Distribution of the Southern Auroral Zone

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Abstract: The historical development of our knowledge of the geographical distribution of auroras in the Antarctic is reviewed. The results for the IGY and later years as given by DAVIS, GARTLEIN, FELDSTEIN, and others are summarized. Data on azimuth of auroral arcs at various hours of the day are presented. The equatorward expansion and broadening of the auroral belt with world-wide features of magnetic storms are noted. Specific instances of auroral belt positions during very great and very weak magnetic disturbances are noted. This belt appears interlinked with the corresponding belt in the Arctic. The spatial relationships to geomagnetic and other geophysical phenomena are summarized.

I. Introduction

Our knowledge of the geographical distribution of auroras in the Southern Hemisphere is necessarily derived from the work of a number of observers, the first of whom on record is Captain COOK, who observed on February 17, 1773, the phenomenon he named the *aurora australis*. There are fewer reported observations of the *aurora australis* than of the *aurora borealis*, in the Northern Hemisphere, as most southern auroral displays occur over ocean areas where they are apt to be unobserved. The southern auroral belt does cross the Antarctic continent, however, and various Antarctic expeditions have reported observations of auroras from land. Since the beginning of the International Geophysical Year (IGY) in 1957, nearly continuous observations have been made at ten or more stations on the Antarctic continent. Rare equatorward expansions of the auroral belt during great magnetic storms have been poorly reported, as this phenomenon can generally be viewed only from ships. However, an extension as far north as Samoa was noted during the great storm of May 14–15, 1921. Although earth satellites have not yet continuously photographed the *aurora australis*, they will eventually be of great value in defining the auroral distribution in the Southern Hemisphere. In the absence of satellite data, it is necessary to rely on results based upon the rather sparse and incomplete observations in lower southern latitudes over the past two centuries, together with the more detailed visual and photographic observations made at some dozen ground stations in Antarctica over periods of from one to several years.

II. Early Auroral Summaries

The first important attempt to collect auroral information on the Southern Hemisphere was made by FRITZ (1873), who summarized observations of the

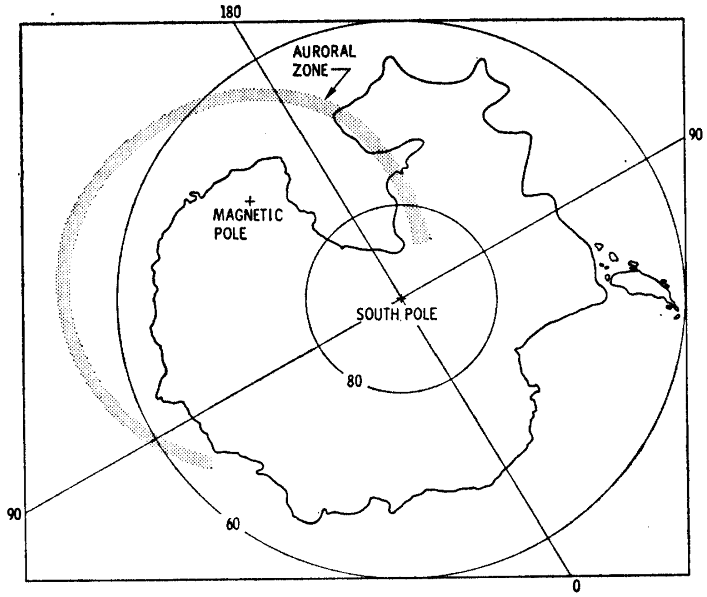
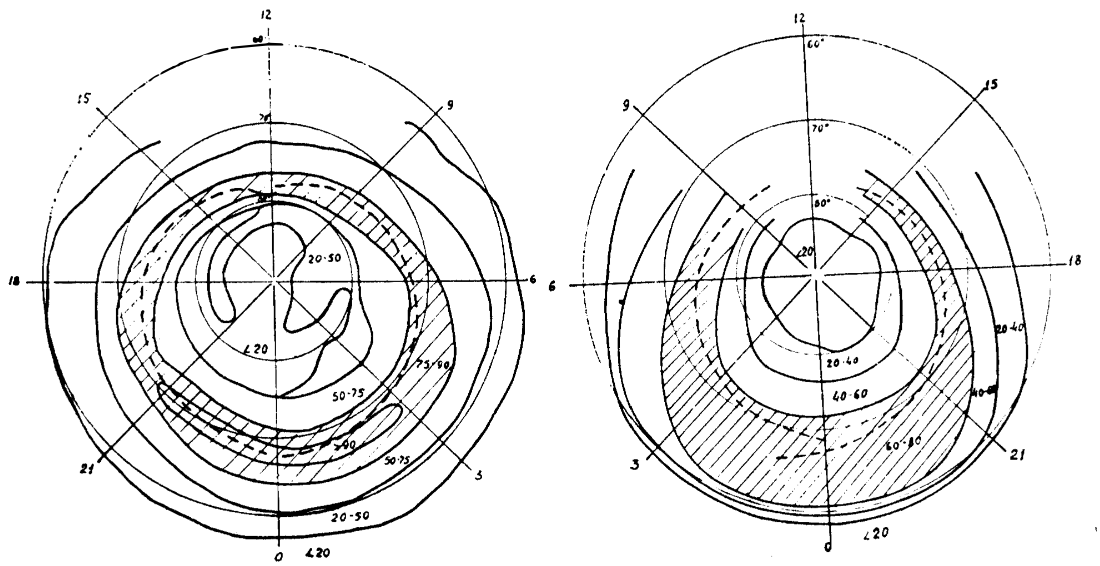


Fig. 1. Early estimate of auroral zone (after GEDDES *and* WHITE*).*



(*a*) (*b*)

Fig. 2. Percentage occurrence of auroras at various locations. (a) Northern Hemisphere, and (b) Southern Hemisphere, geomagnetic hours indicated on meridians (after FELDSTEIN*).*

aurora australis in tabular form. He did not attempt to define the southern auroral zone, which is the belt where nighttime auroras occur most frequently and with highest intensity. In the Northern Hemisphere he found this zone to be near latitude 67°N.

An early attempt to define the southern auroral zone was made by GEDDES and WHITE (1938) based on earlier summaries of data and an extension of studies by DAVIES (1931). Noting that the reported observations of auroras usually range considerably in latitude, GEDDES and WHITE showed the auroral zone as a circular belt with the south geomagnetic pole at its center (Fig. 1). DAVIES had in fact earlier indicated a somewhat wider circular oval. Later summaries were given by VESTINE and SNYDER (1945), GARTLEIN and SPRAGUE (1960), and FELDSTEIN (1960, 1963, 1964), who incorporated the data of the IGY and later years. FELDSTEIN's results in percentages of clear and dark nights are indicated in Fig. 2. The times indicated on meridians are geomagnetic hours.

Conjugate relationships between the zones of midnight auroras in the Northern and Southern Hemispheres have also been discussed (VESTINE and SIBLEY, 1960). These zones, which trace the locus of observed midnight auroras, may be connected by identical lines of force of the geomagnetic field.

In the present paper we review and discuss some of these studies of the Antarctic data, beginning with (b) of Fig. 2.

III. The Antarctic Auroral Oval

A principal achievement of the IGY was the tracing of the geographical distribution of the auroras at hours of the day other than local midnight. It has long been known that individual northern auroral displays undergo a diurnal movement. Moreover, near the center of the auroral zone during 1932–1933 some auroral arcs were reportedly directed from north to south. These features were all brought into greatly sharpened focus by the visual and all-sky camera results of the IGY and later years, which became available largely through the initiative of workers such as GARTLEIN, ELVEY, and others (AKASOFU, 1965; FELDSTEIN, 1960, 1963, 1964; DAVIS, 1962; KHOROSHEVA, 1962; DZUBENKO, 1963). KHOROSHEVA was able to show from actual observations that auroras generally develop in a ring circling the polar cap, with a midnight position corresponding to the conventional auroral zone and a daytime position at a higher latitude. These auroral zone were mapped in detail by FELDSTEIN for nighttime and daytime auroras, as shown in curves 1 and 2 of Fig. 3. The ovals for the Northern and Southern Hemispheres become polar projections of circles taken in the equatorial plane, projected along geomagnetic field lines. These curves are also compared in Fig. 3 with latitudinal distributions of the data of the IGY and other years, relative to the auroral zones. FELDSTEIN estimates that the error in defining the average nighttime auroral zone does not exceed 1° of latitude for the IGY period. This zone also defines the expected orientation of nighttime auroral arcs. Even for the daytime auroras, he estimates an error in average auroral zone position of less than 2° to 3°. These charts are a notable improvement over the previous charts of isochasms given by VESTINE and SNYDER (1945), as the auroral zone of the latter corresponds to nighttime auroras only.

DAVIS (1962) showed that within the auroral zone, auroral arcs are aligned nearly parallel to the earth-sun line, over much of the northern polar cap.

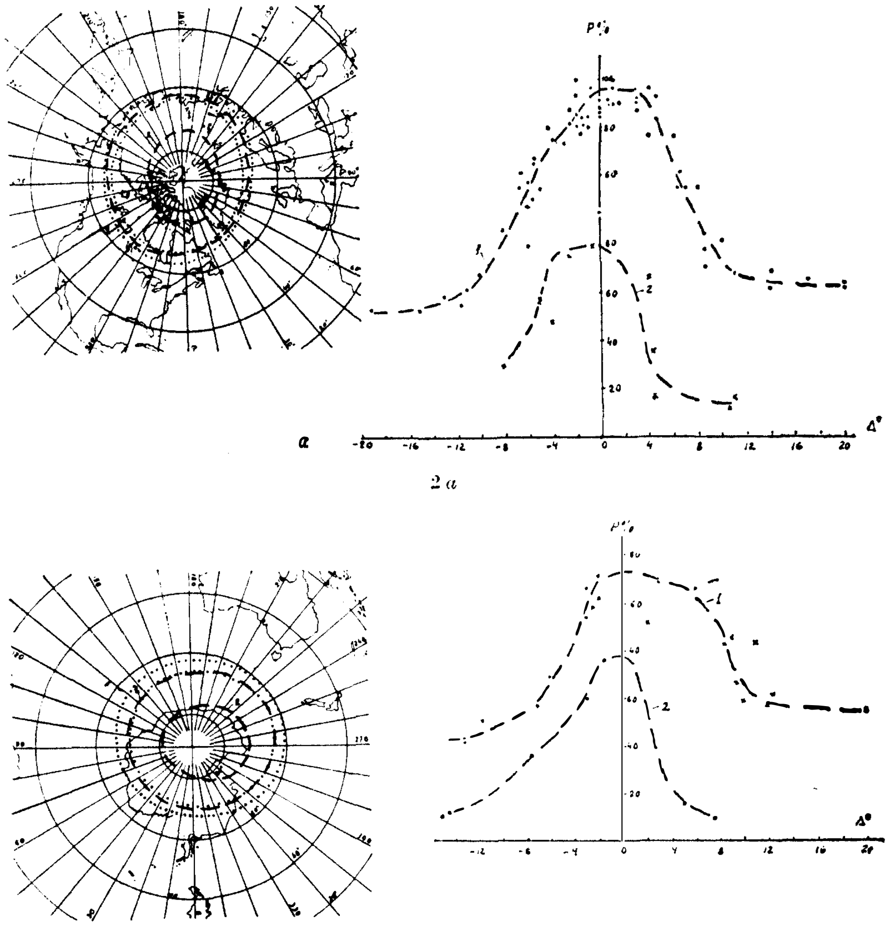


Fig. 3. The zones for midnight auroras are shown as outer broken line (1) and for noon auroras as inner broken line (2); dotted ovals are projections along field lines of circles in the equatorial plane at 5.6 and 7.1 earth radii. Percentage frequency of nighttime (1) and daytime (2) auroras are shown graphically as a function of latitude measured positively poleward from auroral zones (after FELDSTEIN*).*

Results appear to be less complete for the Antarctic, but presumably should be similar. According to WEILL (1958), arc directions rotate with time of day in the region of the Antarctic polar cap, and are oriented nearly along the earth-sun line. A summary comparison shows that the arc directions in both hemispheres rotate very nearly in accordance with geomagnetic time, with arcs and bands appearing in the geomagnetic meridians near geomagnetic noon and midnight in both the northern and southern polar caps (FELDSTEIN, 1964).

Near midnight, auroral arcs appear approximately tangent to the auroral zone (FELDSTEIN, 1964), or to a curve defined by the reflection points at the base of an earth-encircling shell in which auroral particles have constant longitudinal adiabatic invariant properties (VESTINE and SIBLEY, 1960). Figure 4 shows similar curves more conveniently expressed in terms of equatorial shells of radius L, measured in earth-radii, as obtained by VENKATESAN (1965). The $L=6$ shell corresponds closely to the auroral zone curve for overhead auroras at midnight, and turns out to be very nearly coincident with that of FELDSTEIN. The meaning of an L-shell for daytime auroras is uncertain, as daytime field lines are more distorted, though it is clear that the projection of a ring in the equatorial plane is both convenient and instructive, as originally pointed out by HULTQUIST (1961). The physical basis for this projection is clear, in view of the near-coincidence of equatorial rings with L-shells.

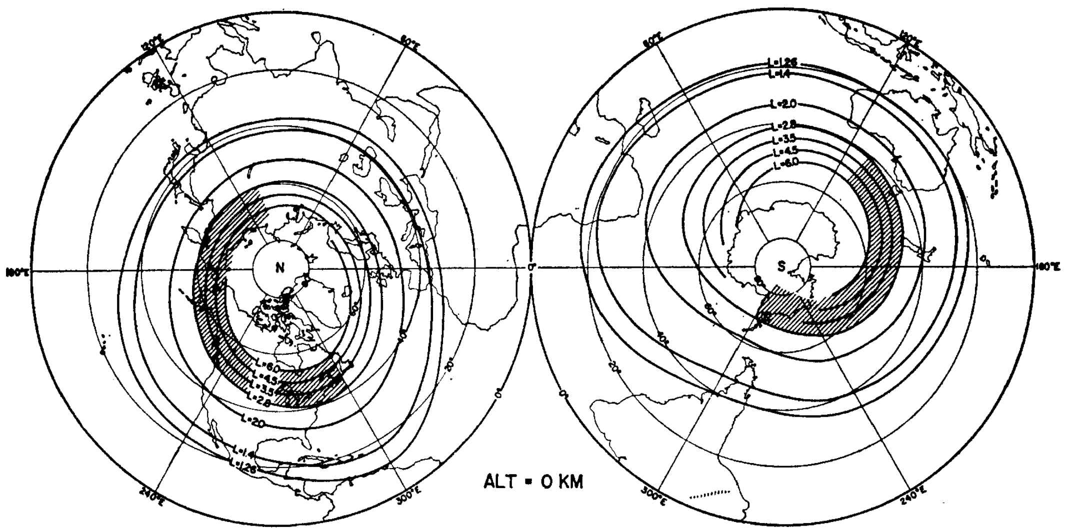


Fig. 4. Expansion of the width of the auroral zone ($L\sim6.0$) to the range $2.8<L<6.0$ at $10^h\ 40^m$ G. M. T., great storm of February 11, 1958.

IV. The Auroral Oval

The curves of Fig. 3 and satellite measurements of particle flux for the outer boundary of the magnetosphere define a physically significant oval related to auroras. This concept of an oval, developed through discussions by FELDSTEIN (1963), KHOROSHEVA (1962), MALVILLE (1959), DAVIS (1962), and others, is shown in Fig. 5, along with a projection over the polar cap of a shell of trapped electrons, measured by FRANK, VAN ALLEN, and CRAVEN (1964). The flux of trapped electrons decreases rapidly toward the poleward side of this projected contour, which lies close to the line of intersection between the ionosphere and the outer boundary of the outer radiation belt. It also serves as the equatorward boundary of the auroral oval defined statistically in Fig. 5 (AKASOFU, 1965).

AKASOFU and CHAPMAN (1963) have shown that the oval expands equatorward with an increase in geomagnetic activity or in the ring-current field, and frequently changes in size or width during geomagnetic disturbances.

An expansion of the oval and its auroral zone curve has long been associated with magnetic disturbances (NAGATA, 1950; AKASOFU and CHAPMAN, 1963),

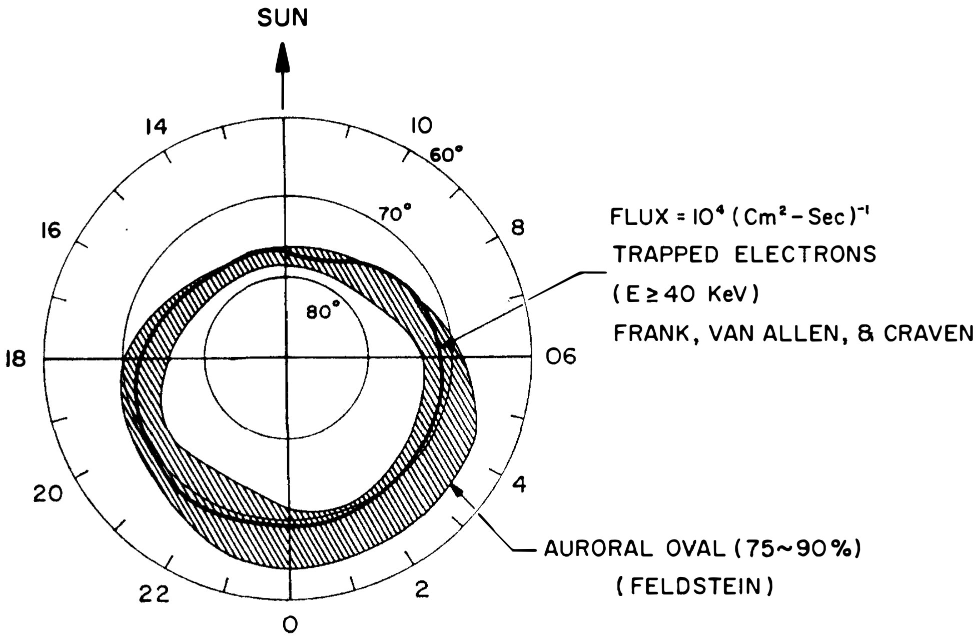


Fig. 5. Average location of auroral oval and outer boundary for flux of electrons.

and with an equatorward shift of the outer radiation belt (MAEHLUM and O'BRIEN, 1963; NESS and WILLIAMS, 1966; WILLIAMS and NESS, 1966).

Figure 4 shows auroral displays observed for the northern auroral oval and an estimated configuration for the Southern Hemisphere at a time of considerable equatorward expansion of both auroral belts.

V. Associated Phenomena and Adiabatic Interpretation of the Auroral Oval and Zones

Figure 6 shows a tentative cross section of the magnetosphere, and the auroral oval in relation to the distorted magnetosphere (AKASOFU, 1965). Also shown are trapping regions at the tail boundary, where auroral particles may be captured by the rejoining of field lines that were separated and dragged tailward by the solar wind (PIDDINGTON, 1965; AKASOFU, 1965). A neutral sheet current in the tail where particles are regionally linked to the auroral oval is also indicated in the figure. Another contribution to the equatorial and polar magnetic field of significance for auroral theory may be made by a current sheet in the magnetic tail of the earth. Its geometrical attitude, with current flow approximately in and parallel to the equatorial plane, reduces its distorting influence earthward, so that the major part of the distorting field may be regarded as instead due to current sheets flowing in the magnetopause (MIDGLEY and DAVIS, 1963; MEAD, 1964). Nevertheless, the current sheet in the tail, presumably caused by changes in the magnetopause currents, may profoundly influence the trapping of auroral particles by opening or closing the long drawn-out geomagnetic field lines in the tail (AKASOFU, 1965). The outer lines of the earth's geo-

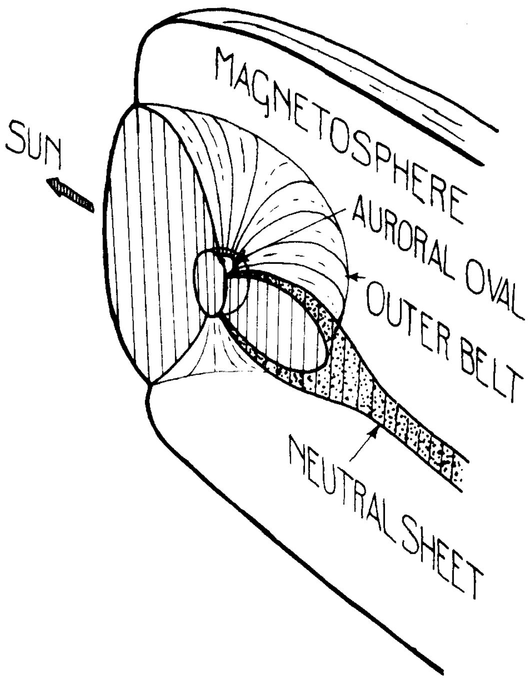


Fig. 6. Schematic cross section of distorted magnetosphere showing auroral oval (after AKASOFU).

magnetic field are also affected by the strength of ring currents in the radiation belts.

It appears that auroral particles are somehow dumped about midnight, but the geometrical arguments for this are presently clearer than the physical explanation. Observationally, one major result is clear. With the occurrence of an auroral event, the oval belt changes in shape and repeatedly expands and contracts. Near midnight during the expansion, quiet auroral arcs within the oval brighten, and brightening immediately extends into the evening sector. Meanwhile, arcs in the morning sector disintegrate into patches and may drift eastward. A slower return to the pre-storm condition follows, the whole process taking perhaps one to three hours.

Descriptions of this kind have appeared many times in literature (STAGG, 1935). Nevertheless, a more precise and comprehensive restatement, based on extensive all-sky observations during the IGY and successive years, can be attributed to the recent work of AKASOFU and DAVIS and their colleagues, and FELDSTEIN and KHOROSHEVA.

The auroral substorm is associated with a polar magnetic substorm — the so-called negative magnetic bay (BIRKELAND, 1905; CHAPMAN and BARTELS, 1940). The current producing the bay is caused by an electric field directed westward along the auroral zone near midnight and enduring about one to three hours or more.

It thus appears probable that the equatorward expansion of the auroral belt is facilitated by the opening of geomagnetic field lines to solar plasma. This relocation of field lines may be occasioned by the addition of ring current and sheet current fields to the outer geomagnetic field near the tailward meridian whenever the solar wind changes, as PIDDINGTON (1965), AKASOFU (1965), WILLIAMS and NESS (1966), and others have indicated.

The distribution of the auroral zone over the polar cap and near midnight and noon may, on the other hand, also be influenced by the sheet current flowing in the magnetopause. The effects of this sheet current, added to that of the ring current flowing in the radiation belts, upon the auroral oval can, of course, be calculated rigorously, although this has not yet been done. A drift of auroral and other particles in the geomagnetic field will ensue as discussed in some detail by TAYLOR and HONES (1965) and WILLIAMS and MEAD (1965). For our purposes it is convenient to discuss the effects of magnetopause currents in simpler terms, using the adiabatic theory of charged particles and an approximate method due to PARKER (1960).

Among the important adiabatic parameters determining the motion of charged particles in the magnetosphere are: the first, $\mu=E/B^2$, where E is the transverse particle energy and B the magnetic field; and the second, given by $J=\int_{m_1}^{m_2} v_{11}\, ds$, where v_{11} is the particle velocity tangential to a line of force with southern and northern mirror points m_1 and m_2, respectively (NORTHRUP and TELLER, 1960). An individual electron drifts eastward as it oscillates between mirror points, its successive mirror points outlining polar caps. An equatorial electron near, say, 5 earth-radii, drifts eastward at the speed

$$v=3c(1/2\, Mw^2)/qBr \qquad (1)$$

where M is the mass, w is the spiral velocity, q is the charge, and the pitch angle is very nearly $\pi/2$. For a 100-kev electron, this gives a drift time to circumnavigate the earth of about 0.6×10^4 second, or about 100 minutes. The third adiabatic parameter specifies the constancy of the flux through the ends of the shell traced out by the moving particle; if this flux changes only slowly during the circumnavigation time (100 minutes in the present case), the particle remains within the shell described during a time of circumnavigation with constant flux. For magnetic changes short compared with 100 minutes, the auroral particle leaves the shell, and the third invariant is violated (CHAMBERLAIN, KERN, VESTINE, 1960; PARKER, 1960). A flux change through the shell in one to five hours, as in a magnetic bay, would permit violation of this invariant by auroral electrons with an energy of 10 kev or less. PARKER's treatment deals with sudden commencements, but if we assume an effect lasting a few hours after the arrival of a more energetic solar wind, the magnetopause currents may be augmented and maintained. The effect may be estimated approximately by replacing the currents by those on a plane slab solar stream with a face normal to the earth-sun line at a distance $-y=l$, with the origin at the earth's center and the z-axis parallel to the earth's dipole and directed to the south pole. In the equatorial plane the image dipole at $-y=2l$ will distort the dipole field having a tangential field B=const. over a circle of radius $r=R$ (say 5 earth-radii for an auroral particle), so that the particles hooked to the field now lie along the circle

$$r=R\left\{1-\frac{R^2}{16l^3}+\frac{R^4}{14l^4}\sin\varphi\right\} \tag{2}$$

where $y=R\sin\theta\cos\varphi$ (PARKER, 1960). This circle has a radius $R=R(1-R^3/16l^3)$ and its center at $y=\varepsilon R$, where $\varepsilon=R^4/14l^4$, and the equivalent equation is

$$r=R'(1+\varepsilon\sin\varphi) \tag{3}$$

The circle of radius R' is not one on which B is constant; B is constant on the equatorial section of the drift shell, for the family of circles of radius

$$R''=R(1+R^3/24l^3) \tag{4}$$

with

$$r=R''(1-\mu\sin\varphi) \tag{5}$$

where $\mu=R^4/16l^4$, with the center in the equatorial plane given by $y=-\mu R$. Hence the various particles distributed along the ring lie on different circular contours of constant B and drift off an electron shell such as that shown in Fig. 5. Only near midnight and noon will the drift be tangential to the particle ring, and a ring once formed will diffuse elsewhere if the solar wind is augmented. The actual diffusion, it should be pointed out, is really rather slight in most encounters of irregularities in the solar wind with the magnetosphere. If auroral particles are indeed dumped at midnight, those particles with higher mirror point will drift around the earth in a shell of radius

$$r=(1+\mu)R \tag{6}$$

with its center at $y=-\mu R$. Measured in the equatorial plane at noon, the shell for the particles drifting from the midnight auroral zone lies at a sunward radial distance $r=(1+2\mu)R$, and at midnight the shell for the particles drifting from the noon auroral zone lies at an anti-solar radial distance $r=(1-2\mu)R$. If we take $R=6.5$ earth radii and suppose by way of illustration that $l=1.1R$, we find that the noon sector of aurora projects about 2° farther poleward than the midnight sector.

In the results of Fig. 3 we see that the shift should be about 8° from midnight to noon; the adiabatic theory for $l=1.1R$ therefore provides only about 25 percent of the required poleward motion. However, the poleward motion near noon is predicted for a region where the field lines extending tailward from the earth are poorly defined. Hence, the fact that the predicted latitude displacement from midnight to noon is actually in the right direction is perhaps significant. A change in l to a value less than $1.1R$ increases the displacement, and for electrons with an energy of 10 kev or less, a change in solar wind energy less sudden than that for a sudden commencement can produce a violation of the third adiabatic invariant, redistributing some electrons within the auroral oval, with effects probably mainly augmented by geometrical features of the general distribution of the magnetic tail.

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