A Magnetosphere Model Based on Two Zones of Precipitating Energetic Particles[1]

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Contrary to widely held ideas on the oval zone of precipitation of energetic particles into the earth's atmosphere, the existence of two quasi-circular zones of precipitation was established several years ago on the basis of geomagnetic activity data. The two zones were found to be of quite a different nature. One of these zones, the higher-latitude one, has its maximum on the day side (latitude ~77°); the other zone, the lower-latitude one, has a considerably longer latitudinal extension and has its maximum on the night side (latitude ~67°). The concept of the oval zone as a single unified zone is not a necessary conclusion and could be a result of insufficient data or of incorrect data reduction. The same conclusion can also be reached on the basis of the analysis performed by Feldstein himself and on the basis of other direct and indirect data. In this paper the main features of two quasi-circular zones are presented on the basis of the instantaneous patterns of the distribution of geomagnetic activity as well as on the basis of the dynamics of these patterns. A magnetosphere model reflecting these features is presented. The suggested model links the lower-latitude zone with processes occurring in the magnetospheric tail, whereas the higher-latitude zone is connected with particle injection through the neutral points.

Introduction

Modern magnetospheric models are derived partly from concepts of zones of particle precipitation into the lower ionosphere; these zones are postulated from the analysis of the complex data on geomagnetic disturbances, aurorae, and other phenomena occurring within the high-latitudinal and polar ionosphere. These concepts, along with many of the related observations, appear in a number of recent articles and review papers [see, for example, *Solar-Terrestrial Physics*, 1967; *IQSY/COSPAR Symposium*, 1968; *Birkeland Symposium*, 1968]. Throughout these papers the concept of a so-called 'auroral oval' is stressed, a single region of energetic particle precipitation into the ionosphere, having an oval shape and representing a projection of the outer boundary of the region of stable trapping of the particles in the earth's magnetosphere upon the ionosphere along the geomagnetic field lines. In contrast to these concepts, the existence of two quasi-circular precipitation zones having a quite different nature was stated several years ago [*Mishin*, 1966; *Mishin and Troshitchev*, 1966; *Vershinina et al.*, 1966; *Mishin and Saifudinova*, 1968]. One of these zones has its maximum on the day side (latitude ~77°), the other one on the night side (latitude ~67°).

The present paper aims to show that (1) the concept of an oval zone is not essential and could appear due to an insufficiency of data or to improper data reduction; (2) the concept of two quasi-circular precipitation zones most fully explains the modern data on geomagnetic activity and aurorae; and (3) on the basis of this concept a magnetosphere model can be constructed that would connect the lower-latitude

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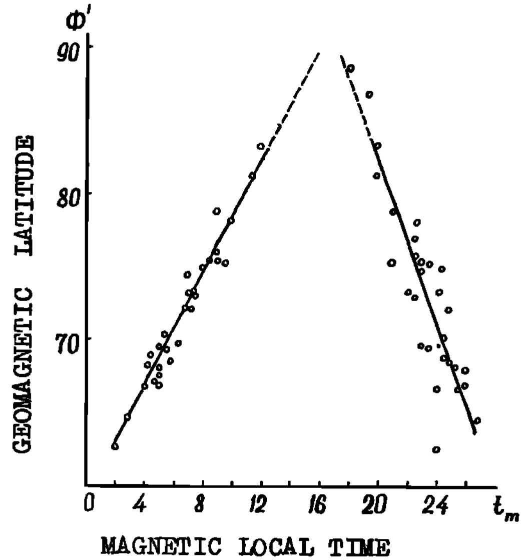

Fig. 1. Times of maxima of diurnal variation of geomagnetic activity versus corrected geomagnetic latitude [*Burdo,* 1957].

precipitation zone with processes in the magnetosphere tail and the higher-latitude one with particle injection through the neutral points.

Historical Development of the Concept of the Oval Precipitation Zone

According to *Alfvén* [1967], the earliest data on the oval-shaped maximum of auroral intensity were obtained by Carlheim-Gyllenskiöld as early at 1882 from observations at Spitzbergen; however, the definite validity of this statement seems to be questionable. The earliest data on the existence of an oval zone of geomagnetic disturbance maxima were obtained from the investigation of the diurnal variation of magnetic activity-Sa [*Stagg,* 1935; *Benkova,* 1948]. These studies showed that the time for principal Sa-maximum shifts with latitude from midnight near ~65° to midday ~80°. *Mayaud* [1954] and *Nikolsky* [1956, 1961] found two Sa maxima; similar data were obtained later by *Burdo* [1957]. Figure 1 shows Burdo's results on the local-time maxima for different latitudes. The same data are shown as a polar plot in Figure 2. The straight lines become spirals, thus producing an oval zone.

It was shown somewhat later that the spiral zones of magnetic activity, forming an oval, practically coincide with the zones of the maxima in the diurnal variation of aurora occurrence frequency, sporadic E_s layer, and some other ionospheric disturbances. An emphasis upon two zones of intensive precipitation, with quite different nature, is typical of those early works. For instance, *Mayaud* [1954], though he did not directly mention two zones, stressed essential morphological peculiarities of both day and night kinds of activities, which have maxima within spatially different zones. *Nikolsky* [1956, 1961] emphasized the difference of the two zones on the morning and evening sides.

In contrast to these works, those by *Khorosheva* [1967], *Feldstein* [1969], and *Akasofu* [1965, 1966] emphasize the unity of the oval precipitation zone as a zone that corresponds to the outer boundary of trapped-radiation, i.e., to the boundary between the most external (as to the earth) closed field lines and the open field lines forming the magnetosphere tail.

Are There One or Two Precipitation Zones?

The magnetic-activity characteristic R, 3-hour equivalent amplitude in gammas, is a function of two space coordinates: latitude and longitude (or local time). The most acceptable coordinates are: φ', Hultqvist latitude, and t', local time in the system of eccentric dipole [*Mishin and Troshitchev,* 1966]. Apparently, the zones of activity-maximum could be determined by conditions

$$\partial R/\partial t' = 0 \quad (1)$$

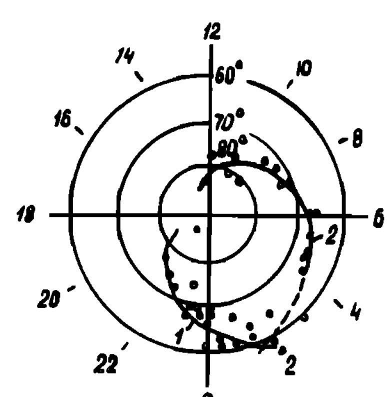

Fig. 2. Spiral distribution of the occurrence of the diurnal variation maxima of geomagnetic activity.

and

$$\partial R/\partial \varphi' = 0 \qquad (2)$$

Zones of diurnal-variation maximum condition (1) are like spiral segments, coinciding in practice with the spirals in Figure 2, whose totality makes the oval; zones of latitudinal-variation maximum condition (2) are quasi-circular zones near $\varphi' = 67°$ and $\varphi' = 77°$ (see Figure 3*a*).

However, only the regions of absolute maximum R values, containing isolines $R(\varphi', t') = \max$ have a clear physical sense. A polar projection of such zones [*Mishin*, 1966; *Mishin and Troshitchev*, 1966; *Vershinina et al.*, 1966] is shown in Figure 3*b*, which confirms the presence of two quasi-circular precipitation zones. The data cited indicate that the oval zone may be obtained by mistake, as a result of coupling of the day and night parts of the two quasi-circular zones. This is quite possible if there is a thin network of stations and if the R isolines are drawn without any preliminary interpolation. The system of two isochronspirals forming the oval zone may be also obtained as a result of the superposition of two quasi-circular zones with maxima both at day and night sides [*Mishin and Saifudinova*, 1968].

It is interesting to note that the conclusion on the existence of two quasi-circular zones can be reached also on the analysis of magnetic activity data that was made by Feldstein [*Feldstein and Zaitzev*, 1965*a*]. In the upper part of Figure 4 results of their analysis are

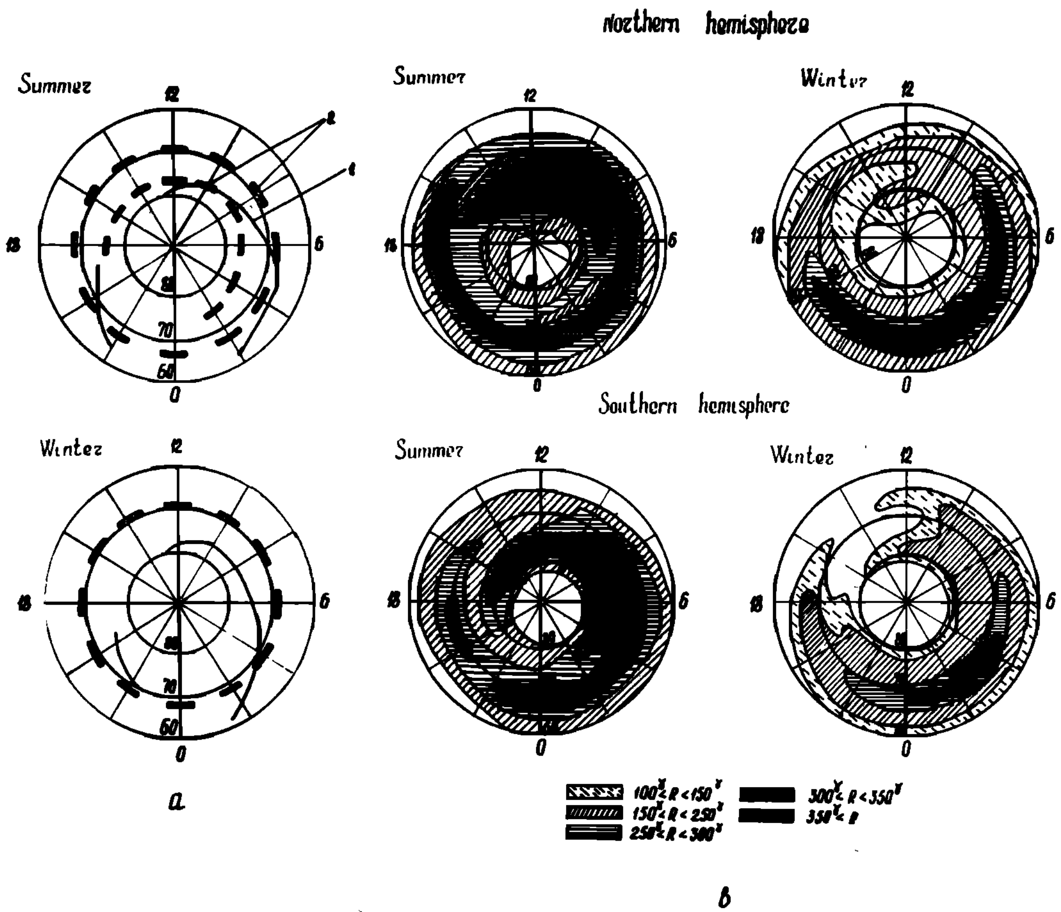

Fig. 3. (*a*) Zones of the maxima of (1) diurnal and (2) latitudinal of geomagnetic activity [*Mishin and Troshitchev*, 1966]. (*b*) 'Instantaneous' maps of geomagnetic activity distribution.

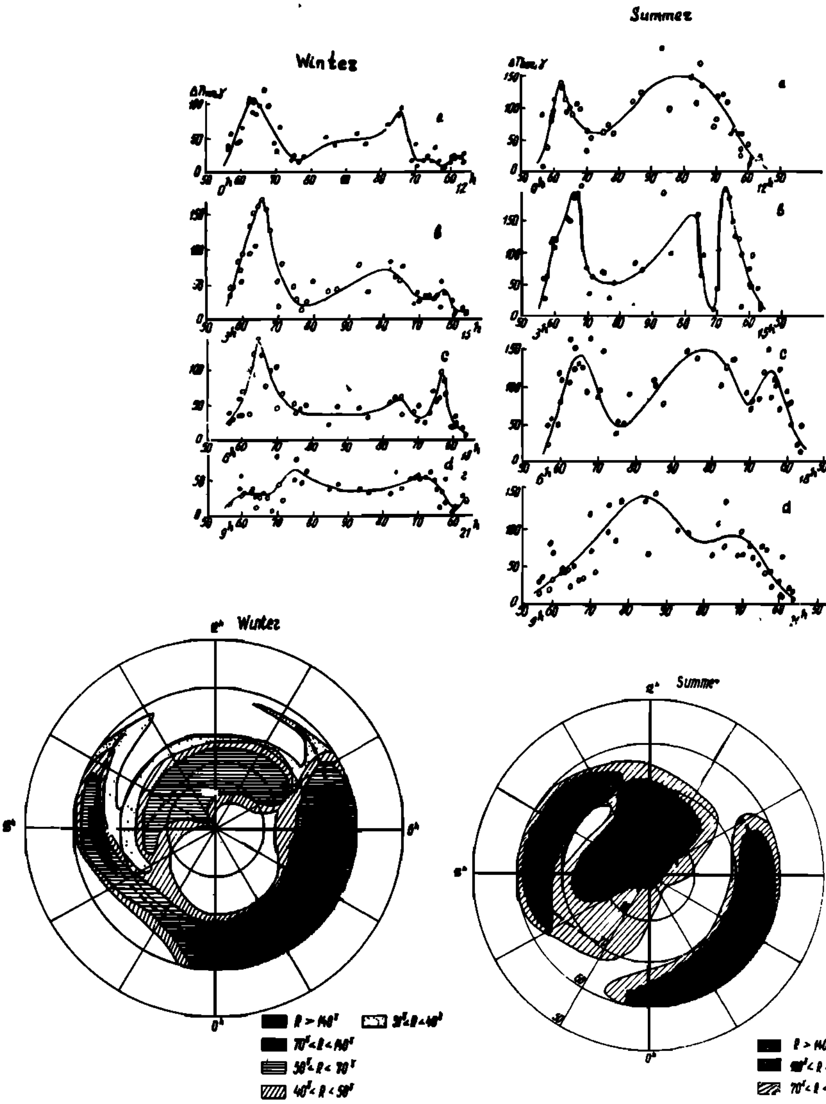

Fig. 4. Latitudinal variations of geomagnetic activity for summer and winter according to *Feldstein and Zaitzev* [1965*a*] and the polar projection of geomagnetic activity constructed from these data.

reproduced, and in the lower part is a polar map of magnetic activity that corresponds to these data.

Thus, on the basis of magnetic data, one may confidently speak about two quasi-circular precipitation zones but cannot insist upon the existence of a single-whole oval zone.

Analogous results were also obtained in the course of a detailed analysis of the distribution of aurorae by *Samsonov* [1968]. Such an analysis showed in particular the presence of both day (latitude 77°–80°) and night (latitude 67°–72°7) zones of aurorae occurrence maxima, with an evident break on the morning and evening sides. His data on the independence of auroral-form occurrence in the auroral zones also speak in favor of such a conclusion. Moreover, Samsonov states directly that Feldstein, while obtaining spatial distribution of aurorae occurrence frequency, was averaging over too large intervals, which smoothed over the discreteness really existing in the latitudinal distribution of the aurorae.

The problem on the existence of discontinuities in the oval cannot be simply solved without interpolation of the observational data within the space between the observatories, since the network of stations is too thin. Feldstein interpolated the isolines of activity by intuition. It would be important to note that such an intuitive interpolation was made on the charts of magnetic-activity distribution, depending on latitude and local time; thus, the function of two variables was interpolated.

We made interpolation in quite a different way [*Vershinina et al.*, 1966]. At first the 3-hour equivalent amplitudes R were presented as follows:

$$R(\varphi, t, T) = \sum_k \rho_k \cos(kt - \alpha_k) + \mu \cos(T - \beta)$$

where the first term corresponds to local-time component, and the second term corresponds to universal-time component. Thus, with the help of harmonic analysis the values of ρ_k, α_k, μ, and β were obtained for the stations with φ_1, φ_2, φ_3, . . . Then, the graphs of latitudinal distribution for ρ_k and β parameters were built, i.e., the one-dimensional interpolation was carried out. This method seems to be more reliable.

One of the strongest, though indirect, arguments in favor of the thesis of a single oval zone can be found in its conformity with the outer boundary of trapped radiation [*Frank et al.*, 1964, Figure 6]. However, data on electrons of similar energies obtained from the Alouette satellite [*Hartz and Brice*, 1967, Figure 16] indicate the presence of a nonoval circular zone. The data on radioechoes from aurorae [*Hartz and Brice*, 1967, Figure 4] show a single oval zone. Indeed, there is a wide gap between the two main maxima of occurrence frequency of discrete radioechoes from aurorae, corresponding to the latitudes of the lower- and higher-latitude quasi-circular zones. The existence of two circular zones can also be inferred from the analysis of satellite measurements of fluxes of low energy precipitating charged particles [*Evans et al.*, 1967].

As a conclusion to this section we need to speak briefly about current systems suggested for the description of polar *DP* substorms. The monovortex system by Feldstein and Akasofu [*Feldstein*, 1963*b*; *Feldstein and Zaitzev*, 1965*b*; *Akasofu et al.*, 1965] is, in the authors' opinion, in accord with the concept of an oval zone. But the magnetic measurements from OGO 2 [*Langel and Cain*, 1968] favor the two-vortex system. The two-vortex current system does not reflect the oval geometry.

The Main Features of the Two Quasi-Circular Precipitation Zones

The difference between the basic characteristics of these zones gives still more conviction of the existence of two separate zones. Considering the location of the central section of the higher- and lower-latitude zones, the activity should be naturally called either daytime or nighttime activity. Both daytime and nighttime types of activities can be observed at all latitudes [*Mishin*, 1962].

1. The daytime activity has a sharp maximum at a geomagnetic latitude of 77°–78°, whereas the nighttime activity peaks at latitudes of 64°–68° (see Figure 3*b*).

2. With the transition from quiet days to disturbed ones, the increase in the nighttime activity level is two or three times as great as the increase in the daytime activity in the higher-latitude zone [*Mayaud*, 1954; *Mishin*, 1962; *Lebeau*, 1965].

3. The differences between annual variations of nighttime and of daytime activities are so great that the higher-latitude zone nearly disappears in winter, whereas the lower-latitude zone is present during the whole year (Figure 3*b*). In summer the daytime disturbances are almost continuously observed within the higher-latitude zone even at $Kp = 0$ [*Mayaud*, 1954; *Lebeau*, 1965; *Bobrov et al.*, 1964; *Feldstein*, 1963*a*; *Mishin et al.*, 1961*a*, *b*].

The annual variation of daytime activity follows a simple sine wave pattern, with the maximum on June 21 in the northern hemisphere and on the December 21 in the southern hemisphere. The relative amplitude of such a wave, i.e., the amplitude divided by the average annual activity level, varies with the latitude according to the value of $(\cos Z)^{1/2}$, where Z is the zenith angle of the sun [*Mishin and*

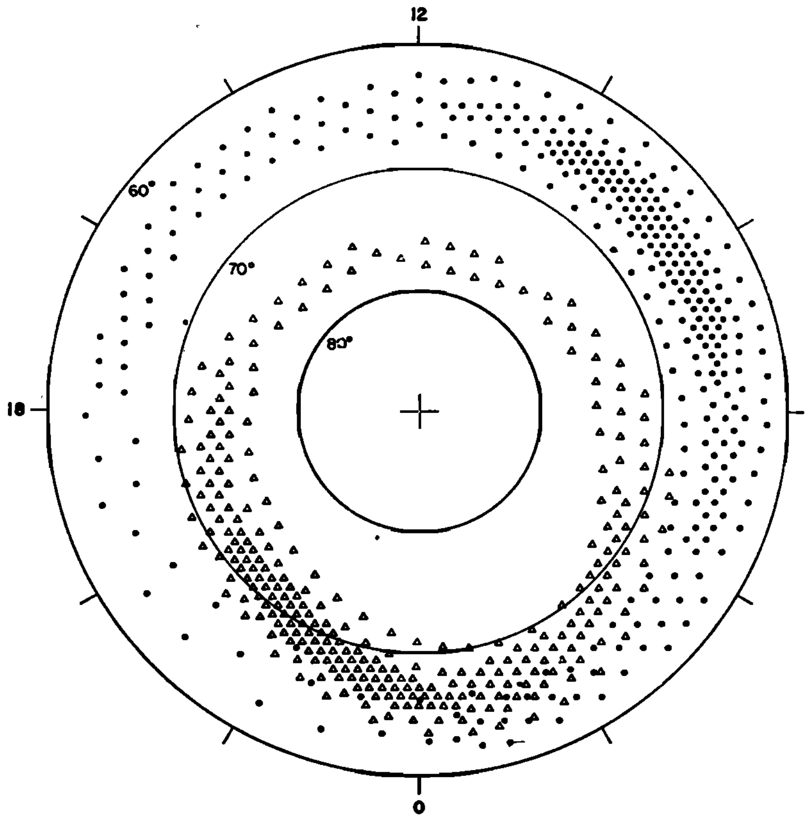

Fig. 5. Idealized representation of two main zones of particle precipitation [*Hartz and Brice*, 1967].

Zhulin, 1962; *Lebeau*, 1965]. The annual variation of nighttime activity follows a double sine wave pattern, with its maxima at the equinoxes; the nighttime activity level in winter is somewhat greater than that in summer.

4. The daytime activity is characterized by shorter time scales than the nighttime activity (quasi-periods of about 10 minutes, and more than 30 minutes, respectively [*Mayaud*, 1954; *Mishin*, 1962; *Lebeau*, 1965; *Bobrov et al.*, 1964; *Maysuradzé*, 1961; *Zhigalov*, 1966].

5. The nighttime activity in the lower-latitude zone is accompanied by an auroral electrojet originating within the lower part of the *E* region at altitudes of 100–115 km, i.e., just where the Hall conductivity is much greater than the Pedersen conductivity [*Maeda and Matsumoto*, 1962; *Cole*, 1960; *Pudovkin et al.*, 1964; *Boström*, 1964]. At the higher-latitude zone electrojet currents are sharply attenuated or even absent. Apparently, the electric currents generated at the higher-latitude zone occur in the region where Hall conductivity does not predominate, i.e., at altitudes above 140 km [*Khorosheva*, 1967; *Yevlashin*, 1961; *Starkov*, 1968]. If this is true, the energies of particles responsible for daytime activity in the higher-latitude zone must be several times smaller (see below).

6. *Mishin et al.* [1961*a*, *b*] and *Mishina* [1967] showed that in the higher-latitude zone the disturbances are mainly influenced by the periphery regions of solar corpuscular streams, while disturbances at the lower-latitude zones are influenced by the near-axis regions of these streams (see also point 2).

7. Phenomena in the higher-latitude zones in the southern and northern hemispheres tend to show less conjugacy than those in the lower-latitude zones.

Thus, the analysis of the geomagnetic-activity distribution as well as of its dynamics suggests the different nature of the particles responsible for disturbances in the inner and outer zones, and shows that the time variations of the disturbances in the two zones are largely independent of each other. Other data on corpuscular precipitation into the lower ionosphere also confirm the above conclusion. In this connection, along with *Samsonov*'s [1968] study, we should emphasize the conclusions of *Sandford* [1964], who showed the existence of a circular auroral zone near 65° latitude.

Hartz and Brice [1967] and *Oguti* [1967] have reviewed the data on precipitation zones. Figure 5 shows the pattern of precipitation zones according to Hartz and Brice. The triangles correspond to discrete-type phenomena, while the dots correspond to phenomena of a diffuse (quasi-continuous) type. It is easy to see that our concept of two precipitation zones is in basic accord with Hartz and Brice's model. An analogous conclusion could be drawn from *Oguti*'s [1967] study.

As a resume to this section, Figure 6 [*O'Brien*, 1967; *Sharp et al.*, 1967] is presented, which shows the latitude distribution of particle precipitation from measurements on a polar-orbiting satellite. These data show explicitly the presence of two precipitation maxima on the day side, and of a quasi-circular zone around 65°–70° latitude. They also confirm the difference in the energy of particles characteristic of the two zones: according to *O'Brien* [1967] and *Sharp et al.* [1967], in the daytime zone near the latitude ~78° electrons with energies about 1 kev would be typical, while at the 68° maximum the electron energies would be more than 20 kev. We recall that the circular zone [*Hartz and Brice*, 1967, Figure 4] corresponds to the electron energies greater than 40 kev.

We have no satellite data available on the nature of the particles precipitating into the ionosphere in the evening sector (18–20h local time, see Figure 3*b*). There are, however, some grounds to suppose that the evening activity in the lower-latitude zone is caused mainly by protons injected from the tail of the magnetosphere and accelerated up to the energies of 30–40 kev. Thus, according to *Sharp et al.* [1967], energetic proton fluxes in the afternoon sector are more intensive than those in the morning sector. Some grounds for the maximum of proton fluxes to be expected during afternoon hours are also cited by *Brice* [1967].

Model of the Magnetophere

A schematic model of the magnetosphere, reflecting the main features of the geomagnetic activity distribution, is shown in Figure 7. The lower-latitude zone (*a*) is associated with proc-

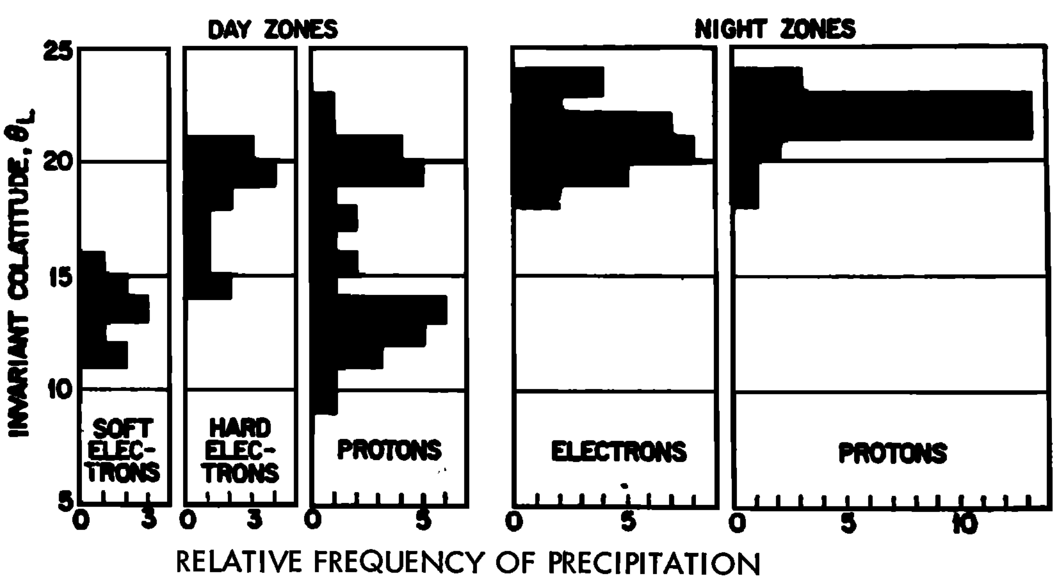

Fig. 6. Latitudinal distribution of particle precipitation [*O'Brien*, 1967].

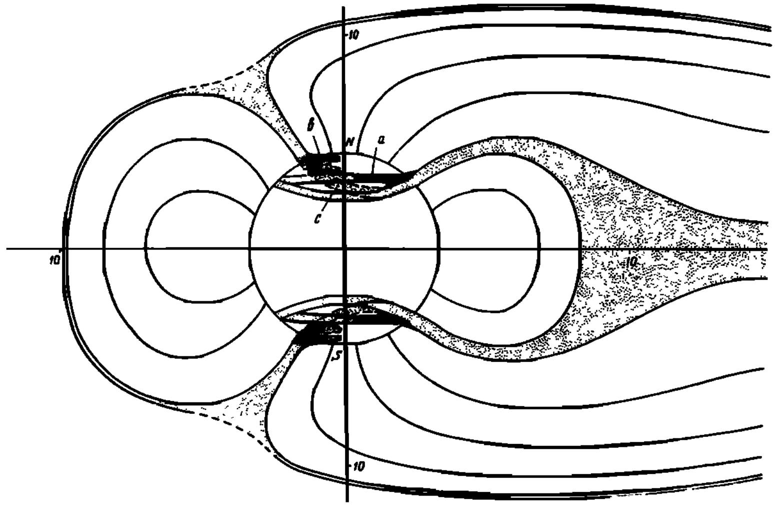

Fig. 7. Schematic model of the earth's magnetosphere. See text for discussion. The earth is enlarged for greater detail.

esses in the magnetosphere tail, while the higher-latitude zone (*b*) is associated with particle injection through the neutral points on the day side. The dashed-line is the so-called oval zone (*c*). It can be easily seen that the suggested magnetosphere model is close to O'Brien's concept of quasi-trapped radiation.

Both the evening and morning disturbance maxima (Figure 3*b*) are located symmetrically with respect to midnight and may be considered to result from particle-drift injection from the magnetosphere tail. This mechanism should certainly be considered as a basic, but not the only possible, one. The fact of simultaneous recording of both protons and electrons at any section of the lower-latitude zone does testify to this.

The quasi-circular character of the higher-latitude zone is not so distinctly seen as that for the lower-latitude zone; this is in accord with the idea of field lines sweeping from the day side of the magnetosphere to its tail. At the same time, it should be emphasized that the higher-latitude zone maximum penetrates deeply enough into the morning and evening sectors to form a semicircle. One possible explanation can be found in the assumption that not all the field lines are subject to a deformation due to the sweeping toward the tail. The deformation of the field lines in the higher-latitude zone is not so great as to completely eliminate the longitudinal drift of particles and the quasi-circular character of this zone.

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