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ENTRY OF SOLAR COSMIC RAYS INTO THE POLAR CAP ATMOSPHERE

BY

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GREENBELT, MARYLAND

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ABSTRACT

World-wide fmin records are used to analyze onset patterns of PCA due to enhanced ionization caused by penetrating solar particles. The initial phase of PCA consists of at least three characteristic stages that occur successively in different zones of the polar region: the first stage is observed as a slightly enhanced ionization near the geomagnetic pole; the second stage as a remarkable development of PCA in the polar cap above 65° (corrected geomagnetic latitude); and the third stage as an extension of the enhanced ionization down to latitudes of 60° or lower. A diffusion model of interplanetary space suggests that the three stages are due to differential arrival of solar electrons, protons and α-particles at the polar atmosphere. The importance of α-particles to the third stage is established by using known incident spectra of both solar protons and α-particles. An empirical relation between particle rigidity and geomagnetic latitude shows a uniform reduction of the Störmer rigidity cutoff by some 70% in the interval 55° - 65° in corrected geomagnetic latitude, and a disappearance of

cutoff in the polar cap above 65°. The former suggests a quiet-time ring current, while the latter may be explained either by a direct merging of the polar cap magnetic field with the interplanetary field or by a particle-energy coupling due to a diffusion process such as in a postulated long geomagnetic tail. Onset patterns of PCA are used as a test for these theoretical models of the geomagnetosphere. Transient times of a few hours usually required for the first and second stages seem to favor the particle-diffusion model.

ENTRY OF SOLAR COSMIC RAYS INTO THE POLAR CAP ATMOSPHERE

1. INTRODUCTION

In recent years it has been well established that the phenomenon of polar cap absorption (PCA) is due to enhanced ionization in the upper atmosphere by incoming sub-cosmic ray particles associated with major solar flares. The general nature of PCA events has been studied extensively by means of world-wide ionograms, riometers and VHF scatter techniques (Obayashi, 1964; Bailey, 1964, and papers cited therein). Nevertheless, little is known about the onset phases of PCA, because of the inhomogeneity of its spatial distribution and the small magnitude of the absorption effect. This problem is particularly important since the developing patterns in the initial phases of PCA must surely provide information about solar cosmic ray particles — especially on the effects of interplanetary modulation, on the particle composition, and on the entry of the particles into the geomagnetic field.

A morphological study of PCA-ionospheric events with the aid of corrected geomagnetic coordinates (Hakura, 1964, 1965a, b) noted the differentiation of the initial phase of PCA into at least three characteristic stages which occur successively at different polar zones, the result suggesting differential precipitation of various solar particles. The present paper considers the mechanisms that differentiate the solar cosmic ray composition (protons, α-particles, and electrons) entering the polar cap atmosphere. The results are used to revise the Störmer theory for charged particles penetrating into the distorted geomagnetic field.

2. INITIAL PHASE OF PCA EVENTS

A morphological study of the initial phases of PCA events has been made (Hakura, 1965) using the fmin data of 50 northern polar ionospheric stations. A typical solar-geophysical event, that of August 16, 1958, is plotted in Figure 1. On that date an intense flare of magnitude 3+, associated with a major type IV radio outburst, occurred at $04^h\ 32^m$. Simultaneously with the onset of the flare, a Sudden Ionospheric Disturbance (SID) was noted in an fmin observation at Alert, Canada; this is attributed to an excessive solar x-ray burst emitted from an excited coronal condensation at the time of the flare. A few hours after the SID, an increase in fmin value started again, indicating the onset of a PCA event. Concurrently, an incidence of solar cosmic-ray protons of energies 10 – 100 Mev was detected by direct measurements of energetic particles by Explorer IV in its orbit.

Figure 2 shows the time sequence of the PCA effect (enhanced ionization and blackout) arranged in order of corrected geomagnetic coordinates. Except for the immediate SID effect, the PCA started first at high latitudes and then spread out to latitude 60° within several hours after the onset. It is notable here that the development of PCA at the initial phase is not gradual but consists of at least three characteristic stages before reaching full development. As viewed from above the North Pole (Figure 3), the first stage consists of a slight increase of absorption near the geomagnetic pole above corrected geomagnetic latitude 80°; in the second stage, the PCA is developed within the latitude of about 65°; while in the third stage it extends down to about 60°.

The PCA patterns in the second and third stages are of more or less circular form, provided that geomagnetic coordinates corrected by higher order spherical harmonic terms are employed. A well-known oval shape of the PCA pattern in the centered dipolar coordinates is transformed into a circle in the corrected system, giving unified boundary latitudes, $\underline{\Phi}_2$ and $\underline{\Phi}_3$, to these stages. It has been shown that these developing processes of the PCA during its initial phase are common for most events, except that the lowest latitude $\underline{\Phi}_3$ in the third stage varies from event to event. As a histogram of $\underline{\Phi}_3$ for 22 events in Figure 4 shows, it varies within the interval 54° – 65°.

3. COMPOSITIONS OF SOLAR COSMIC RAYS AND THEIR PCA EFFECTS

The solar cosmic rays are composed of protons, α-particles, and a few heavier nuclei, as well as electrons (cf. Table 1). Since most of the suprathermal particles would be produced simultaneously in the flash phase of a solar flare, and since all of these components must be in the same rigidity range when they escape from the solar magnetic field, they should propagate through interplanetary space with different mean velocities, and induce the PCA effects at different storm times and in different regions. Such differential precipitation might explain the complex PCA patterns.

It is generally believed that the propagation of sub-cosmic rays through the interplanetary medium is a process of diffusion, as well as one of control by a large-scale twisted interplanetary magnetic field. The time-delay of solar cosmic rays of velocity V in reaching maximum intensity at the earth is given by

$$\tau \sim \frac{1}{2}\left(\frac{R}{\lambda}\right)^2 \frac{\lambda}{V},$$

where $R = 1$ A.U. and the scattering mean free path $\lambda \sim 0.05$ A.U. (Hofmann and Winckler, 1963). The energy of solar protons measured by satellites is of the order of 100 Mev, which yields the time-delay $\tau_p \sim 4$ hours. The velocity of α-particles with similar rigidity to protons is $V_\alpha \sim ½V_p$, and hence $\tau_\alpha \sim 8$ hours. For electrons, since they are certainly of relativistic energies, $\tau_e \sim$ 1.3 hours. These delay-times suggest that the first, second and third stages of PCA correspond to the arrival of electrons, protons and α-particles, respectively.

In a simple model in which particles migrate through an infinitely extensive diffusion medium, the flux of solar cosmic ray particles at the earth is given by

$$j(t, R, P) = j_s(P)\left(\frac{3}{2\pi R^2}\right)^{\frac{3}{2}}\left(\frac{\tau}{t}\right)^{\frac{3}{2}} \exp\left[-\frac{3}{2}\frac{\tau}{t}\right],$$

where $j_s(P)$ is the flux at the sun at $t = 0$. Let the numerical ratio of α-particles to protons at the source be K_s and at the earth be $K_e(t)$; then

$$K_e(t) = K_s \cdot \left(\frac{\tau_\alpha}{\tau_p}\right)^{3/2} \exp - \left[\frac{3}{2} \frac{\tau_\alpha - \tau_p}{t}\right].$$

Since $\tau_\alpha/\tau_p \sim 2$, then

$$\frac{K_e(t)}{K_s} = 2^{3/2} \exp\left[- \frac{3}{4} \frac{\tau_\alpha}{t}\right]$$

It is evident that for $t \geq 0.72\ \tau_\alpha$, $K_e(t)$ exceeds the ratio K_s at the source, and the contribution of α-particles to the PCA in its third stage must be very important unless K_s is very small. In the earlier stages ($t < 0.72\ \tau_\alpha$) the solar protons must be the predominant agent responsible for PCA, except for a possible electron PCA effect in the first stage.

On the other hand, the amount of radio absorption due to the ionization effect is very sensitive to the penetration depth of the incoming particles. Corresponding to a penetrating particle's flux, there is a certain height limit below which enhanced ionization causes little PCA effect. Since the stopping height vs. rigidity relation for protons and α-particles is

$$H_p(P) \sim H_\alpha(2P),$$

α-particles tend to produce the lowest latitude of PCA if the particle fluxes for both compositions are comparable. Thus it seems clear that α-particles play an important role in determining the lowest latitude $\underline{\Phi}_3$ in the third stage of PCA.

Importance of α-particles to the Third Stage of PCA

From known actual incident spectra of both protons and α-particles, the threshold rigidities of detectable absorption, P_{th}^{p} and P_{th}^{α}, may be computed for a given model atmosphere. The higher of the two,

$$P_{th} = \mathrm{Max}\left(P_{th}^{p},\ P_{th}^{\alpha}\right),$$

is related to the lowest PCA latitude $\underline{\Phi}$ at the time of the balloon observation. Figure 5 shows the relation between P_{th}^{p} and P_{th}^{α}, obtained for the 20 Minneapolis observations of solar cosmic radiations (Freier and Webber, 1963), where the marks •, ⊙, and ○ indicate that the α-particle to proton ratios α/p are of the order of 1, 10^{-1}, and 10^{-2} respectively. It is noted here that three-fourths of the observations did detect the α-particle to proton ratio $\alpha/p \sim 1$, and the black marks always lie in the region $P_{th}^{\alpha} > P_{th}^{p}$. Since the over-all threshold rigidity P_{th} is always given by P_{th}^{α} in these cases, it may safely be said that the equatorside boundary of the PCA in its third stage is produced by the α-particles in most of the solar cosmic ray events. The term "solar proton events" so far used in connection with PCA needs some correction because of these results.

It is also noted that a few points marked by o are located in the opposite region: $P_{th}^{\alpha} < P_{th}^{p}$. Since the majority of ionizing radiations consist of solar protons in these exceptional events, we shall call them "pure solar proton events". The May 4, 1960 event is one such PCA event (the abundance ratio being $K_e < 0.02$). As Figure 6 shows, the result is very remarkable in that the cutoff latitude is 65° and the third stage is completely absent.

Possibility of Electron PCA

The first stage suggests a possibility of solar electrons of energies $0.1 \sim 40$ Mev arriving at the earth with intensities above 10^3 cm^{-2} sec^{-1}. Though no mechanism is known that allows particles of such low rigidity to escape from the sun, a recent spacecraft observation seems to favor this speculation. Van Allen and Krimigis (1965) detected 3 cases of 40 kev solar electron bursts observed by the Mariner 4 spacecraft during May-June, 1965. The maximum intensities in these cases were lower than the threshold value of detectable absorption, and no PCA effect was observed in fmin records over the northern polar region. However, they are connected with solar flares of very small scale during minimum solar activity. More intense electron bursts must be confirmed through further cooperative study of satellite and balloon observations and synoptic analysis of related PCA events in the coming period of solar maximum.

4. LATITUDE DEPENDENCE OF NON-STÖRMER CUTOFFS FOR CHARGED PARTICLES PENETRATING INTO A QUIET GEOMAGNETIC FIELD

It is well known that the observed cosmic ray cutoff magnetic rigidities in the polar region are significantly lower than those predicted (viz. $P_d = 14.8 \cos^4 \Phi$) by the Störmer theory for the dipole earth, even in magnetically quiet periods (Akasofu, Lin, and Van Allen, 1963). In the present section, the latitude dependence of the non-Störmer cutoffs during geomagnetically calm conditions will be discussed.

As already mentioned, the cutoff latitude, Φ, of PCA is related to the threshold rigidity of solar cosmic rays P_{th}. They give an empirical relation for the non-Störmer cutoffs. The values for 11 observations made during magnetically quiet periods are plotted by the mark ● in Figure 7, where the computed rigidity vs. geomagnetic dipole latitude curve is also indicated. The dotted line shows the Schwarz correction for the penumbral effect due to the impenetrable earth.

Data on the geomagnetic cutoff in the lower latitude zone are obtained from cutoff rigidities of the galactic cosmic rays (McDonald, 1959; Kellogg and Winckler, 1962). They are designated by the marks ɸ in Figure 7.

Satellite observations of the low energy solar cosmic rays are available for the polar cap region above 65°. Explorer VII observations revealed a "knee" of the solar cosmic ray intensity versus L-value curve, which is designated as Lmin. The mean curve of Lmin vs. the ring-current parameter U was obtained by Lin and Van Allen (as cited in Akasofu, Lin, and Van Allen, 1963):

$$\mathrm{Lmin} = 5.81 - 0.0134\ U.$$

When U = 0, the labeling parameter of the knee becomes

$$\mathrm{Lmin} = 5.81,$$

showing that protons with energies as low as 15 Mev can reach 65.4° in corrected geomagnetic latitude, even in magnetically calm periods. More precise knowledge of the cutoff latitudes for 1.5 Mev protons are given by Stone (1964), who observed cutoffs of 65° on the night side and 67° on the day side. They are shown by the mark ⊙ in Figure 7.

It is evident that the observed rigidity of incident particles is always lower than that expected from the Störmer theory. The general tendencies of the non-Störmer cutoffs may be summarized as follows:

A. Despite considerable scatter, observations in the geomagnetic latitude range 55° - 65°, seem to show a uniform reduction of cutoffs by an average factor of 0.7. Below 55°, the observed rigidities become less reduced and approach those for the dipole earth.

B. There is a sort of "low energy pit" for the particles incident upon the upper polar caps above 65° geomagnetic latitude.

Until recently, many workers have proposed different kinds of explanations for the anomalous entry of solar cosmic radiations (cf. Akasofu et al., 1963; Michel, 1965). However, none gives any complete solution, because the two items mentioned above were not well discriminated. In what follows, some surviving theories will be reviewed.

A Quiet-Time Ring Current

The influence of a possible terrestrial ring current on geomagnetic cutoffs has been studied by several workers including Kellogg and Winckler (1961). On the assumption of an azimathal current on the surface of a sphere of radius R encircling the earth, they obtained a simplified concept of the reduced cutoffs: The curve of critical rigidity vs. latitude has two parts, depending on whether the Störmer pass closes inside or outside the ring current. For the outside branch corresponding to higher latitudes on the earth, the cutoff rigidity is reduced from the Störmer value P_d to

$$P = \frac{P_d}{1 + M_R/M_E} ,$$

where M_R is the magnetic moment of the ring and M_E is that of the earth. The branch of the curve which applies to more equatorial latitudes depends on the parameter M_R/R^3, and rapidly approaches the Störmer cutoff as one proceeds southward from the intersection of the two branches. Using this calculation, Kellogg and Winckler discussed the possibility of a quiet-time ring current. The present results, summarized in Figure 7, will add more information to their conclusion. In the latitude range 55° - 65°, an average reduction factor was

$$\frac{1}{1 + M_R/M_E} = 0.7,$$

and the factor becomes larger, approaching unity in the zone below 55°. These results suggest the existence of a quiet-time ring current with magnetic moment 0.4 M_E, situated at a distance of several earth radii.

The ring current is due to charged particles trapped in the earth's magnetic field in the same way that the particles in the Van Allen Belts are trapped. Recently, several satellites observed the quiet-time ring current at a distance of several earth radii. The most recent one is the observation by the Explorer XII satellite, which revealed the existence of a low-energy proton belt (Davis and Williamson, 1963). Akasofu et al. (1962) identified this as a quiet-time ring having the magnetic moment of some 0.2 M_E. The ring current may be a prevailing factor in reducing the cutoffs in the latitude range 50° - 65°, though we must also consider such an effect of limited radial extent in the geomagnetosphere as discussed by Akasofu et al. (1963) in order to get a better fit to the experimental results.

Merging Between the Geomagnetic and the Interplanetary Magnetic Field

To explain the anomalous entry of the low energy particles into the polar caps above latitude 65°, we must consider a sort of merging of the geomagnetic field with the surrounding interplanetary field. Several years ago, Obayashi (1959) predicted the reduction of the cutoffs on the assumption of a dissipation of the geomagnetic field outside the geocentric cavity by the plasma stream from the sun. In his model, geomagnetic field lines originating in the polar cap, even during magnetically quiet periods, merge with the interplanetary field on the cavity surface which is situated at about 10 earth radii, so that the solar cosmic radiations arriving uniformly on the cavity surface can penetrate into the polar caps regardless of their energies, resulting in the observed anomalous entry.

Recently, the IMP-1 satellite revealed the gross configuration of the geomagnetosphere: the earth's magnetic field is deformed by the solar wind into a comet-like shape with the tail pointing away from the sun (Ness et al., 1966). Theoretical models of an asymmetrically deformed magnetosphere have been proposed by several workers including Dungey (1963), Levy et al. (1964), and Dessler (1964). In the Dungey-Levy model shown in Figure 8(a), field lines in the polar caps are directly connected to the interplanetary magnetic field on the surface of the geocavity. This is topologically analogous to Obayashi's spherical cavity model. It is easily shown that solar cosmic radiations penetrating into these model magnetospheres will uniformly bathe the polar caps within a few minutes.

On the other hand, Dessler proposed a long tail magnetosphere in which the rate of magnetic merging is negligibly small [Figure 8(b)]. Michel (1965) argued that, if the magnetosphere tail is longer than 1 A.U. and has a turbulent component, then diffusion allows soft cosmic radiations to enter the tail and appear over the whole polar caps after some transient stage of a few hours duration in which we would observe an anisotropic penetration of solar cosmic radiations into the polar caps.

Thus the penetration process of solar cosmic radiations seems to be an important clue for testing the validity of these theoretical models. In the following section, the progressive patterns of the PCA event in its initial phase will be examined in greater detail, since they illustrate this transient penetration process.

5. PENETRATION OF SOLAR PARTICLES INTO THE GEOMAGNETOSPHERE, OBSERVED IN THE DEVELOPING PATTERNS OF PCA

In order to reexamine the patterns of PCA from such a point of view, we shall review a PCA event which occurred on July 7, 1958. This event gives one of the most reliable progressive patterns of PCA, since it is a simple F-type event observed in summer when almost all of the northern polar cap is sunlit, and since it started in an extremely quiet geomagnetic condition.

In this event a systematic appearance of PCA was first observed at 02:00 U.T., some 1.5 hours after the flare, in a high-latitude area near the northern pole. As seen on the top viewed patterns in Figure 9(a), expressed by contours of Δfmin, the first stage of the PCA was restricted to a small region above 80° on the sunward side.

In a short time, the ionized region began to propagate towards lower latitude (b), and at 04:00 U.T. (c) a sudden and outstanding intensification of the enhanced ionization was observed along the auroral zone on the solar side. This is an onset of the second stage of the PCA initial phase. The region of polar blackouts (designated by the letter B) gradually widened itself toward the night side, and it took about 4 hours before the whole polar cap above 65° was in a complete blackout condition. The development of polar blackouts in the second stage is illustrated in Figures 9(c) - (f).

In several more hours, the PCA propagated further into the lower auroral zone, and at 14:00 U.T. the whole region above 60° was completely covered by a severe enhanced ionization [cf. Figure 9(g) and (h)]. This is the third stage of the PCA initial phase.

Characteristic times and latitudes for these three stages are summarized in Table 2.

Table 2

Three Characteristic Stages of a PCA Initial Phase, July 7, 1958

	Δt_i (Time After Flare)	Φ_i (Latitude of PCA)	Ionizing Radiations
1st Stage	$+1.5^h$	$\geq 80°$	Electrons or Protons
2nd Stage	$+3.5^h \rightarrow +7.5^h$	$\geq 65°$	Protons
3rd Stage	$+9.5^h \rightarrow$ SC	$\geq 60°$ Changeable 54° - 65°	α-particles and Protons

As to the components of solar cosmic radiation responsible for the PCA, we have already the following conclusions:

1. Among solar cosmic ray components, protons and α-particles are the main ionizing radiations. However, there is also a possibility of electron-PCA, if the sun actually emits sufficient electrons of energy 0.1 - 40 Mev.

2. If interplanetary space is a diffusion field for propagating solar cosmic rays, a characteristic time divides the PCA initial phase into two parts. Before the characteristic time, i.e. in the first and second stages, solar protons are the main ionizing radiations. On the other hand, the contribution of α-particles to the PCA becomes very important in the third stage.

Since we are concerned with the anomalous entry of solar particles into the polar cap, the third stage is excluded from the present discussion. We may derive the following explanations for the first and second stages:

A. If the sun emits electrons of energy 0.1 - 40 Mev at the flash phase of an associated flare, the first stage may be explained by both the models in Figure 8 (a) and (b). In the model (a), the vanguard electrons will enter the polar cap ionosphere through the near-pole geomagnetic field lines that merge directly with the interplanetary field. In the null-merging model (b) the electrons, scattered by the turbulent magnetic field in the transition region, will reach the neutral lines situated on the cavity surface (Mead and Beard, 1964), and enter the near-pole ionosphere, causing the first appearance of enhanced ionization. It must be noted here that we are discussing motion of electrons in a time interval less than τ_{diff}, a diffusion time of electrons in the geomagnetosphere tail. After τ_{diff}, electrons will appear isotropically over the whole polar cap, if the argument of Michel-Dessler (1965) is valid.

The secondary onset of enhanced ionization at 04:00 [Figure 9 (c)] shows the first impact of ionizing protons upon the polar cap ionosphere. The development PCA patterns (c) - (f) shows a series of solar proton penetration processes into the polar cap. The transient time of 4 hours seems to suggest the existence of some diffusion process in the magnetosphere. The progressive pattern, i.e., that the blackout started from the auroral zone and propagated towards the pole, coincides with that predicted in the Michel-Dessler's longtail diffusion model, except its remarkable local time dependence.

B. In order to explain the first stage of PCA by solar protons, we must postulate proton energies of several tens of Mev for a reasonable arrival time. Since such high energy protons obey a quasi-Störmer rule even in the cavity-confined geomagnetic field, the first impact zone must have been somewhere along the auroral zone (Obayashi, 1959). To explain the first impact zone above 80°, the near-pole geomagnetic field must directly be connected with the interplanetary field as in the Dungey-Levy model (a). However, here again a transient time of 6 hours from the first to the end of the second stage is unfavorable to the open polar cap model.

The amount of PCA is a complex function of the incoming particle flux, the energy spectrum, the composition, and the ionosphere condition, so that it is quite difficult to derive a unique solution of the geomagnetosphere model from the onset patterns of PCA. However, the stepwise development of PCA and transient times of a few hours are at least significant, and they suggest electron-PCA as well as some kind of particle diffusion process in the geomagnetosphere for their explanation.

6. CONCLUSIONS

1. The initial phase of PCA consists of at least three characteristic stages which occur successively in different zones of the polar region: the first stage is observed as a slightly enhanced ionization near the geomagnetic pole; the second stage starts as a sudden and outstanding intensification of enhanced ionization along the auroral zone; and in the third stage the enhanced ionization propagates gradually in the lower auroral zone to achieve a complete development of polar cap blackouts.

2. In the composition of solar cosmic rays, protons and α-particles are the main ionizing radiations. However, there is also a possibility of electron PCA, if the sun emits a burst of 0.1 - 40 Mev electrons. A diffusion model of interplanetary space for propagating solar cosmic rays suggests that the existence of the first, second, and third stages is due to differential arrival of solar electrons, protons, and α-particles, respectively.

3. The comparison of the threshold rigidities of protons and α-particles capable of producing the radio absorption shows that the α-particles do form the lowest latitude of the absorption observed during the third stage of ordinary PCA events, where the numerical α-particle to proton ratios $J\alpha/Jp$ are nearly unity.

   There are a few exceptional "pure solar proton events", such as that on May 4, 1960 when the ratio $J\alpha/Jp$ was of the order of 10^{-2}. Throughout this event, the associated PCA was restricted in the polar cap ($\Phi_c \geq 65°$), and enhanced ionizations were produced absolutely by solar protons.

4. The above result in turn gives an experimental relation between particle rigidity and geomagnetic latitude. With additional information from balloon and satellite observations, it clarifies the latitude dependence of non-Störmer cutoffs for charged particles penetrating into a quiet geomagnetic field:

   A. The observed rigidity of charged particles arriving at a given latitude of the earth is some 70% of that expected from the Störmer theory, in the interval 55° - 65° of corrected geomagnetic latitude. Below 55°, the rigidities become less reduced and approach those of the dipole earth.

   B. The cutoffs disappear in the polar cap above 65°, forming a pit for low energy particles. This defines the polar cap in geomagnetically quiet conditions.

5. A quiet-time ring seems to be the prevailing agent for reducing rigidities by 70%, while the null cutoffs in the polar cap suggest a merging of geomagnetic field lines with the interplanetary field, or a particle-energy coupling by diffusion processes in the geomagnetosphere.

6. The progressive patterns of PCA may be used as a test for presently postulated models of the magnetic merging. Transient times required for the first and second stages are usually on the order of hours, and this supports a diffusion process that transfers solar particles in interplanetary space into the polar cap atmosphere.

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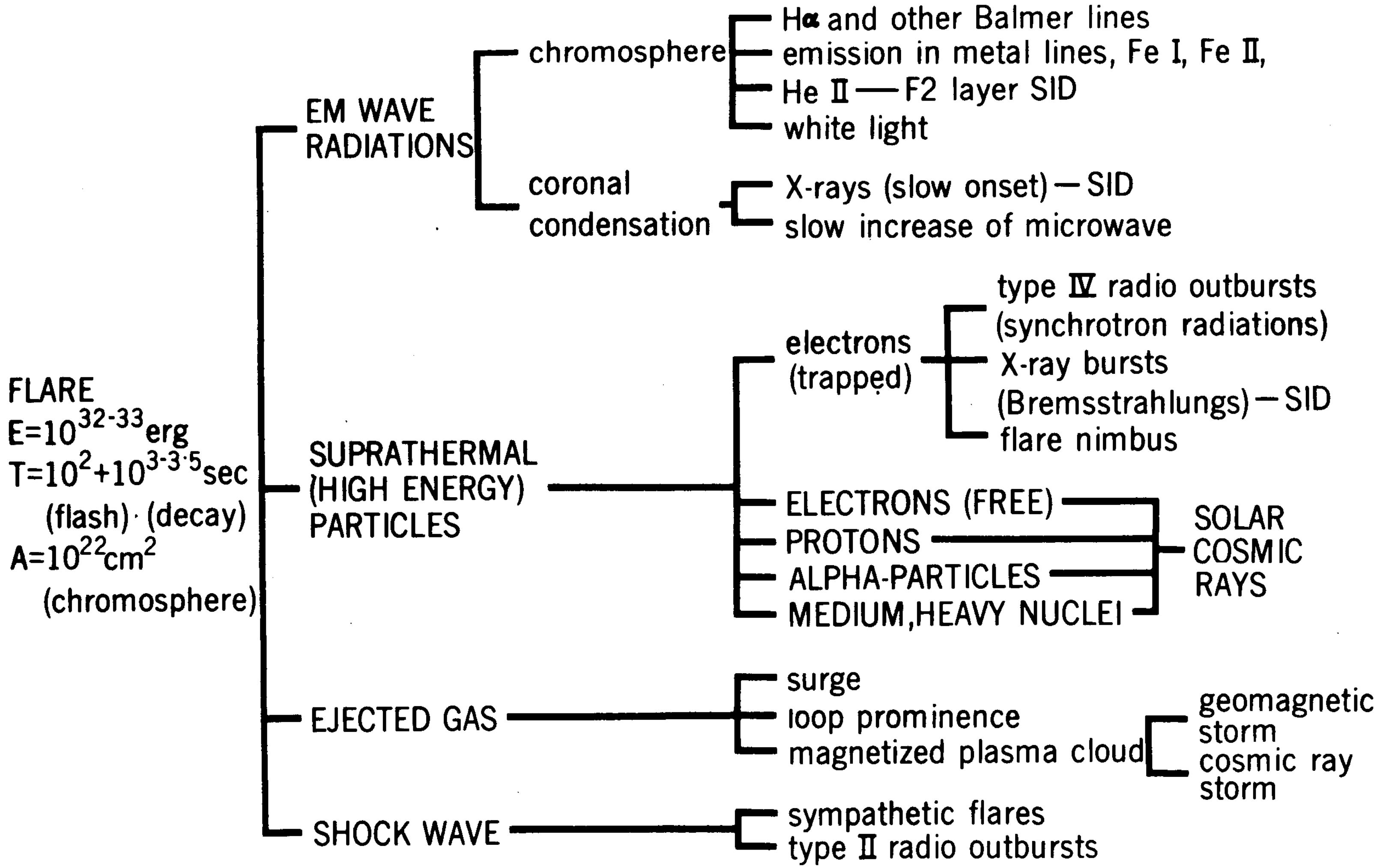
LIST OF ILLUSTRATIONS

Figure 8. (a) Open Polar Cap model proposed by Dungey-Levy. (b) Long tail model proposed by Dessler.

Figure 9. Onset of the PCA Event on July 7, 1958 expressed by contour map of Δf min (in 0.1 Mc/s).

Table 1

Scheme of Solar Flare



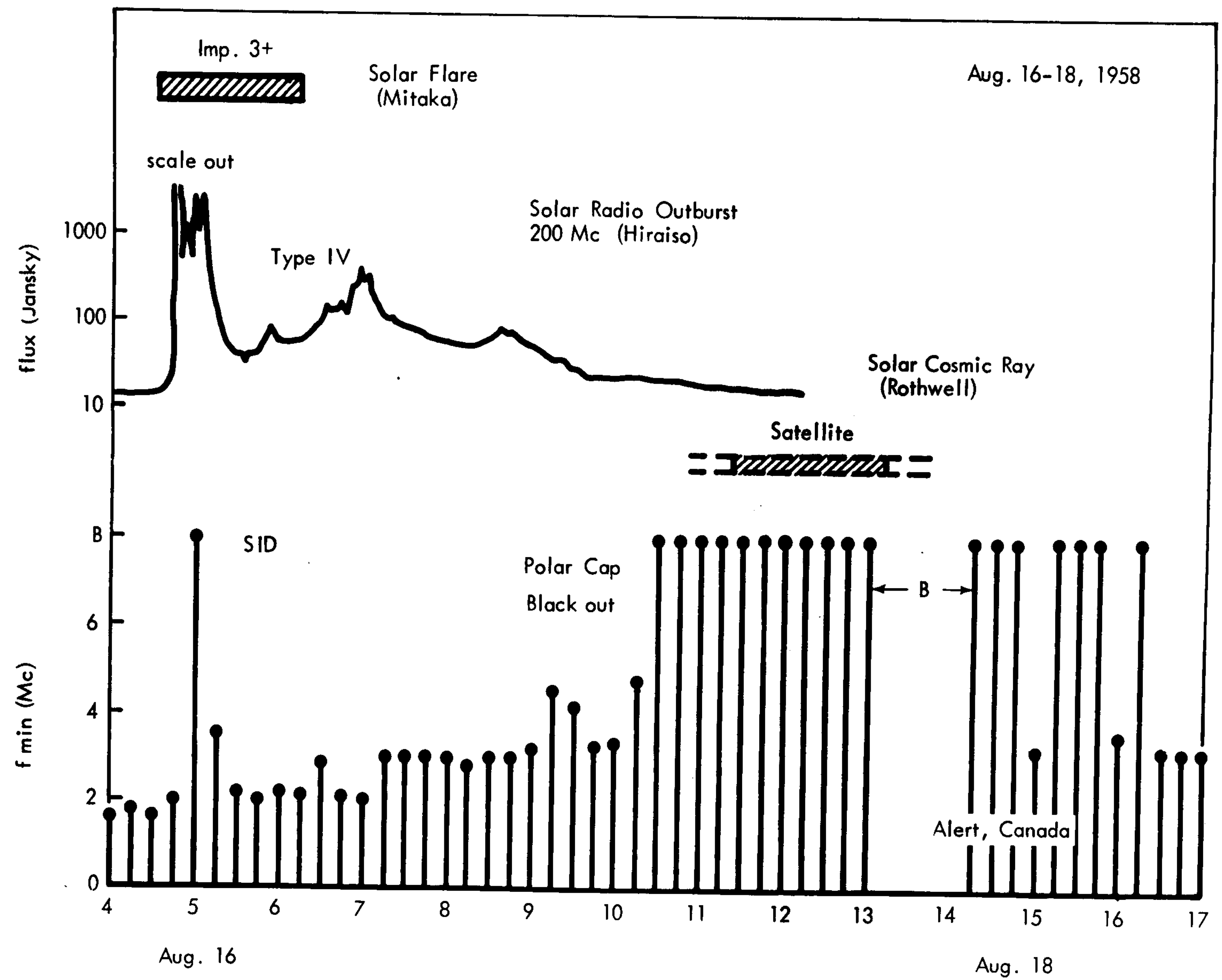
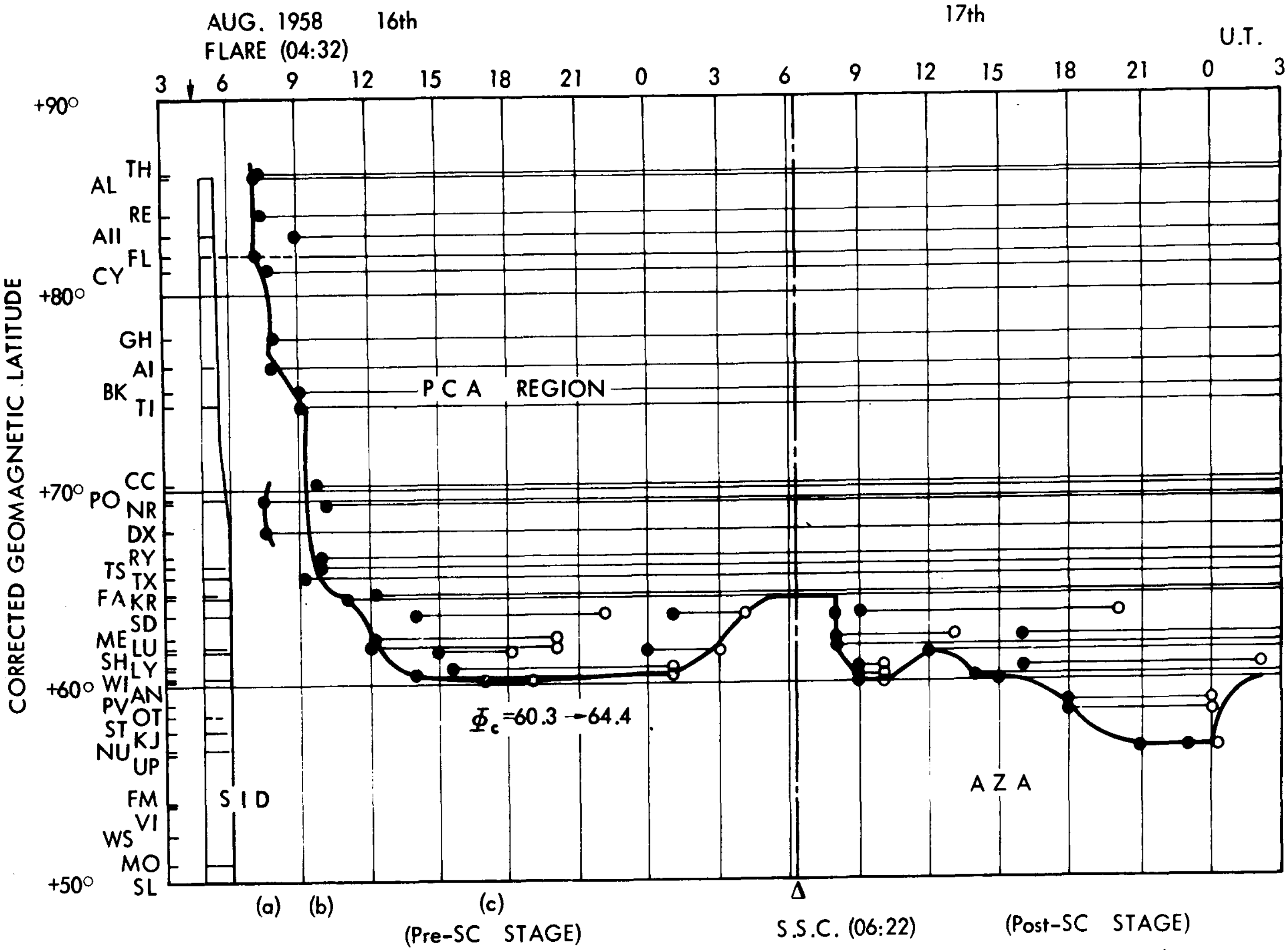
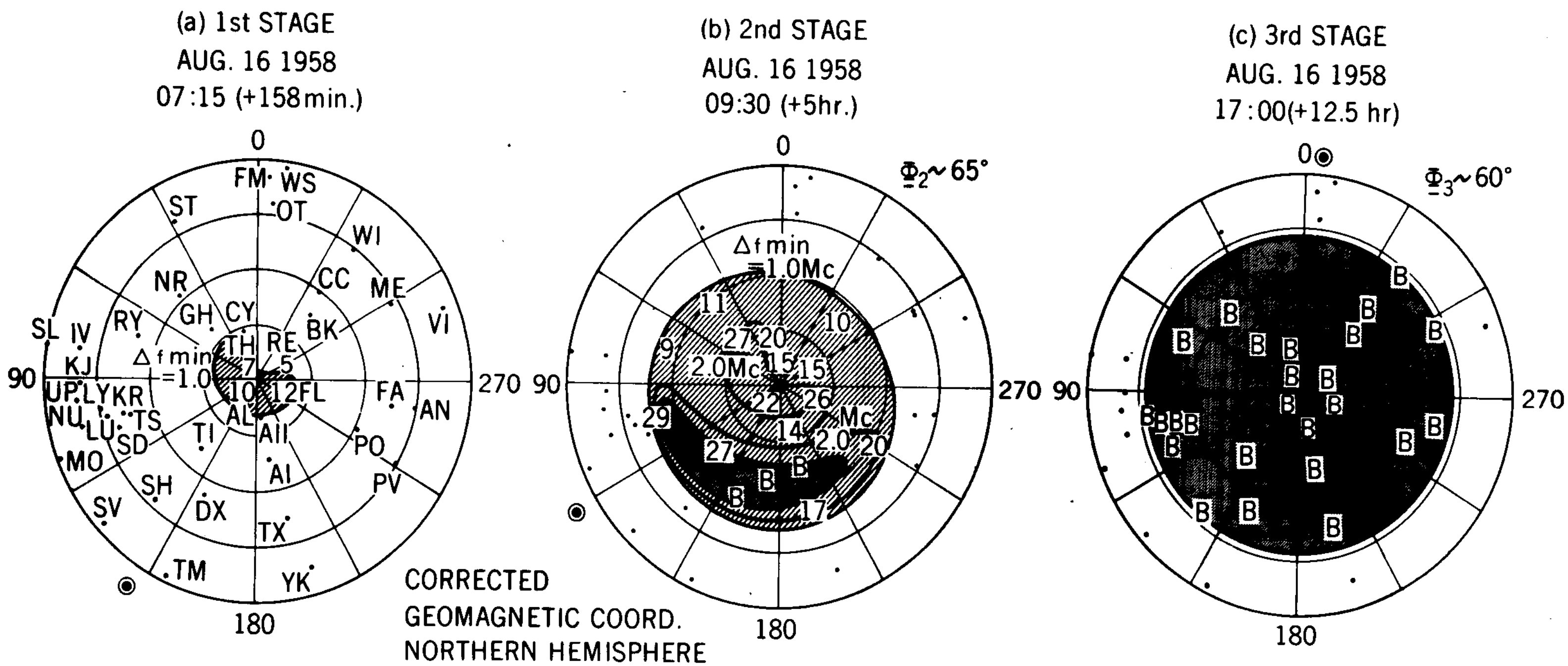


Figure 1. Solar-terrestrial events on August 16-18, 1958.



● —ONSET OF ENHANCED ABSORPTION, o —END, $\Delta f\ min \geq 1$ Mc/s

Figure 2. Development of SID, PCA and AZA events on August 16-18 1958 expressed in the corrected geomagnetic latitudes (the northern hemisphere).



B – Complete Blackout ● – Δf min < 0.5 Mc/s

Figure 3. Initial phase of PCA event on August 16, 1958 expressed by the contour map of Δf min (in 0.1 Mc/s). The regions where Δf min ≥ 1 Mc/s are hatched. Darker hatching shows the region of severe PCA, Δf min ≥ 3 Mc/s.

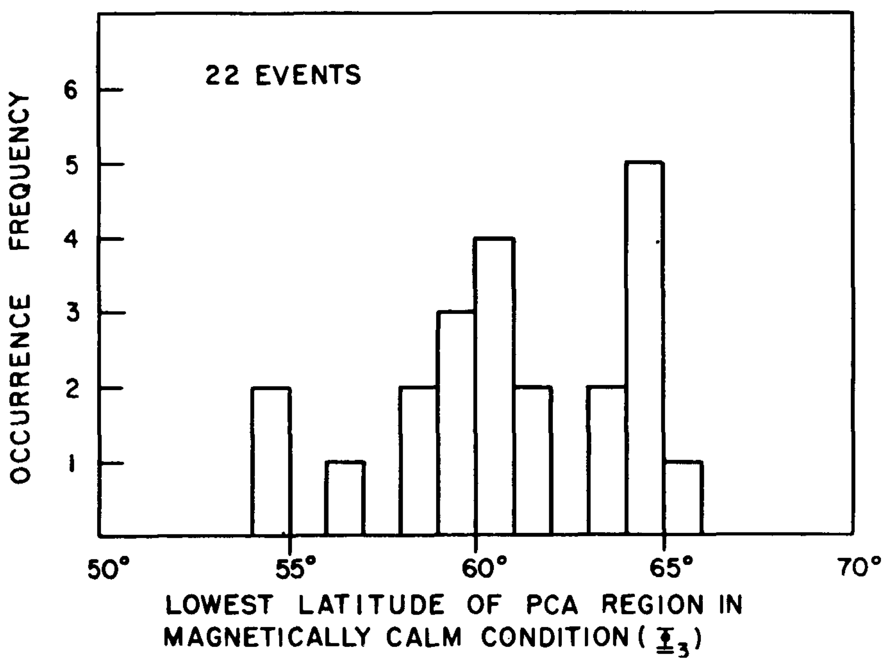


Figure 4: Lowest latitudes Φ_3 of radio absorption for 22 PCA events observed during magnetically quiet periods. Latitudes are expressed in the corrected geomagnetic system.

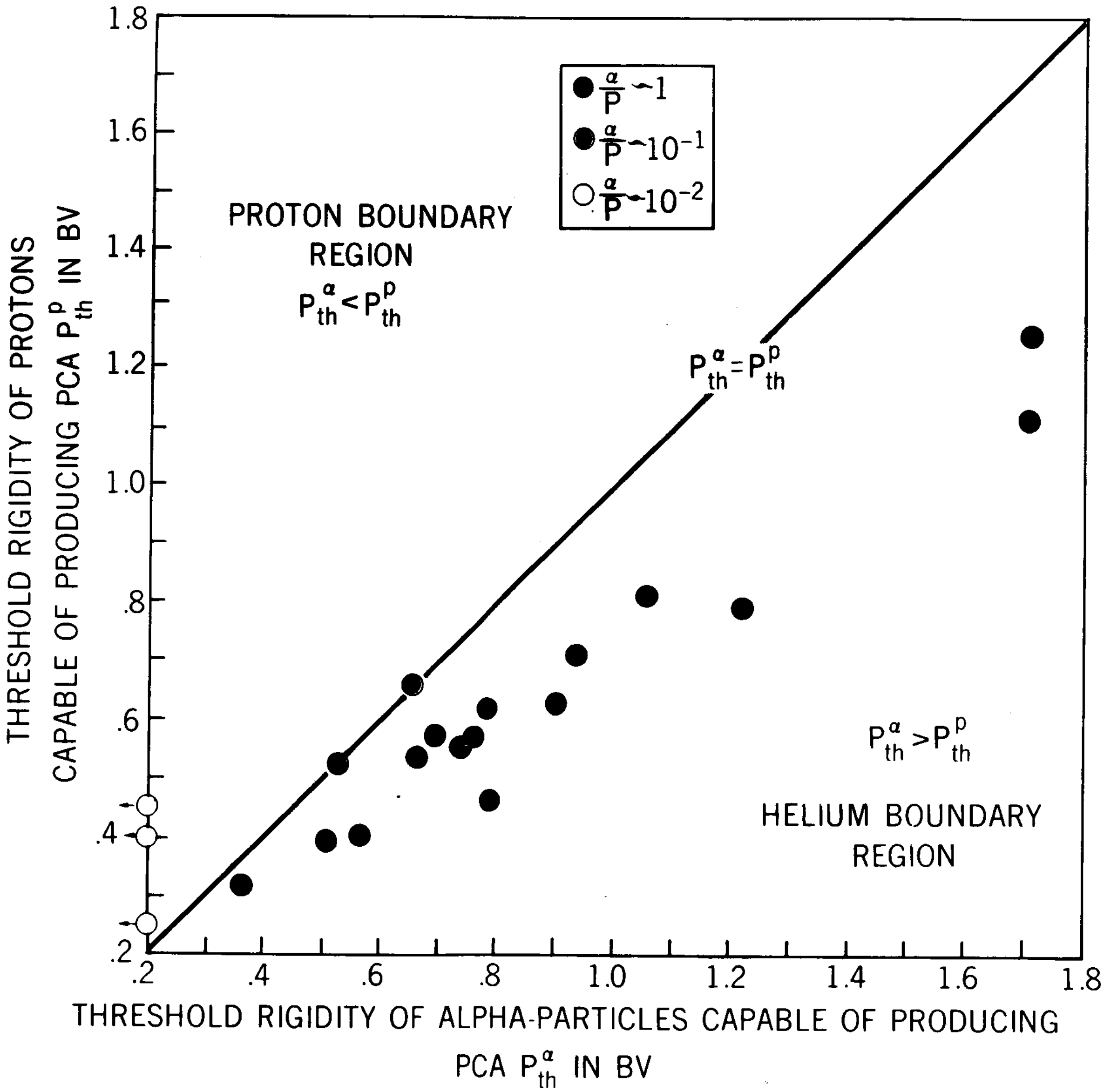


Figure 5. Relation between threshold rigidities of protons and α-particles capable of producing PCA on 20 Minneapolis observations of solar cosmic radiations

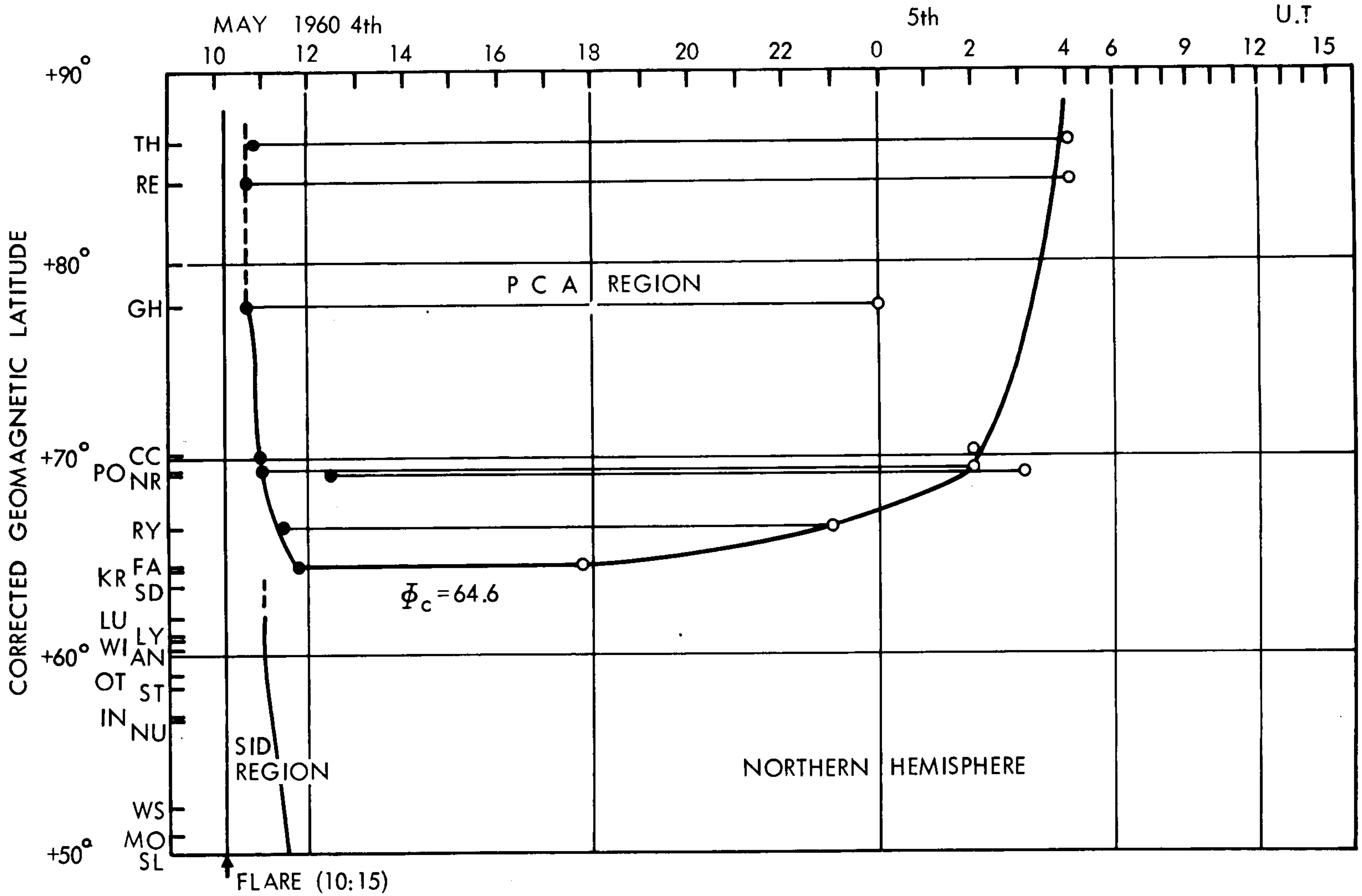


Figure 6. Development patterns of the SID and the PCA observed in the northern hemispheres on May 4-5, 1960, arranged in the order of corrected geomagnetic coordinates.

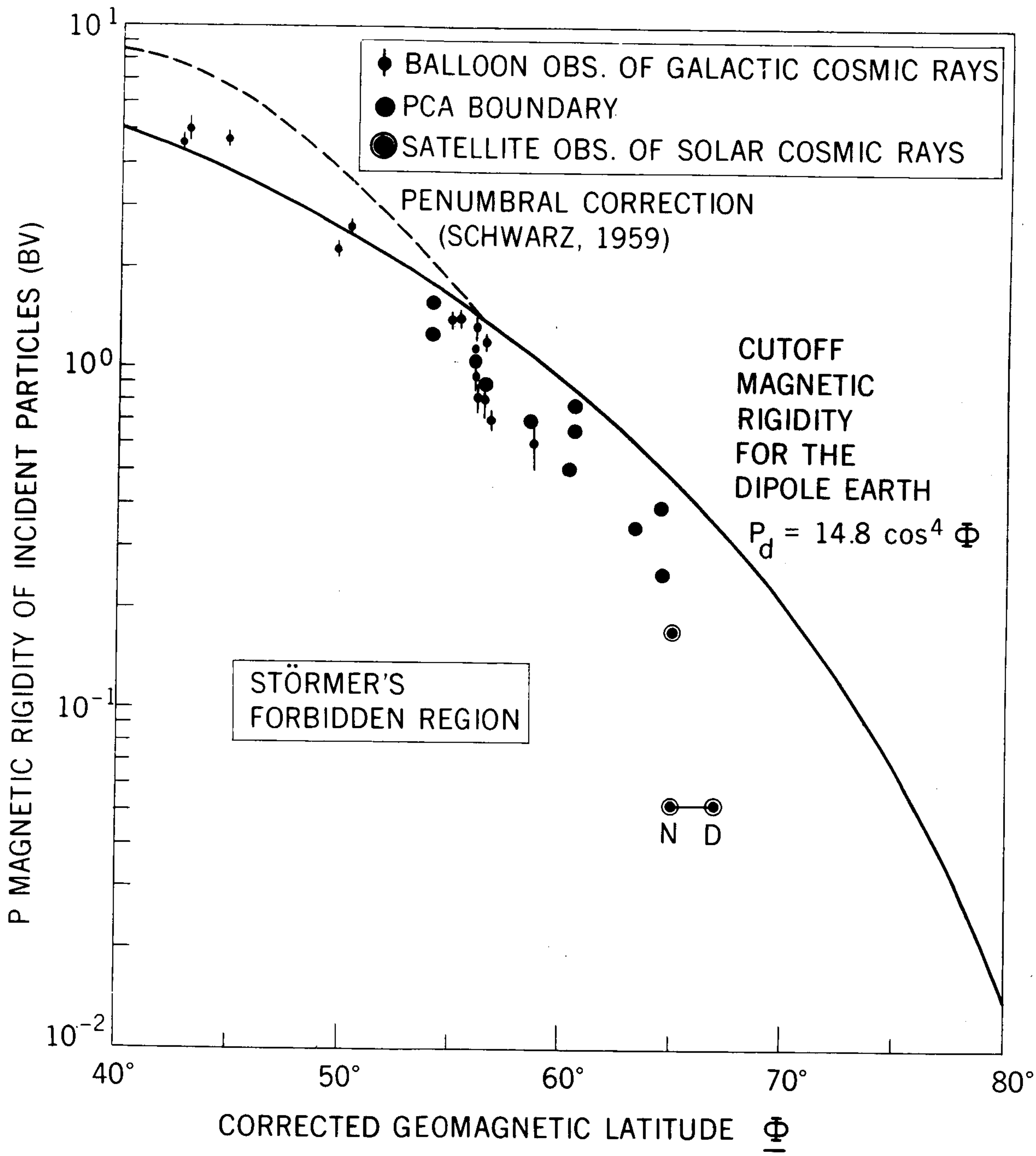


Figure 7. Relation between cutoff magnetic rigidity and geomagnetic latitude during magnetically calm period, obtained on the analysis of the PCA boundary and direct observations by balloons and satellites.

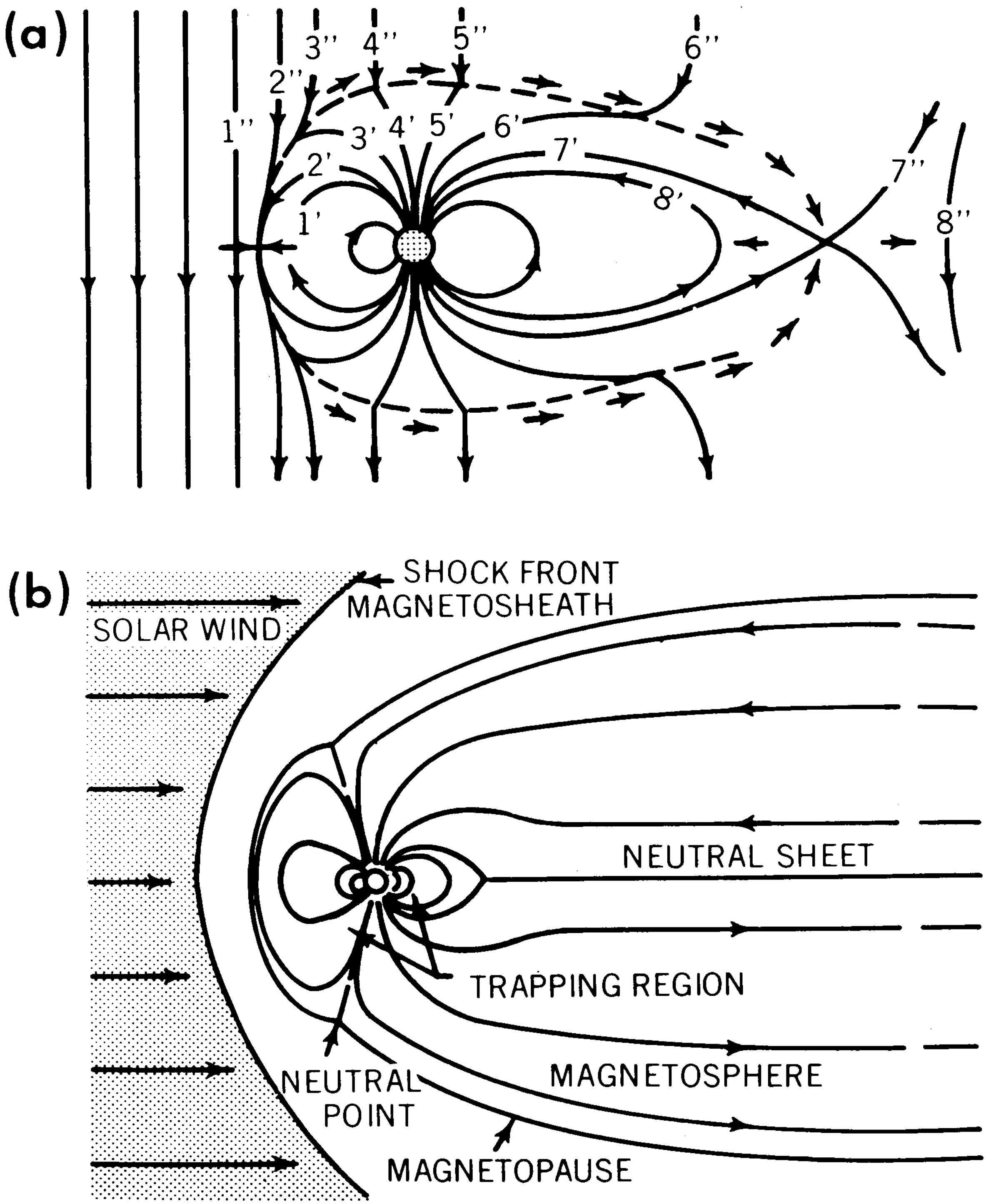


Figure 8. (a) Open Polar Cap Model Proposed by Dungey-Levy
(b) Long Tail Model Proposed by Dessler

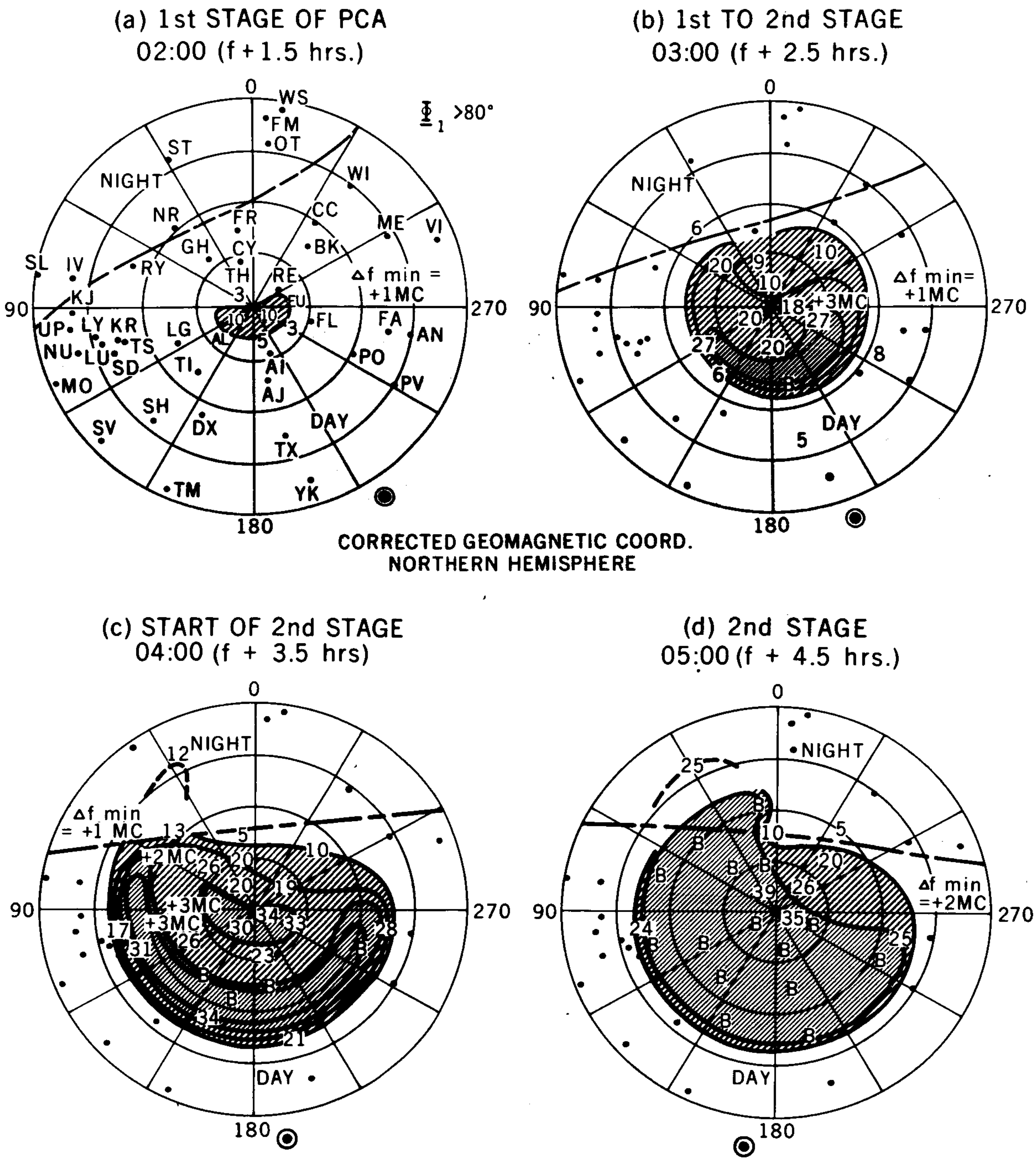


Figure 9. Onset of the PCA Event on July 7, 1958 Expressed by Contour Map of Δf min (in 0.1 Mc/s)

B – Complete Blackout ● – Δf min < 0.5 Mc/s

Chain Lines Show the Divide Between Day and Night at 50 km Height

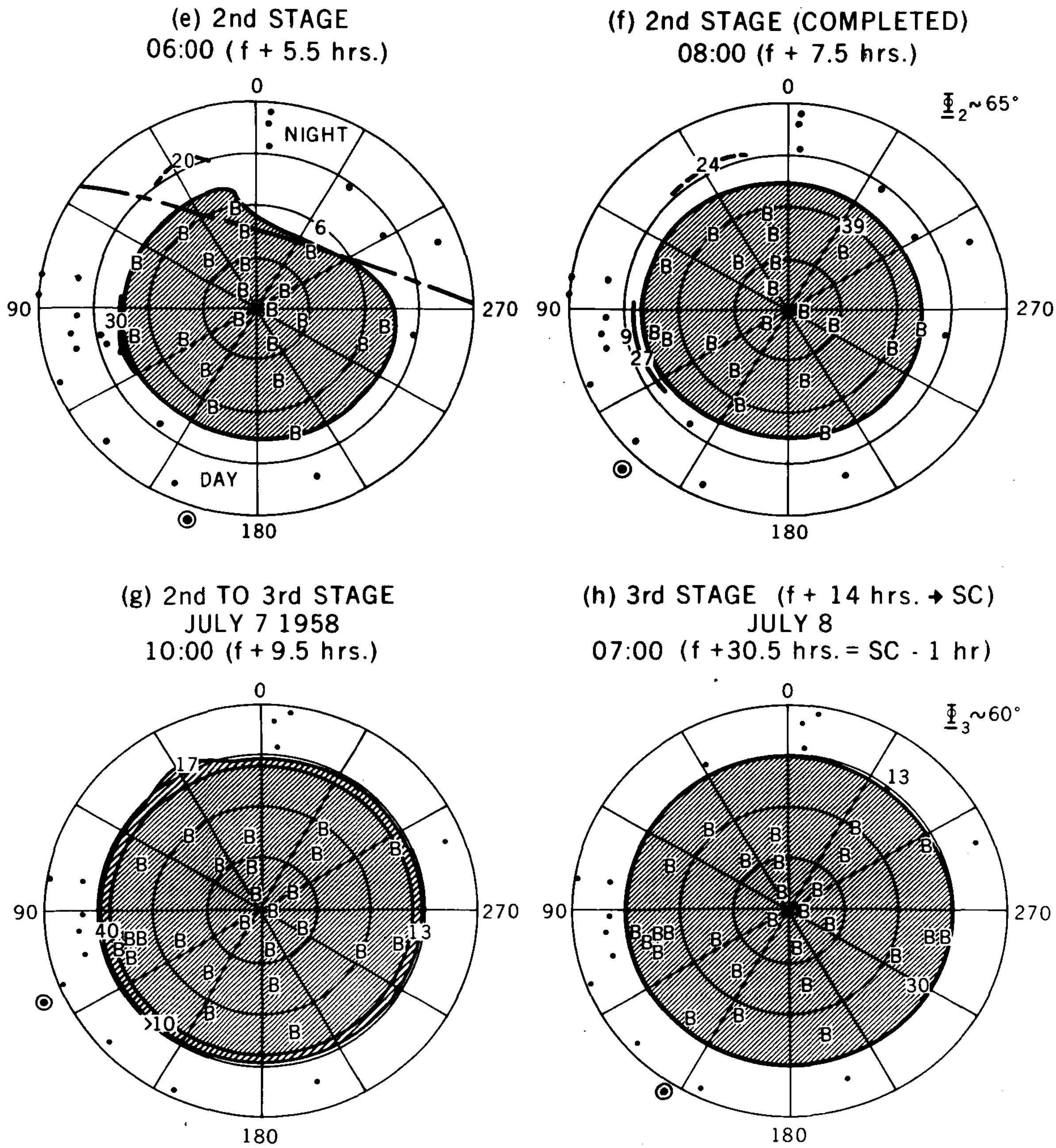


Figure 9. Onset of the PCA Event on July 7, 1958 Expressed by Contour Map of Δf min (in 0.1 Mc/s) (continued)

B – Complete Blackout ● – Δf min < 0.5 Mc/s

Chain Lines Show the Divide Between Day and Night at 50 km Height