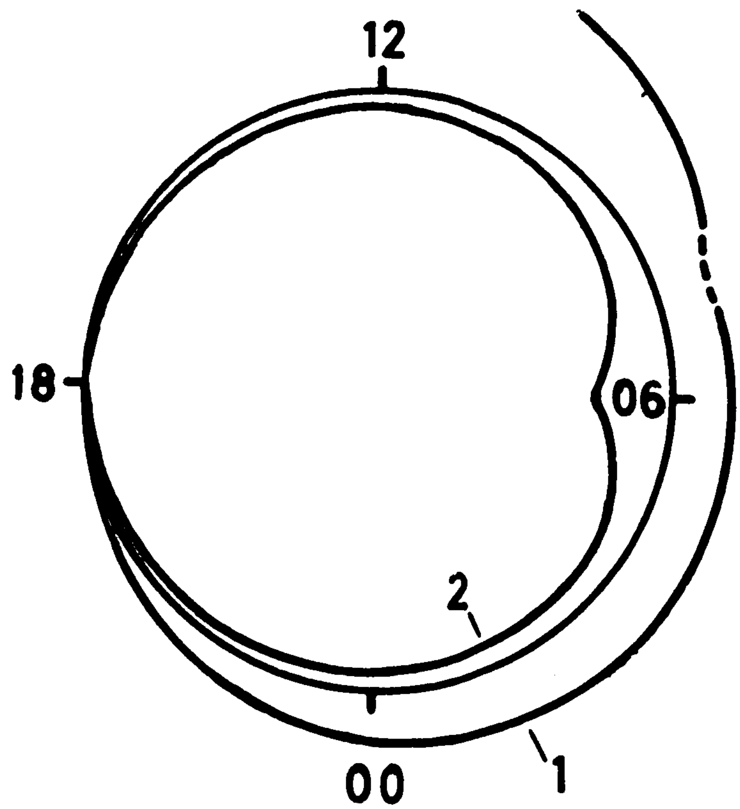


Fig. 2.21–Curve 1 is the auroral zone corresponding to Alfvén's I curve, evaluated from the Kiruna curve of Fig. 17 for diurnal variation in the orientation of quiet auroral arcs. It is corrected for the non-dipole part of the geomagnetic field. Curve 2 is Alfvén's theoretical I curve (see Alfvén, 1950).

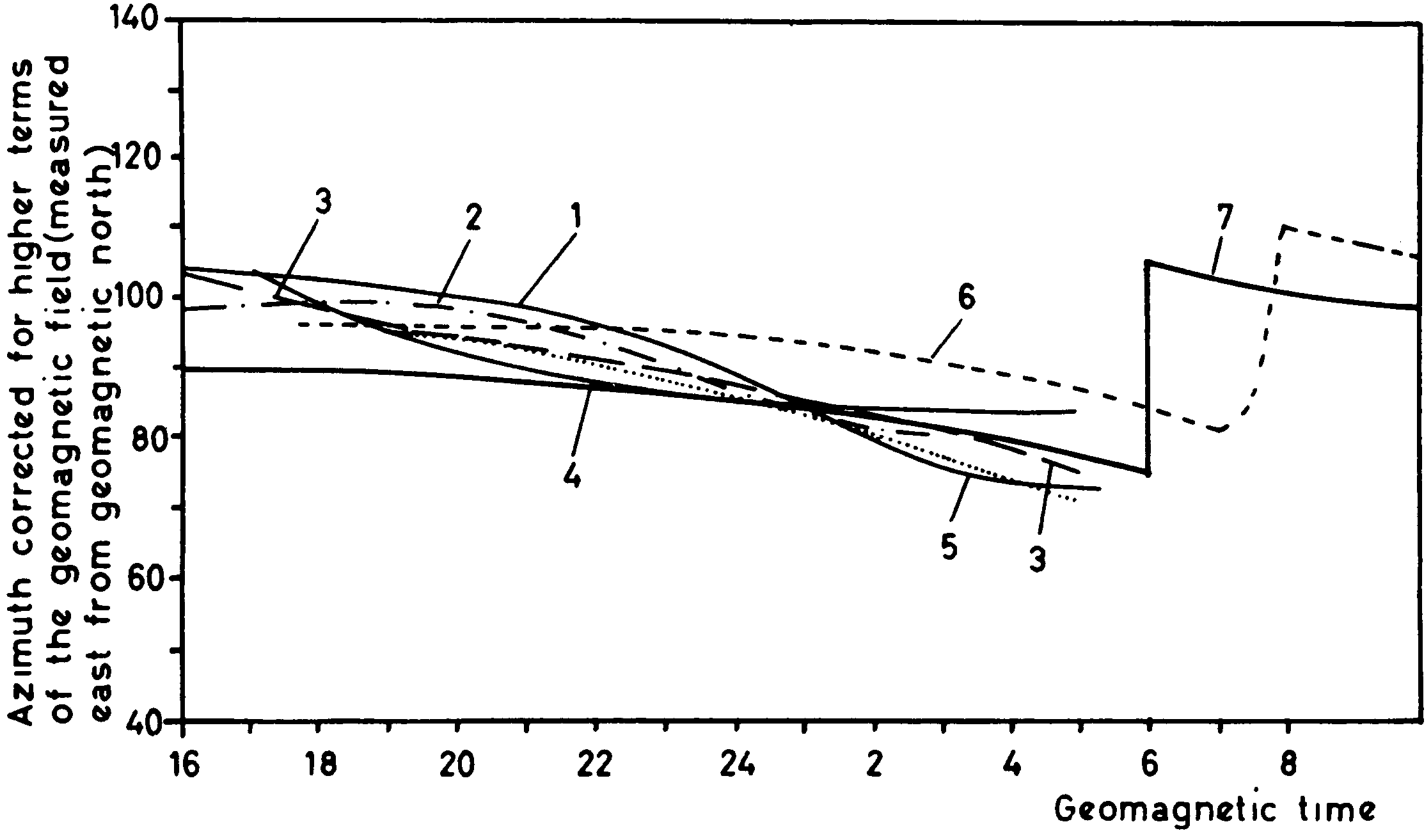


Fig. 2.20—Observed diurnal variation curves (smoothed) for the direction of quiet arcs, corrected for the non-dipole part of the geomagnetic field, given as a function of geomagnetic time for a number of stations situated in or near the northern auroral zone. 1. Barrow (geom. lat. 69°); 2. Fort Yukon (geom. lat. 67°); 3. College (geom. lat. 65°); 4. Farewell (geom. lat. 61°) (curves 1-4 are based on data taken from Davis, 1961); 5. Cape Schmidt (geom. lat. 63°) (based on a curve presented by Feldstein, 1960); 6. Kiruna (geom. lat. 65°); 7. Alfvén's theoretical diurnal variation curve (cf. e.g. Alfvén, 1950).

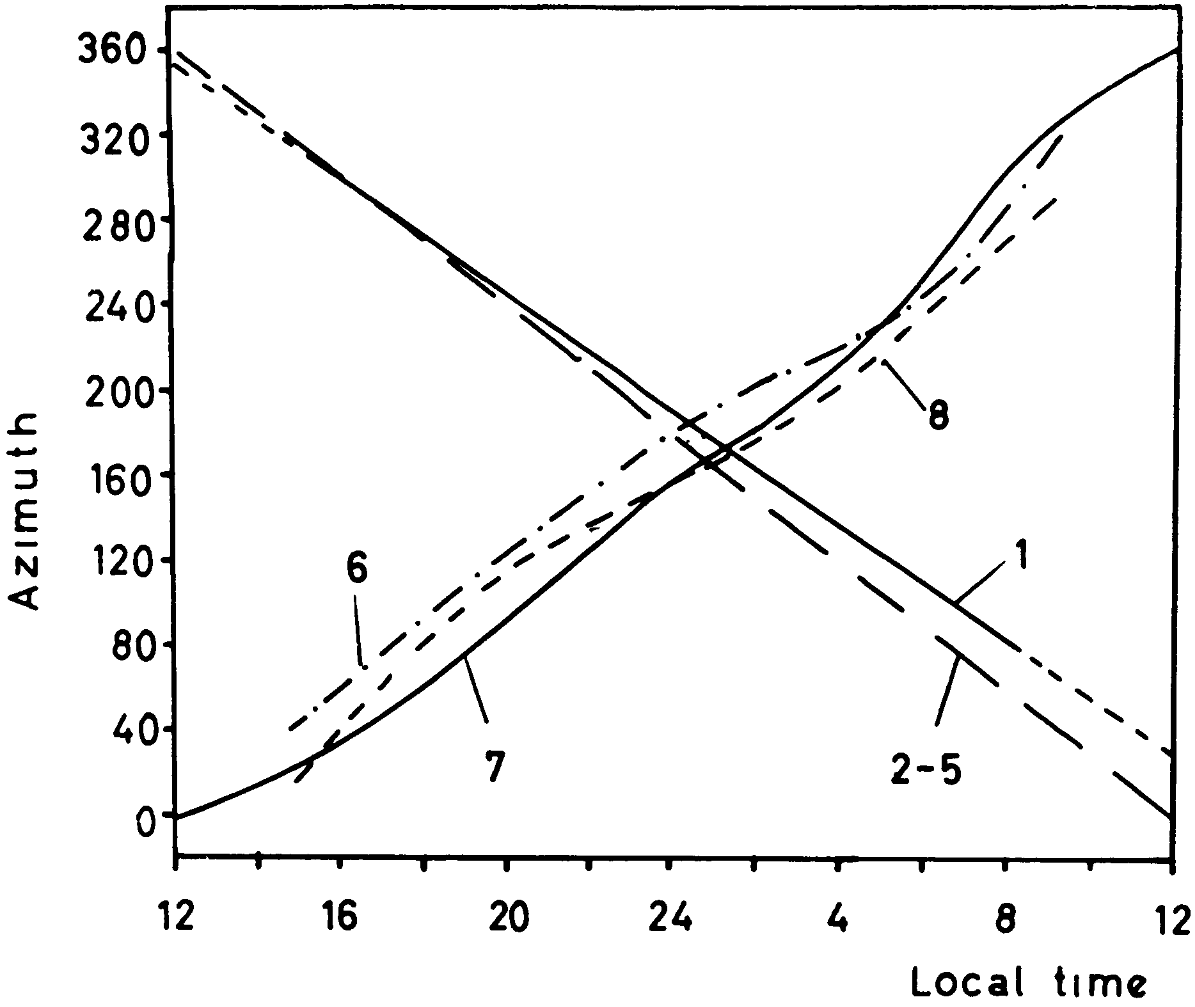


Fig. 2.22–Observed diurnal variation curves (smoothed) for the direction of quiet arcs at stations deep inside the auroral zones. The azimuth is measured towards the east from geographic north for curves 1-5 and from geomagnetic north for curves 6-8. 1. Dumon d'Urville (geom. lat. 76°S) (after Weill, 1958); 2. Wilkes (geom. lat. 77°S); 3. Dumont d'Urville; 4. Scott Base (geom. lat. 79°S); Hallet (geom. lat. 74°S) (the curves for points 2-5 are after Denholm and Bond, 1961); 6. Thule (geom. lat. 88°N); 7. Alert (geom. lat. 86°N); 8. Resolute Bay (geom. lat. 83°N) (the curves for points 6-8 are after Davis, 1961).

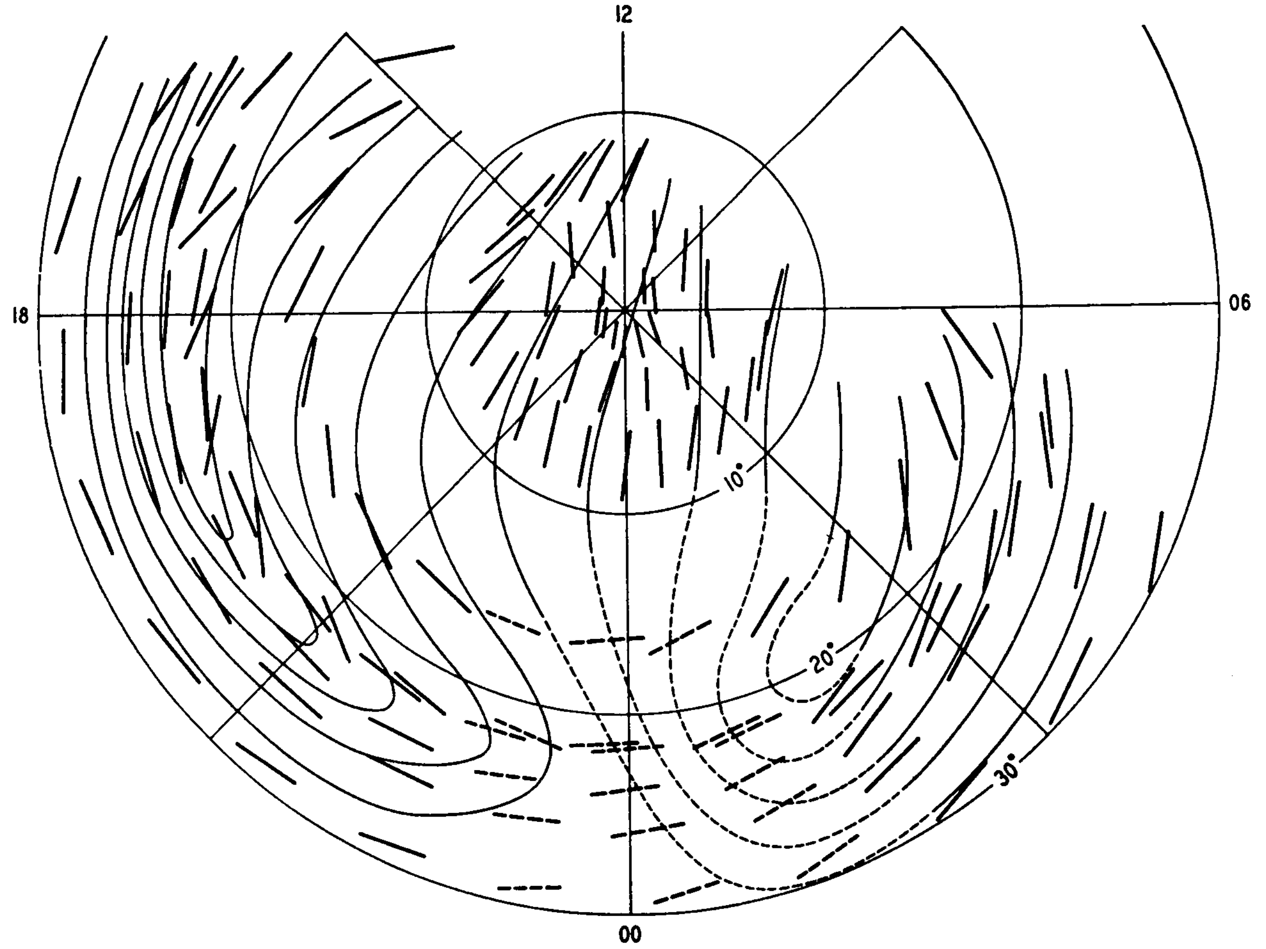


Fig. 2.23–(After Davis, 1962b) The alignment of auroral forms in a polar coordinate system with geomagnetic colatitude and approximate geomagnetic time as polar and azimuthal coordinates. The dashed lines represent the discontinuous post break-up aurora.

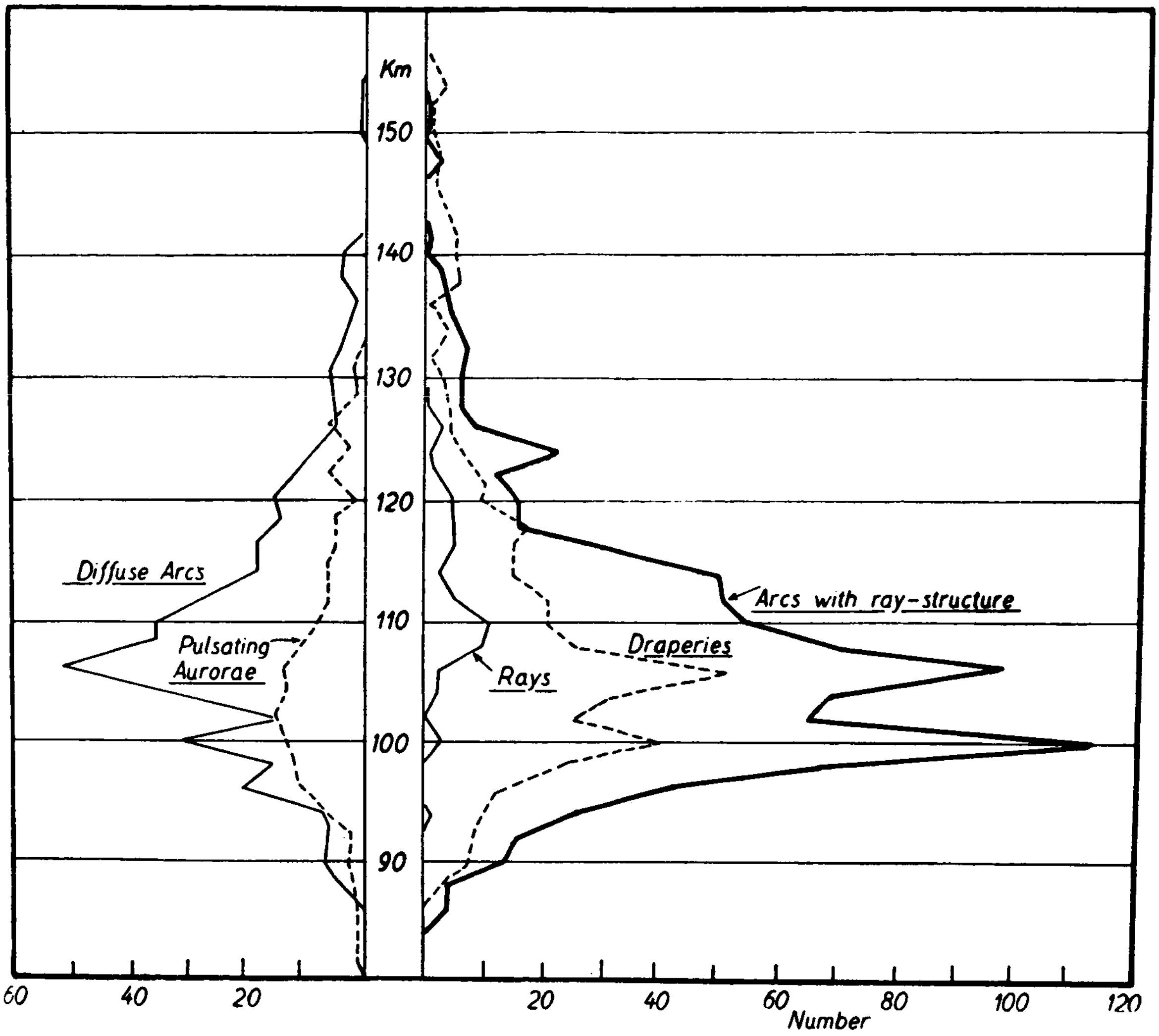


Fig. 2.24-(After Vegard and Krogness, 1920) Distribution of lower limits for different auroral forms.

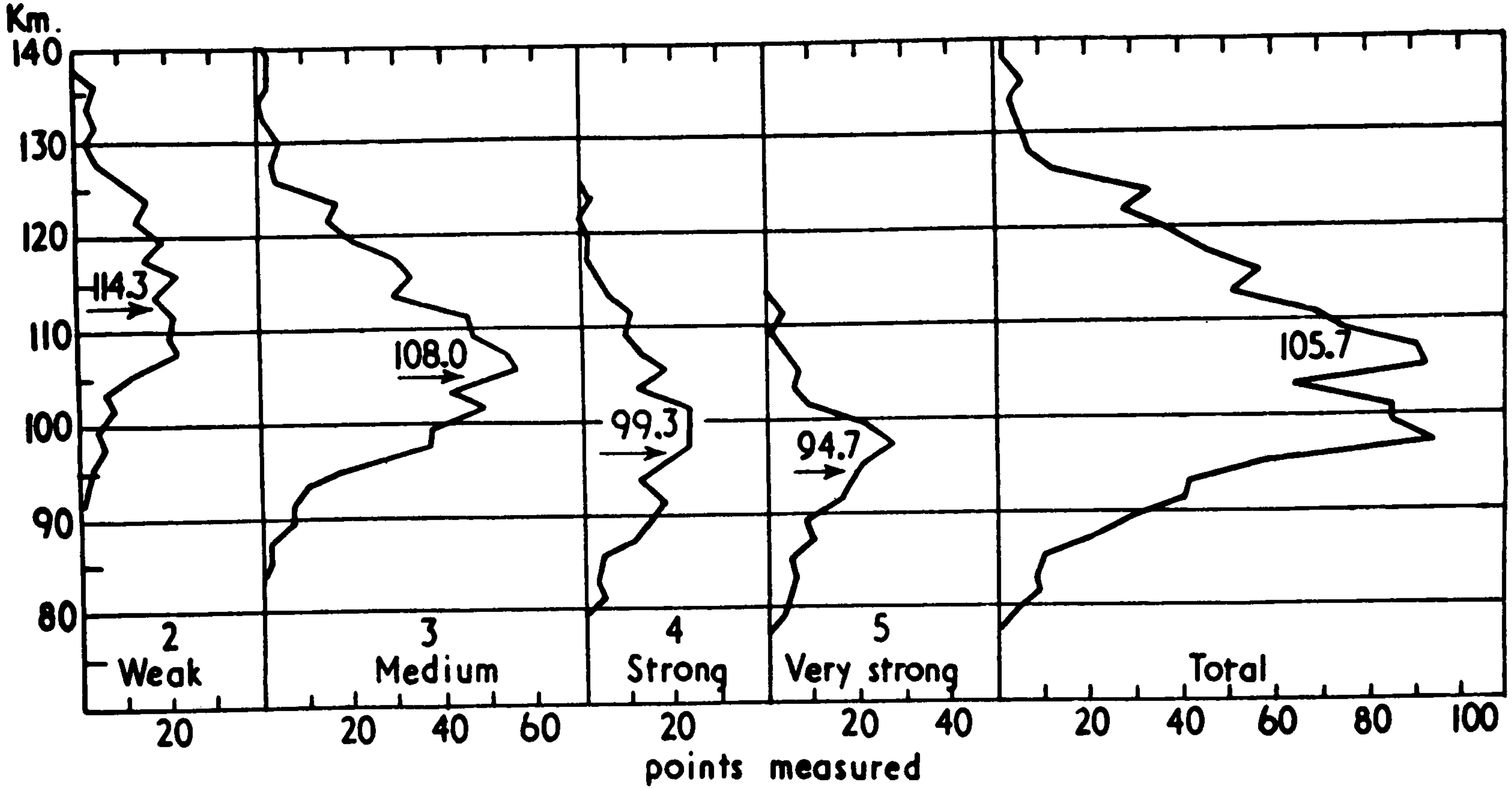


Fig. 2.25-(After Harang, 1944) Lowering of the heights of arcs with increasing intensities, as observed from Tromsö 1929-38.

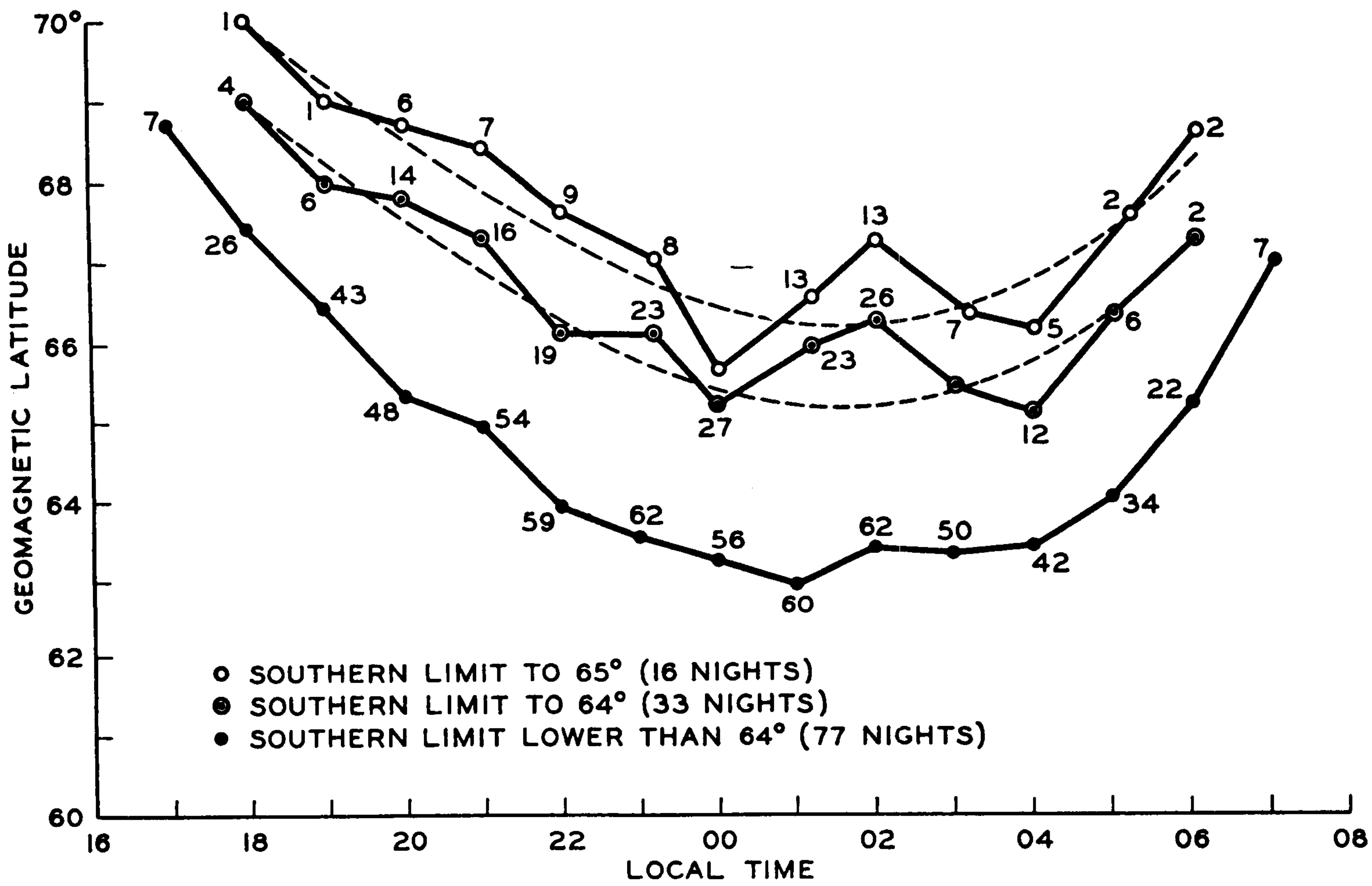


Figure 2.27—(After Davis, 1962a) Diurnal variation of average southern extent for each of three groups of displays extending to geomagnetic latitudes 65°, 64° and beyond 64°. The number beside each point gives the number of displays contributing to that particular mean position.

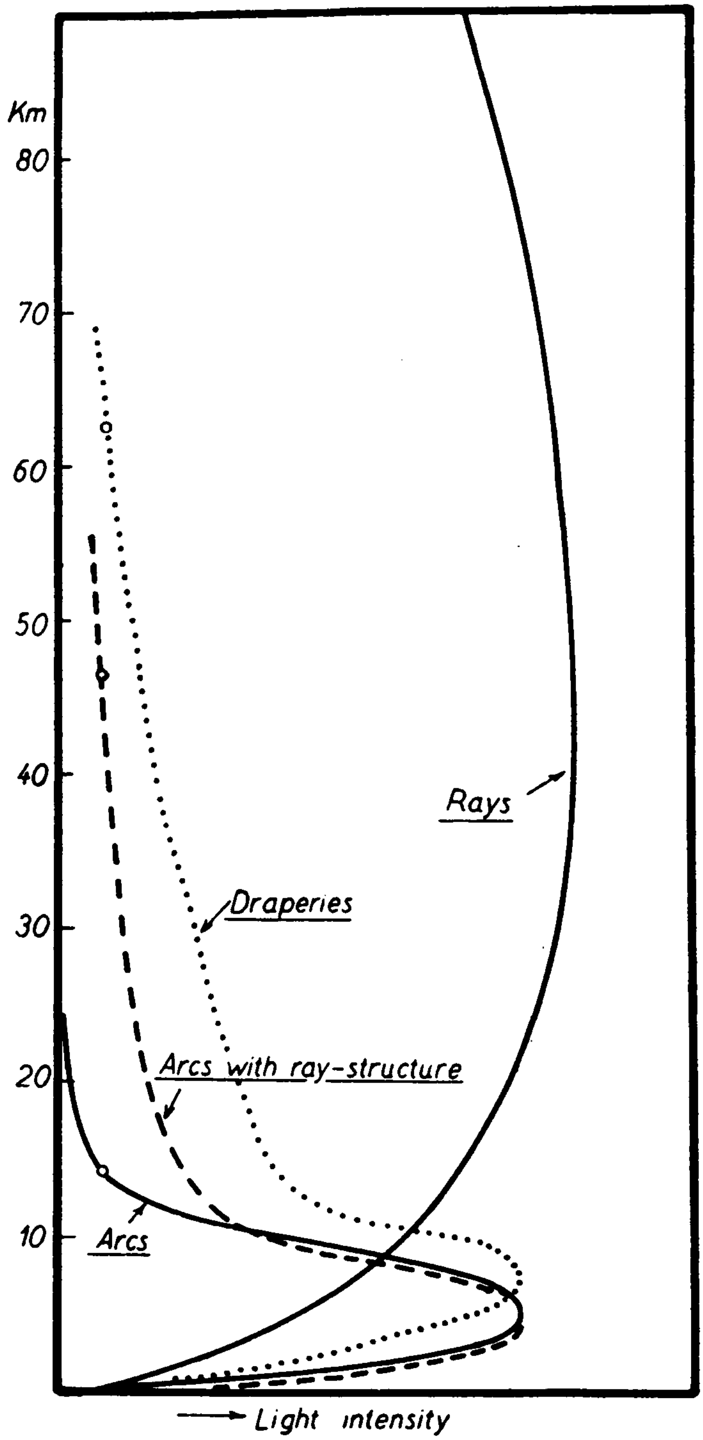


Fig. 2.26–(After Harang, 1951) Distribution of light intensity along different auroral forms.

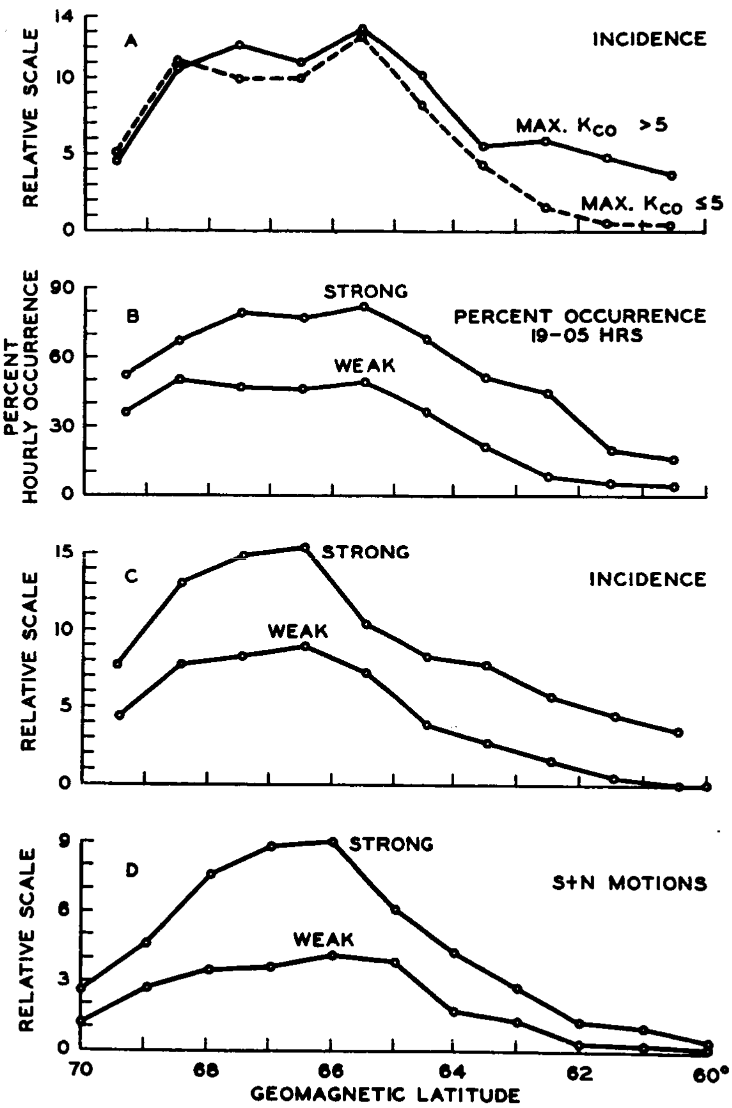


Fig. 2.28–(After Davis, 1962b) Several measures of auroral activity versus latitude for weak and strong displays observed in Alaska in the season 1957-58. (A) Curves of total incidence for 25 displays during which the maximum K-index for College did not exceed 5 (dashed line) and for 25 displays for which it exceeded 5 (solid line). (B) Average percentage hourly occurrence of overhead auroras (local time interval 19-05^h) during 24 strong and weak displays. (C) Total incidence of forms during the 24 strong and 24 weak displays used to draw curves B. (C) Total south and north moving forms observed throughout 31 strong and 30 weak displays.

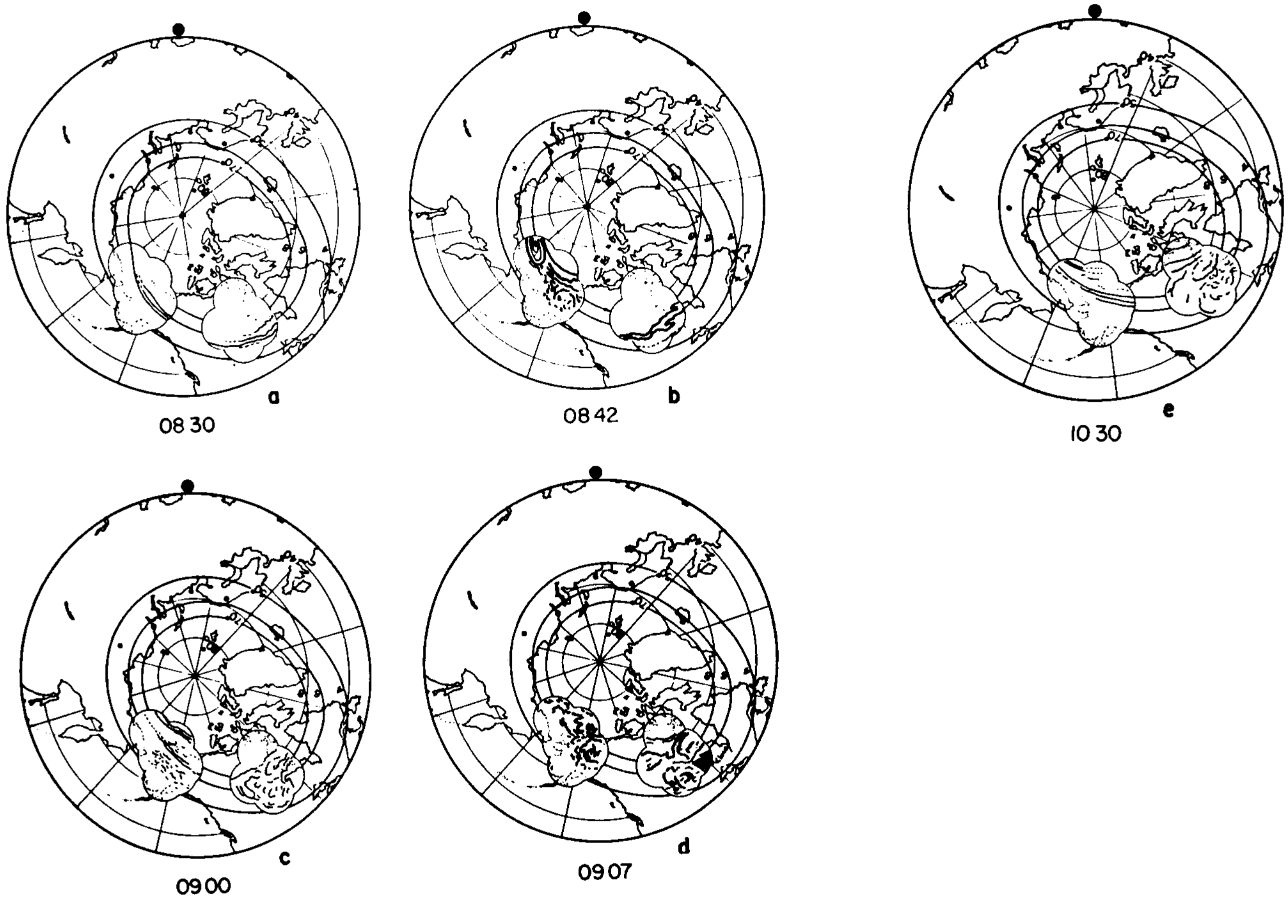


Fig. 2.29–(After Akasofu, 1963) The distribution of the auroras on February 13, 1958. The field of view of each allsky camera station is indicated by a circle of radius 500 km. The dark dot on top of each map shows the direction of the sun. L-curves 4, 6, and 8 are also shown.

3. Correlation with Solar and Geophysical Phenomena

In this section observed statistical relations between visual aurora and solar and geophysical phenomena will be briefly reviewed.

1. Solar Disturbances

Except for the investigations of the variation of the occurrence frequency of aurora with the solar cycle, which have been mentioned in Section 2 (see page 32), detailed investigations of the correlation between visual aurora and solar disturbances seem not to have been made. A large number of studies of relations between solar events and geomagnetic disturbances exist in the literature and are reviewed in Chapter of this book. Since the correlation between occurrence of aurora and planetary magnetic activity is good (cf. below), most of the relevant conclusions reached for magnetic storms are also valid for aurora. The 27-day recurrence tendency seems to be less pronounced for aurora than for magnetic disturbances (Chamberlain, 1961).

2. Geomagnetic Disturbances

That worldwide magnetic disturbances occur at the times when aurora can be observed was discovered in 1741 by Celsius and Hiorter in Uppsala, Sweden (cf. Chapman and Bartels, 1940).

A detailed investigation of the correlation between the occurrence of aurora and the planetary magnetic activity has been made by Bartels and Chapman (1958). It has been known for long to aurora investigators that the start of a magnetic storm in the day almost invariably leads to the occurrence of aurora in auroral zone latitudes in the following night. This is true in subauroral latitudes only when the storm is a strong one – in which cases very little aurora may be seen in the auroral zone (see Section 2).

Over the central polar caps (geomagnetic latitude above 80°) the visual aurora is negatively correlated with the local as well as with the planetary K indices (Davis, 1963). In the region between geomagnetic latitudes 75 and 80° the relationship between auroral occurrence and geomagnetic activity is more complicated and of a transitional nature. Feldstein (1962b) found that auroras are observed in the zenith at Murchison Bay (geomagnetic latitude 75 °N) most frequently when there is a weak magnetic disturbance ($K = 2$-3). When auroras appearing to the south were also taken into account the auroral occurrence frequency increased with the K-index up to high values of it. Morozumi (1963) found positive correlation between auroral occurrence and magnetic disturbance even at 78° geomagnetic latitude (at the South Pole).

There is not only a correlation between the general occurrence of aurora, but a fairly detailed relationship exists between the development of the visual aurora, as seen in auroral zone latitudes, and the development of the associated geomagnetic disturbance. These relations have been studied by Meek (1953, 1954b), Heppner (1954a,b, 1955), Zaborshchikov and Fediakina (1957), Fan (1958), Bless et al. (1959) and Akasofu (1963d).

Heppner (1954b) summarizes his observations at College (geomagn. lat. 64.5° N) in the following way. The magnetic disturbance and simultaneous auroral activity on a large majority of, and perhaps all, nights may be represented by means of two patterns, which apply individually or in combination. This is a consequence of recognizing that magnetic disturbances are made up of individual bay disturbances and that coincident with each bay there is a distinct sequence of auroral activity. The two patterns differ in respect to what happens when the disturbance in the horizontal component of the geomagnetic field changes from being positive to being negative. In the first pattern the aurora undergoes a distinct change in form and in the second it disappears at this time or recedes very far northward. The first pattern is more frequent than the second.

In the early part of the night the aurora is generally far north as seen from College and has quiet forms (arcs and glow). The luminosity advances slowly equatorwards. A positive magnetic bay is generally observed in this period. Close to the moment when a negative bay sets in, the aurora becomes active, moves southward and breaks up (first pattern) or disappears (second pattern). In the first pattern of Heppner the recovery of the horizontal component takes place during the appearance of diffuse and pulsating aurora. In the majority of cases there is a short period following the negative bay in which the horizontal magnetic disturbance component is positive. A homogeneous arc is frequently formed again during this period.

A close correlation between rapid variations in the auroral luminosity and geomagnetic micropulsations has been found by Campbell and Nebel (1959), Campbell (1960 a,b,c), Campbell and Rees (1961) and Berger (1963) (see also Chapter).

3. Earth Currents

The occurrence during the day of induced voltages in long telegraph wires was used by Störmer in his extensive program for paralactic height measurements on aurora with good success for many years as a warning that aurora would occur in the next night. As the electric conductivity of the ground is generally not known with adequate precision it is difficult to relate the details of the induced electrical field and the resulting earth currents to the aurora in individual cases. The correlation of occurrence of the two phenomena is, however, good (cf. e.g. Hessler and Wescott, 1959). Freier (1961) has reported evidence for the accumulation of negative charges at the earth's surface during auroras, corresponding to an influx of negative charges into the upper atmosphere.

4. Radio Aurora

Reflections of radio waves of frequencies well above the critical frequencies of the ionosphere from ionization associated with aurora - radio aurora - were first investigated in 1938 by Harang and Stoffregen (1938, 1940). That radio wave propagation via auroral ionization is possible was, however, discovered earlier in the 1930's by amateur radio operators. After the second world war and particularly during the last ten years radio aurora has been studied by a number of researchers in North America, Britain, Norway, Sweden, Germany, Russia, New Zealand and the Antarctic. For a review of radio aurora with detailed references, see for instance Egeland (1962), Hultqvist and Egeland (1964) and Leadabrand (1964).

The diurnal variation of radio aurora as observed in the auroral zone has an afternoon maximum as well as a night maximum (Fig. 3.1). The seasonal variation in the auroral zone has maxima at the equinoxes. The long term occurrence frequency variation has its maximum about 2 years after the solar activity, as is the case with visual aurora.

Radio aurora is observed in the same general regions as optical aurora. With high power radars auroral type echoes can be recorded very often even in latitudes far from the auroral zones.

The reflection process has been found to take place in a fairly narrow height interval with mean value between 90 and 110 km, i.e. in the same height range as the lower border of visual aurora, by a large number of investigators. Also the motions of radio aurora correlate quite well with those of visible aurora, described in Section 2 (see p.44). Fig. 3.2 shows an example of simultaneous recording of visual and radio aurora. As can be seen, there is a significant but not perfect correlation. The correlation is, however, good only at low elevation angles in a sector centered somewhere around geographic or geomagnetic north, in the northern hemisphere, and south in the southern hemisphere (cf. Fig. 3.3). Even extremely strong aurora overhead does not give any echoes at all.

The mentioned limitations of the regions in which auroral echoes are found is due to the fact that the reflection mechanism is aspect sensitive: reflections occur predominantly from a direction perpendicular to the magnetic field lines at the reflection point. This can be understood if the reflection mechanism is one of weak scattering from small irregularities strongly elongated along the lines of force, as well as if it is a critical reflection from larger magnetic-field-aligned irregularities. Recently it has been suggested that the irregularities may by ion sound waves (Buneman, 1963). The fine structure of the received echoes shows that a large number of reflecting centers are active at the same time.

As radio aurora has been observed for frequencies up to 2850 Mc/s (Groth et al., 1964) it seems most probable that weak scattering from small irregularities in the electron density distribution is the most important process at higher frequencies, whereas critical reflection – i.e. reflection from an electron density so large that the refractive index is zero – may be of importance in the lowermost part of the VHF band. How the irregularities are produced is far from clear. See the above mentioned review papers for more details.

5. Bremsstrahlung X-rays at Balloon Altitudes

In the auroral zone the probability of occurrence of x-rays has been found to be fairly well correlated to large scale magnetic activity. But the detailed correlation between aurora and precipitation of the energetic electrons, which generate bremsstrahlung, is in general quite poor there (cf. Anderson, 1960, 1962; Anderson and Enemark, 1960). It does, however, happen that auroral luminosity and x-ray flux follow each other extremely well (see Fig. 3.4, after Anderson and DeWitt, 1963). This seems to be fairly exceptional in auroral zone latitudes.

In subauroral latitudes strong x-ray events occur almost only during strong magnetic storms, and the correlation between the occurrence of visual aurora and bremsstrahlung at balloon heights is quite good (see the review by Winckler, 1962, for instance).

The balloon observations thus show that the high-energy electrons responsible for the bremsstrahlung production in general do not constitute the high energy tail of the electron spectrum producing the visible aurora in auroral zone latitudes, whereas they usually do in subauroral latitudes. The spectrum of the primary electrons is discussed in some more detail in Section 4.

6. Auroral Absorption.

During aurora and magnetic storms the ionospheric absorption of radio waves recorded by means of riometers most often shows an irregular time structure. Although the period of absorption may last several hours, individual peaks often have durations of only a few minutes. Rates of increase and decrease may be as high as 3-2 db/minute, and the magnitude of the absorption can be 8-10 db at about 30 Mc/s for short periods. The character of the record differs definitely from that seen during SIDs or polar cap absorption events (PCA) (cf. Chapter). This type of absorption is usually called auroral absorption. Thus, the auroral absorption (AA) is defined as all absorption observed when there is no SID or PCA. It is then not surprising that Ansari (1963) has been able to show that AA consists of more than one type of absorption phenomenon, different with regard to the energy spectrum of the ionizing particles. One type, primarily occurring in the pre-breakup phase of aurora, is well correlated with the visual aurora (see also Gustafsson, 1964). It is limited approximately to the luminous forms and its intensity is generally fairly low ($\lesssim$ 1db at about 30 Mc/s). During the break-up of the visual aurora the AA is intensified and is still mostly limited to the luminous forms.

After break-up, and practically only after magnetic midnight at College, strong fairly slowly varying absorption often occurs. It is sometimes associated with faint and diffuse aurora all over the sky, but there is no detailed correlation between light intensity and AA.

Even if there, thus, is a good statistical correlation between auroral absorption and visible aurora, bright coronas may appear without being associated with any measurable amount of absorption (see e.g. Kavadas, 1962). Ansari (1964) reported cases in which the absorption even decreased when an auroral form brightened up.

The auroral absorption has been found to have its maximum average value in a zone located a few latitude degrees further from the pole than the visual aurora (Gorbushina, 1962; Hartz, 1963; Holt, 1963; Basler, 1963).

The height where the auroral absorption takes place is a parameter of great importance for the understanding of the electron reactions in the lowermost ionosphere (see Hultqvist 1963b, 1964). The observation that the effect of sunrise and sunset on AA is much lower than expected on the basis of existing models (see e.g. Hultqvist, 1963a) has been interpreted as indicating that all AA takes place above 90 km (Brown and Barcus, 1963). Such an interpretation is, however, in contradiction with a large body of other experimental data (see Hultqvist, 1963b). Recent extensive multi-frequency riometer measurements (Little et al., 1963) which provide height information for the AA in the interval 35-75 km, have shown that in some 40% of 112 studied cases the height distribution of the absorption per km had its maximum at or below 72 km. In some 10% of the cases the peak was even at or below 60 km.

The multi-frequency riometer technique cannot tell about possible existence of appreciable AA in the E-layer in the presence of AA also below the D-layer, for instance. Analysis of recent satellite measurements of electron precipitation has shown that most of the auroral absorption in general is located between 60 and 90 km (Hultqvist 1964a, b) in good agreement with the riometer measurements mentioned. The satellite data show that AA is due mainly to electrons of energy above 40 kev, whereas the visual aurora is caused by electrons of energies between a few kev and a few ten kev (see the review by Hultqvist 1964c). This is illustrated by Figures 3.5 and 3.6.

Fig. 3.5 shows an estimation of the height distribution of the absorption produced by the primary electrons of a strong visible aurora of International Brightness Coefficient (IBC) between III and IV (curves nos. 1; spectrum of the electrons being that observed by McIlwain, 1960). The absorption due to the bremsstrahlung of those primary electrons (curves 2) and the absorption due to high energy electrons observed in the auroral zone with satallites by Mann et al. (1963) (curves 3). In Fig. 6 the equilibrium electron density profiles produced by the average precipitation fluxes of electrons in the auroral zone, as observed by means of the satellite Alouette (McDiarmid et al., 1963) and Injun 3 (O'Brien, 1964) are shown. For electrons of energy above 40 kev data are available for low ($K_p < 4$) and high ($K_p > 4$) magnetic activity. Curve 1 gives the average distribution for low magnetic activity, while curve 2 gives only an upper limit for the electron density profile when $K_p>4$. Curve 3 finally is due to the average electron flux in the energy range 1-40 kev.

The total absorption values computed from the satellite measured electron fluxes (0.3 db, <1.4 db, and 0.09 db for curves 1, 2, and 3, respectively) for the two ranges of magnetic activity are in quite good accordance with the average absorption during the five most disturbed days and five most quiet days in each month, as observed over several years at College by Basler (1963). For the disturbed days he found a daily average of about 1 db in the summer and between 1 and 2 db in the winter and at equinoxes. This should be compared to the value ~1 db of Fig. 3.6. For the quiet days the daily average observed by Basler was 0.3 db, which is identical to the value obtained from the satellite data.

The bremsstrahlung x-rays are most probably always negligible as compared to the primary electrons for producing AA (Ansari 1963, Hultqvist 1963, 1964, Brown, 1964).

The fluxes of the high-energy electrons causing AA and the low energy electrons producing aurora vary independently of each other. This explains the variable degree of correlation between aurora and AA. One can expect to observe aurora without AA and AA without aurora and all combinations in between. Ansari's (1963) results indicate that the electrons of energy above 40 kev are precipitated mainly after magnetic midnight. In the same way it is also understandable why auroral absorption has its maximum in the morning (Fig. 3.7), while aurora is most frequent in the middle of the night. The good correlation that has been found between AA and bremsstrahlung x-rays (see Brown, 1961, and Pfotzer et al. 1962, for instance) fits also well into the picture.

From the data presented above it seems reasonable to conclude that the absence of a significant influence of sunlight on the auroral absorption cannot be explained by the absorbing ionization being located, as a rule, above 90 km altitude.

For a discussion of other aspects of auroral absorption see e.g. the reviews of Ansari (1963), Holt (1963), and Hultqvist (1963c) and Chapter of this book.

7. Other Ionospheric Disturbances Associated with Aurora

The first phase of an auroral situation in the ionosphere is usually characterized by increasing height of the F2-layer. In about 100-110 km height an auroral sporadic E-layer is formed, which is quite similar to the daytime E-layer but has greater vertical extension. The critical frequency of this layer may rise up to 7-8 Mc/s and has usually well pronounced ordinary and extraordinary components. Multiple reflections are quite common, thus little absorption below this layer is often observed. In the second phase more absorption takes place, the minimum frequency of the E-layer increases and less multiples are recorded. Auroral forms with ray structure is often seen at this time. The third phase is characterized by high absorption of radio-waves, often resulting in black-out and strong aurora with ray-structure (after Stoffregen, 1958).

During the second and third phases low-frequency reflections are often observed at abnormally low altitudes of down to 60 km (Stoffregen, 1958; Stoffregen et al. 1960; Gregory, 1961; Pedersen, 1962; and others).

Only few detailed studies of the correlation between visual aurora and sporadic E in the auroral zones have been reported (Heppner et al. 1952; Knecht, 1956; Hunsucker and Owren, 1962). The most recent one is that of Hunsucker and Owren. They compared auroral type sporadic-E recorded with ionosondes in Alaska during the IGY with simultaneous allsky camera observations and other data for times of auroral activity. They found a high correlation between zenithal aurora and the critical frequency of the sporadic-E layer (fEs). From detailed studies of simultaneous visual aurora and ionospheric sounding data Hunsucker and Owren drew the following conclusions:

The motion of an auroral arc or band from a low elevation angle to a position near the zenith is accompanied by an increase in the value of fEs.

fEs is more than two times as great when there is aurora in the zenith as when there is not.

The highest value of fEs is observed when an auroral arc or band is present at the astronomical zenith (not the magnetic zenith).

A general survey of existing knowledge concerning sporadic-E phenomena of all kinds can be found in the paper by Thomas and Smith (1959). For other ionospheric disturbance effects associated with aurora, see Chapter

8. Scintillation of Radio Waves from Radio Stars and Satellites

Although no statistical studies of the correlation between auroral occurrence and scintillation of radio-waves from point sources outside the ionosphere have been made, it can be said that a good correlation certainly exists. A correlation exists namely between scintillation and geomagnetic activity (cf. e.g. Little et al. 1962, and Liszka, 1963), as well as between occurrence of visual aurora and geomagnetic activity (see above) and a few detailed studies of situations in which the radio waves have propagated through an observed visual aurora have shown that the scintillation is higher when the waves pass through the aurora than when they do not. This has been found both for ordinary aurora (Little and Maxwell, 1952a; Benson 1960; Morcroft and Forsyth) and for the subauroral-latitude red arcs (Roach, 1963).

9. Radio-Noise Emission

There is some evidence for VHF radio noise being emitted by the auroral primary electrons. The situation is still somewhat unclear. If the reported emissions are of auroral origin, a strong solar cycle variation in their occurrence frequency seems to exist. Observations have been reported only for solar activity maximum. Leadabrand (1964) has given a review of published observational results. Synchrotron radiation from the auroral primaries seems to be a possible mechanism of generation (Hower, 1963).

Whereas, thus, the association of aurora with significant VHF noise emission still must be considered as somewhat doubtful or at least as of rare occurrence, observational results showing a close relationship between visual aurora and a type of very-low-frequency noise emissions, the so-called auroral hiss, have recently appeared. Hiss differs from the other types of VLF emissions in that discrete emissions are not distinguishable in the emission spectra. A class of hiss known as "auroral hiss" has been shown to be closely associated with the occurrence of aurora on the basis of ground observations (Martin and Helliwell, 1960; Jörgensen and Ungstrup, 1962; Morozumi, 1962) although VLF hiss emission is sometimes undetectable on the ground even in the presence of an intense and active aurora. Morozumi (1963) has found that VLF hiss usually occurs in the pre-breakup phase of aurora and is well correlated with homogeneous auroral arcs and bands. He observed, however, also that intense auroral hiss sometimes occurs unaccompanied by auroras. Fig. 3.8 shows simultaneous records of VLF noise, visual emission, and precipitated electrons obtained on board Injun 3 (Gurnett and O'Brien, 1964). The agreement between the time functions of the various variables is quite good. The satellite was between 250 and 350 km while the records in Fig. 8 were taken. The photometer was looking along the field lines, and the measured electrons were on their way down into the atmosphere. The antenna on the satellite received the VLF magnetic component perpendicular to the geomagnetic lines of force. The emission spectrum of the auroral hiss record in Fig. 3.8 is essentially a flat noise spectrum starting below 2.7 kc/s and extending above 8.8 kc/s. The Injun 3 measurements suggest that, at least sometimes, the same precipitated electrons cause both visual aurora and VLF hiss emission.

10. Auroral "Sound"

A large number of reports of aural observations of sound in connection with aurora exist. A review has recently been presented by Campbell and Young (1963). According to these reports, some of which have been given by experienced auroral researchers, a sound is heard in a few per cent of the active auroras, mainly in the years of maximum in the eleven-year solar activity cycle. The sounds are said to be at the upper frequency limit of the observers' auditory response.

Chapman (1931, 1932) has pointed out that the mean free path in the height interval where aurora occurs is too large compared with the wave length of sound waves in the audible frequency range, for transmission down to the earth's surface to be possible. The aurora has to reach down below 65 km for the sound waves to be able to propagate to the earth's surface. But if this occurred, the variations in luminous and acoustic intensity could not be simultaneous, as has been reported, because of the low sound propagation velocity (unless the aurora extended to the ground level). It seems probable that the reported acoustic effects are due to the electric fields that are induced in any suspended wire connected to the earth by the geomagnetic variations associated with strong auroras, as proposed by Harang (1951), Störmer (1955) and others. During very strong auroras these voltages may be of sufficient magnitude to produce discharges.

For infrasonic waves in the period range 10-110 seconds the ratio of wavelength to mean free path is large, and propagation to the ground from the auroral altitudes is physically possible. Such waves have also been observed (Chrzanowski et al., 1961, 1962). Maeda and Watanabe (1964) have pointed out that auroral activity is expected to be associated with the appearance of infrasonic waves due to periodic heating of the ionosphere by the primary auroral particles. Such correlation was found by Campbell and Young (1963) in Alaska, where they observed that every night of bright visual aurora, or ionospheric evidence of aurora, was associated with 10-110-sec-period pressure oscillations of about 1 to 10 dynes/cm^2 amplitude. Nights of no auroral activity showed no infrasonic effects.

Figure Captions

Fig. 3.1–Diurnal variation of the occurrence frequency for radio aurora at about 90 Mc/s, observed at Kiruna, Sweden (geomagnetic latitude 65.3°). After Egeland (1962a).

Fig. 3.2–Allsky-camera photographs of visible aurora compared with simultaneous 106 Mc/s radar echoes obtained at College, Alaska. After Bowles (1954).

Fig. 3.3–Mass plot of 398/Mc/s echoes as a function of range and azimuth, College, Alaska, March 26, 1957. The points represent observations. The numbers attached to the various curves give the off-perpendicular angle with regard to the geomagnetic field lines at the reflection point. After Leadabrand et al. (1959).

Fig. 3.4–Comparison of auroral luminosity obtained from allsky-camera pictures with x-ray flux at balloon altitude. After Anderson and DeWitt (1963).

Fig. 3.5–Curves 1 show the height distribution of the absorption produced by the differential energy spectrum $N(E) = 5.10^9 e^{-E/5}$ electrons $(cm^2 \text{ sec ster kev})^{-1}$. The total absorption under the curve amounts to 1.04 db in the day and to 0.89 db at night. Curves 2 give the absorption due to the bremsstrahlung of the mentioned electron spectrum. Total absorption in the day is 0.27 db and in the night 0.061 db. Curves 3, finally, represent the absorption distribution produced by the differential energy spectrum $N(E) = 7.10^4 e^{-E/41}$ electrons $(cm^2 \text{ sec kev})^{-1}$ coming in along the field lines. Total daytime absorption is 1.9 db and the nighttime one is 0.52 db. After Hultqvist (1964a).

Fig. 3.6–Equilibrium electron density profiles due to three energy spectra of precipitated electrons. The spectra as well as the total absorption, A, at 27.6 Mc/s are given in the figure. Curve No. 2 gives an upper limit for the equilibrium electron density distribution produced by the spectrum $3.8 \cdot 10^4 e^{-E/30}$ electrons $(cm^2 \text{ sec ster kev})^{-1}$ which is the equivalent spectrum for the average fluxes when $K_p > 4$ as found by McDiarmid et al. (1963) a lower limit for this spectrum is curve No. 1. After Hultqvist (1964b).

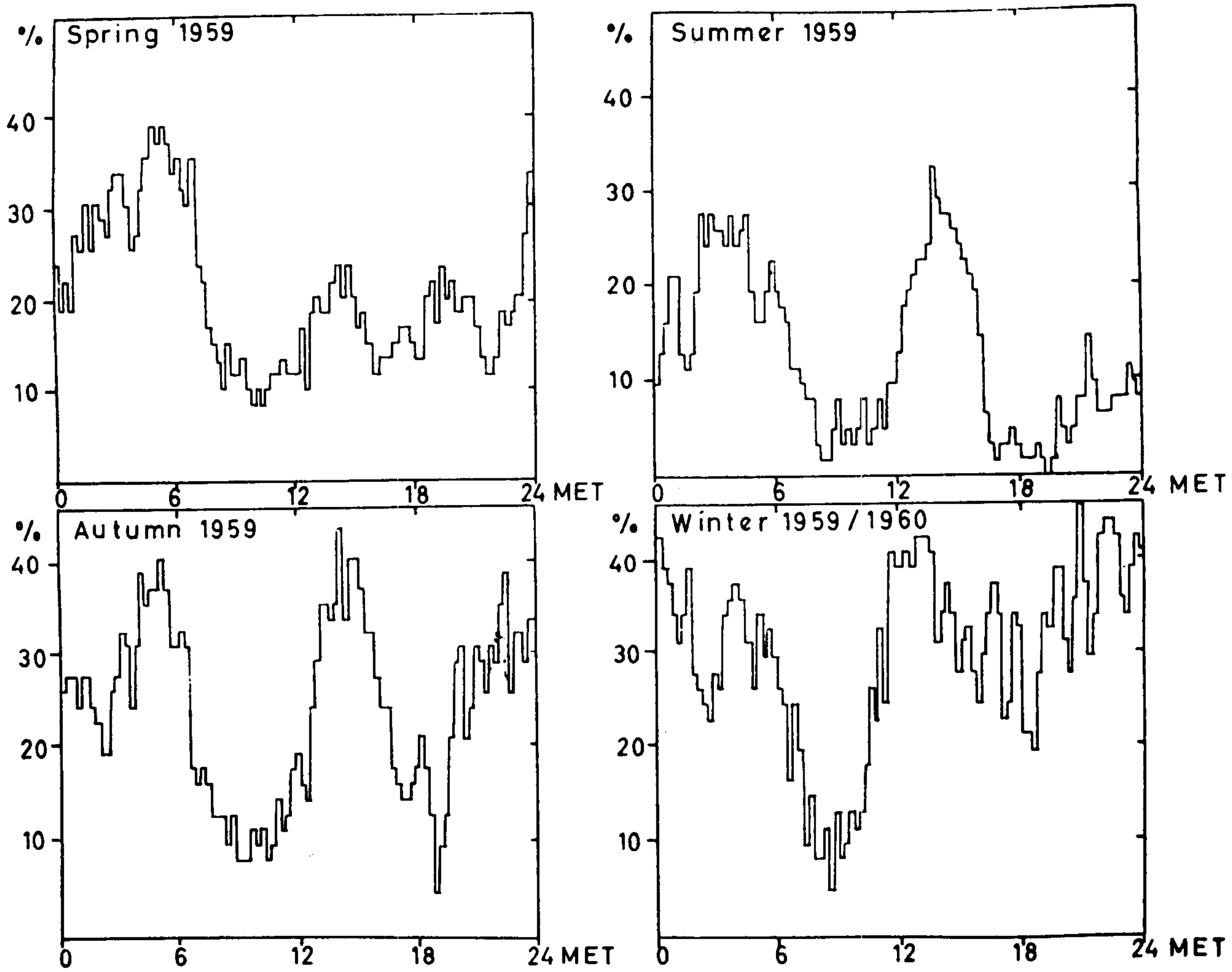


Fig. 3.1–Diurnal variation of the occurrence frequency for radio aurora at about 90 Mc/s, observed at Kiruna, Sweden (geomagnetic latitude 65.3°). After Egeland (1962a).

Fig. 3.7 – Diurnal variation of the average intensity of 27.6 Mc/s cosmic noise absorption for the equinoxes at Kiruna. Months in which PCA's occurred are excluded. Curve 1 represents the average for the following months: April 1959, September 1959, October 1959, March 1960, October 1960, March 1961, April 1961, September 1961, and October 1961. Curve 2 is for September 1961 alone and curve 3 for September 1959. After Hultqvist (1963a).

Fig. 3.8 – A simultaneous observation of VLF electromagnetic emission, auroral luminosity and precipitated electrons on board Injun 3 on March 3, 1963, 0720-0725 UT. After Gurnett and O'Brien (1963).

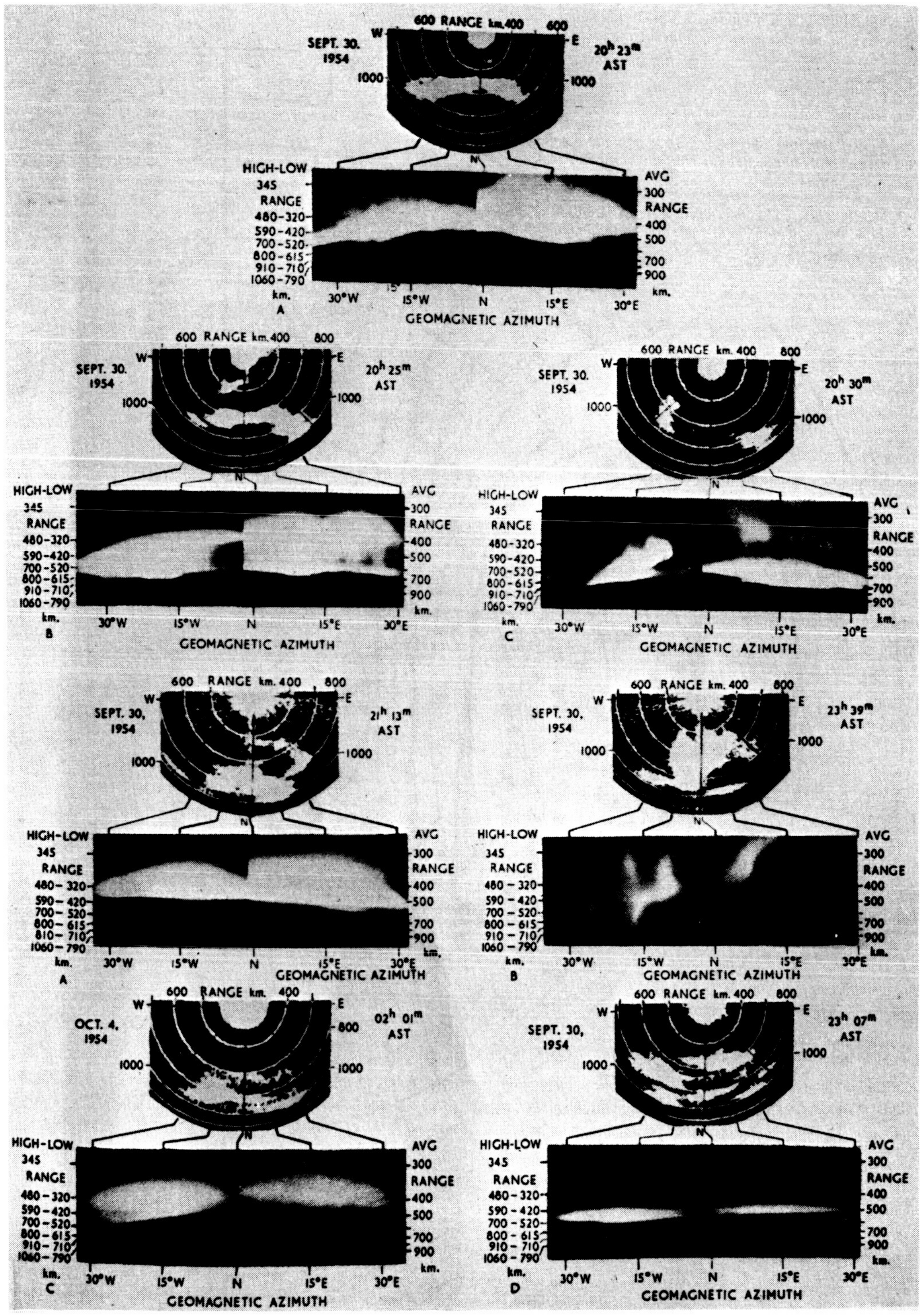


Fig. 3.2—Allsky-camera photographs of visible aurora compared with simultaneous 106 Mc/s radar echoes obtained at College, Alaska. After Bowles (1954).

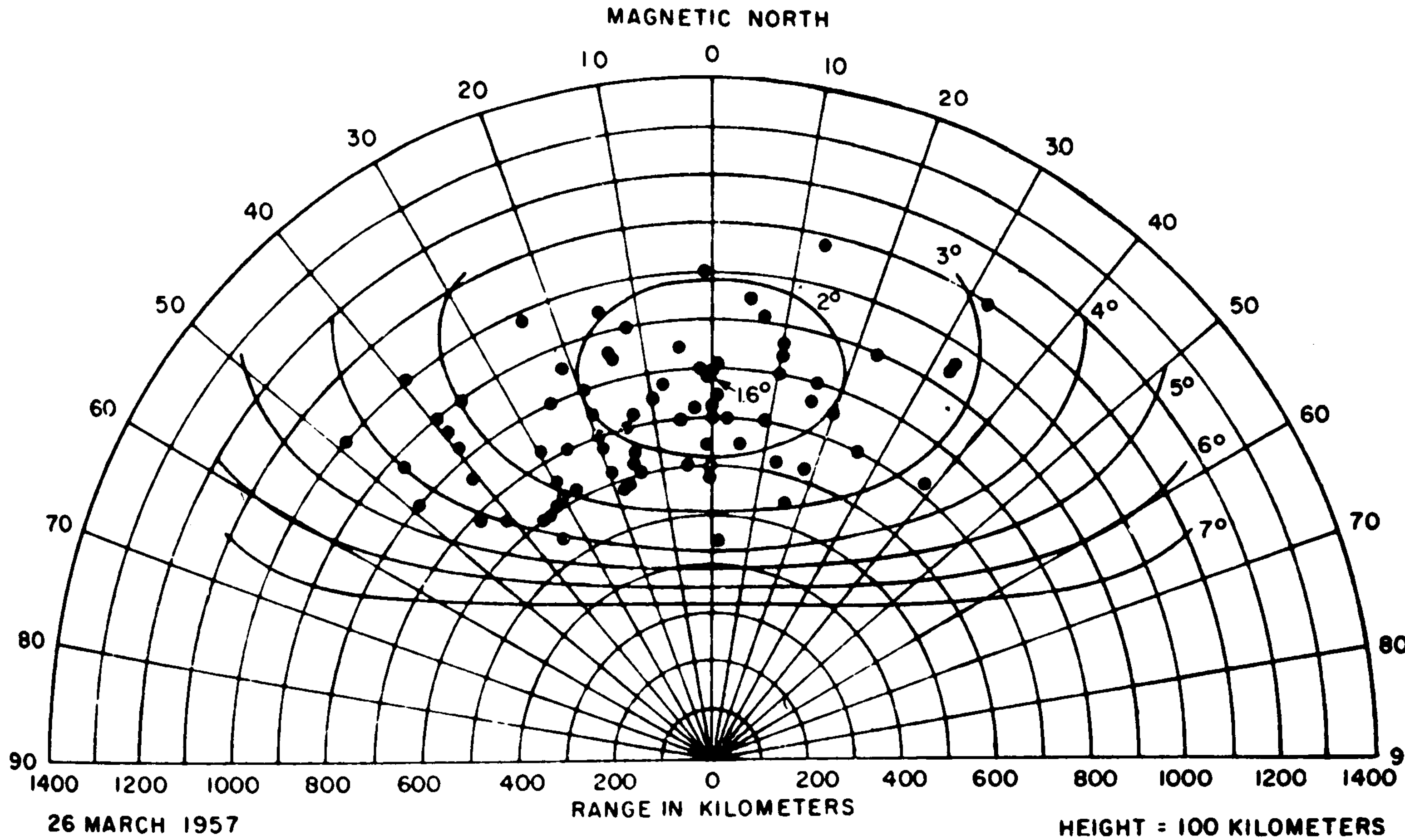


Fig. 3.3–Mass plot of 398/Mc/s echoes as a function of range and azimuth, College, Alaska, March 26, 1957. The points represent observations. The numbers attached to the various curves give the off-perpendicular angle with regard to the geomagnetic field lines at the reflection point. After Leadabrand et al. (1959).

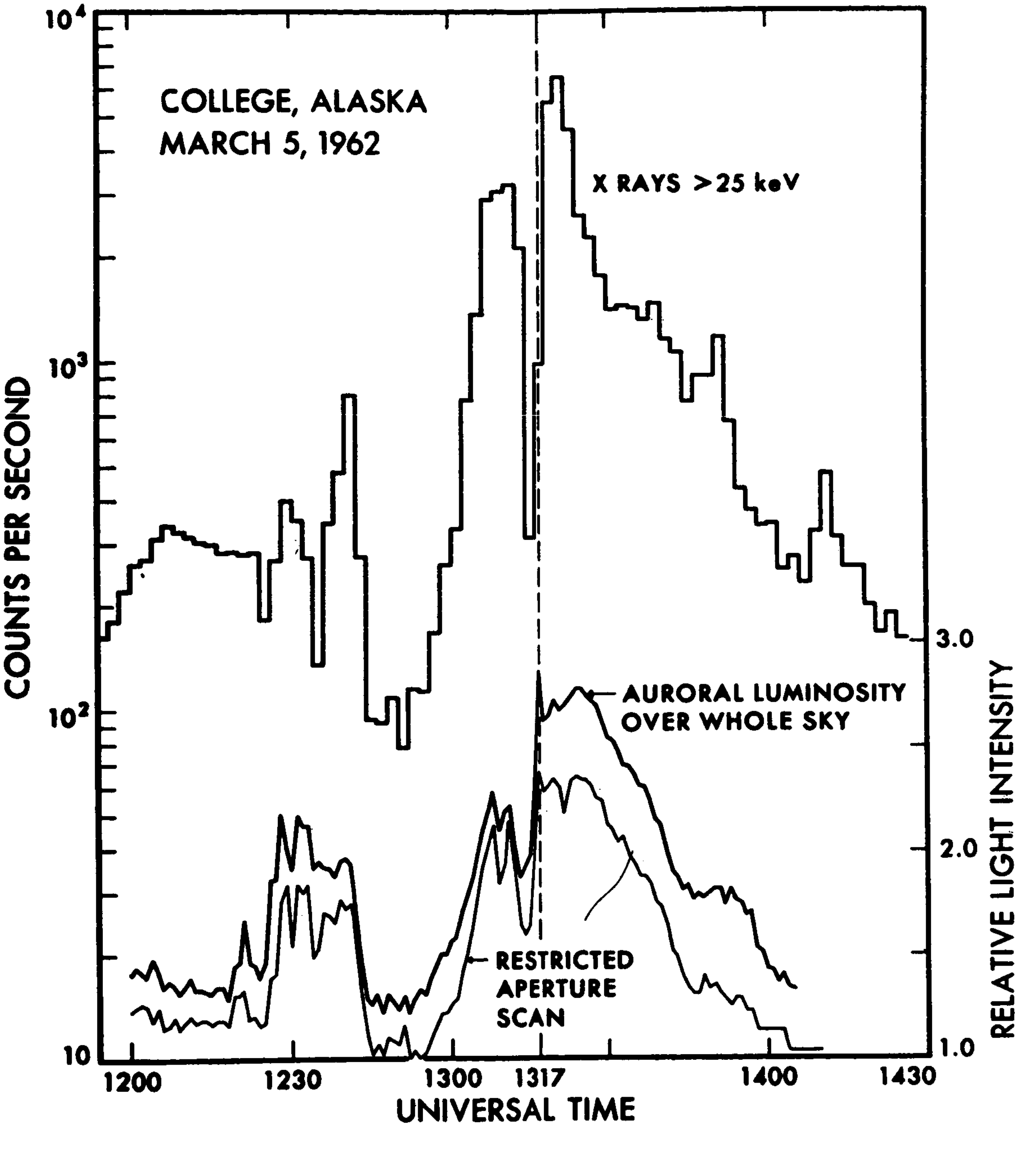


Fig. 3.4–Comparison of auroral luminosity obtained from allsky-camera pictures with x-ray flux at balloon altitude. After Anderson and DeWitt (1963).

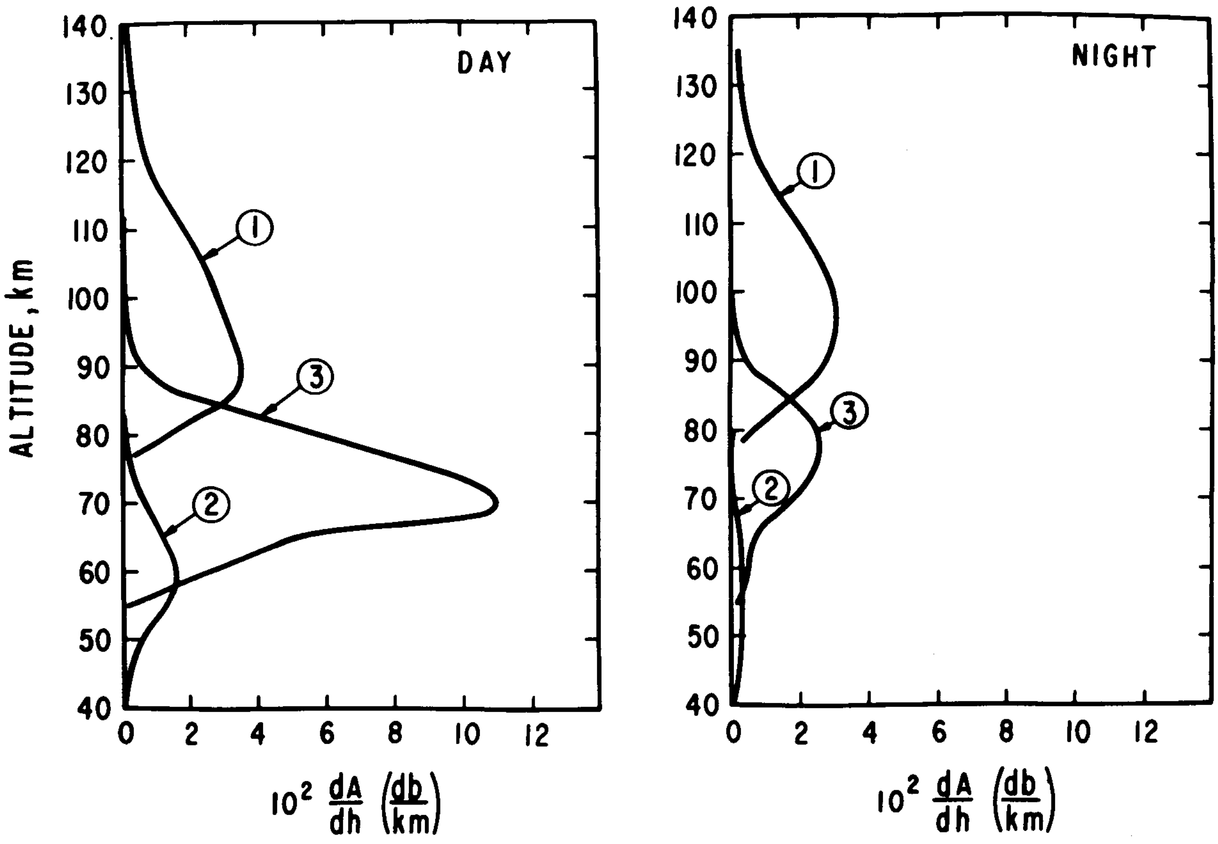


Fig. 3.5–Curves 1 show the height distribution of the absorption produced by the differential energy spectrum $N(E) = 5.10^9\ e^{-E/5}$ electrons $(cm^2\ sec\ ster\ kev)^{-1}$. The total absorption under the curve amounts to 1.04 db in the day and to 0.89 db at night. Curves 2 give the absorption due to the bremsstrahlung of the mentioned electron spectrum. Total absorption in the day is 0.27 db and in the night 0.061 db. Curves 3, finally, represent the absorption distribution produced by the differential energy spectrum $N(E) = 7.10^4\ e^{-E/41}$ electrons $(cm^2\ sec\ kev)^{-1}$ coming in along the field lines. Total daytime absorption is 1.9 db and the nighttime one is 0.52 db. After Hultqvist (1964a).

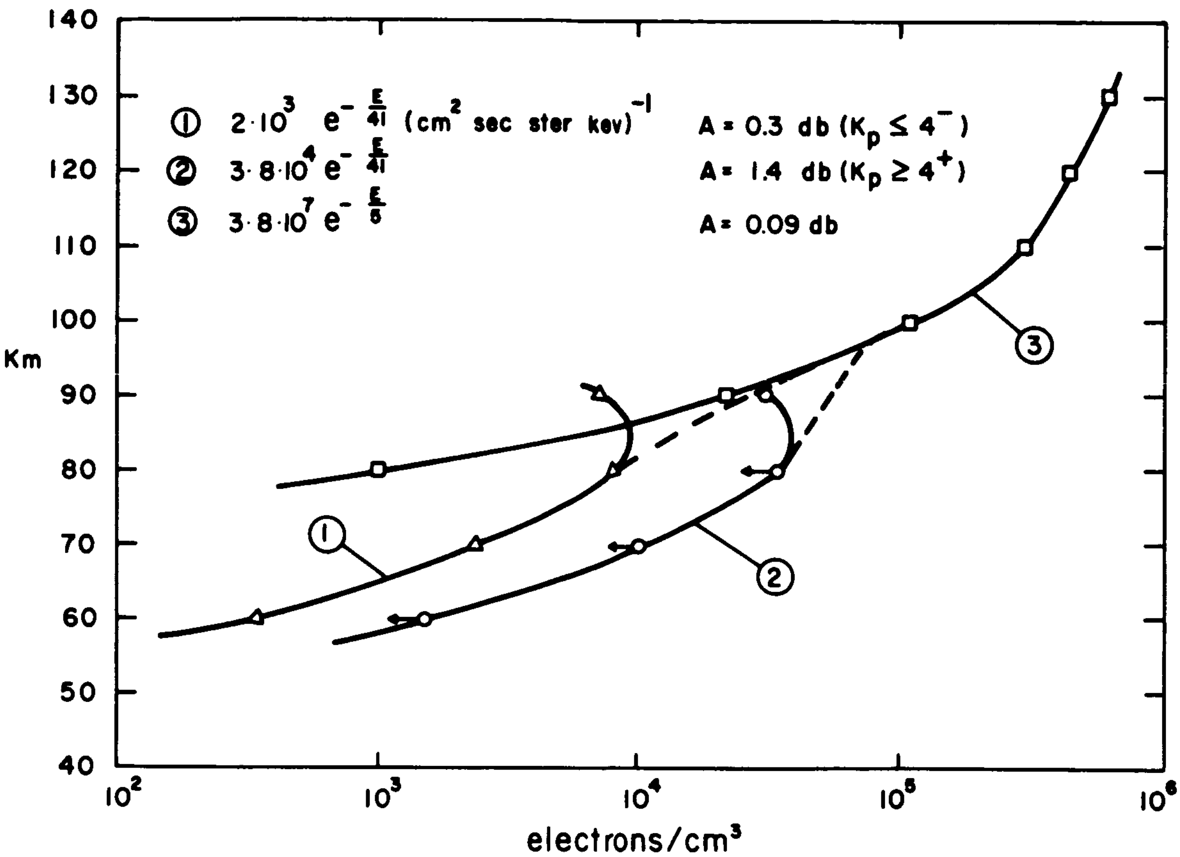
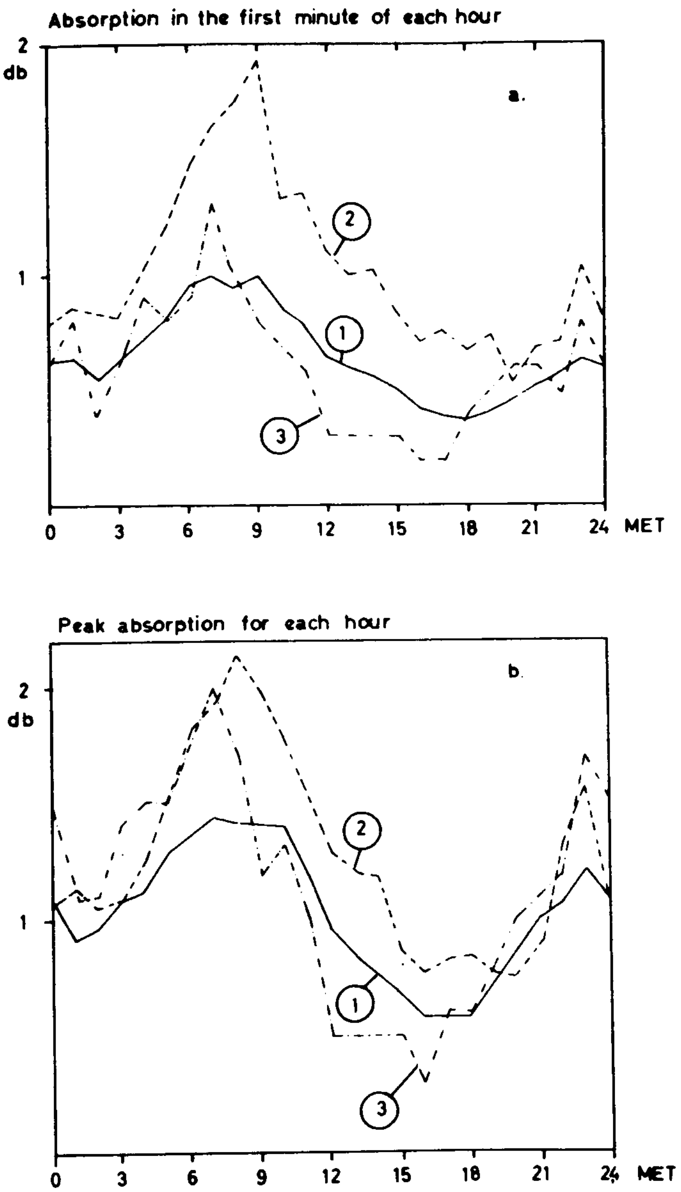


Fig. 3.6–Equilibrium electron density profiles due to three energy spectra of precipitated electrons. The spectra as well as the total absorption, A, at 27.6 Mc/s are given in the figure. Curve No. 2 gives an upper limit for the equilibrium electron density distribution produced by the spectrum $3.8 \cdot 10^4\ e^{-E/30}$ electrons $(cm^2\ sec\ ster\ kev)^{-1}$ which is the equivalent spectrum for the average fluxes when $K_p > 4$ as found by McDiarmid et al. (1963) a lower limit for this spectrum is curve No. 1. After Hultqvist (1964b).



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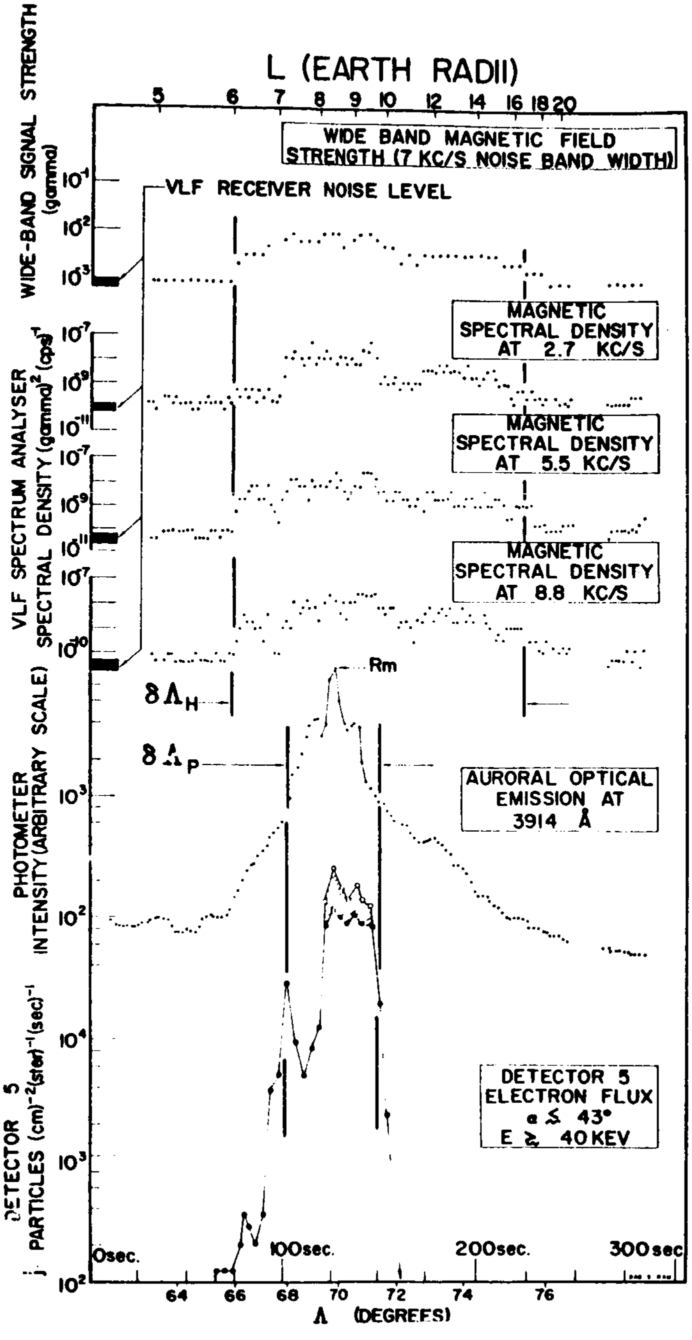


Fig. 3.8–A simultaneous observation of VLF electromagnetic emission, auroral luminosity and precipitated electrons on board Injun 3 on March 3, 1963, 0720-0725 UT. After Gurnett and O'Brien (1963).

4. Direct Observations of Energetic Particles Associated With Aurora

1. Introduction

The first definite observational evidence for fast charged particles entering the earth's upper atmosphere along the geomagnetic field lines was obtained from a spectrogram taken by Meinel (1950a, b, 1951). He pointed his instrument toward the magnetic zenith during a strong aurora and obtained an $H\alpha$ profile that was shifted—as well as broadened—with its peak corresponding to a doppler velocity of roughly 500 km/sec, but the short wavelength tail of the profile extended to more than 2000 km/sec. In the direction of the magnetic horizon the profile was not shifted but only broadened to about 500 km/sec on either side of the center. The broadening on the red side arises probably in part from scattering of light from other parts of the sky and in part from motions of protons away from the observer. The latter may be due to many small-angle scatterings of protons that initially were moving nearly perpendicularly to the magnetic field.

Proton fluxes as high as 10^8 $(cm^2\ sec)^{-1}$ with velocities below 500 km/sec have been deduced from spectroscopic measurements (Malville, 1960). That proton velocities much above 2000 km/sec have not been observed, does not mean that higher velocities do not exist in the incoming proton beam. The observed limit is due to the effect that much more rapid protons cannot take up electrons to form neutral hydrogen atoms which then can emit the hydrogen lines on its continued way.

In this section will be given a brief review of some recent direct measurements of particles related to aurora which have been made by means of balloon-, rocket-, and satellite-borne instruments

2. Observed Fluxes and Energy Spectra of Electrons Precipitated Into the Upper Atmosphere

In the summer of 1953 a group from the State University of Iowa when carrying out a program for study of the low-energy end of the primary cosmic-ray spectrum recorded an anomalous soft radiation by means of rockoons launched from a ship west of Greenland (Meredith et al., 1955). The radiation was identified as x-rays of energy 10-100 kev. Some two dozen rockoon launchings at various latitudes showed that the latitude dependence of the radiation intensity was very similar to that for the occurrence of visual aurora (Van Allen, 1957).

X-rays directly coincident with auroras were first observed at balloon levels in 1957 (Winckler et al., 1958). A few rockets were launched through visible auroral forms in 1958 (Davis et al., 1960; and McIlwain, 1960). The first proof that electrons are precipitated into the atmosphere from altitudes of 1000 km or more was obtained from Sputnik 3 in a period of about one minute on May 15, 1958, by Krasovskii et al. (1962). A number of reports of measurements on electrons precipitated into the atmosphere have been collected in Table 1. Nos. 1-3 are rocket measurements, no. 4 refers to the rockoon results of the Iowa group, nos. 5-9 are measurements obtained by means of balloons (only x-ray measurements for which the existence, or nonexistence, and characteristics of visual aurora in the period of measurement have been reported are included in Table 1), nos. 10-21, finally are satellite results.

The early rocket measurements (Davis et al., 1960; McIlwain, 1960) as well as the satellite results (e.g., O'Brien, 1962a, 1964) have verified the conclusions of Omholt (1957, 1959) based on spectroscopic observations of aurora that the protons play a very minor role in the excitation of most auroras.

The first somewhat detailed satellite studies of particles that were definitely precipitated into the atmosphere were made by means of Injun 1 (O'Brien, 1962a, b). O'Brien and others working with satellite data define precipitated particles as such which would mirror at or below 100 km altitude (if the atmosphere had not been present). The satellite results have also shown that electrons on the average carry much more of the energy to the lower ionosphere than do protons (O'Brien, 1962b).

(a) Latitudinal Distribution and Other Spatial Characteristics

The recent simultaneous measurements on Injun 3 (O'Brien and Taylor, 1964) of flux of precipitated electrons and of auroral light emission below the satellite have shown that above auroras there are electron fluxes several orders of magnitude larger than outside the aurora (see Fig. 4.1).

Fairly extensive statistical data on the spatial characteristics of precipitated electrons have recently been published by O'Brien (1962a, b, 1964) and McDiarmid et al. (1963). Fig. 4.2 shows the scatter diagram of the Injun 3 observations of precipitated electrons of energy above 40 kev for the range of the invariant latitude Λ (defined by $\Lambda = \cos^{-1} (1/L)^{1/2}$ and at the most a few degrees different from geomagnetic latitude in the latitude range of interest here) between 45 and 76 degrees. As can be seen from the figure, the precipitated flux of electrons of $E \gtrsim 40$ kev has a maximum of about 10^5 $(cm^2 \text{ sec ster})^{-1}$ for Λ between 60 and 70 degrees. The flux is 2-3 orders of magnitude lower in subauroral latitudes. Fig. 2 also shows that some 10 degrees inside the auroral zone the precipitation rate is down by 1-2 powers of ten. Similar results have been found by McDiarmid et al. (1963) for electrons of energies above 40 kev and above 250 kev. Fig. 4.3 shows their data presented in a manner different from that of O'Brien (1964).

The histograms give, for two different ranges of magnetic activity, the percentage of passes in which the intensity of precipitated electrons with $E \gtrsim 40$ kev was above $1.5 \cdot 10^4$ $(cm^2 \text{ sec ster})^{-1}$ (corresponding to 0.2 db absorption at about 30 Mc/s). The flux of $1.5 \cdot 10^4$ $(cm^2 \text{ sec ster})^{-1}$ was one half of the maximum average intensity for $K_p < 4$ and 1/20 for $K_p > 4$. Fig. 3 shows that during quiet geomagnetic conditions the precipitated intensity was greater than half the average value during some 25% of the passes through $\Lambda = 65°$, while for moderately disturbed conditions—there were no strong storms represented in the data—the intensity exceeded 1/20 of the average value in about 72% of the passes over that latitude.

Simultaneous observations on two satellites indicate that at least sometimes the area of precipitation has a fairly limited longitudinal extent (O'Brien and Laughlin, 1962). On the other hand the precipitated flux seems on occasions to be uniform over as much as 80 degrees of longitude, i.e., over more than 4000 km (O'Brien, 1964).

The flux of precipitated electrons has its maximum close to the poleward boundary of the region of trapped electrons, as observed on the same satellite (McDiarmid et al., 1963, O'Brien, 1964).

Electron precipitation occurs simultaneously in magnetically conjugate areas at least sometimes, according to balloon observations of x-rays (Brown et al., 1963). This is in accordance with observations of aurora (cf. e.g. DeWitt, 1962).

A 100 fold change in the flux over two km has often been observed by Injun 3, which is in agreement with results of rocket measurements in aurora by Davis et al. (1960). They found the electron flux being concentrated in the visible auroral forms, whereas protons were found over a much larger volume than that occupied by the aurora.

The statistical latitude profile of the intensity of dumped electrons with $E \gtrsim 40$ kev has been found by O'Brien and Taylor (1964) to have its maximum at a few degrees lower latitude than the frequency of occurrence of visual aurora as observed on the same satellite. Sometimes the visual emission has been found to extend to higher latitudes than the precipitation of electrons with energy greater than 40 kev, indicating electrons of $E < 40$ kev are being precipitated up to higher latitudes than the higher energy ones. The lower latitude limit of the aurora coincides with the lower latitude limit of appreciable precipitation (O'Brien, 1964; O'Brien and Taylor, 1964).

Precipitation was found all the time in the auroral zone by Injun 3 (O'Brien, 1964). It can be seen in Fig. 4.2 that at $L = 6$ there was never observed any flux lower than about 80 electrons $(cm^2 \text{ sec ster})^{-1}$.

The corresponding continuous photon emission in the auroral zone is evident from Fig. 4.4. The minimum emission rate is, however, below visual threshold even in the auroral zone.

Figs. 4.2 and 4.4 also give a good impression about the enormous variability of precipitation and photon emission at all latitudes, but especially near the auroral zone. At $L = 6$ there are values of about $6 \cdot 10^6$ electrons $(cm^2 \text{ sec ster})^{-1}$ shown in the figure. This is some 10^5 times the minimum value observed there.

The latitudinal extent of the precipitation can be very restricted (e.g., over $L \sim 1$ earth radius) or very extensive (over $L > 20$ earth radii). This is illustrated in Fig. 4.5.

(b) Time Characteristics of Precipitation

It is not possible to differ between time and space variations in satellite measurements. Balloon observations show, however, that time variations as rapid as of periods of a tenth of a second can occur in the electron flux (Winckler et al., 1962).

No systematic variation in the intensity of electron precipitation over periods as long as a day could be found by O'Brien (1964) from the Injuns 1 and 3 measurements, in contrast with the case for trapped electrons. Sharp et al. (1964) observed a higher nighttime than daytime precipitation flux of electrons in the energy range 0.08—24 kev—as well as of protons—during the 5 days lifetime of an oriented polar-orbiting satellite. They also found the energy distribution of the electrons to be harder on the dayside than on the nightside of the earth (Johnson et al., 1964). With the enormous variability of the precipitation phenomenon a large amount of data seems, however, necessary for deducting statistically significant diurnal variation curves.

(c) Pitch Angle Distribution

Figure 1 shows that over the aurora, where the precipitation is intense the directional flux of precipitated electrons becomes equal to the flux of trapped electrons, which also is increased over the aurora. Figure 1 illustrates a general rule that has been found by O'Brien (1962a, b, 1964) namely that for electrons of $E \geq 40$ kev the pitch angle distribution approaches isotropy in the regions of intense precipitation. An isotropic pitch angle distribution in regions of strong precipitation has also been observed by Krasovskii et al. (1962) at an energy of about 10 kev. No cases have been found in which the directional flux of precipitated electrons has been higher than the corresponding value for trapped electrons. The mentioned observations were made fairly close to the earth's atmosphere.

The tendency to isotropy seems to indicate that the acceleration of the electrons—if it is directed along the field lines—takes place far away from the atmosphere. This, as well as the mentioned observations of precipitation of electrons from above 1000 km in auroras, suggest that the role of the ionosphere in the production of the energetic electrons is not important. O'Brien (1964) found a flux upwards along the field lines, which was some 10% of the precipitated electron flux. He interpreted these observations as backscattering of electrons from the atmosphere.

(d) K_p – Dependence of Precipitation

The K_p dependence of the precipitation of electrons of energy above 40 kev is illustrated in Fig. 4.3. The average intensity was ten times higher near the auroral zone when K_p was above 4 than when it was below 4. The data material for the higher K_p range in Fig. 4.3 does not contain data from any strong magnetic storm, so still higher values may be expected.

O'Brien (1964) found that the flux of precipitated electrons above 40 kev increased on the average by a factor of 5 for every step of K_p. A close correlation between precipitation intensity was also observed for the 0.08–24 kev energy range by Sharp et al. (1964). O'Brien's results, obtained on Injun 3 in a low orbit, are shown in Fig. 4.6 together with the dependence of the omnidirectional flux above 40 kev as observed in the equatorial plane far from the earth by Explorer 12 (Freeman, 1963). As can be seen, the K_p dependence is very much larger close to the earth (at one end of the field line) than in the equatorial plane (at the middle of the field line). If one assumes that both increases are due to a common acceleration mechanism it follows that it acts preferentially parallel to the geomagnetic field lines (O'Brien, 1964).

The change of omnidirectional flux above 40 kev with K_p, shown in Fig. 4.6b, is opposite to what has mostly been observed for electrons of $E \gtrsim 2$ Mev (Arnoldy et al., 1960; Hoffman et al., 1962).

The dependence of the poleward boundary of precipitation on magnetic activity has been studied by Maehlum and O'Brien (1963). They used data for trapped electrons, but since O'Brien (1964) has shown that the precipitation has its maximum close to the poleward boundary of the region of trapped electrons, their results may be interpreted in terms of possible extension of precipitated electrons.

Maehlum and O'Brien (1963) found that during magnetic storms there was a very sharp boundary of the region where trapped electrons of energy above 40 kev could be observed at about 1000 km altitude. For this boundary, measured in L, they used the symbol L_n. It can be seen as a function of the K_p index during one geomagnetic storm in Fig. 4.7. When K_p reached its maximum value of 9, L_n had its minimum value of 4. Maehlum and O'Brien (1963) also found that the poleward edge of strong radio wave absorption followed the L_n quite closely during the storm.

The effect of K_p on L_n is similar to the equatorward movement of the region of visual aurora during strong magnetic storms, which has been studied in the last few years in detail for some storms by Akasofu (1962, 1963a,b) Akasofu and Chapman (1962) and Davis and Kimball (1962).

(e) The Spectrum of Precipitated Electrons

Up to now only rough measurements of the energy spectrum of the precipitated electrons have been reported. In most cases the proposed spectra have been obtained from two instruments with different energy characteristics. They thus are to be considered as rough equivalent spectra for measurements made in a defined way. In addition, it has been found that the equivalent spectrum is highly variable both in space and time (cf. O'Brien et al., 1962). Nonetheless the available spectral data are of great interest at the present stage of knowledge in the field, and they even make it possible to draw some interesting conclusions about ionospheric effects of the precipitated electrons (see Section 3).

Most spectra that have been reported hitherto can be divided in two categories if they are expressed in an exponential form. On one hand, the e-folding value, b, in the spectrum of precipitated electrons, written in the form $\propto \exp(-E/b)$, has been found often to be in the range 2-8 kev (McIlwain, 1960; Stilwell, 1963; Sharp et al. 1964 a,b,c.) This is a very steep spectrum, but even steeper ones have been observed. McIlwain interpreted his rocket measurements in a strong aurora as indicating a monoenergetic flux of electrons with an energy of about 6 kev. Krassovskii et al. (1962) has observed steep spectra for precipitated electrons with a most common equivalent energy value of 14 kev.

The majority of the existing measurements have been made with Geiger tubes, for which the minimum detectable electron energy is about 40 kev. These measurements have mostly given e-folding values much higher than those mentioned above, namely between 20 and 45 kev.

(Davis et al. 1960; McDiarmid et al. 1960; O'Brien et al. 1962; Mann et al. 1963; McDiarmid et al. 1963; O'Brien and Taylor, 1964). Mann et al. (1963) found from measurements during only some 20 orbits that the values within this range were grouped in two classes, 25 ± 5 kev and 42 ± 3 kev.

The balloon measurements of x-rays at 30-35 km altitude also, in general, give spectra of a fairly flat type, corresponding to e-folding energies in the range 20-45 kev mentioned (see e.g., Anderson and Enemark, 1960), although power law spectra often are found to fit the observations somewhat better than exponential spectra.

Recently the first direct measurements of precipitated electrons below 1 kev energy have been reported (Sharp et al. 1963, 1964c; Evans et al. 1964). They showed that there is generally not very much energy flux below 1 kev. This is also evident from observations of the luminosity distribution with height in aurora. (O'Brien and Taylor, 1964). It therefore seems probable that the spectrum, in general, does not increase very fast below 1 kev, which means that it is not of the power law type at these low energies.

Sharp et al. (1964c) reported a significantly harder spectrum on the dayside than on the nightside of the earth. This observation agrees with multifrequency riometer measurements of auroral absorption by Lerfald et al. (1964) according to which the absorbing ionization is located lower down in the atmosphere in the day than in the night.

Of special interest are the statistical data on electron precipitation, published recently. As mentioned earlier the precipitation is most intense near the auroral zone. O'Brien (1964) found an average flux of 4.10^5 electrons/cm^2 sec in the precipitation cone at an invariant latitude of 65°. Injun 1 had a CdS detector, measuring electrons of energy above about 1 kev (O'Brien, 1962b). O'Brien and Taylor (1964) stated that the flux of 4.10^5 electrons/cm^{2}sec of energy greater than 40 kev was associated with an energy flux of 4 erg/cm^2 sec for electrons of $E \gtrsim 1$ kev. These data should be considered as accurate to a factor of about three. Using these two values an equivalent electron spectrum in the range 1-40 kev can be deduced. It is found to be $n(E) = 7.8 \cdot 10^7$ $e^{-E/5.7}$ electrons (cm^2 sec kev)$^{-1}$.

For the energy values 40 and 250 kev similar average fluxes have been obtained from the Alouette measurements reported by McDiarmid et al. (1963). While the flux above 40 kev had its maximum at an invariant latitude of 65 degrees, the flux above 250 kev was maximal at about 60 degrees. McDiarmid et al. (1963) did not present any details for the latitudinal variation of this latter integral flux. By applying a rough correction factor of 0.1 for the latitude variation of the average flux above 250 kev from 60 to 65 degrees invariant latitude the following approximate equivalent spectra for the energy range 40-250 kev can be derived for two ranges of magnetic activity in the auroral zone, if isotropy is assumed for the upper hemisphere:

$$K_p < 4: \quad n(E) = 1.2 \cdot 10^4 \; e^{-E/41} \quad \text{electrons} \; (\text{cm}^2 \, \text{sec kev})^{-1},$$

$$K_p > 4: \quad n(E) = 2.4 \cdot 10^5 \; e^{-E/30} \quad \text{electrons} \; (\text{cm}^2 \, \text{sec kev})^{-1}$$

(cf. Hultqvist, 1964b). The applied latitude correction is probably too large and the resulting spectra are thus too steep rather than too flat. As mentioned, the spectra of precipitated electrons are very variable. There is also an important latitude variation in the steepness which increases with latitude (O'Brien et al. 1962; McDiarmid et al. 1963; O'Brien, 1964). On the other hand there seems to be no significant dependence of the spectrum on pitch angle or on the intensity of precipitation (O'Brien, 1964). The averaging on which the equivalent spectra given above are based has been made over a large number of measured fluxes. With a variation of a factor of 10^5 the use of averages may be questioned. It is also questionable whether average integral fluxes are the best values to use when the interest is in the average electron density produced by the particle influx. The average electron density is then defined by the averaging process, and this method of averaging is not identical with the averaging made in measuring the ionospheric absorption, for instance. It can, however, be shown that the average electron density produced by the precipitated electrons can be expressed in the average integral fluxes measured on satellites (Hultqvist, 1964b). Since only two experimental integral flux values are available one has to fit a two-parameter energy relation for the average flux to these experimental data, as has been done above.

3. Observed Fluxes and Energy Spectra of Protons Precipitated Into the Atmosphere

The number of observations of protons on their way down into the atmosphere is much less than that for electrons. Some rocket results observed in passing through aurora or close to distinct auroral forms, or from launchings made under quite disturbed upper atmosphere conditions with no auroral information available, are collected in Table 2.

While electrons were observed only within the auroral form in the case of no. 1a, protons were found over much larger volumes. In the flights 1b, c, and d, when no auroral form was penetrated and no electrons were recorded, protons (and/or heavier ions) were found in appreciable amounts. The proton precipitation thus seems to have that wide spread and diffuse character that the hydrogen emissions generally show. This may possibly be due to protons taking up an electron also well outside the atmosphere. As a neutral atom it is not locked to the magnetic field lines and the particle flux may be spread out before reaching the atmosphere (Shklovskii, 1958). In all cases of Tables 1 and 2 in which both electrons and protons were measured, the energy flux of the electrons was about two orders of magnitude, or more, greater than the proton energy flux.

The satellites Injun 1 and Injun 3 did not measure any auroral event in which the electrons were not the dominant constituent in radiation of a given penetrability (O'Brien and Taylor, 1964). The possibility that there were as many protons/cm^2sec with an energy about 40 kev, say, as there were electrons/cm^2sec with the same energy could, however, not be excluded on the basis of the Injun measurements. Such protons would be stopped above the normal auroral heights and one would expect hydrogen emissions well above the ordinary aurora. They could, however, be quite weak, especially as the protons flux generally is spread out over a much larger surface than the electron flux, as mentioned above. It seems difficult to judge on these things on the basis of ground observations, as the hydrogen emissions are mostly diffuse and therefore unsuitable for height determination with standard ground techniques. Rocket measurements of the height distribution of the hydrogen emissions would be valuable.

4. Quantitative Relations Between Electron Precipitation and Photon Emission in Aurora

There are two direct measurements reported of the quantitative relations between precipitation and photon emission which will be discussed here, namely those of McIlwain (1960) and O'Brien and Taylor (1964). It is of interest to compare their results with what is expected on theoretical grounds.

McIlwain did not use any filter, but measured the photon flux integrated over the transmission curve of the photomultiplier. If we assume that 1/5 of the light was λ3914 Å, the measured photon flux corresponds to an emission rate of about 3 kilorayleigh at this wavelength. The fraction 1/5 is fairly arbitrary, but it seems reasonable (cf. e.g. Dalgarno, 1964) and is probably in error by less than a factor of 2 and

1/2, respectively, for an ordinary auroral-zone aurora. McIlwain's (1960) measured electron flux corresponds to an energy flux of 20 erg/cm^2 sec if the spectrum obtained was extrapolated to E = 0. Thus, the resulting electron energy flux required per unit of λ3914 Å emission rate is 7 ergs cm^{-2} sec^{-1} per kR.

O'Brien and Taylor (1964) reported an average λ3914 Å intensity of 2 $\left(^{+4}_{-1.5}\right)$ kR at the maximum of the latitude distribution i.e. in the auroral zone. As mentioned before the electron measurements gave a corresponding average of the electron flux above 40 kev of $4 \cdot 10^5$cm^{-2} sec^{-1} and an average energy flux for E $\gtrsim$ 1 kev of about 4 ergs cm^{-2} sec^{-1}, which values they consider as accurate to a factor of about three. In order to get a value directly comparable with that of McIlwain one would have to extrapolate the energy spectrum from 1 kev down to E = 0 and evaluate the total energy flux. Using the equivalent exponential spectrum, we find 5 ergs cm^{-2} sec^{-1} for E > 0. Thus the Injun 3 results give 2.5 ergs cm^{-2} sec^{-1} per kR. Considering the uncertainties in measurements and the method of evaluation, this is a good agreement.

What energy flux per kR does one expect on the basis of existing knowledge about the emission processes? Omholt (1957, 1959) Chamberlain (1961), Rees (1963) and Dalgarno (1964), among others, have discussed this. It has been shown by Stewart (1956) that the ratio between the excitation cross section for the λ3914 Å band of N_2^+ and the total ionization cross section is constant at least up to 200 ev energy and has the value 0.02. Assuming that this value is true over the whole energy range of interest, one finds that 50 electrons-ions pairs are produced for each 3914 Å photon. Since the mean energy expended by fast electrons in nitrogen per electron ion pair is 35 ev (at least for energies down to a few hundred ev; it is assumed the figure is correct down to zero energy) we find that 50 x 35 = 1750 ev is dissipated per 3914 Å photon. Since each photon has an energy of 3.2 ev, the efficiency with which energy is converted into 3914 Å radiation is $1.80 \cdot 10^{-3}$. When the initial energies of the fast electrons fall below perhaps 100 ev, these efficiencies must decrease sharply (Dalgarno and Griffing, 1958; Dalgarno, 1964). 1 kR of 3914 Å photons corresponds to an energy influx of 2.8 erg/cm^2 sec, if the efficiency figure $1.8 \cdot 10^{-3}$ is employed. Dalgarno (1964) has used the value $1 \cdot 10^{-3}$. With this conversion efficiency we find the energy flux requirement to be 5.1 erg cm^{-2} sec^{-1} per kR. The agreement between these values and the experimental ones of McIlwain (1960) and O'Brien and Taylor (1964) is much better than expected, when the uncertainties in the analysis are taken into account.

The total efficiency of converting particle energy into photons of any energy is expected to be about 1% on theoretical basis (cf. Chamberlain, 1961). McIlwain found from his rocket measurements a value of only 0.2%, while preliminary Injun 3 results point towards 1% (O'Brien and Taylor, 1964).

5. Relation of Precipitated Electrons to the Outer Radiation Belt

The idea about the relations between the electrons that are precipitated into the atmosphere in auroras and elsewhere and the trapped radiation in the radiation belts, which was prevailing one or two years ago, was roughly that the precipitated particles were dumped from the large storage of energetic trapped particles in the magnetosphere through the influence of disturbing effects caused by the solar plasma, as, for example the magnetic disturbances. The number of trapped particles was thought to be sufficiently large to allow the precipitation rates observed to occur with only weak and perhaps independent processes of injection and acceleration required to replenish the particles in the radiation belt, and the occurrence of which is necessary to be assumed in any case for understanding the existence of the trapped radiation. This picture has been completely changed recently, through the investigations by O'Brien (1962b, 1964) of the measuring results of Injun 1 and Injun 3 and also through a number of balloon studies of x-ray fluxes in the lower atmosphere (Winckler et al., 1962; Anderson, 1964).

O'Brien (1962b) estimated the lifetime of the trapped electrons in the outer radiation belt assuming that the source was stopped but the loss mechanisms operated at the same rate as observed by Injun 1. He found that the outer zone beyond $L \sim 2$ would drain empty of electrons in a few hours. Similar average lifetimes have also been evaluated from x-ray measurements (cf. e.g. Winckler et al. 1962 and Anderson, 1964). Sometimes precipitation rates several orders of magnitude above the average (more than 1000 ergs/cm^2 sec) have been observed (Krasovskii et al. 1961; O'Brien and Laughlin, 1962, Winckler et al., 1962). Thus Winckler et al. (1962) recorded an electron burst reaching 10^{11} electrons (cm^2 sec)$^{-1}$, a flux which would have used up the total energy of trapped particles in the field tube in half a second, but yet it persisted for about 100 seconds.

O'Brien (1964) has also shown that the flux of trapped radiation increases when precipitation takes place instead of diminishing, which would be expected if the trapped particles were simply dumped into the atmosphere. An acceleration mechanism seems to influence precipitated and trapped particles simultaneously.

Finally, O'Brien (1964) has demonstrated that the precipitation is highly energy dependent. There was no significant ($< 10\%$) precipitation or change in the flux of electrons of energy greater than 1.5 Mev observed in the middle of a strong burst of electrons of energy above 40 kev. This demonstrates that the precipitation could not be due simply to a lowering of the mirror point through a decrease in the geomagnetic field, since such a mechanism would be active over the whole spectrum.

Taken together, this new evidence clearly demonstrates that the precipitated electrons which produce aurora and ionospheric ionization are not produced by simple dumping of trapped electrons into the atmosphere. An acceleration mechanism must be involved. This mechanism must be one that can act with full strength very quickly (in a fraction of a second) and it should not change the flux of Mev electrons more than 10% when the simultaneous changes for trapped electrons of energy above 40 kev is a hundredfold, and of the precipitated electron flux above 40 kev is more than three orders of magnitude.

Table 1

Precipitated Electrons

No.	Reference	Flux (above the atmosphere)		Spectrum or energy range	Time of obs.	Place of observat. geomagn. lat.	Visible aurora		Magn. disturb.	Radio-wave absorpt.	Method of measur.	Remarks
		Number of particles	Energy				Intens.	Location with regard to part. measurement				
1a	Davis et al. (1960)	$N(E \geq 10\ kev) = 2-6 \cdot 10^7\ (cm^2\ sec\ ster)^{-1}$	$0.5-2.5$ erg $(cm^2\ sec\ ster)^{-1}$ $8\ kev < E < 100$	$N(>E) \sim E^{-1}$ for $5\ kev < E < 50\ kev$	Jan. 26, 1958 0421 UT	Churchill, $\Lambda = 68.8°N$	Fading rayed structure and const. diffuse surface of IBC ~ I; after break-up.	Passed through rayed structure during ascent, and through diffuse surface on both ways. Peak altit. 178 km.			Rocket scintill.	Protons present. El. flux isotropic within ±15% between magn. zenith angles 9° and 81°.
1b	Davis et al. (1960)		< 0.01 erg $(cm^2\ sec\ ster)^{-1}$	$8\ kev < E < 100\ kev$	Mar. 16, 1958 0454 UT	Churchill, $\Lambda = 68.8°N$		No penetrat. Weak arc moved to the north.			Rocket scintill.	Protons present.
1c	Davis et al. (1960)		< 0.06 erg $(cm^2\ sec\ ster)^{-1}$	$8\ kev < E < 100\ kev$	Mar. 22, 1958 0641 UT	Churchill, $\Lambda = 68.8°N$		No penetrat. Fading arc moved to south.			Rocket scintill.	Protons present.
1d	Davis et al. (1960)		< 0.02 erg $(cm^2\ sec\ ster)^{-1}$	$8\ kev < E < 100\ kev$	Nov. 16, 1958 0658 UT	Churchill, $\Lambda = 68.8°N$		No penetrat. Bright arc just to the north.			Rocket scintill.	Protons present.
1e	Davis et al. (1960)	$< 10^9\ (cm^2\ sec\ ster)^{-1}$ $30\ ev < E < 1000\ ev$			During 1a, b, c, d	Churchill, $\Lambda = 68.8°N$						
2a	McIlwain (1960)	$N(> 3\ kev) = 2.1 . 10^8\ (cm^2\ sec\ ster)^{-1}$ *	1.7 erg $(cm^2\ sec\ ster)^{-1}$ $E > 3$ kev	$N(>E) = 3.9 \cdot 10^8$* $\exp(-E/5\ kev)$ electrons $(cm^2\ sec\ ster)^{-1}$	Feb. 22, 1958 0537 UT	Churchill, $\Lambda = 68.8°N$	Faint glow	Passed through the aurora. Peak altitude 120 km.			Rocket scintill.	Protons present.
2b	McIlwain (1960)	$N(E \sim 6\ kev) = 5.10^{10}\ (cm^2\ sec\ ster)^{-1}$	2000 erg $cm^{-2}\ sec^{-1}$	Approx. monoenergetic $E \sim 6$ kev	Feb. 25, 1958 0551 UT	Churchill, $\Lambda = 68.8°N$	Bright arc; after break-up	Passed through the aurora. Peak altitude 120 km	$\Delta X > 1000\gamma$		Rocket scintill.	No protons present.
3	McDiarmid et al. (1962)	$\leq 2.10^6\ cm^{-2}\ sec^{-1}$ for $E > 30$ kev		$N(>E) \sim \exp(-E/22\ kev)$ $E > 30$ kev	Oct. 28, 1960 1223 UT (about sunrise)	Churchill, $\Lambda = 68.8°N$			$\Delta Z > 1000\gamma$ before and after	~3 db (30 Mc/s)	Rocket GM-tube.	Protons present. El. flux very irregular. Peak alt. 150 km.
4	Van Allen (1957)	$10^6-10^8\ cm^{-2}\ sec^{-1}$	$0.01-1$ erg/cm^2 sec^1	10-100 kev	Summers of 1953-1955	$\Lambda = 54-88°$					Rockoons	Lat. dep. as for visual aurora.
5	Anderson & Enemark (1960)	$\leq 2.10^5\ cm^{-2}\ sec^{-1}$ for $E > 25$ kev	0.1 erg $cm^{-2}\ sec^{-1}$ for $E > 25$ kev	$N(>E) \sim e^{-E/28}$ for $E > 25$ kev	Aug. 18, 1959 0745 UT	Churchill, $\Lambda = 68.8°N$	Strong active auroral forms overhead		$\Delta Z \sim 250\gamma$	≤ 1.5 db at 30 Mc/s	Balloon x-rays	X-rays present 40% of time. Poor correl. with visible aurora.
		$10^5\ cm^{-2}\ sec^{-1}$ for $E > 25$ kev										Time average over many days.
6	Winckler (1960)	$8.10^9\ cm^{-2}\ sec^{-1}$ for $E > 40$ kev			Sep. 23, 1957 1050 UT	Minneapolis $\Lambda \sim 55°N$	Very strong ray structure at 30° elevation		Weak dist. (during recovery phase of storm)		Balloon x-rays	
7	Bhavsar (1962)	$\leq 10^9\ cm^{-2}\ sec^{-1}$ for $E > 22$ kev		$N(>E) = 0.66 . 10^{15} . E^{-5}\ cm^{-2}\ sec^{-1}$ for $E > 22$ kev	May 12, 1959	Minneapolis $\Lambda \sim 55°N$	Strong overhead aurora				Balloon x-rays	
8	Anderson (1962)	$\sim 10^7\ cm^{-2}\ sec^{-1}$ for $E > 25$ kev			Mar. 27-28, 1961 ~1100 UT	Fairbanks $\Lambda = 64.5°N$	No apprec. visual aurora				Balloon x-rays	No correl. visual aurora x-rays.
9	Anderson & DeWitt (1963)	$5.10^7\ cm^{-2}\ sec^{-1}$ for $E > 25$ kev	3 erg $cm^{-2}\ sec^{-1}$	$N(>E) \sim E^{-4}$	Mar. 5, 1962 1320 UT	Fairbanks $\Lambda = 64.5°N$	Strong glow over entire sky; over. int. ~60 kR			~6 db (riometer)	Balloon x-rays	Very good correl. visual aurora x-rays.
10	Krasovskii et al. (1962)		10^{-2} to > 20 erg/cm^2 sec ster	Equivalent energy most often 14 kev	1958	Over a very wide latitude range					Sputnik 3	Neither energy flux nor spectrum depend significantly on pitch angle.
11	O'Brien (1962a)	Aver. $10^4\ (cm^2\ sec\ ster)^{-1}$ for $E > 40$ kev	$\geq 0.6.10^{-3}$ erg $(cm^2\ sec\ ster)^{-1}$ for $E > 40$ kev		June 30-July 2, 1961	L ~2-10			$K_p = 0-4$ No correl. with magn. act.		Injun I, 12 passes during period of rapid spin	Occurs more on day side than on night side; uncorrel. with lat. and long. of observ.
12	O'Brien & Loughlin (1962)	$6.10^7\ (cm^2\ sec\ ster)^{-1}$ for $E > 40$ kev $[10^{10}\ (cm^2\ sec\ ster)^{-1}$ for $E > 10$ kev$]$	400 erg $(cm^2\ sec\ ster)^{-1}$ for $E > 1$ kev	$N(E) \sim E^{-5}$ for $E > 10$ kev	Sep. 25, 1961 2237:10 UT LT 1835	Lat. 59.0° Long. 303° L 8.82 Alt. 1011 km			Magn. disturbance		Injun I	Measured part. were not precip. but there is evidence that electron flux was isotropic.
		$3.10^6\ (cm^2\ sec\ ster)^{-1}$ for $E > 40$ kev $[6.10^{10}\ (cm^2\ sec\ ster)^{-1}$ for $E > 0]$		$N(E) \sim \exp(-E/6)$ Very rapid variat. in spectrum	Sep. 25, 1961 2236:25 UT LT 1835	Lat. 57.3 Log 300° L 8.04 Act. 1011 km						
13	O'Brien (1962b)	$4.10^3\ (cm^2\ sec\ ster)^{-1}$ $8.10^3\ (cm^2\ sec\ ster)^{-1}$ $4.10^4\ (cm^2\ sec\ ster)^{-1}$ $10^5\ (cm^2\ sec\ ster)^{-1}$ $7.10^4\ (cm^2\ sec\ ster)^{-1}$ $6.10^4\ (cm^2\ sec\ ster)^{-1}$		$E > 40$ kev	June 29-Sep. 6, 1961	$\cos^{-1}(L^{-1/2})$ = 45-50° 50-55° 55-60° 60-65° 65-70° 70-75°					Injun I	Aver. intens. at 1000 km altitude. Only order of magnitude significant.
14	O'Brien et al. (1962)	$3.10^6\ (cm^2\ sec\ ster)^{-1}$ for $E > 40$ kev	~1 erg $(cm^2\ sec\ ster)^{-1}$ for $E > 40$ kev	$N(E) \sim E^{-3}$	July 21, 1961 ~1600 UT	L ~ 5.3					Injun I	
		$[\sim 10^8\ (cm^2\ sec\ ster)^{-1}$ for $E > 5$ kev$]$	~9 erg $(cm^2\ sec\ ster)^{-1}$ $1\ kev < E < 40$ kev	$N(E) \sim E^{-3}$							Injun I	

Table 1 (Continued)

No.	Reference	Flux (above the atmosphere): Number of particles	Flux (above the atmosphere): Energy	Spectrum or energy range	Time of obs.	Place of observat. geomagn. lat.	Visible aurora: Intens.	Visible aurora: Location with regard to part. measurement	Magn. disturb.	Radio-wave absorpt.	Method of measur.	Remarks
15	Mann et al. (1963)	4.10^4 (cm^2 sec ster)$^{-1}$ for $80 < E < 108$ kev		N(E) ≈ exp (-E/5 kev)	1500 UT Sep. 1 – -0130 UT Sep. 2, 1961	1/4 to 1/3 of a great circle; in high latitudes			Correl. with magn. disturb.		Discoverer 29 magnetic el. spectromet.	Polar orbit with altitude varying between 160 and 610 km. Directional measurements along radius vector from earths center.
		2.10^5 (cm^2 sec ster)$^{-1}$ for $E > 80$ kev		Two groups of spectra: N(E) ≈ exp (-E/25 ± 5) and N(E) ≈ exp (-E/42 ± 3)	Aug. 30- Sep. 3, 1961	In the auroral zones			Correl. with magn. disturb.		Discoverer 29 magnetic el. spectromet.	
16	Stilwell (1963)	~10^8 (cm^2 sec ster)$^{-1}$ for $E > 10$ kev	~2 erg (cm^2 sec ster)$^{-1}$ for $E > 10$ kev	N(E) ≈ exp (-E/4) $E > 10$ kev Mean energy < 10 kev	Mar. 3, 1963 0721 UT LT-2220	L = 8-10	~20 kR of λ3914Å	Along the field line the satell. is on			Injun 3 Rev. 994	Angular distrib. isotropic
17	McDiarmid et al. (1963)	$3 \cdot 10^4$ (cm^2 sec ster)$^{-1}$ for $E > 40$ kev	Aver. value correspond to exponential equival. mean spectrum at $\Lambda = 65°$	Equiv. mean spectrum at $\Lambda = 65°$ $N(E) = 2.10^3 \cdot e^{-E/41}$ el (cm^2 sec ster kev)$^{-1}$ or	Oct. 1962– Jan. 1963	Invariant lat. $\Lambda = 65°$			$K_p \leq 4^-$		Alouette	Average values at peak of latitude distribution.
		$1.9 \cdot 10^3$ (cm^2 sec ster)$^{-1}$ for $E > 250$ kev	0.03 erg (cm^2 sec)$^{-1}$	$N(E) = 8 \cdot 10^8$ $E^{-2.8}$ el (cm^2 sec ster)$^{-1}$ for $40 < E < 250$ kev)	Oct. 1962– Jan. 1963	Invariant lat. $\Lambda = 60°$			$K_p \leq 4^-$		Alouette	Average values at peak of latitude distribution.
		$3 \cdot 10^5$ (cm^2 sec ster)$^{-1}$ for $E > 40$ kev	Aver. value correspond to exponential equival. mean spectrum at $\Lambda = 65°$	Equiv. mean spectrum at $\Lambda = 65°$ $N(>E) = 4 \cdot 10^4$ $e^{-E/30}$ el (cm^2 sec ster kev)$^{-1}$ or	Oct. 1962– Jan. 1963	Invariant lat. $\Lambda = 65°$			$K_p > 4^+$		Alouette	Average values at peak of latitude distribution.
		$2.6 \cdot 10^3$ (cm^2 sec ster)$^{-1}$ for $E > 250$ kev	0.3 erg (cm^2 sec)$^{-1}$	$N(>E) = 4.4 \cdot 10^{11} \cdot E^{-3.9}$ el (cm^2 sec ster)$^{-1}$ (for $40 < E < 250$ kev)	Oct. 1962– Jan. 1963	Invariant lat. $\Lambda = 60°$			$K_p \geq 4^+$		Alouette	Average values at peak of latitude distribution.
18	O'Brien (1964) O'Brien and Taylor (1964)	Average: $4 \cdot 10^5$ cm^{-2} sec^{-1} for $E > 40$ kev	Average: 4 erg cm^{-2} sec^{-1} for $E > 1$ kev	Equiv. mean spectrum at $\Lambda = 65°$ $N(E) = 7.8 \cdot 10^7$ $e^{-E/5.7}$ el (cm^2 sec kev)$^{-1}$ or $N(>E) = 1.4 \cdot 10^9$ $E^{-2.2}$ el. cm^{-2} sec^{-1} (for $1 < E < 40$ kev)	First months of 1963	Invariant lat. $\Lambda \sim 65°$	$2\left(^{+4}_{-1.5}\right)$kR	On the same field line where the part. were measured			Injun 3	Average values at peak of latitude distribution. 100-1000 times less at subauroral lat. Variations of a factor of 10^5 in auroral zone.
19a	Sharp et al. (1964b)	Max. 10^8 el/cm^2 sec ster above 2 kev		$N(E) \approx e^{-E/8}$ in burst	March 1, 1962 10:40 UT	Over Alaska		Homogeneous arc			Total energy scint. detect on board a short-lived polar orbiting satellite.	Very little contribution from protons to energy flux
b	Sharp et al. (1964b)	Max. 8.10^9 el/cm^2 sec ster above 2 kev	Max. ~ 100 ergs/cm^2 sec ster above 2 kev	$N(E) \approx e^{-E/E_0}$ with $E_0 \approx 4 - 9$ kev	March 2, 1962 0918 UT	Over Alaska		Auroral arc				
c	Sharp et al. (1964b)		Max. ~ 100 erg/cm^2 sec ster above 2	$N(E) \approx e^{-E/E_0}$ with $E_0 = 3 - 5$ kev	March 2, 1962 1048 UT	Over Alaska					"	Very little contribution from protons to energy flux.
20a	Sharp et al. (1964c)		0.60 erg/cm^2 sec ster above 0.18 kev	$N(E) \approx e^{-E/E_0}$ with $E_0 \sim 2.2$ kev between 0.18 and 10 kev	May 1963 LT ~ 05	61.3°N 124.9°W geographic coord.					Total energy scint. detector and electro-static retard. detector with postacceleration on board a short-lived polar orbiting satellite.	"Typical Orbits"
			0.035 erg/cm^2 sec ster above 10 kev									
			0.0087 erg/cm^2 sec ster above 31 kev									
b	Sharp et al. (1964c)		0.83 erg/cm^2 sec above 0.18 kev kev	$E_0 = 2.4$ kev between 0.18 and 10 kev	May 1963 LT ~ 05	65.3°N 141.3°W geographic coord.					"	"Typical Orbits"
			0.065 erg/cm^2 sec ster above 10 kev									
c	Sharp et al. (1964c)		0.21 erg/cm^2 sec ster above 0.18 kev	$E_0 = 4.9$ kev between 0.18 and 10 kev	May 1963 LT ~ 05	68.7°N 156.5°W geographic coord.					"	"Typical Orbits"
			0.084 erg/cm^2 sec ster above 10 kev									
d	Sharp et al. (1964c)		0.34 erg/cm^2 sec ster above 0.18 kev	$E_0 = 4.0$ kev between 0.18 and 10 kev	May 1963 LT ~ 05	62.3°N 131.4°W geographic coord.					"	"Typical Orbits"
			0.096 erg/cm^2 sec ster above 10 kev									

Table 1 (Continued)

No.	Reference	Flux (above the atmosphere): Number of particles	Flux (above the atmosphere): Energy	Spectrum or energy range	Time of obs.	Place of observat. geomagn. lat.	Visible aurora: Intens.	Visible aurora: Location with regard to part. measurement	Magn. disturb.	Radio-wave absorpt.	Method of measur.	Remarks
21a	Sharp et al. (1964c)		4.4 ergs/cm^2 sec ster above 0.080 kev 4.4 ergs/cm^2 sec ster above 1.5 kev 0.25 erg/cm^2 sec ster above 21 kev	E_0 = 4.6 kev between 1.5 and 21 kev Cutoff above 1.5 kev	2 Nov. 1963 ~ 20 UT	60.5°S 76.4°E geographic coord.					Total energy scint. detector and electro-static retard. detector with postacceleration on board a short-lived polar orbiting satellite.	Sample of a "representative orbit."
b	Sharp et al. (1964c)		1.1 erg/cm^2 sec ster above 0.080 kev 1.1 erg/cm^2 sec ster above 1.5 kev 0.04 erg/cm^2 sec ster above 21 kev	E_0 = 4.1 kev between 1.5 and 21 kev Cutoff above 1.5 kev	2 Nov 1963 ~ 20 UT	54.5°S 76.1°E geographic coord.					*	Sample of a "representative orbit."
c	Sharp et al. (1964c)		1.2 erg/cm^2 sec ster above 0.080 kev 1.2 erg/cm^2 sec ster above 1.5 kev 0.86 erg/cm^2 sec ster above 21 kev	E_0 = 20 kev between 1.5 and 21 kev Cutoff above 1.5 kev	2 Nov. 1963 ~20 UT	71.5°N 68.6°E geographic coord.					*	Sample of a "representative orbit."
d	Sharp et al. (1964c)		0.63 erg/cm^2 sec ster above 0.080 kev 0.45 erg/cm^2 sec ster above 1.5 kev 0.44 erg/cm^2 sec ster above 21 kev	E_0 = 95 kev between 1.5 and 21 kev	2 Nov. 1963 ~20 UT	62.1°N 114.7°W geographic coord.					*	Sample of a "representative orbit."

*This value is obtained from the energy flux value in the way described by McIlwain (1960). It is, however, a factor of about 2π smaller than the value given by McIlwain himself.

Table 2

Precipitated Protons (and other ions)

No.	Reference	Flux (above the atmosphere): Number of particles	Flux (above the atmosphere): Energy	Spectrum or energy range	Time of observ.	Place of observ. Geomagn. lat.	Visible aurora intensity and location with regard to part. measurement	Magn. disturb.	Radio-wave absorpt.	Method of observ.	Remarks
1a	Davis et al. (1960)	$1.2 \cdot 10^5$ (cm^2 sec ster)$^{-1}$ 100 < E < 800 kev	$3 \cdot 10^{-2}$ erg (cm^2 sec ster)$^{-1}$	$N(>E) \propto E^{-3.2}$	Jan. 26, 1958 0421 UT	Churchill, Λ = 68.8°	Passed through fading rayed structure during ascent and through diffuse surface of IBC I on both ways.			Rocket Scintill.	Definitely protons.
1b	Davis et al. (1960)	$4 \cdot 10^3$ (cm^2 sec ster)$^{-1}$ 100 < E < 800 kev	$1.5 \cdot 10^{-3}$ erg (cm^2 sec ster)$^{-1}$	$N(>E) \propto E^{-1}$	Mar. 16, 1958 0454 UT	Churchill, Λ = 68.8°	No penetrat. of aurora. Weak arc moved to the north.			Rocket Scintill.	
1c	Davis et al. (1960)	$\sim 3 \cdot 10^3$ (cm^2 sec)$^{-1}$ ster)$^{-1}$ 100 < E < 800 kev	$\sim 1.2 \cdot 10^{-3}$ erg (cm^2 sec ster)$^{-1}$	$N(>E) \propto E^{-1.7}$	Mar. 22, 1958 0641 UT	Churchill, Λ = 68.8°	No penetrat. of aurora. Fading arc moved to the south.			Rocket Scintill.	
1d	Davis et al. (1960)	$8.5 \cdot 10^3$ (cm^2 sec ster)$^{-1}$ 100 < E < 800 kev	$2 \cdot 10^{-3}$ erg (cm^2 sec ster)$^{-1}$	$N(>E) \propto E^{-3.3}$	Nov. 16, 1958 0658 UT	Churchill, Λ = 68.8°	No penetrat. Bright arc just to the north.			Rocket Scintill.	
2a	McIlwain (1960)	$2 \cdot 10^5$ (cm^2 sec ster)$^{-1}$ for E > 80 kev		$N(>E) = 2.5 \cdot 10^6 \cdot \exp(-E/30)$ (cm^2 sec ster)$^{-1}$ for 80 < E < 200 kev	Feb. 22, 1958 0537 UT	Churchill, Λ = 68.8°	Passed through a faint glow			Rocket Scintill.	Most probably protons.
2b	McIlwain (1960)	< 4.10^3 (cm^2 sec ster)$^{-1}$ for E > 100 kev			Feb. 22, 1958 0551 UT	Churchill, Λ = 68.8°	Passed through bright arc (after break up of aurora)				
3	McDiarmid et al. (1962)	$3 \cdot 10^3$ cm^{-2} sec^{-1} for E > 500 kev			Oct. 28, 1960 1223 UT	Churchill, Λ = 68.8°	*	$\Delta Z > 1000\gamma$	~3 db (30 Mc/s)	Rocket GM tube	

Figure Captions

Fig. 4.1—Data from a northbound pass of Injun 3 over North America, which shows simultaneous detection of an aurora, of the precipitated electrons (pitch angle $\sim 50°$) partially responsible for causing it, and of trapped electrons. Note the approach to isotropy of the particle flux over the aurora. No attempt has been made to subtract the low-latitude contamination of the photometer signal, part of which was the detection of Cleveland, Ohio, and its surrounds. (After O'Brien and Taylor, 1964).

Fig. 4.2—Samples of precipitated fluxes over North America in January 1963. Each point is an 8-sec average of thirty-two measurements made at half-integral values of L. The solid line gives the average flux. (After O'Brien, 1964.)

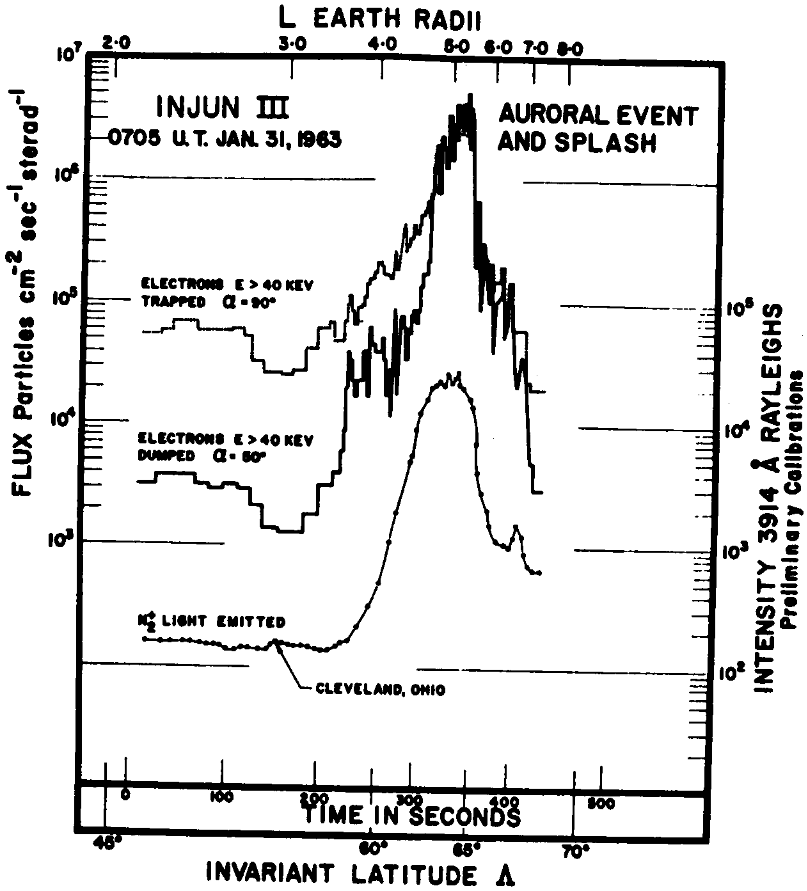
Fig. 4.3—Percentage of passes in which the intensity of precipitated electrons with energies greater than 40 kev is greater than 1.5×10^4 cm^{-2} sec^{-1} $sterad^{-1}$ plotted against invariant latitude. (After McDiarmid et al., 1963.)

Fig. 4.4—Intensity of 3914 Å auroral light averaged over 4 sec at half-integral values of L in about fifty passes of Injun 3 early in 1963. (After O'Brien and Taylor, 1964.)

Fig. 4.5—Comparison of the latitude, or L profile, of precipitation for two successive passes at about the same local time. Arrows illustrate range of fluctuation of intensities at given locations. (After O'Brien, 1964.)

Fig. 4.6—Illustration that the flux of precipitated electrons (in A) varies more with K_p than does the omnidirectional flux (mainly of trapped electrons) in the equatorial plane (in B). Each point shows the maximum respective flux encountered on an outer-zone pass. (After O'Brien, 1964.)

Fig. 4.7—Variation of the northern boundary of trapping with K_p during a geomagnetic storm, as observed by Injun 1 at a height of about 1000 km. (After Maehlum and O'Brien, 1963.)



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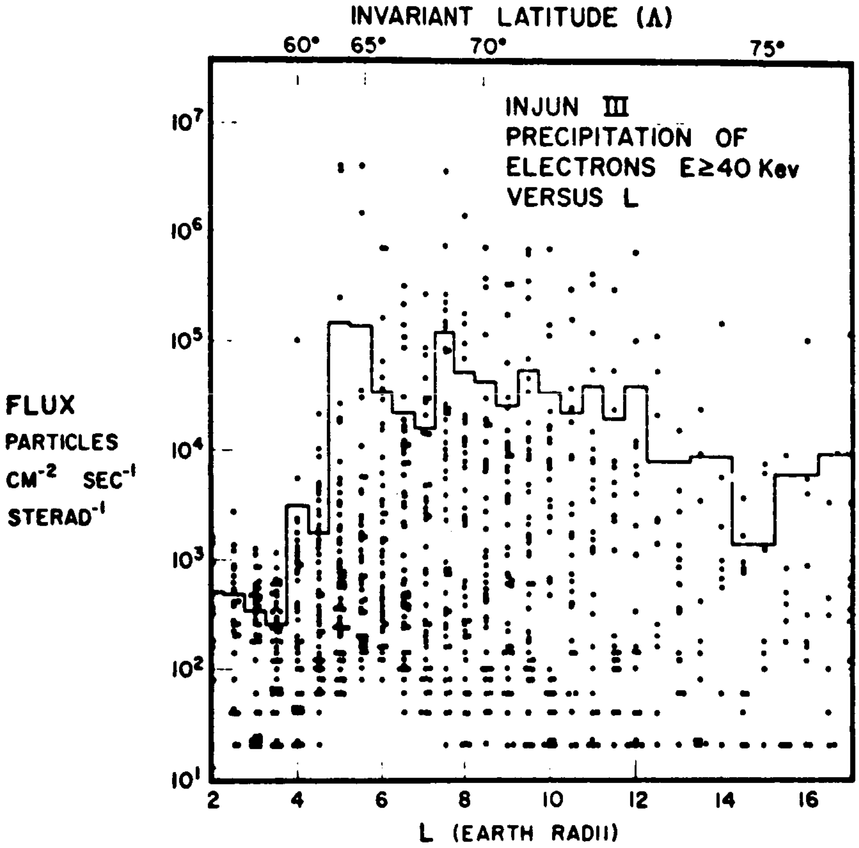

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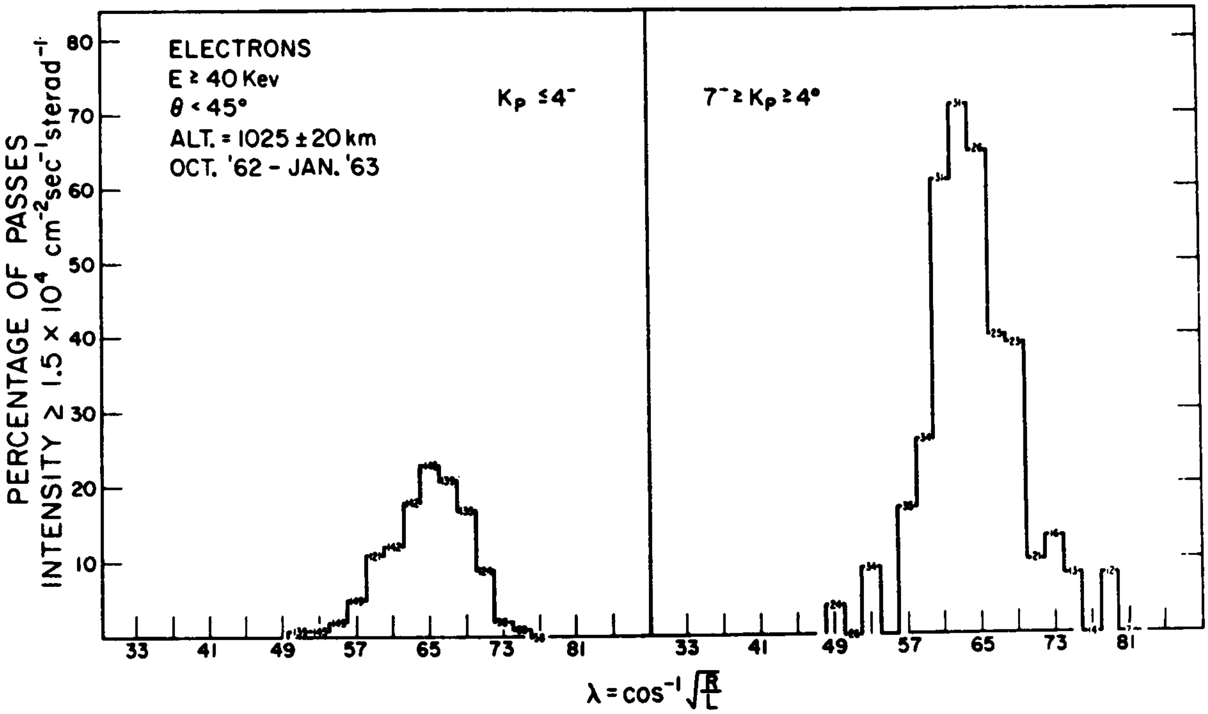

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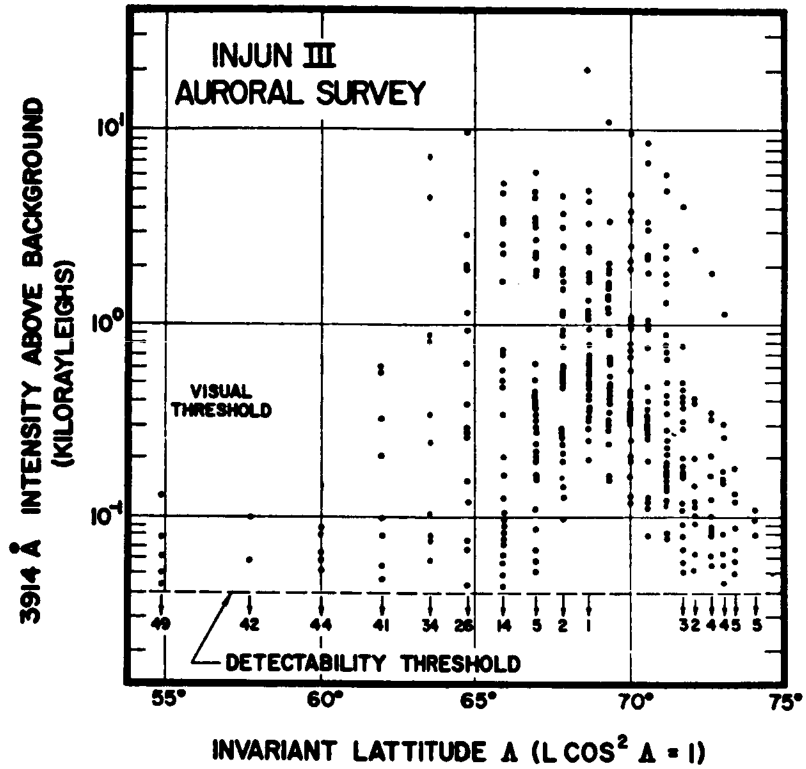

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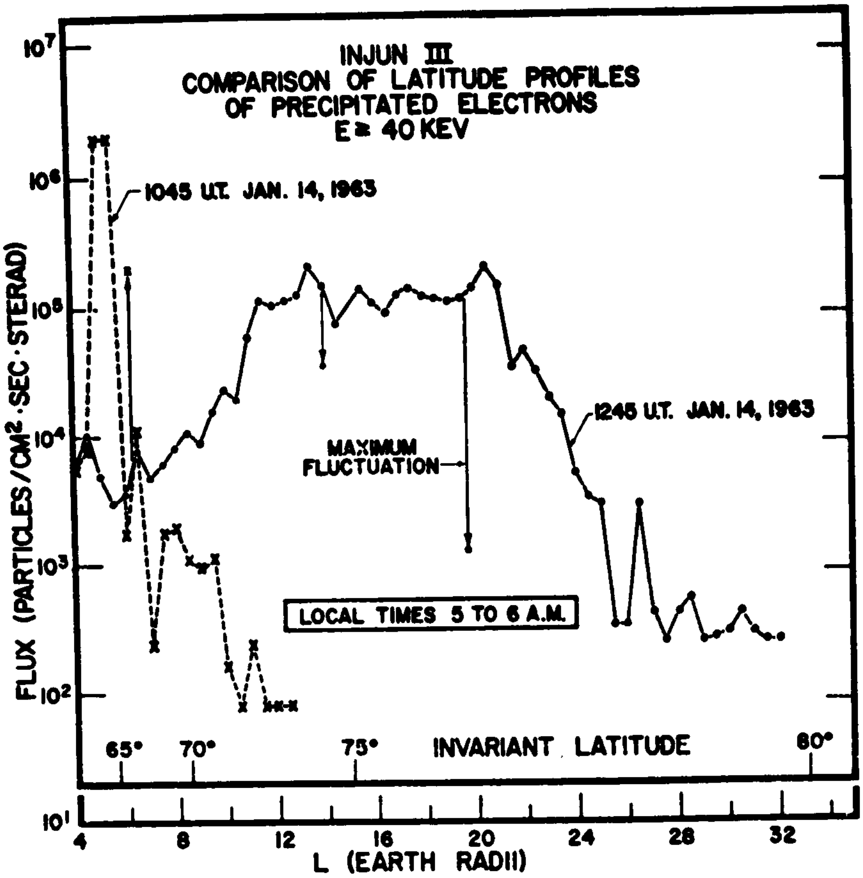

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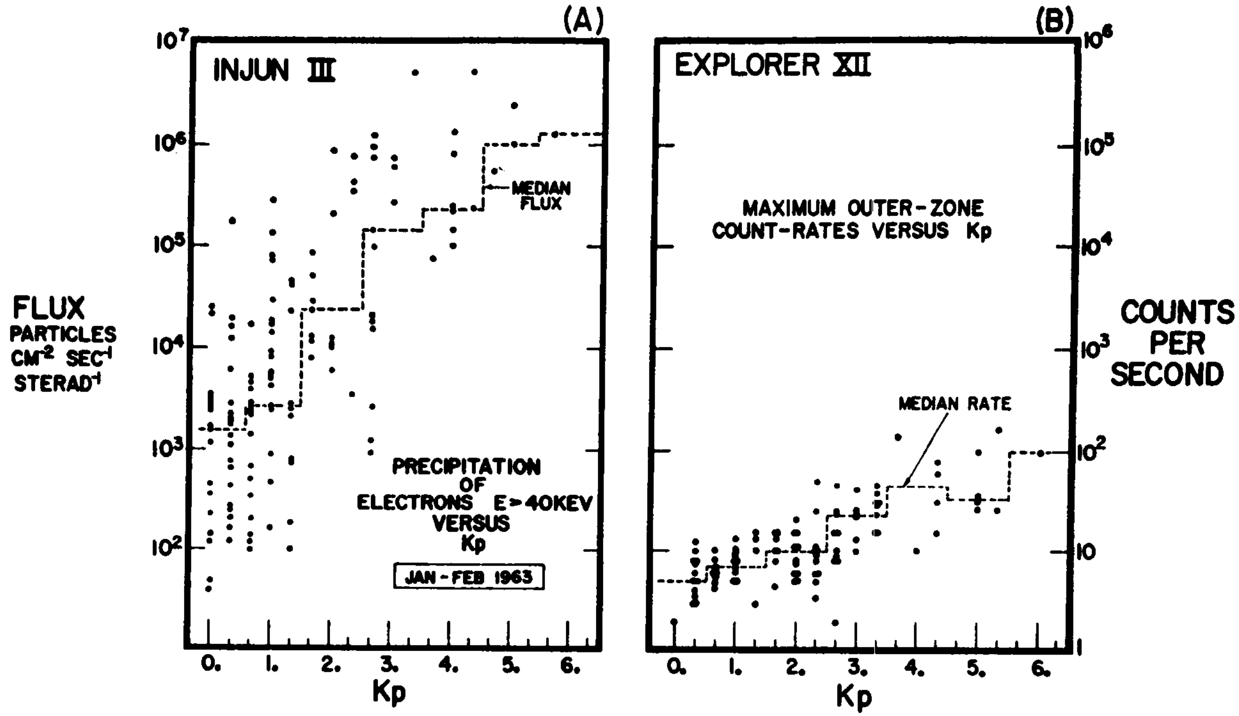

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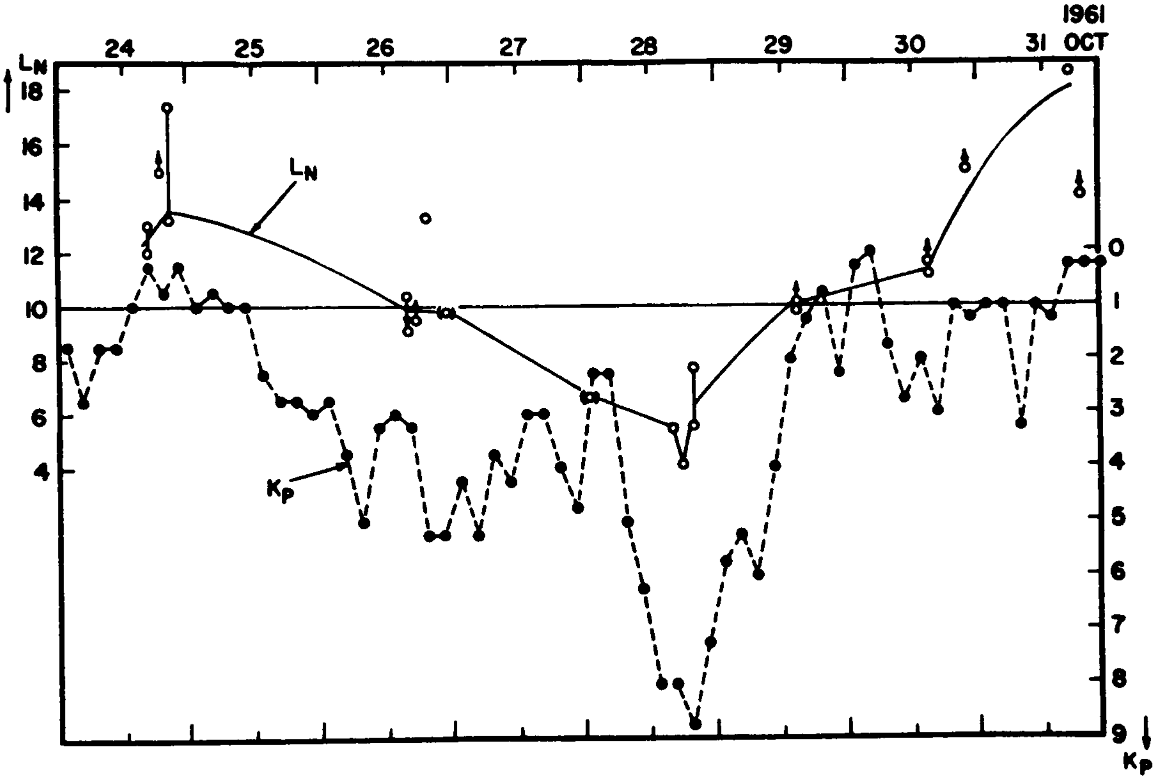

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5. Theoretical Models

1. Introduction

In the last few years many new observational facts have been added to the picture of the aurora. Important new information has been obtained primarily from satellites, but also through detailed synoptic studies of individual auroral storms on the basis of allsky camera recordings taken during IGY.

Some important examples of such new information, some of which have been mentioned earlier in this review, are the following. Electrons are precipitated into the atmosphere over a very wide latitude range, with the maximum intensity in the auroral zone where some precipitation always takes place. The flux of trapped electrons of energy above 40 kev increases simultaneously with the precipitated flux. The increase is such that isotropy over the upper atmosphere is approached. The precipitated flux has never been found to be greater than the trapped flux.

The precipitation mechanism has been found to be energy dependent. During strong precipitation of electrons of energy greater than 40 kev the flux of Mev electrons was not significantly changed. During strong storms the poleward boundary, L_N, of the precipitation zone is very distinct and may be located at L-values as low as 4. During the quiet phase no aurora is seen on the poleward side of a certain L-value, probably identical with the L_N boundary. Following the break up, the aurora may extend rapidly polewards from the pre-break-up position as far as 10° of latitude or even more. Then it returns slowly toward the low L boundary again. It has also been definitely established that the energy content of the particles precipitated into the atmosphere in a period of the order of a minute may be orders of magnitude greater than the total energy content of the particles trapped in the corresponding field tube. Both virtually monoenergetic electrons and exponential and power law spectra have been observed in aurora. Evidence has accumulated that the local properties of the geomagnetic field in the upper atmosphere is not very important for the aurora. This indicates that drift motion around the earth of the particles which at some stage are precipitated into the atmosphere is not an important process. It has been proven that discharge acceleration within the ionosphere is not necessary for auroral production (O'Brien, 1962b).

Special chapters in this book are devoted to the description of some theoretical models of the relations between solar disturbances and geophysical effects, thereamong aurora. The reader is referred to them for details about the models.

The development of our experimental knowledge about the aurora and of our understanding of the physical processes in it is very rapid at present. It is, therefore, not a suitable stage for summing up and comparing experimental data with theoretical models. In this section only a very short summary of some main lines of proposed theories will be given in connection with a comparison of the models with some observational data which seem to be significant today.

2. Some Specifications of the Theoretical Problem.

There is a general agreement that auroras, as well as magnetic storms, are caused by plasma streams which are emitted from disturbance centers on the sun. The problem of the interaction between the solar plasma and the geomagnetic field is one of great complexity, which has not as yet been solved in quantitative detail in a rigorous way. Simplified models have been used and the broad picture obtained differs very much depending on the theoretical approach.

Observations by Mariner II (Snyder and Neugebauer, 1963) and other space vehicles have shown that the interplanetary space usually has a number density, N, of charged particles of the order 10 cm^{-3}, the equivalent temperature, T, obtained from the velocity dispersion of the plasma, for instance, is typically a few times 10^5 degrees Kelvin, there exists a magnetic field, B, of the order of a few gamma, mostly directed about 45° from the sun-earth line in the equatorial plane (see e.g. Ness, 1964). This means that the mean free path for Coulomb collision is a few astronomical units (see e.g. Parker, 1962, Kellogg, 1962, and Alfvén and Fälthammar 1963). In the plasma beams from disturbance centers on the sun somewhat higher values (but less than one order of magnitude higher) of N, B and T have been observed. A plasma of the mentioned characteristics is a "low density plasma" when the system sun-earth is considered (cf. e.g. Alfvén and Fälthammar, 1963). For such a plasma the ordinary fluid theory cannot be applied, as the statistically defined parameters have no meaning. Especially, the electric conductivity is not defined and the hypothesis that the magnetic field lines are "frozen" into the plasma may possibly not be applicable. Electric fields may exist along the geomagnetic field lines (Persson, 1963, Alfvén and Fälthammar, 1963). No macroscopic theory for the interaction of a low density plasma with the geomagnetic field seems to have been developed.

The plasma contained in the magnetosphere is probably also a low-density plasma, at least during disturbed conditions according to Alfvén and Fälthammar (1963) and Alfvén et al. (1964).

Although the theoretical basis for fluid-dynamic models of the interaction between the solar plasma and the geomagnetic field, which have been proposed, thus must be considered as weak at the present time, some of the characteristics of these models agree well with observations. They all require that the geomagnetic field shall be enclosed in a finite region around the earth, the so-called magnetosphere. A discontinuity in the magnetic field has been observed by Explorers XII, XIV and XVIII (Cahill and Amazeen, 1963; Freeman et al., 1963; Ness, 1964) at distances of about 10 earth radii on the side facing the sun, where it is expected to be according to the fluid-theory models.

The discussion below will be limited to a comparison of some observations with results of two fundamentally different types of theoretical approach, namely the fluid-dynamic (macroscopic) one, leading to a closed magnetosphere, and a microscopic model in which the plasma penetrates into the geomagnetic field to some extent.

3. Closed Magnetosphere Models

Chapman and Ferraro (1930, 1931, 1932, 1933) first discussed a model containing a confinement of the geomagnetic field lines in a finite volume around the earth. They considered a neutral unmagnetized plasma beam approaching the earth with a velocity of about 1000 km/sec and applied the boundary condition that the magnetic pressure is equal to the dynamic pressure of the plasma. Their model did not contain any details about the generation of aurora. The basic concept treated by Chapman and Ferraro has in recent years been further developed. Accurate calculations of the shape of the boundary of the magnetosphere have been made, the most recent and accurate one being that of Mead and Beard (1964). Extensive qualitative models of the geophysical effects caused by the solar plasma have been worked out on the basis of the Chapman-Ferraro model. The most comprehensive one is that of Axford and Hines (1961). In this model the acceleration of the particles is due to the plasma in the interface between magnetosphere and solar beam being convected into the interior of the magnetosphere, during which process it is adiabatically compressed. The theory is described in detail in Chapter

The closed magnetosphere models are characterized by a distinct boundary between the magnetosphere and the interplanetary medium. No model contains any details about how particles can enter the magnetosphere. For stable flow no particles can pass the boundary, except possibly at the neutral points. As the energy of the particles precipitated into the atmosphere with all probability must originate in the solar beam, one has made hypothesis about how the energy transport takes place over the boundary. Magnetohydrodynamic waves have been proposed. Axford and Hines assumed that some type of viscous interaction takes place at the boundary of the magnetosphere. Other types of instabilities have also been invoked (cf. e.g. Gold, 1962). It seems to be common to all of the proposed ways of energy transport over the magnetospheric boundary that only a minor fraction of the energy content in the solar wind is transferred to the magnetospheric plasma.

The existing fluid theories all are based on the assumption that the magnetic field lines are equipotential lines and are "frozen" into the plasma. Therefore, acceleration of particles inside the magnetosphere must in these models be due to other effects than electrostatic fields along the lines of force. Of known acceleration processes the Fermi and betatron mechanisms and possibly electromagnetic radiation in the VLF band may be of importance in the magnetosphere (see Kaufmann, 1963, for a review). All these mechanisms require a large number of acceleration steps, and therefore fairly long time, and they produce a wide energy spectrum due to statistical fluctuations in the process. It has also been proposed that electric fields perpendicular to the magnetic field lines may cause acceleration of electrons and ions along neutral lines, i.e. lines where the geomagnetic field is zero (see Kaufmann, 1963). The existence of neutral lines has been proposed and their properties discussed by Dungey (1958, 1961, 1963) and by Akasofu and Chapman (1961).

Since the discovery of the radiation belts and up till recently it was fairly generally believed that the trapped radiation was the source of those particles which produce the aurora, as was mentioned in the previous section. The density of trapped radiation was then thought to be three or four orders of magnitude greater than now (cf. e.g. O'Brien, 1963b). It was considered possible that some of the slow acceleration mechanisms mentioned above might be responsible for the acceleration of the particles from their energy in the solar wind to that observed inside the magnetosphere, although no quantitative theories existed neither for the particle transport into the magnetosphere nor for the acceleration of the particles in the outer radiation belt. An important unsolved problem was and is still how the electrons, which are most important in aurora, are energized, since most of the mentioned acceleration mechanisms give most energy in the ions.

The precipitation of the primary aurora particles into the atmosphere was thought to be produced by more or less transient instabilities of various kinds. A number of such were proposed by Akasofu and Chapman (1961), Chamberlain (1961, 1963), Kern (1962) and others. Other studies of possible auroral effects associated with adiabatically invariant motions of trapped charged particles, some of which are scattered into the atmosphere, were those of Chamberlain et al. (1960), Kern and Vestine (1961) and others.

The recent observations mentioned in the introduction to this section have completely changed the picture in regard to the importance of the trapped radiation as source for the aurora.

The fact that precipitated energies have been found sometimes to be several orders of magnitude greater than the total particle energy in the corresponding magnetic field tube (see previous section) shows that dumping without acceleration cannot be the important process for precipitation of electrons into the atmosphere, at least on some occasions. The observations of O'Brien (1964) that the flux of trapped particles always increases when precipitation takes place and is never less than the precipitated flux demonstrates clearly that the trapped radiation is not the source of the precipitated ones but is rather produced by the same acceleration mechanism that accelerates the precipitated electrons.

The observation of energy dependence of the precipitation mechanism (O'Brien, 1964) demonstrates that the precipitation is not due to a lowering of the mirror point by some geomagnetic disturbance, since such a lowering would affect the whole energy spectrum, contrary to what has been observed.

The acceleration mechanism responsible for the production of trapped as well as precipitated particles according to this mentioned picture is unknown. An electrostatic voltage of the order of 10 kilovolt along the magnetic field lines was mentioned as a possible source of acceleration by O'Brien (1964). That electrostatic field acceleration is important in aurora is supported by the observation by McIlwain (1960) of monoenergetic electrons of 6 kev energy in strong aurora. In the closed magnetosphere models that have been presented electrostatic fields along magnetic field lines cannot exist. The mechanism must therefore be an unknown one.

In the described "splash-catcher" model of O'Brien (1962b, 1964) the precipitated electrons are "fresh," i.e. they have existed with the energy they have at precipitation only for a very short time. This means that drift motion around the earth of the source of auroral primaries is not important, which is in agreement with the earlierly mentioned independence of the isoauroral curves on the mirror height.

The recent observations described above have thus modified the early closed magnetospheric models considerably. Some of the observations are even difficult to accommodate in such models. This is true for the very high energy fluxes of precipitated electrons which have been observed. While, in the average, only of the order of one percent of the solar wind energy has to be converted into kinetic energy of precipitated electrons (O'Brien and Taylor, 1964) an appreciable fraction of the solar wind energy has to be given off in electron precipitation during strong magnetic storms. This is difficult to associate with a closed magnetosphere, where energy is transported over the boundary by second order effects.

Another important difficulty with models of the closed magnetosphere type which have been proposed hitherto, is that the solar plasma is supposed to be unmagnetized, whereas observations by a number of space vehicles have shown that the interplanetary plasmas are magnetized. Alfvén (1964) has pointed out that the difference between the two cases with unmagnetized and magnetized solar plasma is more than a question of mathematical method. As the magnetic flux passing through a certain mass of gas must be fairly constant during the motion, a plasma with an initial magnetization may be brought into a stronger field if it is compressed. Thus a plasma with any value of the initial magnetization may be brought into a strong magnetic field. If the initial magnetization is zero this is not the case. The assumption $B=0$ leads therefore to conclusions which are fundamentally different from the assumption $B \neq 0$ even if B is very near zero.

The entire surface of the closed magnetosphere maps into one neutral point in each hemisphere. These are not in the auroral zones and there are no obvious reasons for the precipitation of particles taking place preferably in the auroral zones. Some complicated mechanism, like the one devised by Axford and Hines (1960), is needed to get the aurora in the proper regions of the earth.

The topology of the magnetospheric field lines is very complicated in some regions of the closed models. Aurora shows a fairly high degree of order on the earths surface with arcs often being aligned along L-curves (see e.g., Akasofu, 1963; Akasofu and Chapman, 1962 and Hultqvist, (1962). This corresponds to high degree of order also in the equatorial plane with the processes taking place at about constant distance from the earth, if the field is axisymmetric. If such an auroral arc is projected to the equatorial plane along the field lines in the closed magnetospheric model, the equatorial cross section of which is shown in Fig. 5.1, curves are found which seem to have no relation to simple physical processes. They differ significantly from particle drift surfaces, for instance (Hones, 1964).

4. Model with the Solar Plasma Penetrating into the Geomagnetic Field

Alfvén (1939, 1940, 1950, 1955; Alfvén and Fälthammar, 1963; Alfvén et al., 1964) has pointed out that a low-density magnetized plasma can penetrate into the geomagnetic field through the action of the electric field that is associated with a moving magnetic field. The depth of penetration is determined by the electric and magnetic fields and the temperature in the incoming plasma and not by the dynamic pressure as in hydromagnetic models. The penetration is stopped at a forbidden region, from which electrons and protons may be accelerated down into the atmosphere by an electric field. The acceleration field is thought to be due to charge separation, which takes place during the invasion of the geomagnetic field. The particles from the forbidden zone moving along the field lines reach the auroral latitudes, if the properties of the plasma are in agreement with space vehicle observations. The particles may be accelerated to energies of tens or hundreds of kev.

In the first model of Alfvén it was assumed that no space charges are collected around the earth, but that immediate discharging takes place along the magnetic lines of force as soon as space charges start to build up. Karlsson (1963) has investigated the case of maximal space charge accumulation. He assumed that no discharging at all takes place along the field lines. In that way he found that the general picture derived by Alfvén is preserved when space charges are taken into account. The forbidden zone is, however, smaller and more nearly circular than in the case studied by Alfvén. The general picture is thus not influenced very much by the amount of space charge accumulation.

There seems to be no basic difficulties in incorporating the above mentioned large fluxes of precipitated particles, observed by Winckler et al. (1962) and others, in the Alfvén model. This mechanism may well be active in the presence of simultaneous dumping of trapped particles due to disturbances of the geomagnetic field. For the mechanism to meet the requirements that O'Brien (1962b) has derived from the Injun 1 data, it is necessary that a rapid diffusion of particles scattered into trapped orbits takes place from the forbidden zone into the inner part of the radiation belt. If the quantitative requirements can be met is not known to this author.

Together with other large-scale charge-separation mechanisms, Alfvén's has the difficulty that electrons and protons are expected to be precipitated in two distinctly separated areas over the earth. Spectral observations from the ground as well as satellite observations of particle precipitation (Evans et al., 1964) show that electrons and protons often are precipitated simultaneously in the same auroral form.

Electrostatic acceleration of electrons and protons into the atmosphere is an inherent feature of Alfvén's model. The observations of O'Brien (1962b, 1964) thus fit well into his model in this respect. On the other hand it does not contain the observed discontinuity in the geomagnetic field at about 10 earth radii from the center of the earth, which have been observed by means of Explorers XII, XIV, and XVIII. Alfvén's model was made with the magnetic field of the solar plasma parallel to the earth's magnetic field in the equatorial plane. This direction was originally chosen in order to have the model fit observed diurnal variations in auroral occurrence. Dungey (1961, 1963) has discussed the case with the magnetic field of the solar plasma being antiparallel to the geomagnetic field in the equatorial plane. In that case neutral points or lines occur. The plasma does not penetrate further than to the neutral line and is precipitated from there along the field lines into the atmosphere. Recent laboratory experiments with magnetized plasma beams moving towards and interacting with a dipole magnetic field (Alfvén et al., 1963) have verified that there is a fundamental difference between the cases with parallel and antiparallel magnetic fields in the equator plane.

The observed discontinuity in the magnetic field may thus be due to Dungey's mechanism. Magnetic field measurements on space vehicles seem, however, to indicate that the interplanetary magnetic field lines mostly form only a small angle with the geomagnetic equatorial plane and the component parallel or antiparallel to the geomagnetic field lines is generally small and variable in magnitude and sign (Ness, 1964). In spite of this the discontinuity in the field seems always to have been observed by Explorer XVIII, at least on the side of the earth facing the sun. This does not seem to fit Dungey's model.

It is probable that within the near future space vehicles will provide experimental information that will make it possible to determine which of the two above-mentioned types of approach is relevant to nature – if any.

The theories discussed concern the large scale configuration of the auroral precipitation pattern. For the breakup of aurora and the extremely complicated phenomena that then occur on a global scale (see p. 49) no comprehensive theoretical models exist. The theories for this certainly will have to be sought in the realm of plasma instabilities, a field where the theoretical understanding of many basic phenomena still is poor.

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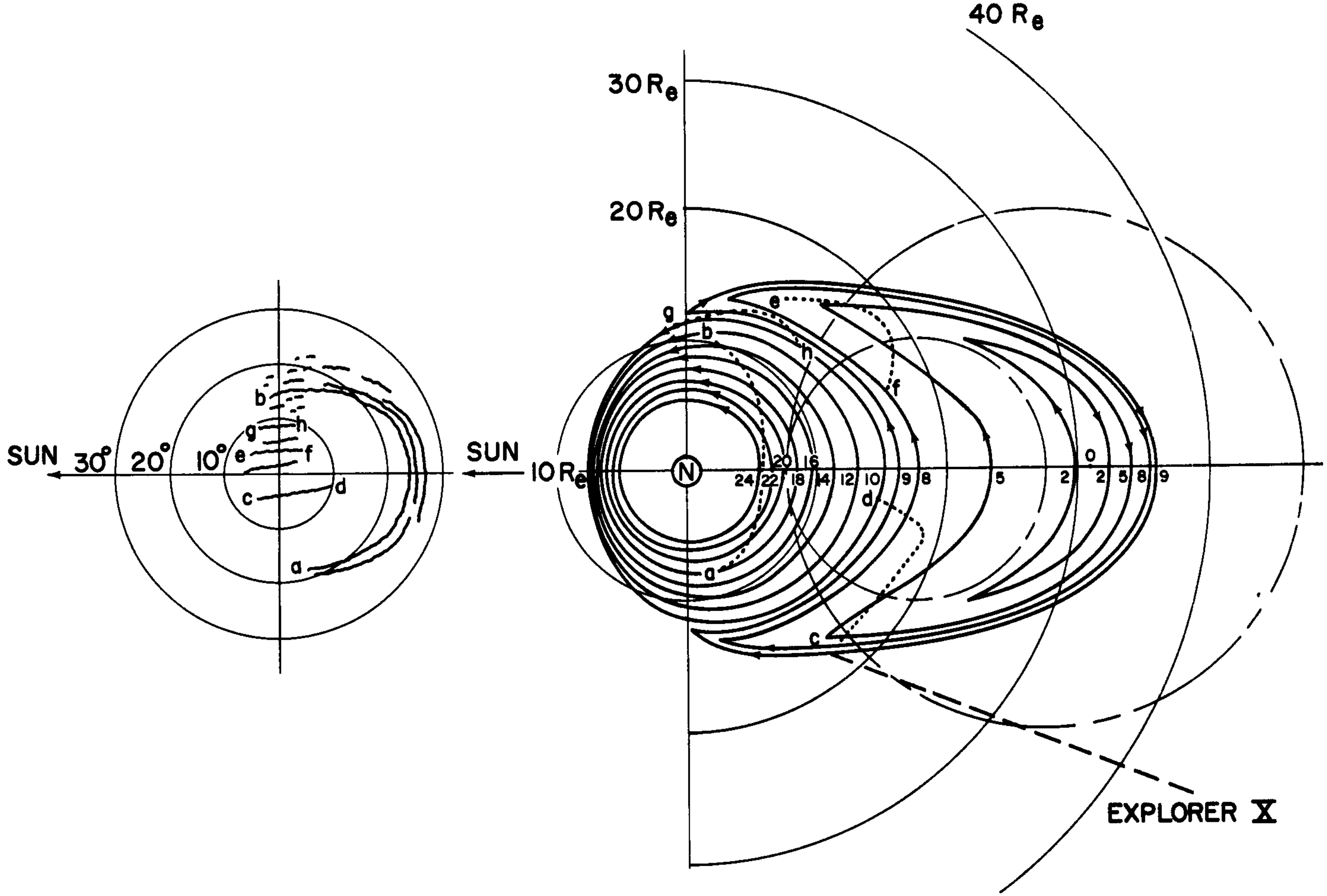
Figure Caption

Fig. 5.1—Projections of auroral arcs along the geomagnetic field lines to the equatorial plane in a closed magnetosphere model. The letters a-h in the two figures indicate corresponding points in the earth's atmosphere and in the geomagnetic equatorial plane (Courtesy, Dr. E. W. Hones, Jr.).



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