Department of Physics and Astronomy

THE UNIVERSITY OF IOWA

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ELECTRODYNAMICS OF THE MAGNETOSPHERE:
Geomagnetic Storms*

by

Syun-Ichi Akasofu

Department of Physics and Astronomy
University of Iowa
Iowa City, Iowa

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3225

ABSTRACT

Geomagnetic and auroral storms provide a great deal of detailed information on the interaction between the solar plasma flows and the magnetosphere. Vast numbers of observations have been accumulated, and many theories have been developed to explain them. However, many of the most vital features of the interaction remain unsolved. The purpose of this paper is to provide the background for future work by summarizing fundamental morphological data and by reviewing critically the proposed theories.

The paper consists of four sections. In the first section, the structure of the solar plasma flows and the magnetosphere are briefly discussed. Effects of the direct impact of the plasma flows on the magnetosphere are described in section 2. Both sections 3 and 4 are devoted to the discussion of the major phase of geomagnetic storms, namely the formation of the asymmetric ring current belt and the development of the auroral and polar magnetic substorms, respectively.

1. Introduction

1.1 Solar Plasma Flow

There are at least two types of solar plasma flows which disturb the steady-state configuration of the magnetosphere and thus cause geomagnetic disturbances.

The first is generated by intense activity in young centers of activity, namely, in the vicinity of bipolar sunspot groups; and the other is a fairly continuous flow whose origin has been inferred to be old centers of activity, namely, unipolar regions. These plasma flows interact not only with a steady solar wind, but also with each other. Therefore, an extremely complicated flow pattern can be expected, particularly during active periods of the sun. The surface of these interactions is often sharply defined as shock waves (both compression and rarefaction) or has complicated irregular structures because of the development of instabilities [cf. Parker, 1958, 1963, 1964; Dessler and Fejer, 1963; Spreiter, Summers, and Alksne, 1966; Colburn and Sonett, 1966].

The magnetosphere can be considered to be a long cylindrical bubble embedded in such complicated flows. The bubble suffers from a direct impact of the flows, as well as an internal inflation by the entry of the flow energy into it. The direct impact causes a compression, expansion, or vibration of the bubble. In section 2, we examine some of the effects of such an impact. A part of the plasma energy enters deep into the magnetosphere and a storm-time radiation belt, the ring current. Its effect on the magnetosphere has commonly been expressed by the inflation. Section 3 is devoted to the discussion of the ring current. Another part of the plasma energy is converted into the energy of energetic electrons, which by interacting with the polar (neutral) atmosphere, causes an oval band-shape light (the aurora) around the dipole pole and an intense current (the polar electrojet). It is the subject of section 4.

(a) The Structure of the Solar Plasma Flow Generated by Solar Flares

A two dimensional configuration of the solar plasma flow generated by solar flares can be studied by observing it simultaneously by space probes distributed at a number of points in interplanetary space. It is also possible to study it statistically by examining characteristics of geomagnetic storms caused by solar flares in different sectors on the solar disk. For example, a solar plasma flow generated by a central meridian flare gives us information on its structure along the solar radius passing through the flare;

western limb flares tell us the structure near the right wing (viewed from the sun) of the plasma flow. Some of such early attempts were made by Obayashi and Hakura [1960], Bell [1961], Warwick and Haurwitz [1962] by using the K_p index.

Akasofu and Yoshida [1966] examined the magnitude of storm sudden commencements (DCF) and the magnitude of the main phase decrease (DR) as a function of central meridian distance of the responsible solar flares. The first quantity gives us the magnitude of the pressure jump across the sharp discontinuous structure associated with the plasma flow as a function of the angle between the solar radial through the flare and the sun-earth line. The second quantity gives us the distribution of the energy which causes the main phase of geomagnetic storms. Figs. 1 and 2 show those relations; note that the pressure jump is proportional to $(DCF)^2$. Such a statistical study is well substantiated by examining individual geomagnetic storms caused by solar flares at different central meridian distances. In the left column of Fig. 3, all the geomagnetic storms caused by limb flares (central meridian distances greater than 60°) with the importance 3 or 3^+ during the period 1956-1961 are shown. The geomagnetic storms in the middle and right columns are caused by central flares (central meridian distances less than 75°) with the importance 3^-, 3 or 3^+.

The above study suggests some kind of 'jet' structure of the plasma flow, since the energy for both quantities are greatly concentrated along the radius through flares. On the other hand, the time interval elapsed between the onset time of a solar flare and of the storm sudden commencement is found to have no definite relation with the central meridian distances. The mean transit time is of order 40 hours, regardless of the central meridian distance of flares; thus, the front of the plasma flow must have nearly a spherical surface. Therefore, the solar plasma flow generated by solar flares can neither be a simple jet of the plasma nor a simple spherical (or spherically symmetric) wave.

Gold [1955] was the first to suggest that the pressure jump associated with the plasma flow is caused by an interplanetary shock wave. Parker [1961, 1963] proposed that the shock wave is generated by a sudden heating of the corona. However, it seems to be difficult to attribute the dependence of the magnitude of ssc's on the central meridian distance to this type of simple spherical wave.

A more likely situation would be the generation of a semi-spherical shock wave in the solar wind by a jet of the solar plasma ejected by solar flares [cf. Hirshberg, 1965]. The solar wind plasma will be most seriously compressed at the front of the advancing jet (causing the largest pressure jump and thus the largest ssc), but much less at the sides. The situation may be like a shock wave which is formed near the front of a blunt body moving supersonically. Figure 4 shows schematically this situation. Such a gas dynamic consideration of an almost collisionless solar plasma flow may be justified by the fact that the observed geometry of the bow wave at the front of the magnetosphere agrees with the result of gas dynamic calculation made by Spreiter and Jones [1963].

The geometry of the shock wave generated in the quiet solar wind by the solar plasma ejected during solar flares depends on various factors, such as the geometry of the solar plasma, its Mach number with respect to the quiet solar wind, the ratio of specific heat (γ) and the magnetic field ($\underline{B}$) [cf. Van Dyke [1958], Fuller [1961], Belosterkorskii and Chushkin [1965]]. An application of this problem to interplanetary and magnetospheric problems has been discussed by Colburn and Sonett [1966], Spreiter, Summers, and Alksne [1966].

The front of the advancing plasma can be described by either the contact discontinuity or the tangential discontinuity. When such discontinuities sweep across the magnetosphere, we would expect changes in the density ρ, speed v or the magnetic field $\underline{B}$, and thus in their combined effect, namely changes in $p^* = p + B^2/8\pi$ by a ground magnetometer. Some of the changes in $\underline{B}$ may be seen also in the Forbush decrease.

Fig. 5 shows a collection of geomagnetic storms with the main phase decrease of more than 200 γ observed at Kakioka (Japan) since 1935. This choice of the magnitude of the main phase is made because they were likely to be caused by central flares (Fig. 2), and thus there is a great possibility of a direct contact between the magnetosphere and the discontinuities. It is quite obvious that many of the storms have a very complicated structure during the initial phase of geomagnetic storms; some of them clearly have a double, triple, or multiple structure. This feature was noticed by Newton and Milson [1953]. Therefore, the discontinuity seems to have a complicated structure, rather than a simple one schematically illutrated in Fig. 4. Note that many of the irregular features seen in the later phase of the storm are due to local ionospheric currents.

Changes of the intensity of galactic cosmic rays provide also an important clue to the structure of the plasma flow. One of the striking features is that the Forbush decrease of less than about 8% has a distribution of points similar to that shown in Figs. 1 and 2, while Forbush decreases of more than a 9% decrease are separated from the above group and were caused mostly by eastern flares (nine out of 11 events). In a simple situation, illustrated in Fig. 4, both the shock wave and the tangential discontinuity should be associated with the Forbush decrease, since the tangential component (namely, the azimuthal component with respect to a solar radius) has a discontinuity there, and it is this discontinuity that affects the intensity of galactic cosmic rays behind it [Parker, 1961]. The symmetric part of the Forbush decrease is likely to be due to the shock wave in a way discussed by Parker [1961], while the intense asymmetric part may be explained in a way suggested by Haurwitz, Yoshida, and Akasofu [1965]; it is due to a characteristic magnetic field asymmetry that develops as a natural consequence of the interaction between the expanding solar plasma and the spiral type interplanetary magnetic field.

Energetic particles generated during solar flares (protons, α-particles, neuclei of heavier elements, and electrons) provide also important information on interplanetary space and on the structure of solar plasma flow. For details, see review papers by Obayashi [1964] and Roederer [1964].

(b) The M-stream

The sun has another mode of plasma emission in the form of what Bartels called M-streams. The first important indication that the sun emits a long lasting stream was shown by Chree [1908] who devised the so-called 'method of superposed epochs' and applied it to the daily (geomagnetic disturbance) character figure C. As yet their source region on the solar disk has not been certainly identified, but it is possible that this particular region may coincide with UM regions, as H. W. and H. D. Babcock [1955] suggested in 1955. Ness and Wilcox [1965] have recently shown that the signs of UM regions (namely, $\underline{B}$ directed outward or inward to the solar disk) are well correlated with the sign of interplanetary magnetic fields at the earth's distance ($B \simeq 5\ \gamma$) (namely, directed away from the sun or toward the sun). This suggests that M-streams draw out magnetic fields from UM regions. Dessler and Fejer [1963] proposed an interesting idea that M-region geomagnetic storms are due to sheets of turbulence or irregularities that are generated by the collision of a region of high solar wind velocity with a low velocity region. Undoubtedly, this collision is an important interplanetary feature, but its relation to M-storms is uncertain (see Section 1.3). This problem has been studied further by Razdan, Colburn, and Sonett [1965], and Colburn and Sonett [1965]. For details of M-streams, see Mustel [1964].

Snyder, Neugebauer, and Rao [1963] showed that there is a very good correlation between K_p and the velocity of the M-streams. They obtained an empirical relation

$$v\ (\mathrm{km/sec}) = 8.44\ \Sigma K_p + 330\ .$$

1.2 The Magnetosphere

(a) Magnetospheric Boundary

The magnetosphere provides the basic frame to which all the geomagnetic storm phenomena can be referred. The solid earth can be considered to be the 'core' of the magnetosphere, which provides a dipolar magnetic field. Both act as an obstacle in the solar plasma flow, resulting in a bubble or a cavity, called the magnetosphere. Strong *et al.* [1966] have shown recently that the quiet solar wind is rather cool, $T \simeq 2 \times 10^4$ °K.

Chapman and Ferraro's study [1931a, b] on the interaction of a dipole field and the solar plasma has recently been extended by a number of authors [cf. Beard, 1964; Mead, 1964]. The essential process of this interaction can be considered to be a shielding, so that the solar plasma (B = 0) is separated from the geomagnetic field by a thin layer where the shielding current flows. Since the geomagnetic field is confined within the cavity, $\underline{B}$ should be parallel to the boundary surface, except at the two points (one in each hemisphere) called the neutral points. Therefore, the determination of the boundary shape is reduced to finding the magnetic field $\underline{B}$ which satisfies two boundary conditions; namely, near the earth's center it should be dipolar and at the boundary $B^2/8\pi$ is equal to the plasma pressure ($2mnv^2\cos^2\theta$), where θ denotes the angle between the velocity vector $\underline{v}$ and the normal to the boundary surface. Further, since electric currents are allowed to flow only in a thin layer near the boundary, $\nabla \times \underline{B} = 0$ inside the cavity.

Instead of the above 'particle-approach', Spreiter, Summers, and Alksne [1966] considered the plasma flow to be a continuous medium and showed that the MHD approach gives essentially the same shape of the boundary [see also Levy, Petschek, and Siscoe, 1964]. Furthermore, the MHD approach has predicted the existence of a shock wave at the front of the magnetosphere [Axford, 1962; Kellogg, 1962; Spreiter and Jones, 1963; Sozou, 1965; Spreiter, Summers, and Alksne, 1966; Spreiter, Alksne, and Abraham-Shrauner, 1966]. Figure 6 shows the magnetospheric boundary suggested by Lees [1964].

Alfvén [1950, 1955] considered the flow pattern of a tenuous magnetized plasma around a dipole field. The guiding center approximation was assumed to be applied, and thus each particle has the magnetic moment μ. In general, the velocity $\underline{v}_G$ of the guiding center is given by

$$\underline{v}_G = \underline{F} \times \underline{B}/eB^2 \qquad (2)$$

where F denotes the force given by

$$F = e\underline{E} - \mu\nabla\underline{B} - m\, d\underline{v}/dt \qquad (2)$$

Therefore, the particle drifts in the magnetic field with a velocity such that in its own frame of reference the 'effective' electric field is given by $\underline{F}/e$ [cf. Helmer, 1963].

Ignoring $md\underline{v}/dt$ and assuming that $\underline{E}$ is uniform (or ignoring the space charge) and further $\underline{B}$ is unaffected by the plasma flow (namely $\underline{B}$ is known), Alfvén [1950] demonstrated that there exists a forbidden region where 'diameter' is of order 2L

where

$$L = \left(\frac{M\mu}{eE}\right)^{1/4}$$

M = the magnetic moment of the earth.

Karlson [1962, 1963] extended Alfvén's work by using the full equation (2) and showed that the space charge does not alter seriously the essential feature of Alfvén's theory and that Alfvén's scale of the forbidden region should be reduced by a factor of 2.

Chapman-Ferraro's and Alfvén's conditions may be considered to be the two extreme cases and the true situation must lie between the two, although as a first approximation the compression of the magnetosphere is observed to be the major process; in other words, contrary to Alfvén's assumption that the plasma flow does not change B, the earth's field is compressed and confined in a cavity. Therefore, an important modification of the theory is necessary. On the other hand, satellite observations indicate the existence of interplanetary magnetic fields. Dungey [1958, 1961, 1963] proposes that interplanetary fields play an important role on the interaction between the solar plasma and the magnetosphere.

At present, none of the approaches can explain satisfactorily an extended tail of the magnetosphere. The tail seems to have a cylindrical structure; the magnetic field is nearly parallel to the axis of the cylinder, and is directed toward the sun in the upper half region and away from the sun in the lower half region. These two regions are separated by the neutral sheet. This extended tail was first predicted by Piddington [1960] and confirmed by Ness [1965].

In Chapman and Ferraro's theory, all the solar particles are specularly reflected at the boundary, so that they make an 'elastic collision' and thus do not deposit their energy on the boundary. There have been some efforts to try to find mechanisms which make their collision 'inelastic', and further interactions (between the solar plasma flow and the magnetosphere) which produce a resistive force against the solar plasma flow.

Piddington [1960] suggested that a two-stream instability occurs in the thin shielding layer (since the shielding current is carried by streaming electrons; for details, see Beard, 1964) and that this instability tends to convert a part of the streaming energy of electrons to their thermal energy. Bernstein, Fredricks, and Scarf [1964] suggested that if the electrons temperature becomes higher than the ion temperature by this instability, ion acoustic waves will be generated and propagated against the direction of the solar plasma flow, causing an interaction between them. Possible instabilities which occur on the magnetospheric boundary are discussed in section 2.

On the other hand, Dessler [1964] proposed that the radiation pressure of hydromagnetic waves tend to prevent the tail from closing and that the tail extends as long as 20 to 50 astronomical units. Van Allen [1955] showed, however, that there is no indication of an extended tail at a distance of 3300 earth radii.

(b) Internal Structure

As mentioned earlier, the solid earth may be considered to be the core of the magnetosphere. This core is surrounded by the neutral atmosphere. Beyond 70 km height, the ionization process becomes increasingly important. Although the neutral component is a predominant constituent even at 300 km level, a 100 km level can be considered to be the transition region between the neutral atmosphere and the magnetospheric plasma; this height corresponds to the E region of the ionosphere. Above this region, both ions and electrons are gyro-free, namely they can execute many gyrations between two collisions with other particles. We shall see in section 4 that important polar geophysical phenomena, such as the polar electrojet, occur in the transition region. At the ionospheric level, the diffusive separation of the constituent begins to overcome the mixing, and thus the proportion of lighter elements increases with height. There is a layer of helium, and beyond that the outermost region which consists of mainly hydrogen. There is an evidence that the plasma density falls down rather abruptly at about a geocentric distance of 4 earth radii [Carpenter, 1962; 1963; Carpenter and Smith, 1964; Carpenter, Dunckel and Walkup, 1964; Taylor, Brinton, and Smith, 1965].

The magnetosphere has roughly been divided into two regions. In the first region, energetic particles can be durably trapped, so that their adiabatic invariants (the magnetic moment, the longitudinal invariant I, and the third flux invariant Φ) should not be easily violated. This region is called the trapping region and all the major radiation belts are located in it. Geomagnetic field lines in the trapping region are said to be 'closed'. Figure 7 shows the noon-midnight meridian cross-section of the magnetosphere; the trapping region is hatched. One of the most important features of the trapping region is its asymmetry with respect to the dipole axis. Because of this asymmetry, the intersection line between the outer boundary of the trapping region and the ionosphere has an oval shape which is eccentric with respect to the dipole poles. Figure 8 shows the intersection line determined by Frank, Van Allen, and Craven [1964] on a polar map. Added to this is the instantaneous region of the aurora, the auroral oval, determined by Feldstein [1963]. We had long considered that the auroral zone (dp lat 67°) was a unique region of the earth. However, recent extensive studies show that the auroral zone is simply the locus of the midnight part of the auroral oval where active auroras are most frequently seen.

We shall see in section 4 that the major polar geophysical phenomena occur along the auroral oval. Therefore, the auroral oval can be considered to be a natural frame of reference to which major polar geophysical phenomena can be referred. For example, the region encircled by the auroral zone had been called the polar cap, but the actual (or instantaneous) polar cap should be the region encircled by the auroral oval. By the early definition, a point at dp lat 72° should be permanently in the polar cap. However, by the new definition, the point lies in the polar cap only between 19 and 05 local times.

Auroral activity is seen twice there when the point crosses the oval. On the other hand, at a point at dp lat 67°, auroral activity tends to peak in the midnight sector when the point is under the oval. The concept of the auroral oval has been established by a combined effort of a number of workers; among them are Feldstein [1963], Khorosheva [1962], Malville [1959], Davis [1962], Sandford [1964], and Lassen [1964].

Geomagnetic field lines which are anchored in the polar cap cross the equator outside the trapping region, namely in the extended tail region or may be connected to interplanetary field lines.

It is important to note that the auroral oval coincides approximately with the intersection line between the outer boundary of the magnetosphere and the ionosphere. The aurora, as well as other major polar geophysical phenomena, must be closely related to the internal structure of the magnetosphere.

During very quiet periods of the sun, the auroral oval tends to shrink poleward. On the other hand, during geomagnetic storms with an intense ring current it shifts toward the equator. It can be easily inferred from Fig. 7 that the equatorial shift of the oval is associated with the equatorward movement of the outer boundary of the trapping region. This will be discussed further in section 3.4. This indicates that a point at dp lat 67° will be well outside the auroral oval during very quiet periods of the sun and well inside the polar cap during intense geomagnetic storms. Therefore, our natural frame of reference is a flexible one, and in fact, such a flexible coordinate can clarify a considerable statistical confusion. For example, it is well known that there exists an excellent correlation between auroral activity and low and medium K_p indices at an auroral zone station. However, the correlation tends to break down when K_p indices become very high. This is simply because during a great storm an auroral zone station can become temporarily a polar cap station, when the oval shifts well equatorward side of the station.

1.3 The Variety of the Development of Geomagnetic Storms

Geomagnetic storms have long been classified into two major types, the so-called 'standard type' and 'gradually commencing type'. The onset of the first type is characterized by their sudden commencement. In low and middle latitudes, this commencement is recorded as a sudden increase in the horizontal component, at almost the same instant all over the earth and has been called the storm sudden commencement (abbreviated by ssc).

The average characteristics of the standard type are as follows: After the sudden commencement, the horizontal component remains above the initial undisturbed value for a period of two to four hours. This positive phase is called the initial phase. Thus, in the simplest case, the horizontal component trace in a normal-run magnetic record during the early phase of geomagnetic storms shows a step function-like variation. The initial phase is then followed by the main phase which is characterized by a decrease in the horizontal component of a much greater magnitude than that of the initial phase. After attaining the minimum value, there is a slow recovery towards the initial undisturbed value; this phase is called the recovery phase.

Geomagnetic storms of the second type show no clear indication of the sudden onset (which is a very prominent feature of the standard type), so that they have been called the gradually commencing storms (abbreviated by Sg). Characteristics of these storms are, however, essentially the same as those of the main phase of the standard type. Except for Newton and Milson's extensive study of geomagnetic storms [1953], little attention has been given to this type of storm, partly because its time of onset is not very evident.

It should be noted, however, that individual geomagnetic storms do not necessarily develop in such a manner. Some of them show a large ssc and a long initial phase (~ 10 hours), but no significant main phase. Some of them have a very short initial phase, less than 30 minutes. Therefore, the duration of the initial phase can vary greatly. Further, some storms tend to develop the 'main' phase before the storm sudden 'commencement', and some have only the 'main' phase. Fig. 9 shows several examples of geomagnetic storms to illustrate such a variety. It is not difficult to conclude that in low latitudes geomagnetic storms consist mainly of two elementary types of disturbance fields, the field caused by the compression of the magnetosphere and the field produced by the ring current. The variety of the development of geomagnetic storms can be simply interpreted as due to a combination of these two fields in different ratios and with different times of growth and decay. This is possible only when the two fields are almost independent of each other.

The above conclusion was first pointed out by Akasofu [1960] and Akasofu and Chapman [1963a, b] and implies that the kinetic energy flux of the solar plasma has no obvious relation to the K_p index. This has been well demonstrated by Fig. 10 which is based on the Imp I satellite observation [Wilcox, 1966].

It should be noted also that changes of the kinetic energy flux can contribute to small K_p values by compressing or making forced oscillations of the magnetosphere. However, such changes cannot contribute to large K_p values, such as 6, 7, 8 and 9. This is quite obvious from the fact that even the most intense impact of the plasma flow associated with the shock wave or the tangential discontinuity has never produced a ssc of 800 γ (which corresponds to $K_p = 9$). Large K_p values are mainly produced by intense polar magnetic substorms whose growth does not have any obvious relation to the kinetic energy flux; note that the magnetic observatories contributing to the K_p index are located in a narrow belt between 45° and 63°. Dessler and Fejer [1963] proposed that K_p is an index of the time rate of change of the plasma pressure (p*) on the magnetosphere. It is clear that such a proposal is partly based on a misinterpretation of the K_p index. In fact, Snyder and Neugebauer [1963] showed that even when the solar plasma velocity was continuously high for a few days, K_p did not become small. They conclude thus that the K_p is a measure of plasma velocity and not a measure of the time rate of change of plasma velocity.

Section 1

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Figure Captions

Fig. 1.1 The magnitude of storm sudden commencements and sudden impulses as a function of the central meridian distance of their responsible flares.

[Akasofu, S.-I. and S. Yoshida, Planet. Space Sci., 1966]

Fig. 1.2 The magnitude of the main phase decreases as a function of the central meridian distance of their responsible flares.

[Akasofu, S.-I., and S. Yoshida, Planet. Space Sci., 1966]

Fig. 1.3 (a) Left column: geomagnetic storms caused by limb flares (central meridian distance > E 60° or W 60°) of importance 3 or 3^+.

(b) Central and Right column: geomagnetic storms caused by central flares (central meridian distance < E 15° or W 15°) of importance 3^-, 3, or 3^+.

[Akasofu, S.-I., and S. Yoshida, Planet. Space Sci., 1966]

Fig. 1.4 The schematic illustration of the structure of the solar plasma flow generated by solar flares.

[Akasofu, S.-I., and S. Yoshida, Planet. Space Sci., 1966]

Fig. 1.5 The collection of intense geomagnetic storms with the main phase decrease of order 200 γ or more. The records are the horizontal component traces from Kakioka observatory.

[Akasofu, S.-I., and S. Yoshida, Planet. Space Sci., 1966]

Fig. 1.6 The flow of solar plasma around the magnetosphere; length unit = 9.3 earth radii.

[Lees, L., AIAA Journal, 2, 1576, 1964]

Fig. 1.7 The noon meridian cross-section of the magnetosphere. The trapping region is hatched.

[Ness, N. F., J. Geophys. Res., 70, 2989, 1965]

Fig. 1.8 The location of the auroral oval obtained by Feldstein [1963] and of the iso-intensity (the flux = $10^4/cm^2$ sec) contour line of the trapped electrons of energies greater than 40 keV.

[Frank, Van Allen, and Craven, 1964]

[Akasofu, S.-I., Planet. Space Sci., 1966]

Fig. 1.9 The variety of the development of geomagnetic storms.

Fig. 1.10 The relation between the K_p index and the kinetic energy flux of the solar plasma flow.

[Wilcox, J. M., Private Communication, 1966]

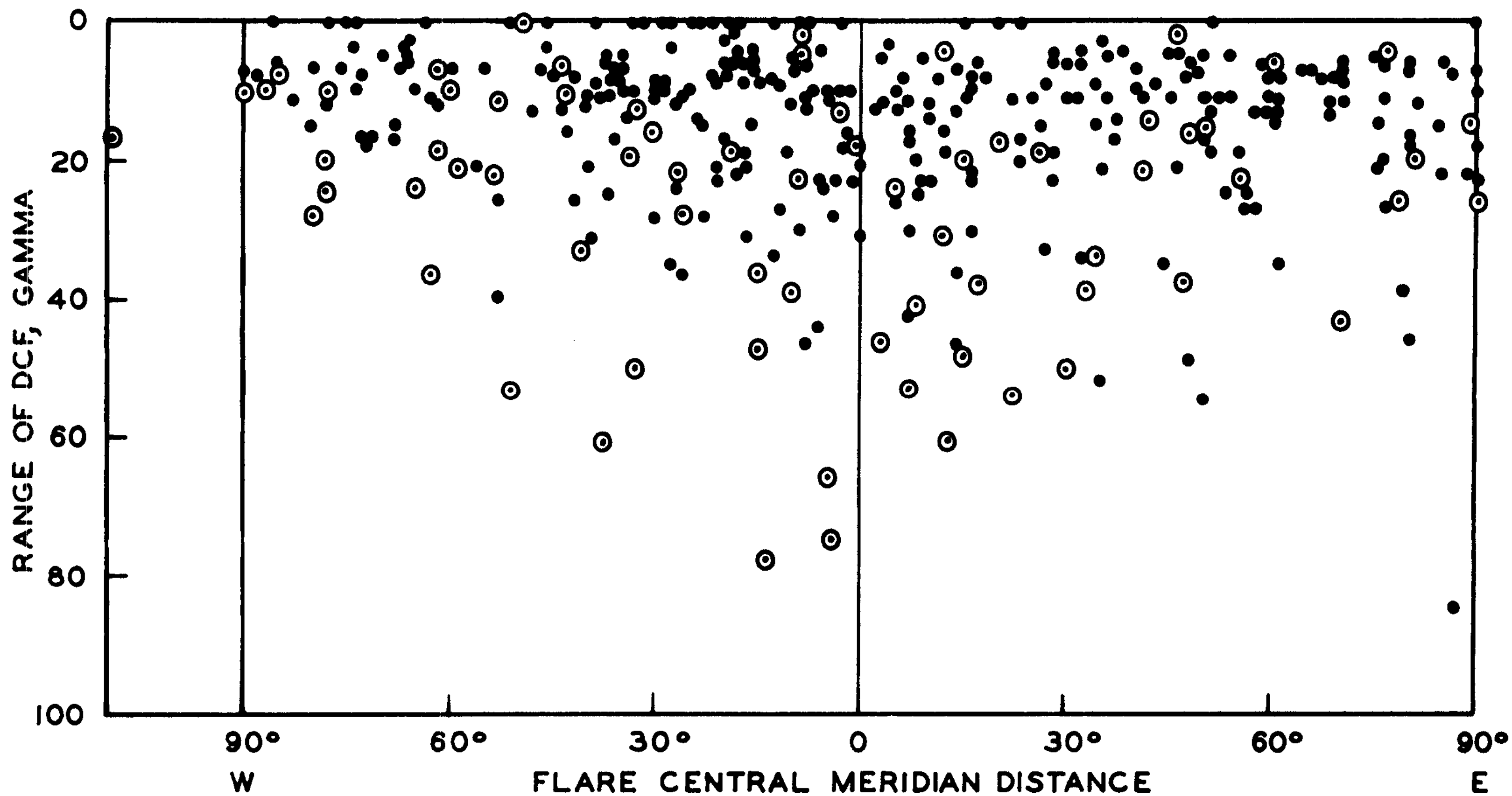
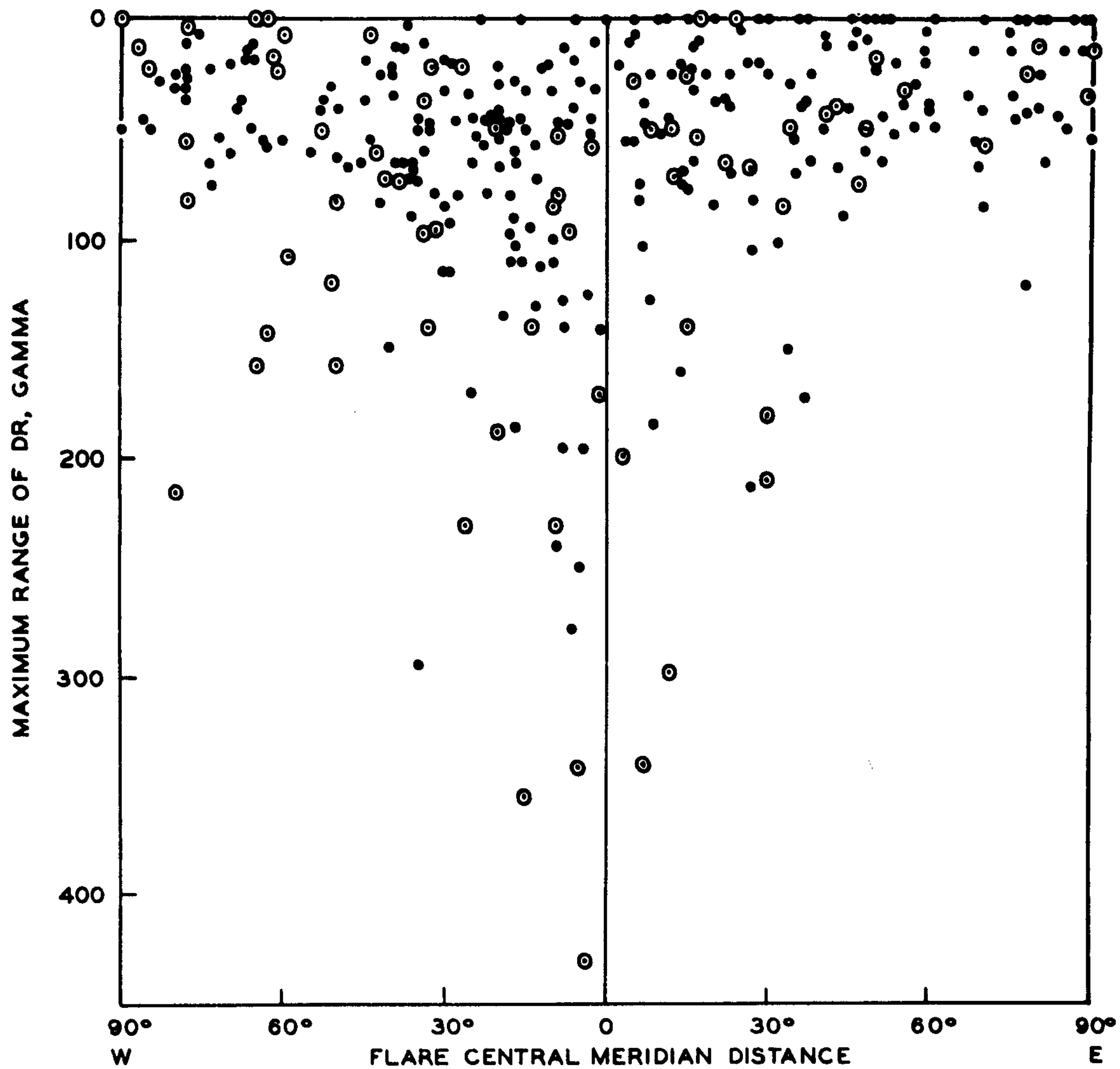

RANGE OF DCF, GAMMA
0
20
40
60
80
100
90°
W
60°
30°
0
30°
60°
90°
E
FLARE CENTRAL MERIDIAN DISTANCE

Figure 1.1


0
100
200
300
400
MAXIMUM RANGE OF DR, GAMMA
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W
60°
30°
0
30°
60°
90°
E
FLARE CENTRAL MERIDIAN DISTANCE

Figure 1.2

G-66-252

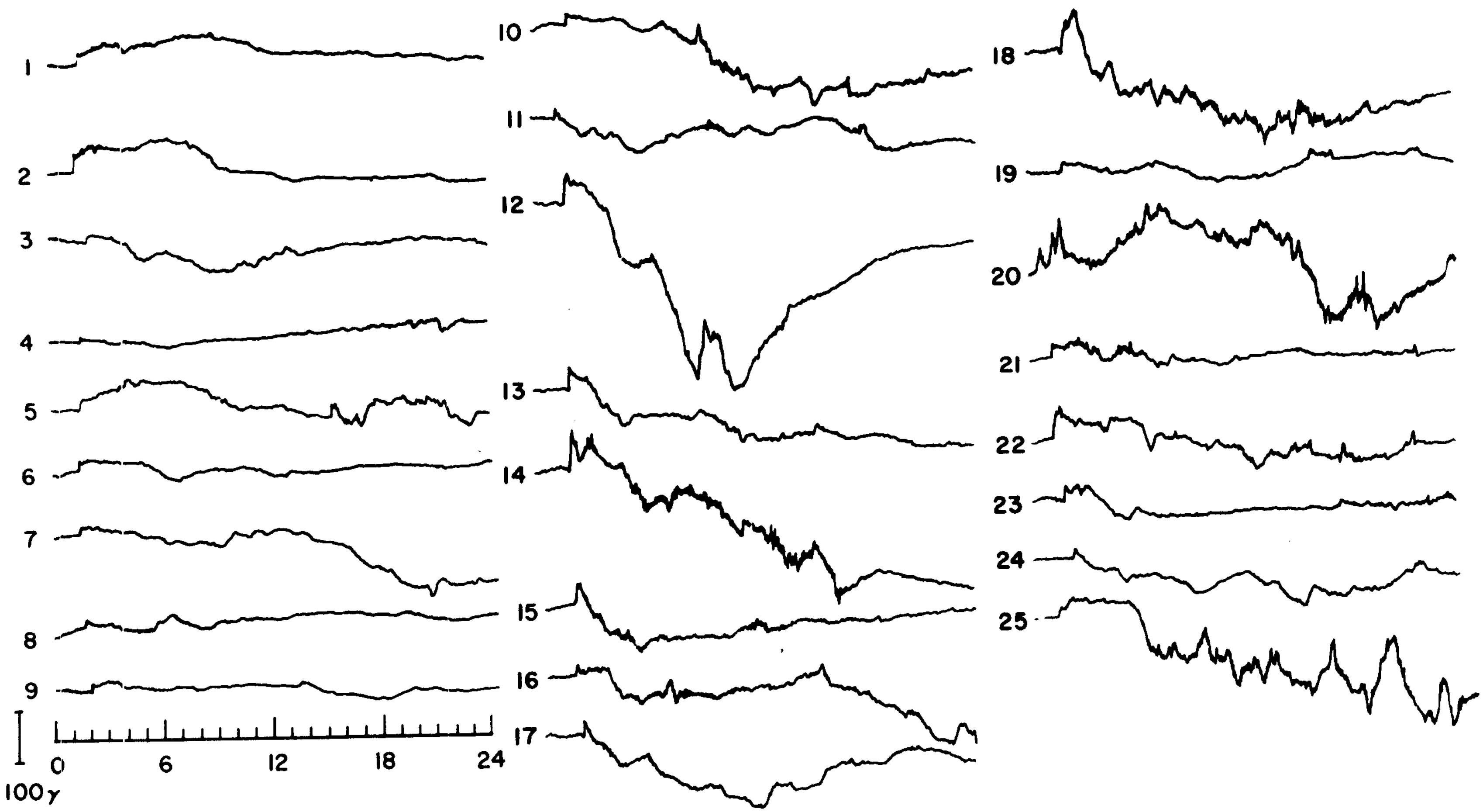

Figure 1.3

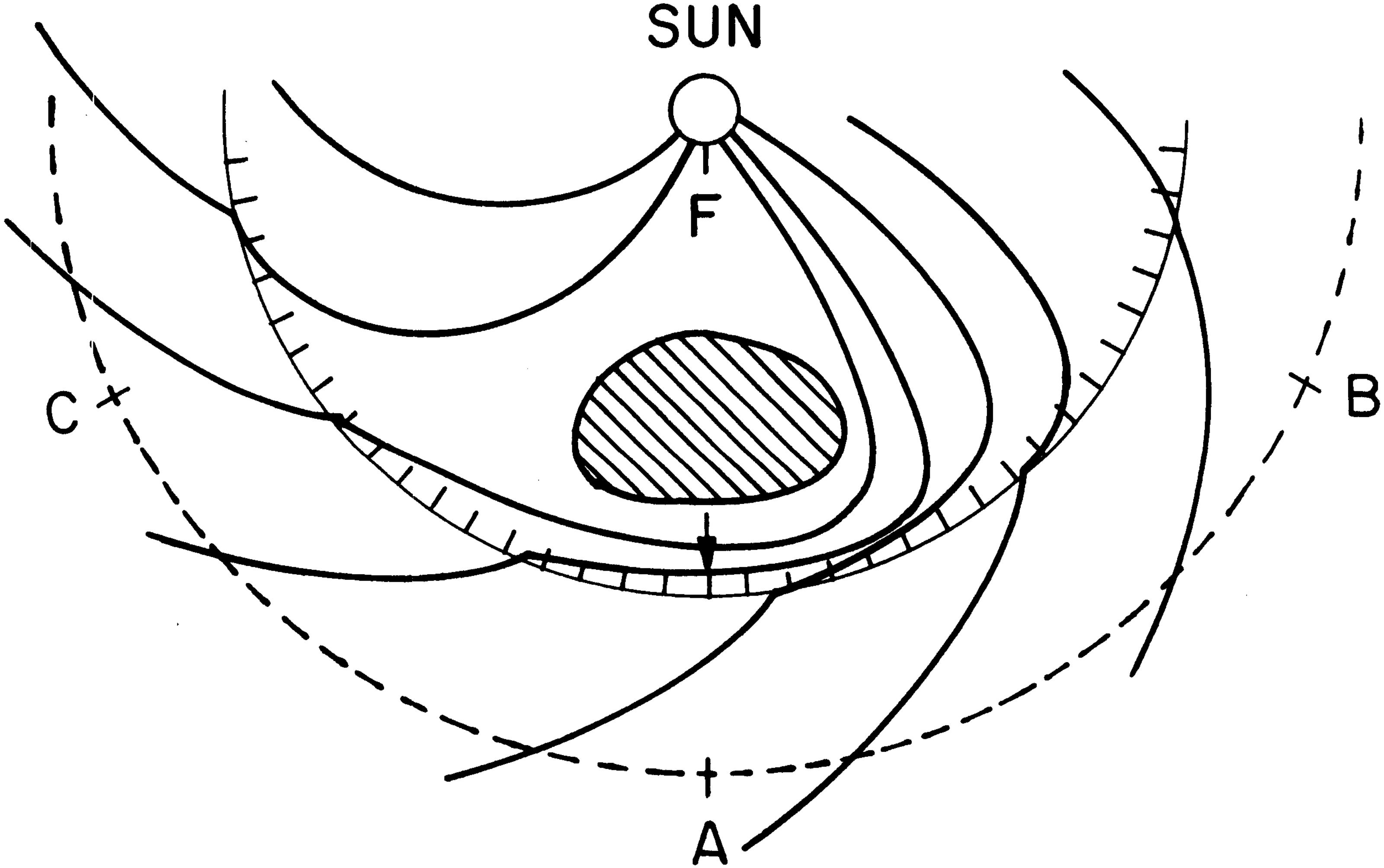

Figure 1.4

G 66-253

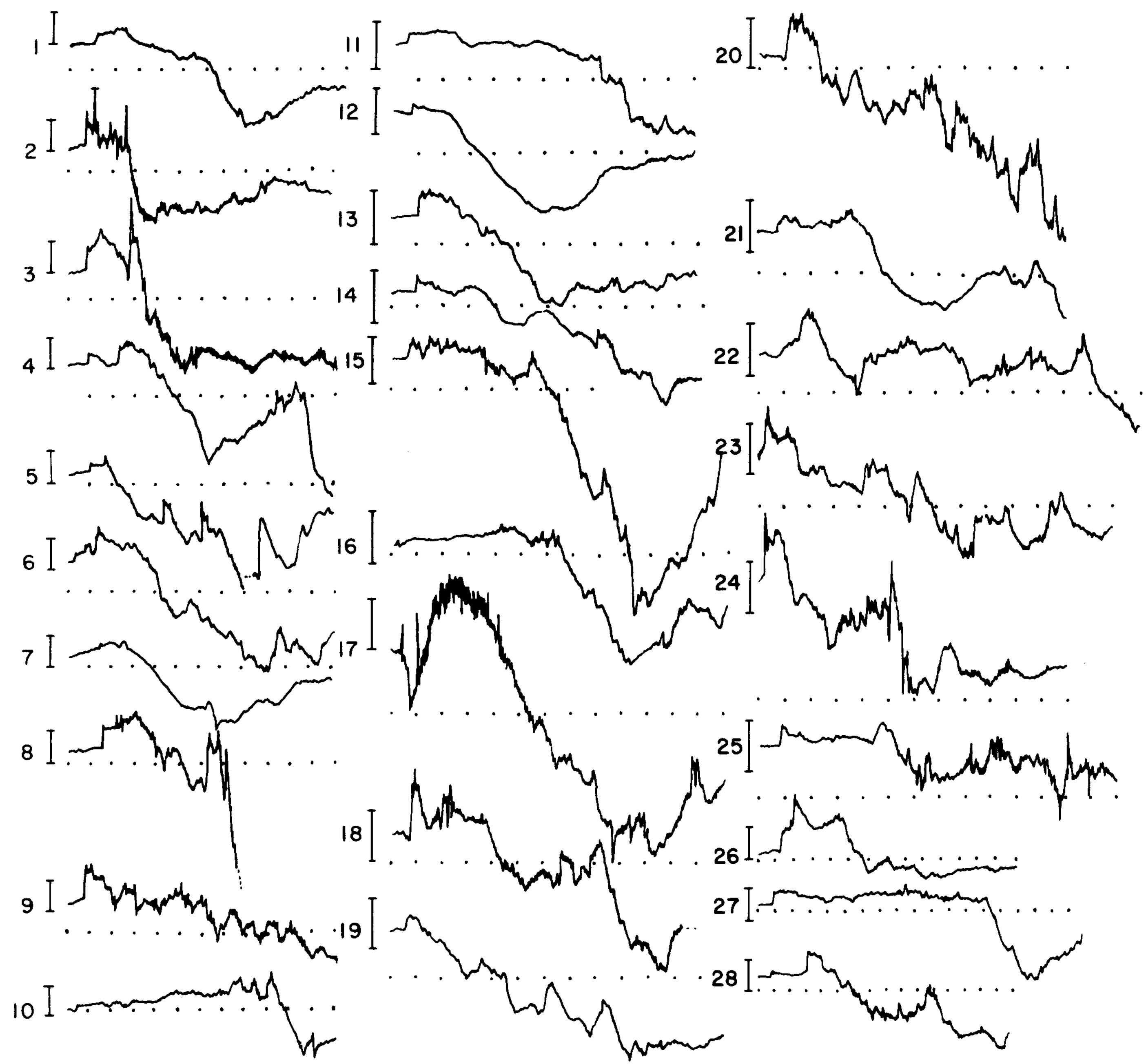

Figure 1.5

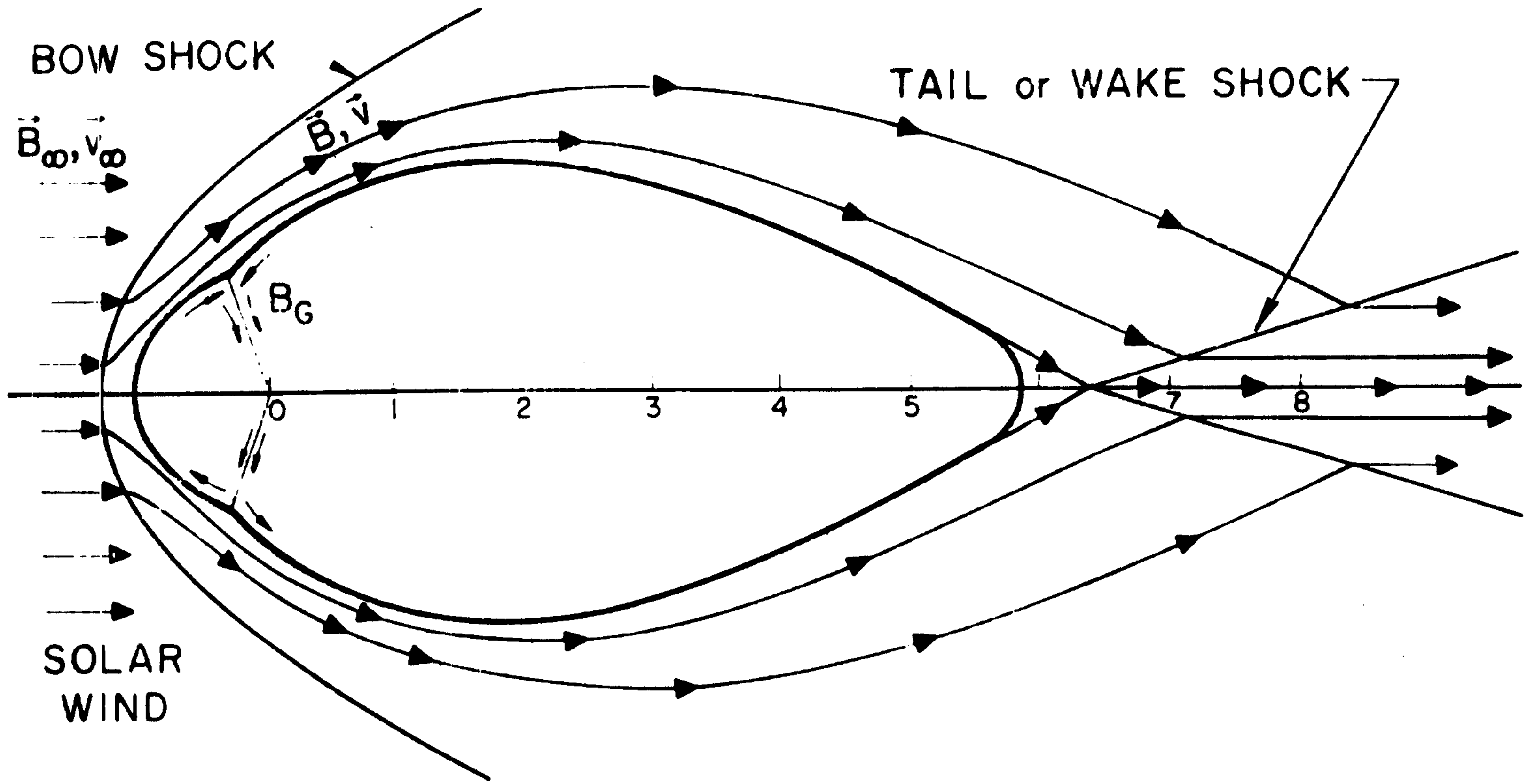
BOW SHOCK
$\vec{B}_\infty, \vec{v}_\infty$
$\vec{B}, \vec{v}$
B_G
TAIL or WAKE SHOCK
SOLAR
WIND
0
1
2
3
4
5
7
8

Figure 1.6

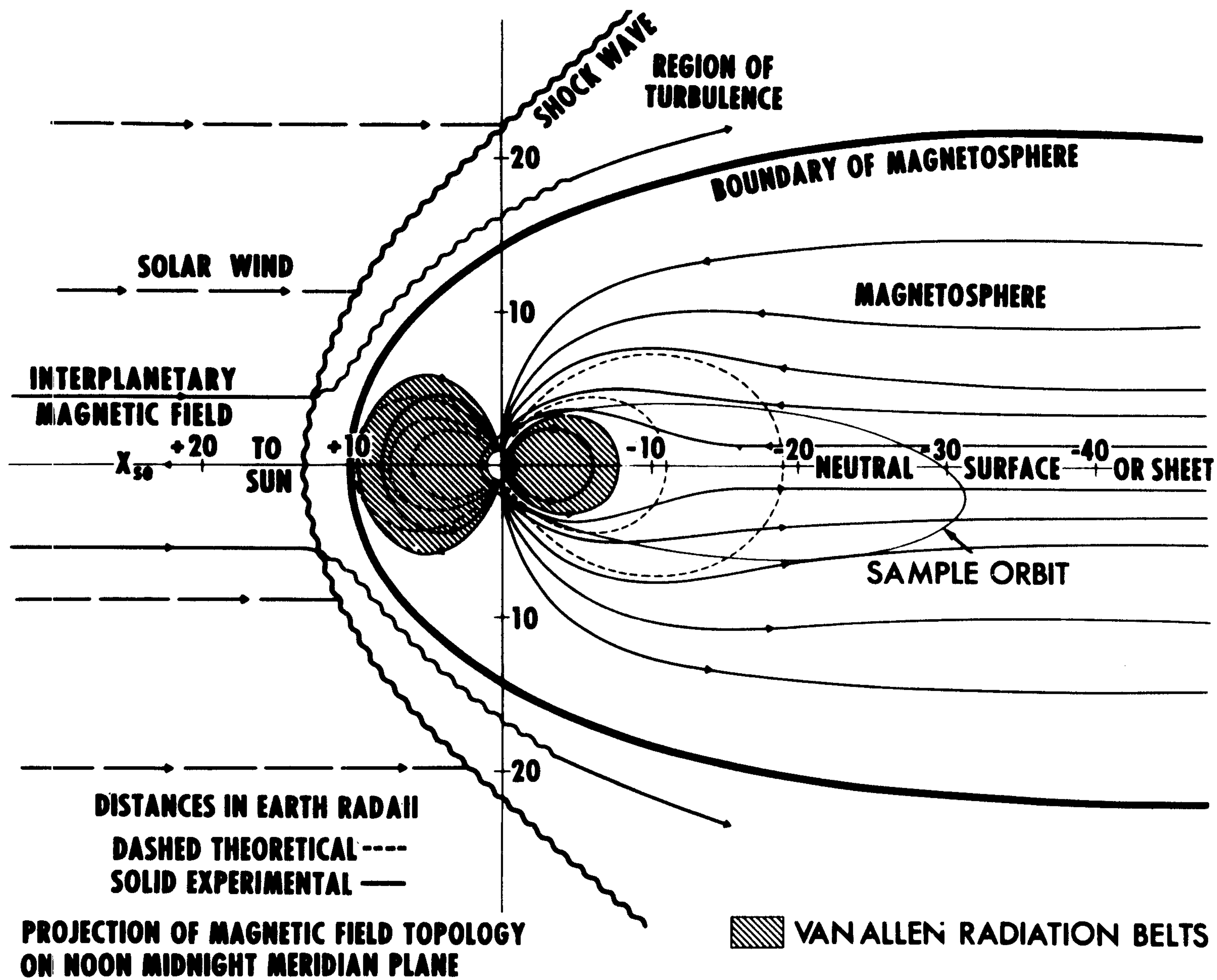
SHOCK WAVE
REGION OF TURBULENCE
BOUNDARY OF MAGNETOSPHERE
SOLAR WIND
MAGNETOSPHERE
INTERPLANETARY MAGNETIC FIELD
X
+20
TO SUN
+10
-10
-20
NEUTRAL
-30
SURFACE
-40
OR SHEET
20
10
10
20
SAMPLE ORBIT
DISTANCES IN EARTH RADAII
DASHED THEORETICAL ----
SOLID EXPERIMENTAL ——
PROJECTION OF MAGNETIC FIELD TOPOLOGY ON NOON MIDNIGHT MERIDIAN PLANE
VAN ALLEN RADIATION BELTS

Figure 1.7

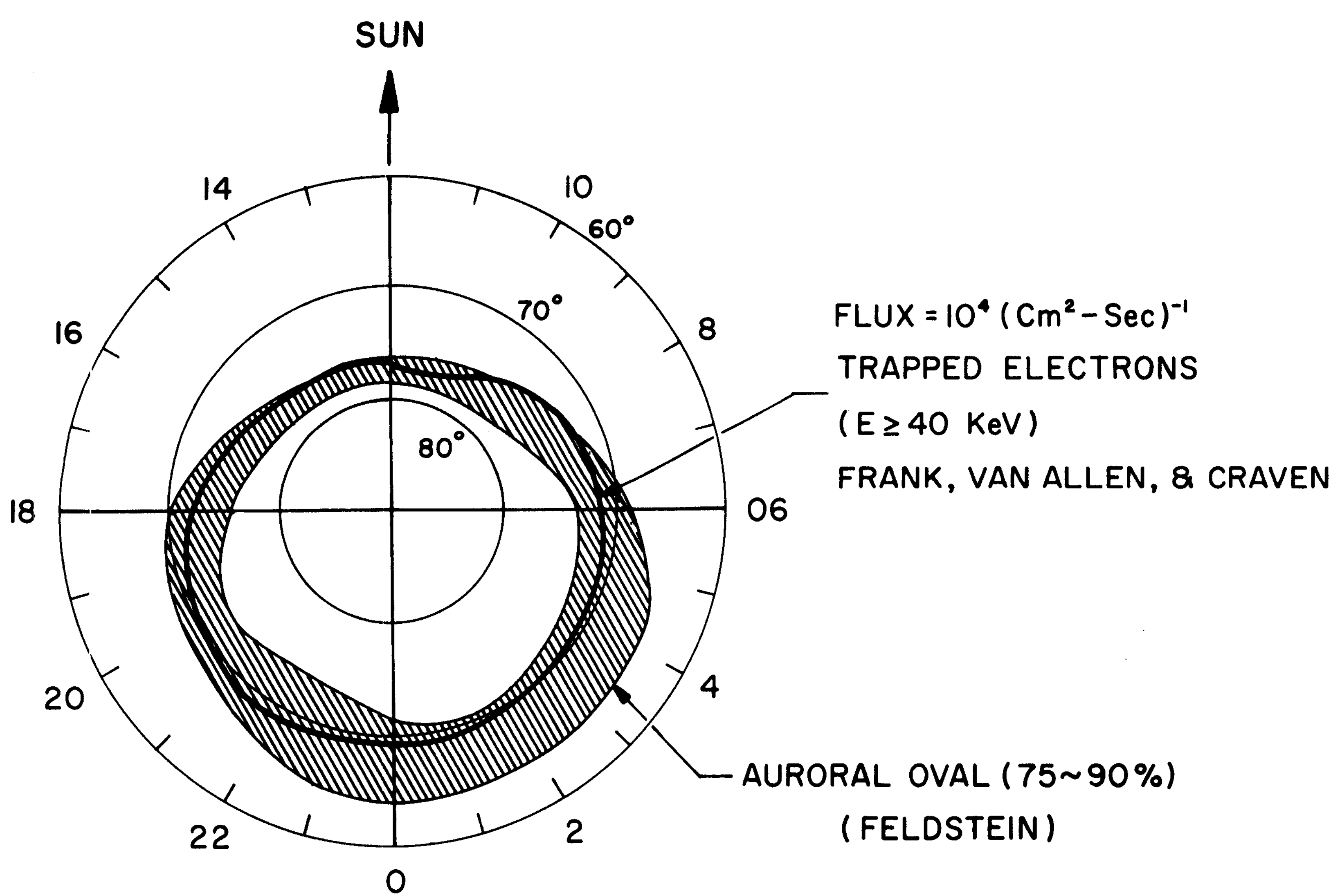
SUN
14
10
60°
70°
16
8
80°
18
06
20
4
22
2
0
FLUX = 10⁴ (Cm² - Sec)⁻¹
TRAPPED ELECTRONS
(E ≥ 40 KeV)
FRANK, VAN ALLEN, & CRAVEN
AURORAL OVAL (75~90%)
(FELDSTEIN)

Figure 1.8

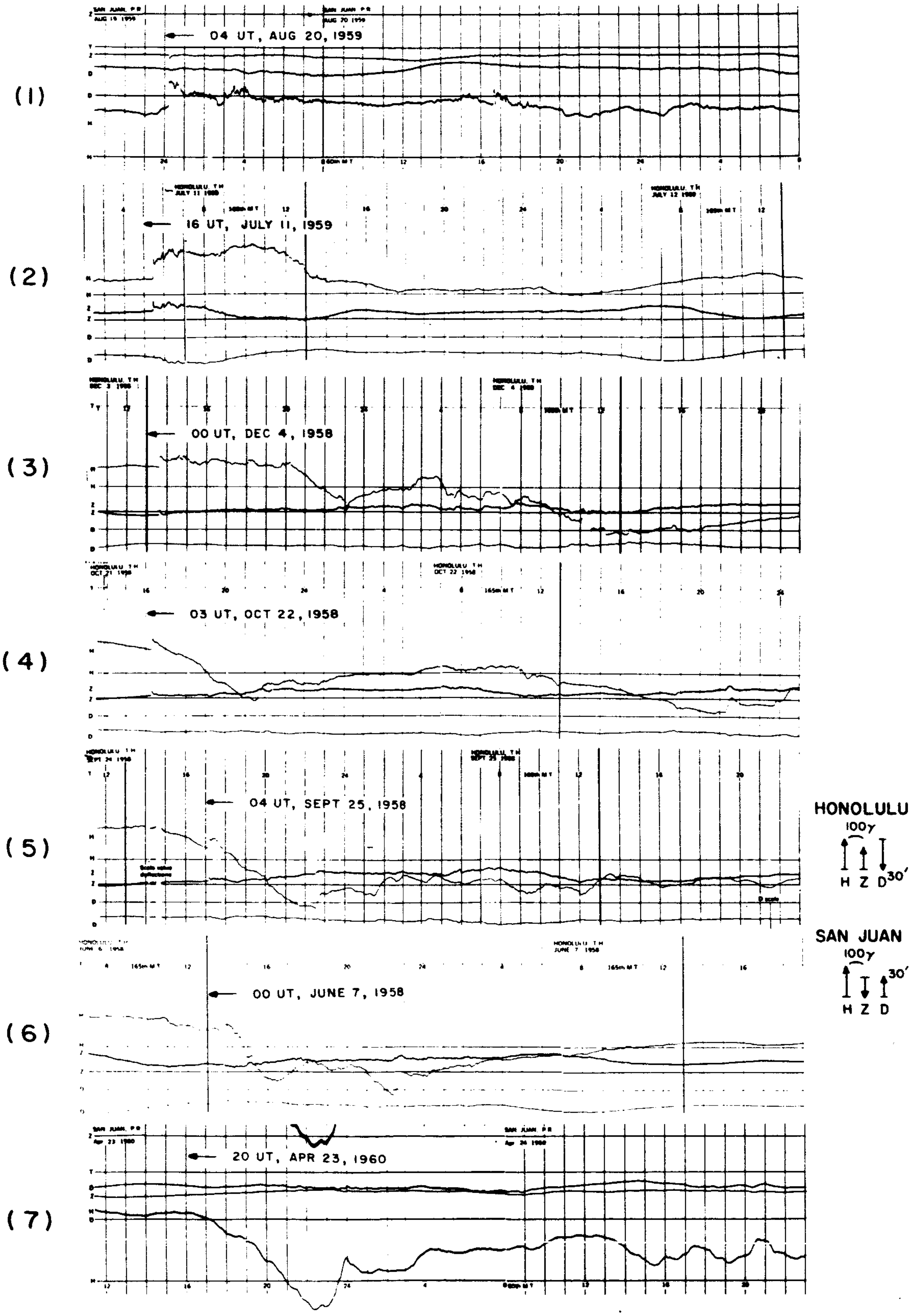
(1)
04 UT, AUG 20, 1959
(2)
16 UT, JULY 11, 1959
(3)
00 UT, DEC 4, 1958
(4)
03 UT, OCT 22, 1958
(5)
04 UT, SEPT 25, 1958
(6)
00 UT, JUNE 7, 1958
(7)
20 UT, APR 23, 1960
HONOLULU
100γ
H Z D 30′
SAN JUAN
100γ
H Z D 30′

Figure 1.9

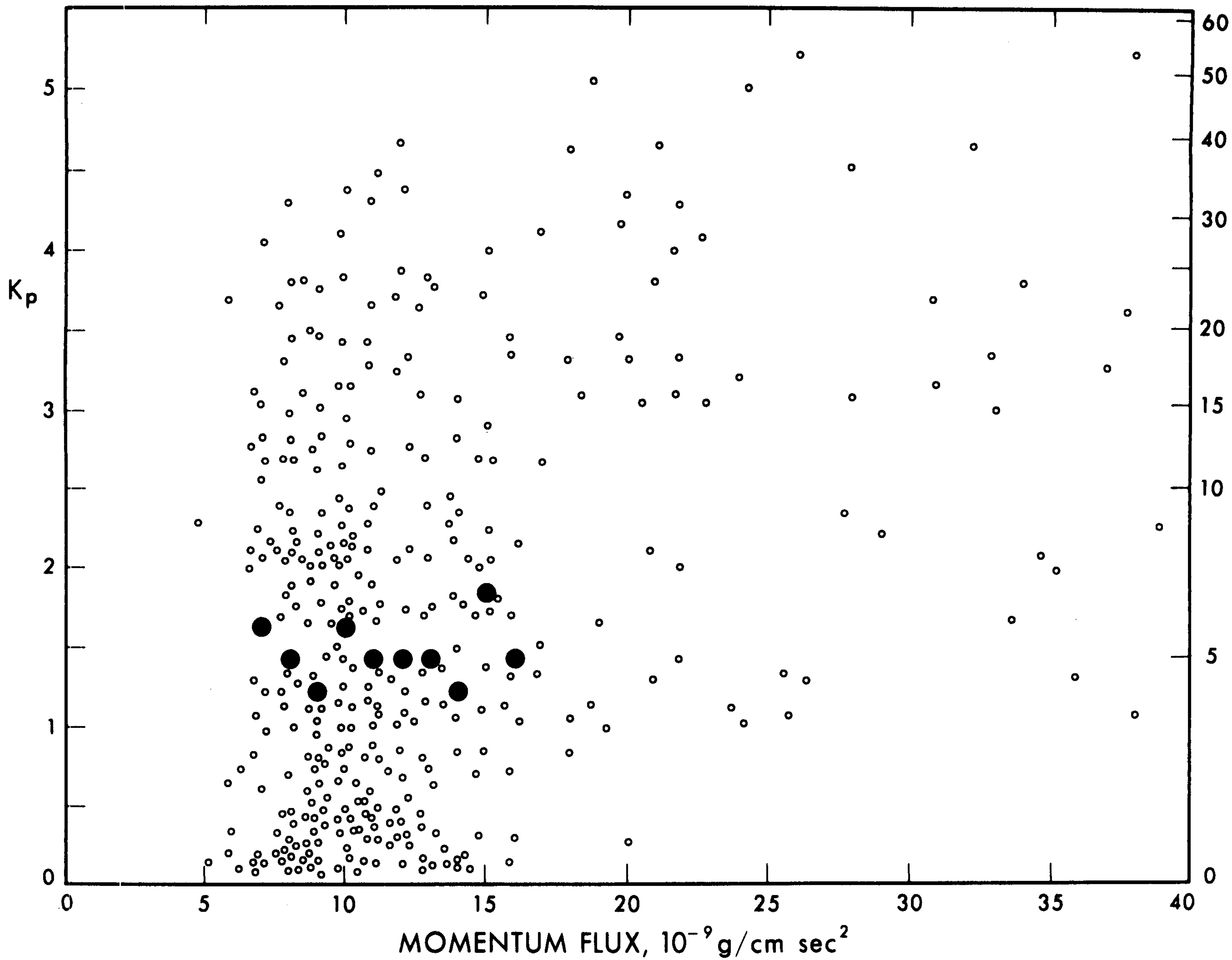
Kp
Ap
0
1
2
3
4
5
0
5
10
15
20
30
40
50
60
0
5
10
15
20
25
30
35
40
MOMENTUM FLUX, 10^{-9} g/cm sec^2

Figure 1. 10

2. Storm Sudden Commencement and Initial Phase

2.1 Introduction

The sudden onset of many geomagnetic storms is one of the most striking features of geomagnetic disturbances. At many stations, especially in low latitudes, it is commonly characterized by a sudden increase in the H component. A few examples of typical ssc storms are illustrated in section 1.3.

This step-function like change has been attributed by Chapman and Ferraro [1931 a, b; 1940] and Ferraro [1952] to a sudden impact of solar plasma flow on the geomagnetic field. Their theory is the basis of the present concept of the magnetospheric cavity formation (section 1.2).

As mentioned in section 1.1, recent progresses in interplanetary physics have suggested that the suddenly enhanced plasma flow is an interplanetary shock wave generated by solar plasma ejected during solar flares or by interactions of the quiet solar wind and M-streams, rather than a sudden and direct impact of a fresh solar plasma.

Our main concern in this section is consequences of the interaction between the shock wave and the magnetosphere.

2.2 Morphology

(a) General

Although changes of the geomagnetic field caused by the impact of the interplanetary shock wave are typically step-function-like in low latitudes, there are considerable variety of changes, particularly in high latitudes. Therefore, much of the earlier studies have been confined by classifying various types of storm sudden commencement (ssc) and examining their occurrences over the earth [cf. Newton, 1948; Ferraro, Parkinson, and Unthank, 1951; McIntosh, 1951; Jackson, 1952; Ivanov, 1961; Matsushita, 1962; Kazumi, 1963; see also a review paper by Akasofu and Chapman, 1960]. In particular, the daily variation of the occurrence frequency in middle latitude attracted much attention. Newton [1948] showed that at Greenwich and Abinger the occurrence of ssc's and si's has a distinct minimum at about 8 in local time and also a smaller minimum at about 18 LT. Another interesting feature is a step-function like change preceded by a sharp negative impulse in high latitudes (called ssc^* or the primary reverse impulse 'PRI'). Figure 2.1 shows the occurrence of ssc^*, obtained by Matsushita [1962], as functions of dipole latitude and local time.

They tend to occur in the afternoon hours and also in the sunlit hours along the dip equator.

It has become clear by these studies that the daily variation of the occurrence frequency is only an apparent one and is caused by a superposition of at least two additional types of geomagnetic changes which occur at the time of the sudden impact.

Nagata and Abe [1955], Oguti [1956], and Obayashi and Jacobs [1957] have made a detailed study of ssc* and have suggested that the disturbance field can be expressed by two oval equivalent current systems (the PRI current) over the polar region a few minutes before the main positive impulse (Fig. 2.2). Obayashi and Jacobs [1957] showed also that the directions of the two oval currents are reversed soon after the main (positive) impulse arrives (reversed PRI current). Both Sato [1961, 1962] and Sano [1962/3] made a further extensive synoptic study of geomagnetic variations associated with ssc by using quick-run records and were able to reveal rapid variations of both the PRI and reverse PRI current systems. During the brief transition period, the two currents can exist together (Fig. 2.3). Much of the complicated features of the sudden commencement in middle and high latitudes are thus caused by the superposition of the magnetic fields of these two current systems and perhaps some others on the step-function like variation.

Recently, Wilson and Sugiura [1961] found that the ssc disturbance vectors constructed by using both the H and D component records show a counterclockwise or clockwise rotation, depending on the latitude and local time. In an auroral zone station, like College, Alaska (dp lat 64.7° N), the vectors rotate counterclockwise between 2200 and 1000 LT and clockwise in the early afternoon hours. On the other hand, an Antarctic auroral zone station, like Byrd (dp lat 70.6° S), shows the opposite rotations (Fig. 2.4).

(b) Simultaneity

Early studies of the simultaneity were greatly hindered by inaccuracy of the records [cf. Adams, 1892; Bauer, 1910; Chapman, 1918]. Even with present improved instruments, the difference of the onset time in low latitudes cannot be determined accurately. Gerad [1959] found time differences of order up to a few seconds and suggested that the sun controls the hemisphere in which the sudden commencement first appears. However, such a difference is of order of the timing accuracy. Both Williams [1960] and Sato [1961] have, however, shown that the ssc variations tend to occur a few to several minutes earlier in high latitudes than in low latitudes. Figure 2.5 shows the ssc of the September 29, 1957 storm; there is about one minute difference of the onset time between high (College) and low latitude (Honolulu) stations. Yamamoto and Maeda [1961] obtained a similar conclusion for sudden impulses.

(c) Rise Time

In a normal run magnetic record, ssc's appear as a step-function like change, but it is not an instantaneous change. The H component reaches the maximum value in a few to several minutes. Ondoh [1962/3] showed that the rise time has a marked daily variation, the minimum value at about noon (150 sec or less) and the maximum value at about midnight (200 ~ 300 sec) (Fig. 2.6).

(d) Daily Variation of the Range

Sugiura [1953] showed that the range of ssc's at Huancayo, almost on the magnetic equator, shows a large daily variation, which is reminiscent of the abnormal enhancement of the solar quiet day daily variation. He demonstrated this by showing the daily variation of the ratio of the range of ssc's at Huancayo to that at Fredericksburg (dp lat 49.6° N). The ratio becomes as large as 6 during the noon hours, although it becomes approximately unity between 1600 and 0400 local times. Later Maeda and Yamamoto [1960] showed that such an enhancement is observed at stations along the dip equator: Fanning (dp lat 10.3° N), Jarvis (dp lat 2.2° N), M'Bour (dp lat 17.9° N), Ibadan (dp lat 6.3° S), Mantinlupa (dp lat 14.1° N), Koror (dp lat 0.05° S), and Guam (dp lat 12.9° N). Forbush and Vestine [1955] showed that the initial phase is also enhanced at Hyancayo.

(e) Angle of the Incidence of the Shock with Respect to the Earth's Dipole Field

When the dipole axis and the incident shock front are parallel (or when the velocity vector $\underline{v}$ of the plasma particles is perpendicular to the dipole axis), the ssc field is fairly uniform in the vicinity of the earth and parallel to the dipole axis. An equivalent current system is then a concentric current flowing approximately along dipole latitude circles with their common center at the dipole pole. Maeda, Fukushima, and Nagata

[1964] showed that when the earth's dipole axis and the incident shock are not parallel, the center of the concentric equivalent current displaced from the dipole pole.

2.3 Sudden Impulses

There are various types of sudden changes of the geomagnetic field, which are not followed by intense storminess, although this 'storminess' is a relative matter. They have thus been called sudden impulses, rather than ssc. Nishida and Jacobs [1962] showed, however, that their characteristics are essentially the same as those of ssc's, except that the main impulse can be either positive or negative in the H component. This suggests that there occur frequently rarefaction shock waves in interplanetary space; when such waves pass by the magnetosphere, a sudden outward motion of the magnetospheric boundary will occur. This has been observed by satellites [Nishida and Cahill, 1964]. Figure 2.7 shows an example of a large negative sudden impulse; note that an intense storm began after this particular impulse. Sudden impulses appear sometimes as a group, suggesting the occurrence of intense turbulence in interplanetary space. Figure 2.8 shows an example of intense si activity which happened to occur during the recovery phase of the April 23, 1959 storm;

that they are of interplanetary origin can be inferred from the fact that an intense Forbush decrease was associated with the si activity [Yoshida and Akasofu, 1966].

2.4 Theoretical Discussion

Because of the existence of tenuous plasma within the magnetospheric cavity, the effect of any interaction of the interplanetary gas with the magnetospheric boundary cannot propagate with the speed of light and hydromagnetic waves must be generated [cf. Dungey, 1954]. Dessler [1958] pointed out that an impact of the solar plasma generates a hydromagnetic shock wave which is propagated towards the earth, causing the storm sudden commencement.

An enhanced plasma pressure associated with the shock wave causes the compression of the magnetosphere. Since the speed of the shock wave is of order 500 ~ 1000 km/sec, it will take at least 120 seconds for the shock to pass through the major part of the front side of the magnetosphere (~ 20a). The compression is associated with an enhanced electric current near the equatorial plane of the magnetosphere, resulting in a current loop. Thus, the development of the shock wave may be visualized by supposing the extending eastward current toward both the dawn and dusk side of the magnetospheric boundary and also the expanding current loop into the magnetosphere [Piddington, 1964]. When the current loop encloses the earth, a sudden increase of the H component is produced, particularly in low latitudes.

Since in the steady state the magnitude of the H component field (ΔH) produced by the eastward boundary current is related to the distance r_o between the earth's center and the apex of the magnetosphere [Mead, 1964] by

$$\Delta H = \frac{25000}{r_o^3} \quad (\text{in } \gamma) \; ;$$

a small change in r_o increases ΔH by

$$\delta \, (\Delta H) = \frac{75000}{r_o^4} \, dr \qquad (\text{in } \gamma) \; .$$

This change is a characteristic of the isotropic mode of a hydromagnetic wave which is associated with the disturbance magnetic field ($\underline{b}$) parallel to $\underline{B}$ and also with compression or rarefaction of the medium. In general, three modes of hydromagnetic waves exist in a hydromagnetic medium, the pure Alfvén wave, the fast (or isotropic) wave and the slow (or transverse) wave.

When hydromagnetic waves are generated from a point source, the isotropic wave travels spherically, transmitting $\underline{b}_{\parallel}$, with the speed of the Alfvén wave ($V_A = B/\sqrt{4\pi\rho}$), while the transverse mode travels, transmitting $\underline{b}_{\perp}$, with a speed given by $V_A \cos \phi$, where ϕ denotes the angle between $\underline{B}$ and the direction of propagation. Therefore, the transverse wave tends to propagate along the geomagnetic field lines.

Although a qualitative aspect of the step-function type variation in the H component is now understood in terms of the propagation of the isotropic mode, there are a number of problems to be examined quantitatively. Dessler, Francis, and Parker [1960] suggested that the rise time of a few to several minutes can be explained by an accumulation of the hydromagnetic signals generated at different locations of the magnetospheric boundary. However, their use of the ray path theory can be hardly justified in the magnetospheric medium (see also Stegelman and von Kenschitzski [1964]). The problem will be further complicated by the fact that in our three dimensional magnetosphere the isotropic mode can be converted into the transverse mode along its pass, which is then propagated along the field lines [Tamao, 1964 a, b].

Another important problem is the remarkable enhancement of the magnitude of ssc's in the day sector along the dip equator. There is little doubt that the equatorial electrojet is enhanced during the compression. Jacobs and Watanabe [1963] proposed that the electric field associated with the isotropic hydromagnetic shock wave causes a downward drift motion of the ionozation in the upper ionosphere; the result is an enhanced conductivity in the lower ionosphere (the E region) and thus an enhanced electrojet.

The appearance of ssc* along the dip equator is another problem. Akasofu and Chapman [1963] showed that the equatorial electrojet is greatly affected by the polar electrojet during magnetic storms; this is because the polar electrojet polarizes the whole ionosphere and changes the electrostatic field along the dip equator (see section 4.5); note that the equatorial electrojet is driven entirely by the Sq electrostatic field.

Piddington [1964] indicated that the total force exerted by the solar wind on the magnetosphere amounts to as much as 10^4 tons, which must be transferred to the ionosphere and the earth as the Lorentz force $\underline{j}_E \times \underline{B}$ (otherwise, the magnetosphere would be blown away by the solar wind). He suggested that the current $\underline{j}_E$

flows from the dawn to the dusk sides in the polar region, resulting in the return currents in lower latitudes.

There has been a great effort made to understand the PRI and reverse PRI currents which appear particularly strong in the polar region. Vestine and Kern [1962] pointed out that the PRI current can be generated by space charges (a positive space charge at the center of the afternoon oval current and a negative space charge at the center of the forenoon oval current in Fig. 2.2), and computed the distribution of the charges from the observed current system by using the spherical harmonic technique.

Tamao [1964 a, b] have recently made a detailed study of the propagation and interactions of isotropic and transverse hydromagnetic waves in a three-dimensional cold plasma and suggested that the PRI current is caused by the impact of what he calls the mixed transverse wave which results from such an interaction. The wave has no direct magnetic effect on the ground but it carries an electric dipole-type space charge. This electric field generates the two oval Hall currents when the wave reaches the E region of the ionosphere, and it is this current system that is detectable on the ground (Fig. 2.9).

Obayashi and Jacobs [1957] attributed the PRI current system to a dynamo action in the upper level of the ionosphere when injected energetic particles cause an abnormal ionization in the ionosphere. The dynamo theory of the polar current system will be discussed later in section 4.6 so that it is not given here. In order to explain the reverse of the direction of the PRI current (namely, the growth of the reverse PRI current), they proposed that in the lower ionosphere the direction of the wind is opposite to that in the upper ionosphere.

Later, a more attractive explanation of the reverse PRI current was given by Piddington [1962]. Piddington proposes that a frictional interaction between the enhanced plasma flow and magnetic field lines in the dawn and dusk meridian plane tend to bend the field lines away from the sun. The frictional force must be the Lorentz force $\underline{f} = \underline{j} \times \underline{B}_o$ and be directed against the direction of the solar wind velocity vector. The current $\underline{j}$ associated with the force must be flowing into the magnetosphere in the dawn sector boundary and out from the magnetosphere in the dusk sector. Looking toward the earth, from the dawn sector, the magnetic field $\underline{b}$ ($\nabla \times \underline{b} = 4\pi \underline{j}$) forms a clockwise loop, corresponding to counterclockwise twisting the field when $\underline{b}$ is superposed on $\underline{B}_o$

(Fig. 2.10). The twisting generates what he calls the twist (transverse) wave which is propagated towards the earth with velocity of the Alfvén wave V_A. This wave is also not detectable on the ground because there exists a non-conducting region below the ionosphere. However, the wave is associated with a radial electromotive force (of magnitude $V_A b$) with respect to $\underline{B}_o$ which generates two oval shaped Hall current systems (one in the dawn sector and the other in the dusk sector) in the E region of the ionosphere, which then becomes detectable on the ground.

These ideas are to illustrate some of the complexities of the problem of the impact of the shock wave and the magnetosphere and subsequent consequences. First of all, changes of the geomagnetic field at the time of the sudden commencement have not been well established yet. For example, it is not possible to reconcile the rapid rotation of the disturbance vectors revealed by Wilson and Sugiura [1961] with the fixed pattern of the PRI current system obtained by Nagata and Abe [1955] and others. Using Mead's model magnetosphere [Mead, 1964], Sugiura [1965] inferred the displacement of the geomagnetic field lines by a sudden enhancement of the solar wind. He showed that high latitude field lines suffer a tangential displacement which may generate transverse hydromagnetic waves. However, he was not concerned with the PRI current. A considerable improvement of the network of observatories, with suitable quick-run magnetometers, is required to improve the morphology of ssc*.

It would also be of great interest to examine geophysical phenomena which occur at the time of the sudden commencement. Brown, Hartz, Landmark, Leinbach, and Ortner [1961] observed an intense x-ray flux and riometer absorption along the auroral zone at the time of ssc. This problem was further studied by Matsushita [1961] and Ortner et al. [1962].

2.5 Initial Phase

(a) Introduction

As mentioned in section 1.3, the initial phase that follows the ssc should be considered to be the period between the end of the transient stage of the compression and the onset of the entry of the energy of the solar plasma into the magnetosphere in a form other than hydromagnetic waves transmitting the initial compression effect. The entry of the energy of the solar plasma is characterized by the growth of the ring current, the auroral substorms and polar electrojets. In many geomagnetic storms, the entry of the energy may occur almost simultaneously with the ssc, so that such storms do not have a simple initial phase. As mentioned also in section 1.3, a number of geomagnetic storms caused by western solar flares tend to produce the 'main phase' before the sudden commencement, namely the arrival of the interplanetary shock wave. For such storms, there is no 'initial' phase. In this section we are concerned with a simple initial phase.

(b) Geomagnetic Disturbance During the Initial Phase

In middle and low latitudes, the disturbance field of a typical initial phase may be considered to be a new steady state after the impact of the shock wave. In the polar region, particularly at about dp lat 80° in the sunlit noon sector, a considerable increase in geomagnetic activity occurs after the sudden commencement [Wescott and Akasofu, 1963]. Figure 2.11 shows an example of a simple step-function type ssc recorded at Kakioka (dp lat 26.0° N); see the bottom trace. The figure shows also both the D and H component records from Kakioka, College (dp lat 64.7° N) and Godhavn (dp lat 79.9° N); the upper three traces are the D records and the lower three traces are the H records. Both the Kakioka and College records show only a little change during the first two and half hours after ssc. However, at Godhavn, which happened to be located in the noon sector (Godhavn local time = UT - 4), a considerable increase of 'irregular' disturbance began after the ssc. At this latitude of the noon sector, intense disturbances exist even when the midnight sector of the auroral oval is magnetically quiet (namely, when there is no appreciable jet current along the auroral oval and thus the K_p index is 0). Such disturbances are called the daytime agitation and are discussed in detail in section 4.11. The enhanced activity seems to be an enhanced daytime agitation.

Figure 2.12 a-d shows another example of a typical initial phase of the geomagnetic storm of December 4, 1958. Figure 2.12a shows the horizontal component record from Honolulu and College. The Honolulu record shows a fairly simple step-function like ssc, and the College record a typical ssc*. Much of irregular changes seen during the initial phase at Honolulu are seen at College, indicating that the plasma pressure was irregularly changing. This inference can be substantiated by Fig. 2.12b which shows a collection of magnetic records from the northern auroral zone; the record indicates a complete absence of the polar jet activity in the northern polar region; the aurora was also absent at College during this period. Note the development of the jets after 08 UT. Figure 2.12c shows a collection of records from the northern polar cap stations; they show a little sign of disturbances, but not significant. However, the southern polar cap stations in Fig. 2.12d and e, Wilks (dp lat 77.7° S) and Scott Base (dp lat 79.0° S), show a considerable increase of magnetic disturbances and a little less activity at Little America (dp lat 74.0° S) and Mawson (dp lat 73.1° S): Wilks local time = UT + 7.5 and Scott Base local time = UT + 10.5, Little America local time = UT - 10, Mawson local time = UT + 4. The southern auroral zone stations (Macquarie, -61.1° S) and Halley Bay (dp lat 65.8° S) show only a similar activity (Macquarie local time = UT - 3).

By using some simultaneous magnetic records from Honolulu (dp lat 21° N) and Sitka (dp lat 60° N), Dessler [1961] argued that the magnetospheric boundary is stable against the solar wind during the initial phase of geomagnetic storms. It can be seen from the above study that his argument is not conclusive, since the dp lat of Sitka is only 60° (or L = 4.0). Depending on the interpretation of the daytime agitation, the conclusion could be entirely different.

Two instabilities are known to exist at a discontinuous interface plane, which may have some bearing on the stability problem of the magnetospheric boundary. One of them is called the Rayleigh-Taylor instability. This instability occurs where a plasma is accelerated by a magnetic field [cf. Thompson, 1964]. A radially accelerated cylindrical shell in a magnetic field was discussed by Harris [1962]. The other is called the Kelvin-Helmholtz instability which occurs at a plane interface with a finite velocity discontinuity. It is known that any small velocity discontinuity gives rise to the instability when the two fluids are incompressible and non-conductive. However, the situation becomes complicated when the fluids are permeated by a magnetic field and are compressible and conductive [Sen, 1963; Fejer, 1964; Talwar, 1964, 1965]. While the existence of the magnetic field tends to reduce the instability effect, the compressibility tends to oppose such an effect. Talwar [1964] concluded that the magnetospheric boundary is likely to be unstable in the tail region under comparatively quiet conditions.

Section 2

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Figure Captions

Fig. 2.1 The occurrence of ssc^* (the primary reverse impulse) as a function of dipole latitude and local time.
[Matsushita, S., J. Geophys. Res., 67, 3753, 1962]

Fig. 2.2 The distribution of the equivalent current arrows and current system of ssc^* at 0625 UT, May 29, 1933.
[Nagata, T., and S. Abe, Rep. Ionosphere and Space Res. Japan, 9, 39, 1955]

Fig. 2.3 The equivalent current systems for ssc^* (PRI current or DS_p^c), reversed PRI current (or DS_m^c), and the combination of both during the transition period.
[Sano, Y., J. Geomag. Geoelec., 14, 1, 1962/63]

Fig. 2.4 The rotation of the ssc disturbance vectors as a function of dipole latitude and local time. A counterlockwise rotation is indicated by a black circle and clockwise rotation by an open circle.
[Wilson, C. R., and M. Sugiura, J. Geophys. Res., 66, 4097, 1961]

Fig. 2.5 The rapid-run magnetic records of the horizontal component at the ssc of the September 29, 1957 storm
[Sato, T., Rep. Ionosphere and Space Res. Japan, 15, 215, 1961]

Fig. 2.6 The ssc rise time as a function of local time.
[Ondoh, T., J. Geomag. Geoelec., 14, 198, 1962/63]

Fig. 2.7 The large sudden negative impulse which initiated the onset of the main phase of the January 10, 1960 storm.

[Akasofu, S., Planet. Space Sci., 12, 573, 1964]

Fig. 2.8 The intense si activity which happened to occur during the recovery phase of the April 23, 1959 storm. Its world wide nature can be seen from the fact that each impulse is seen in all the records collected from seven stations in low latitudes.

[Akasofu, S.-I., Planet Space Sci., 12, 801, 1964]

Fig. 2.9 The schematic diagram to show two oval type Hall current systems generated in the ionosphere by the mixed transverse wave and also the current system generated by the pure transverse wave (thick line); view from the sun.

[Tamao, T., Rep. Ionosphere and Space Res. Japan, 18, 16, 1964]

Fig. 2.10 The schematic illustration of the generation of the twist waves and the ionospheric current system generated by them; view from above the north dipole pole.

Fig. 2.11 The great enhancement of the daytime agitation in the sunlit polar cap during a simple step function-type ssc in middle and auroral latitudes.

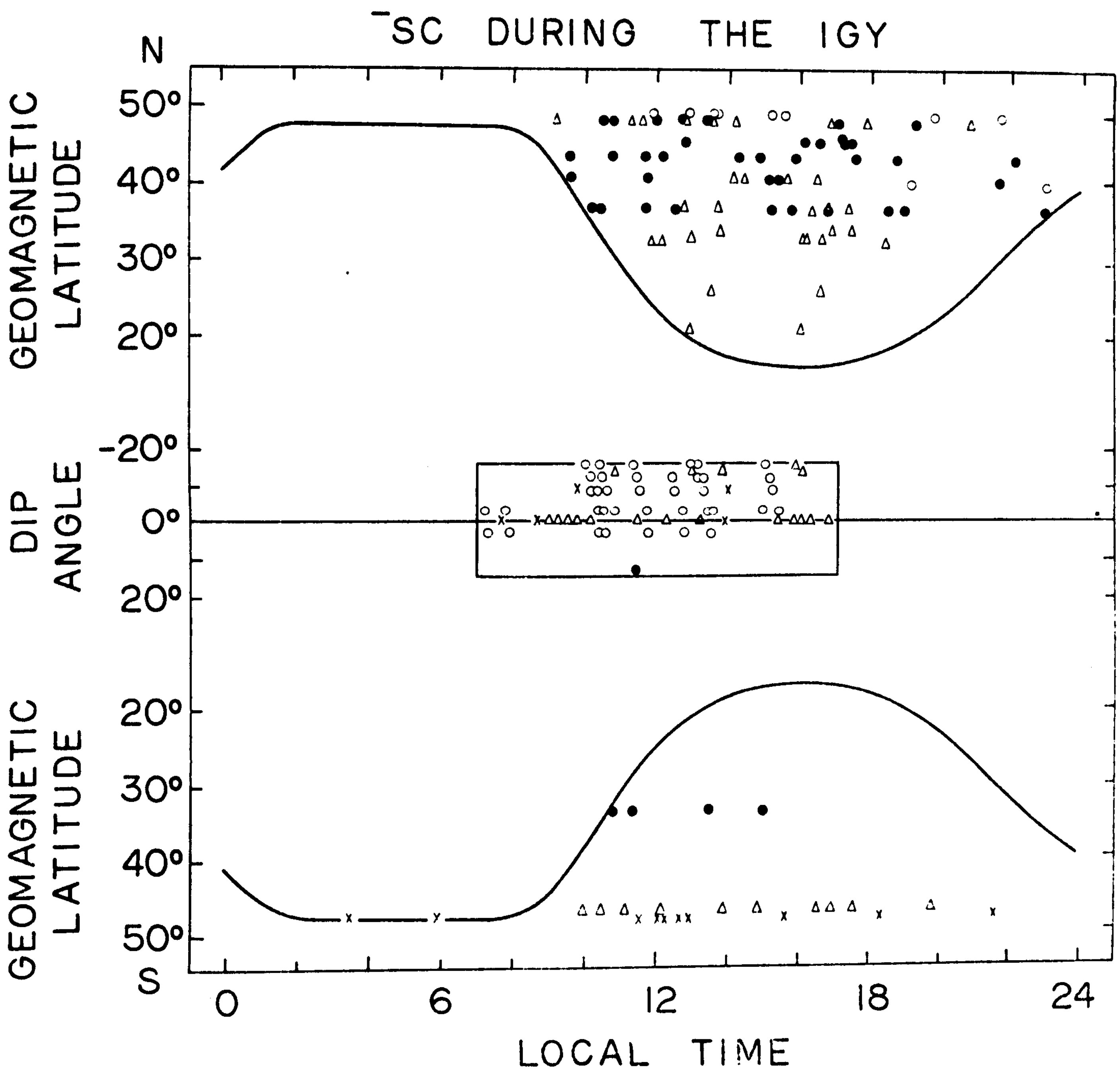
[Wescott, E. M., and S.-I. Akasofu, 1964]

Fig. 2.12 a-d The magnetic records of the December 4, 1958 storm:

(a) College and Honolulu, (b) Northern auroral zone,

(c) Northern polar cap, (d) Southern polar cap, and

(e) Southern auroral zone.



‾SC DURING THE IGY
N
50°
40°
30°
20°
GEOMAGNETIC LATITUDE
-20°
0°
20°
DIP ANGLE
20°
30°
40°
50°
S
GEOMAGNETIC LATITUDE
0
6
12
18
24
LOCAL TIME

Figure 2.1

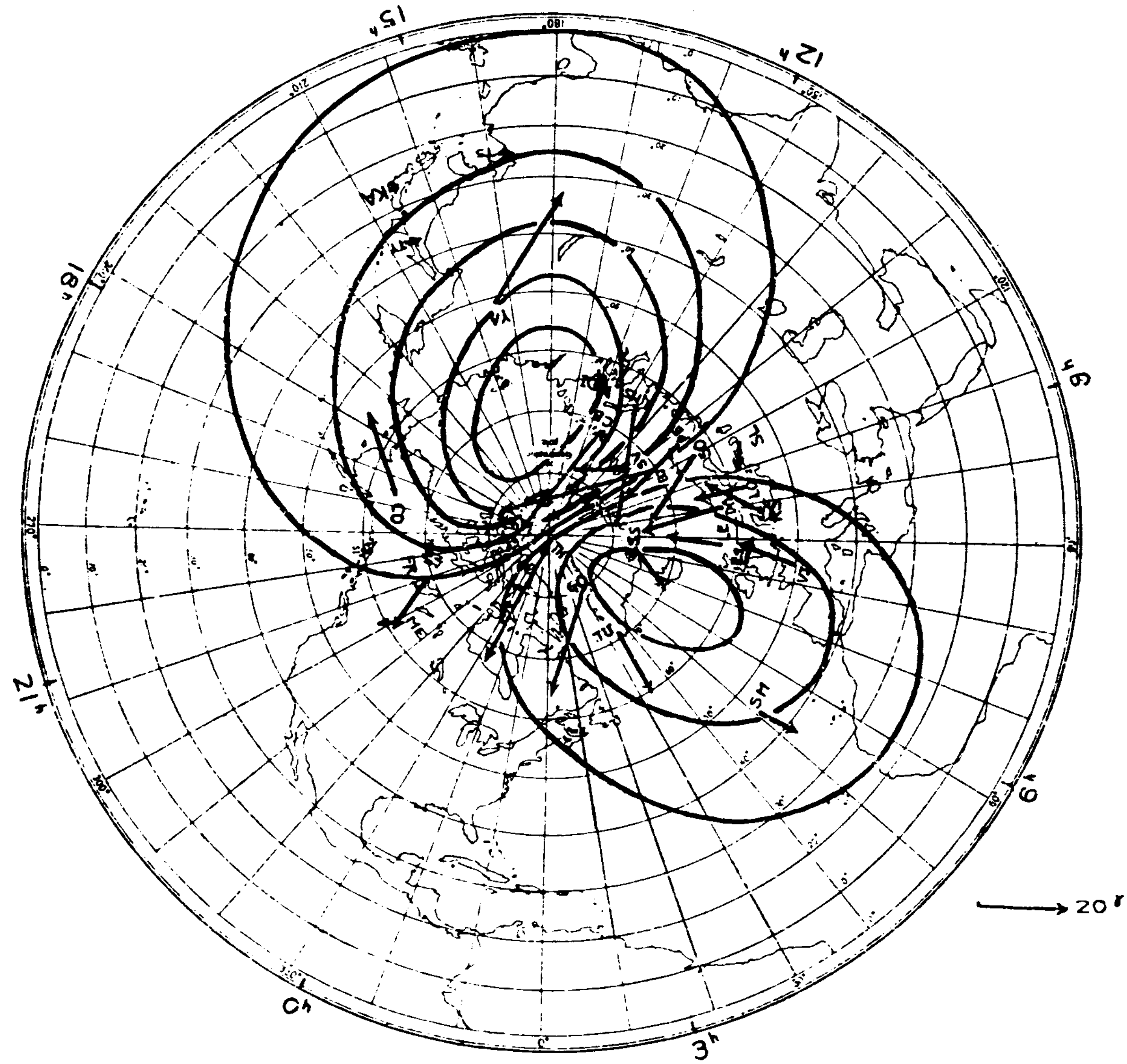


Figure 2.2

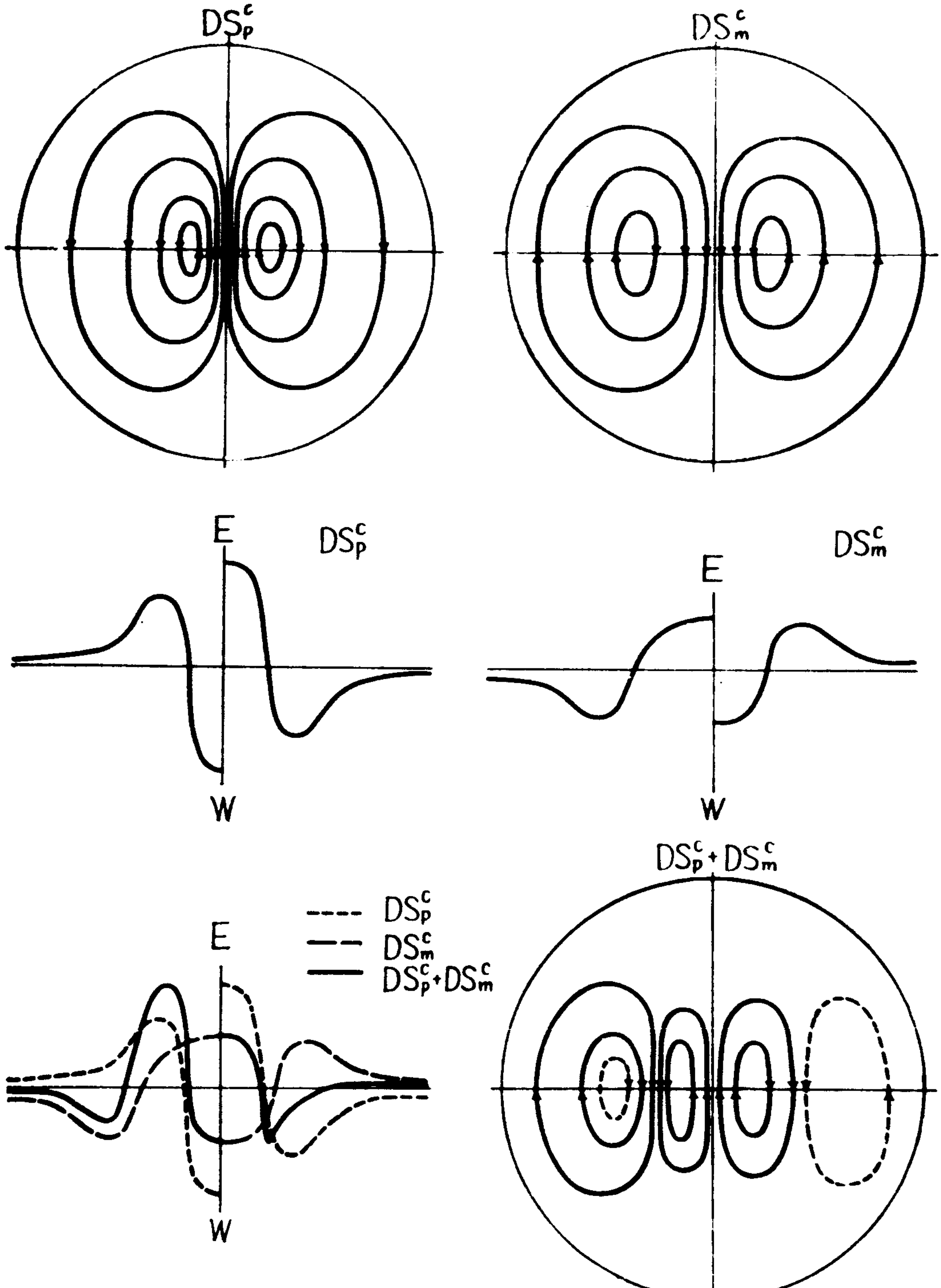


Figure 2.3

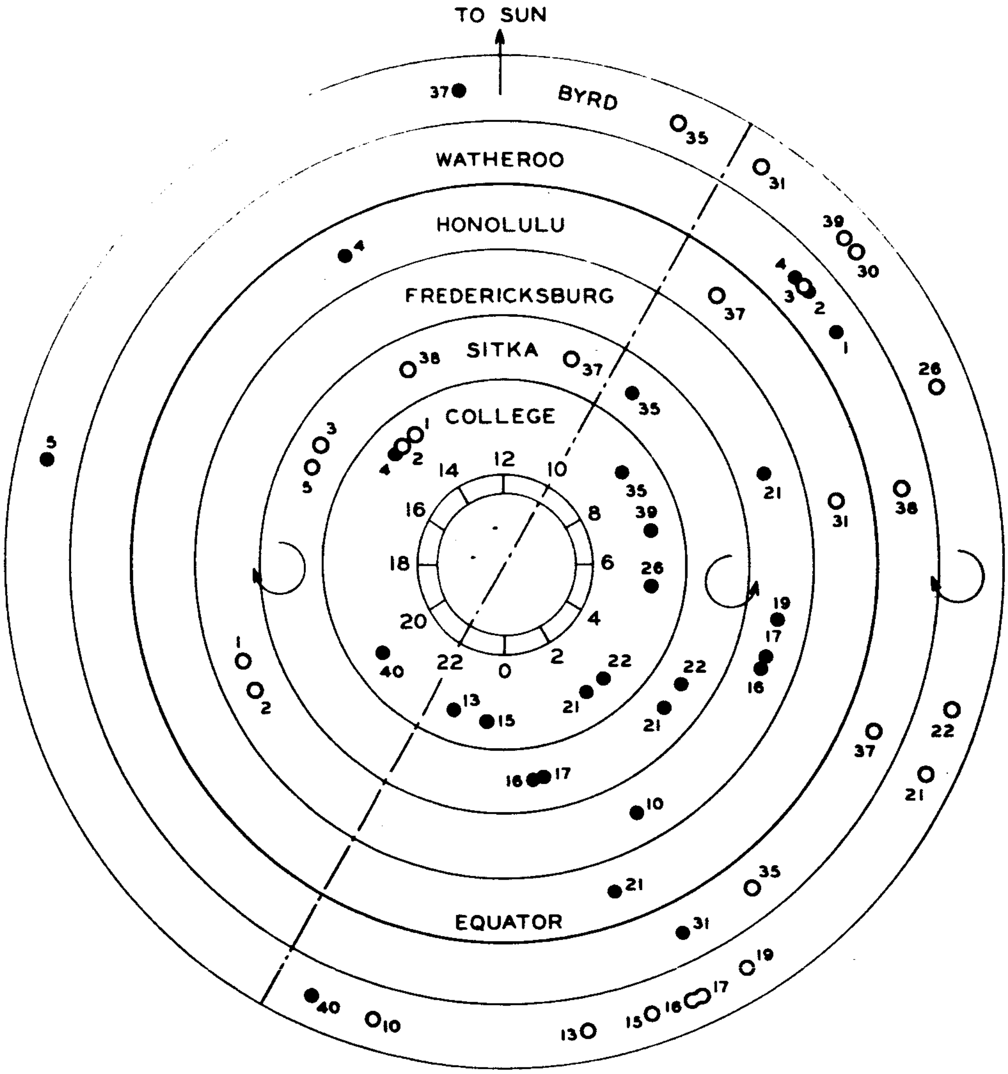
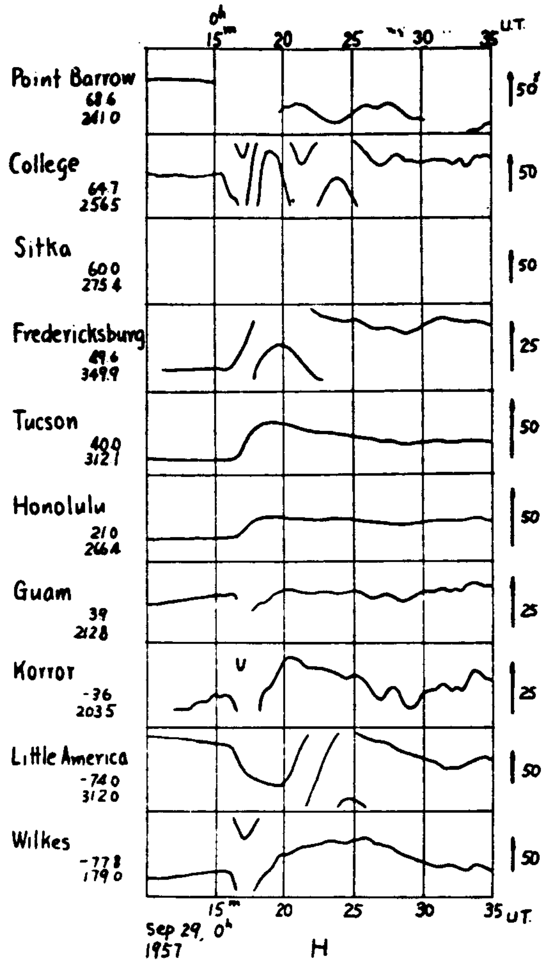

TO SUN
BYRD
WATHEROO
HONOLULU
FREDERICKSBURG
SITKA
COLLEGE
EQUATOR

Figure 2.4



0h
15m
20
25
30
35 U.T.
Point Barrow
68.6
241.0
College
64.7
256.5
Sitka
60.0
275.4
Fredericksburg
49.6
349.9
Tucson
40.0
312.1
Honolulu
21.0
266.4
Guam
3.9
212.8
Korror
-3.6
203.5
Little America
-74.0
312.0
Wilkes
-77.8
179.0
50γ
50
50
25
50
50
25
25
50
50
Sep 29, 0h
1957
H

Figure 2.5

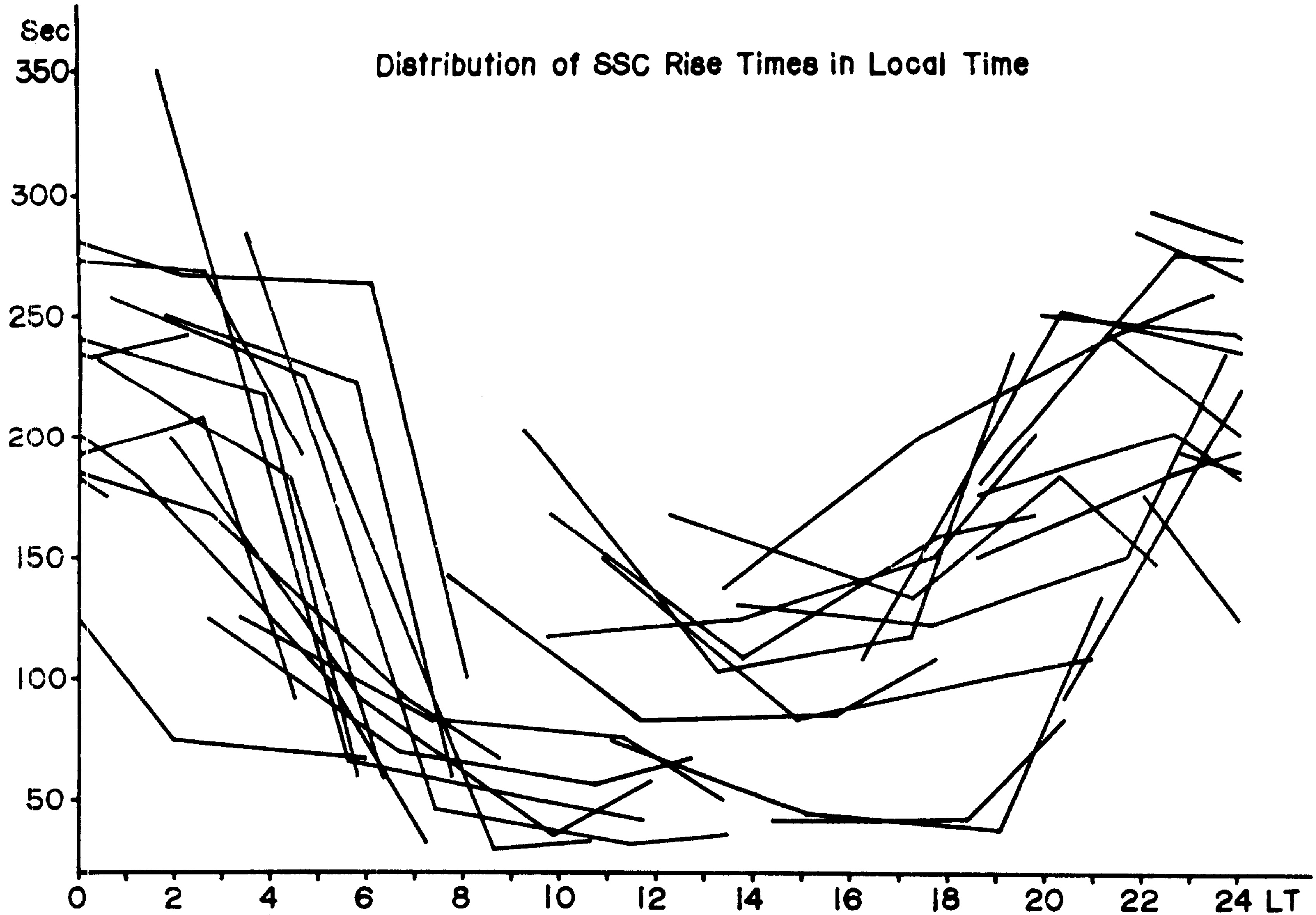

Distribution of SSC Rise Times in Local Time
Sec
350
300
250
200
150
100
50
0
2
4
6
8
10
12
14
16
18
20
22
24 LT

Figure 2.6

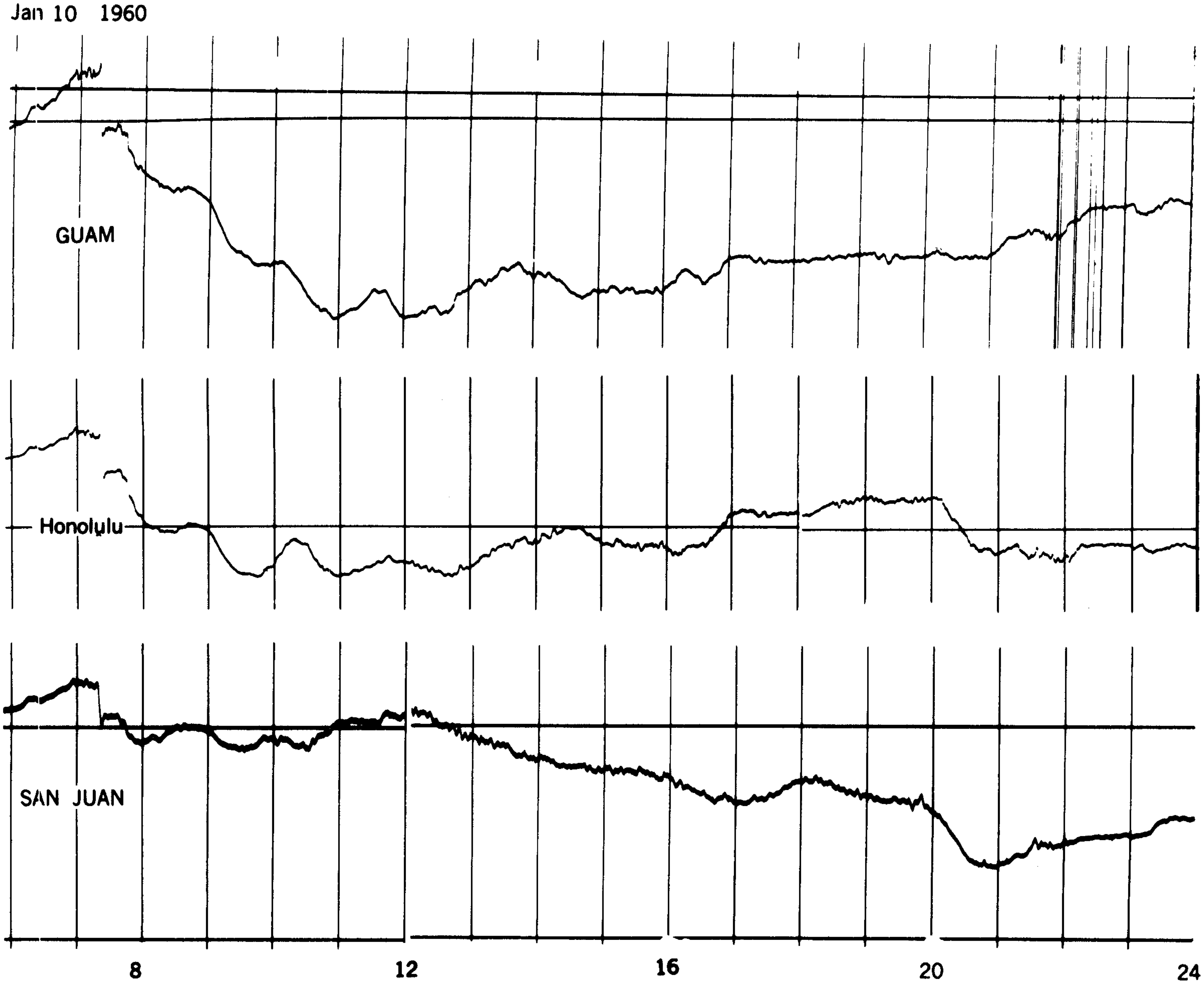
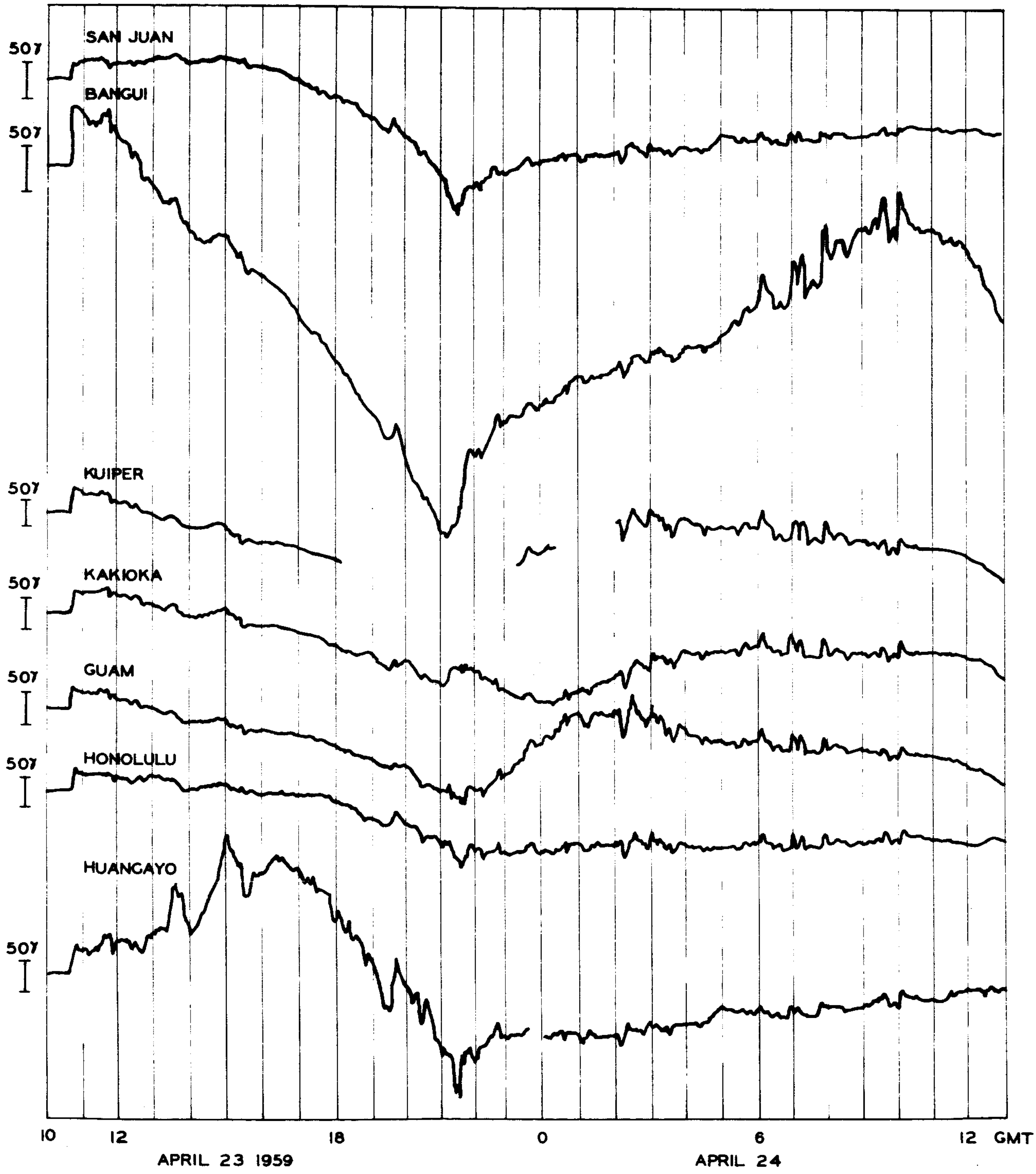


Figure 2.7



SAN JUAN
BANGUI
KUIPER
KAKIOKA
GUAM
HONOLULU
HUANCAYO
50γ
50γ
50γ
50γ
50γ
50γ
50γ
10
12
18
0
6
12 GMT
APRIL 23 1959
APRIL 24

Figure 2.8

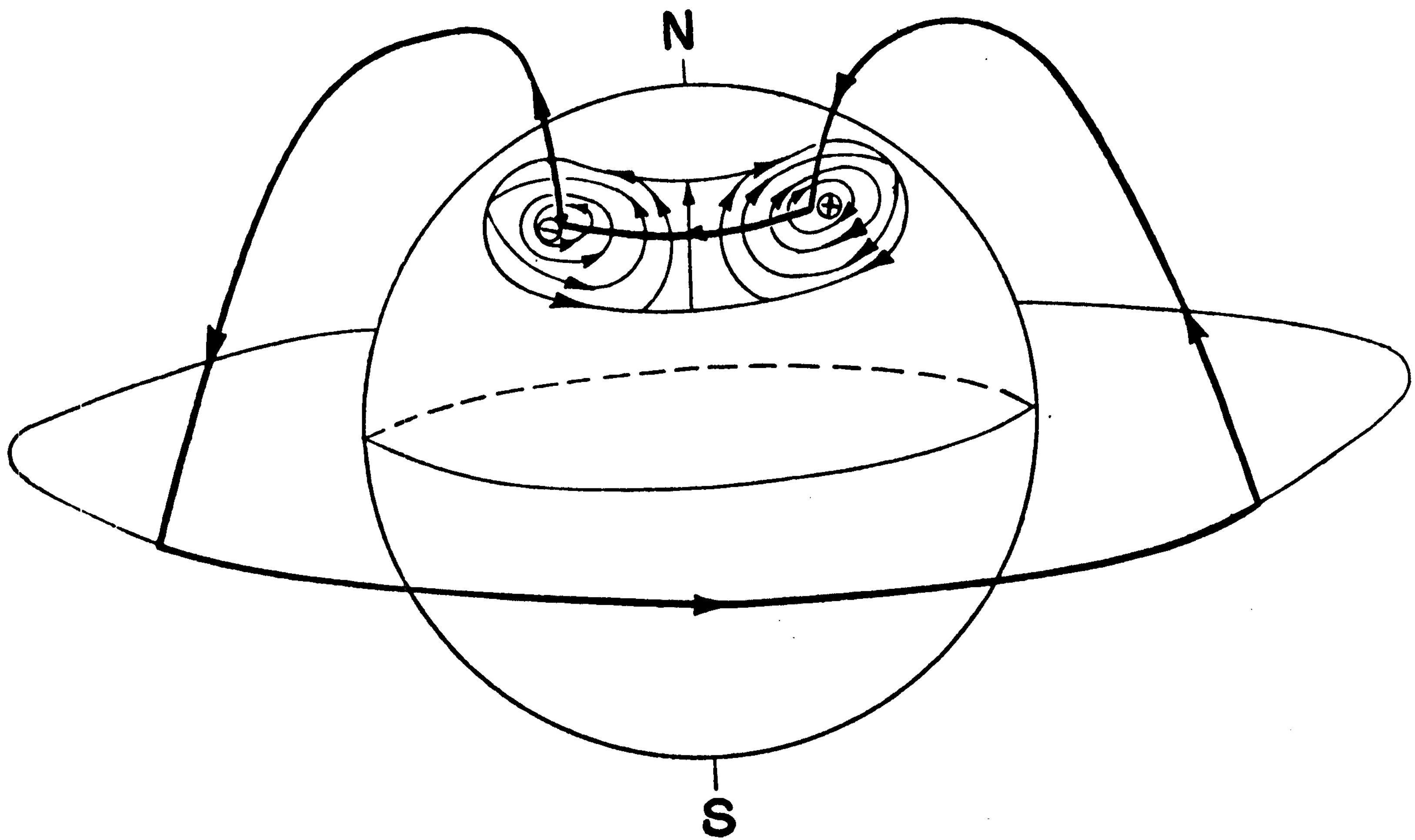


Figure 2.9

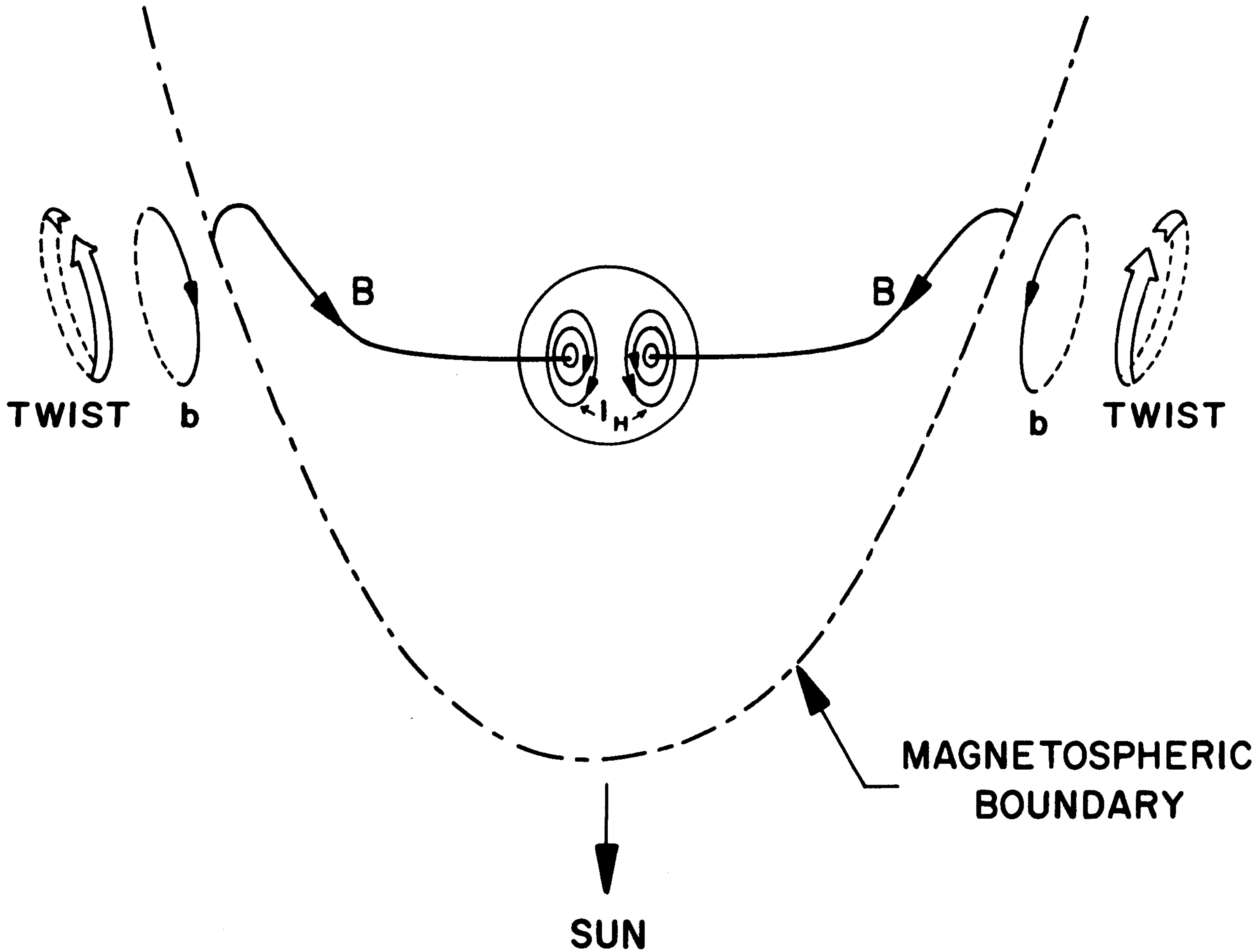
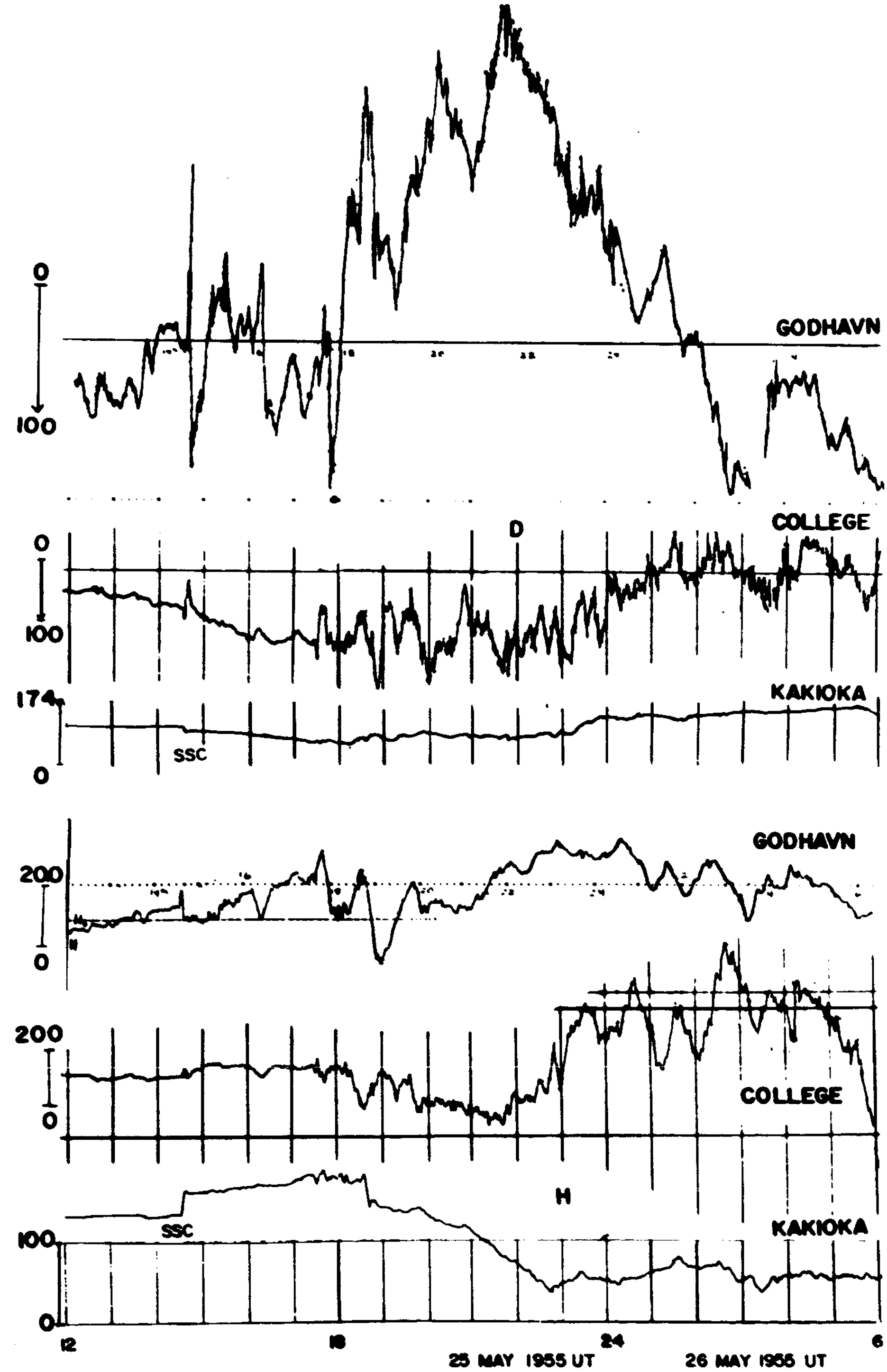


Figure 2.10



0
100
GODHAVN
COLLEGE
D
0
100
KAKIOKA
174
SSC
0
GODHAVN
200
0
200
COLLEGE
0
H
SSC
KAKIOKA
100
0
12
18
24
6
25 MAY 1955 UT
26 MAY 1955 UT

Figure 2.11

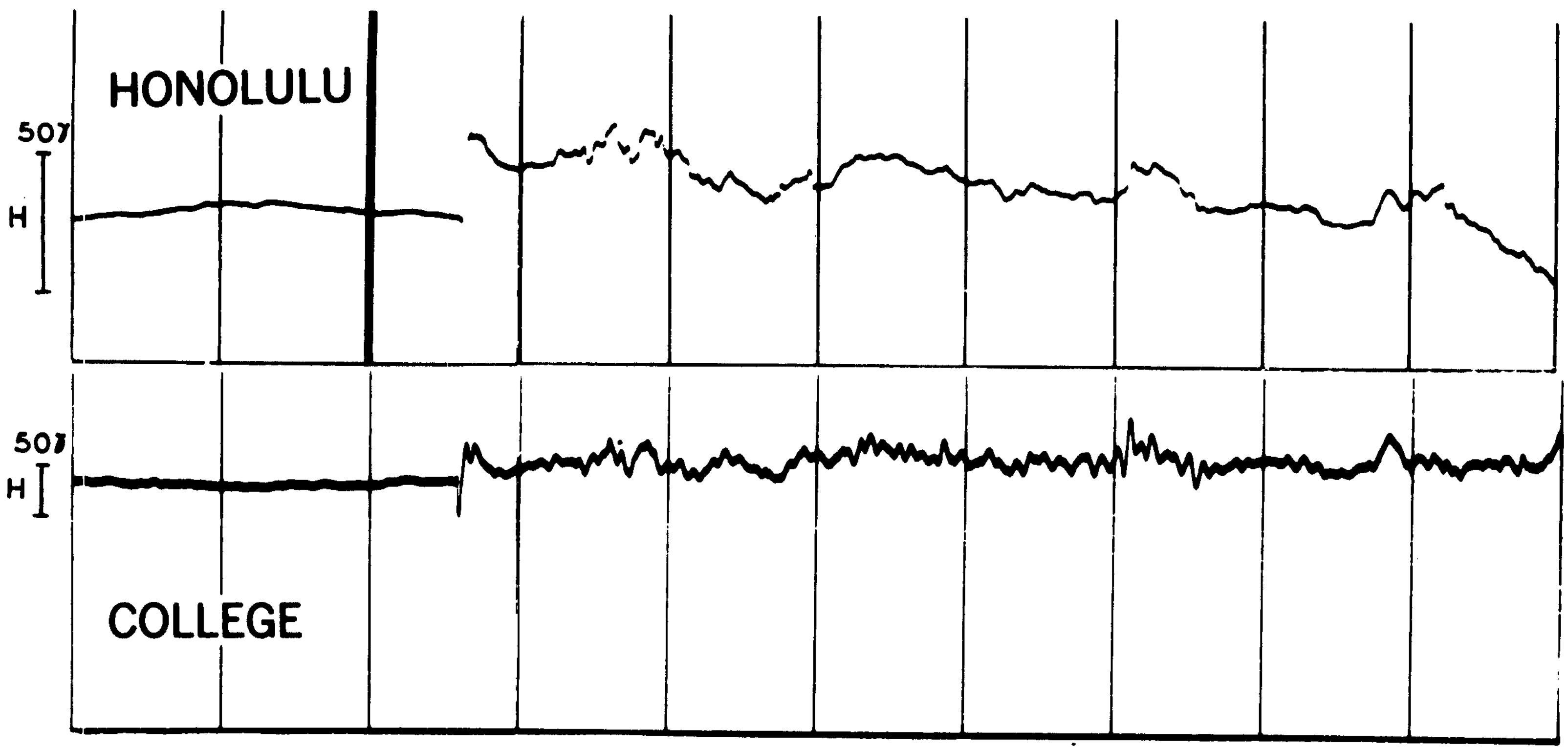


Figure 2.12 (a)

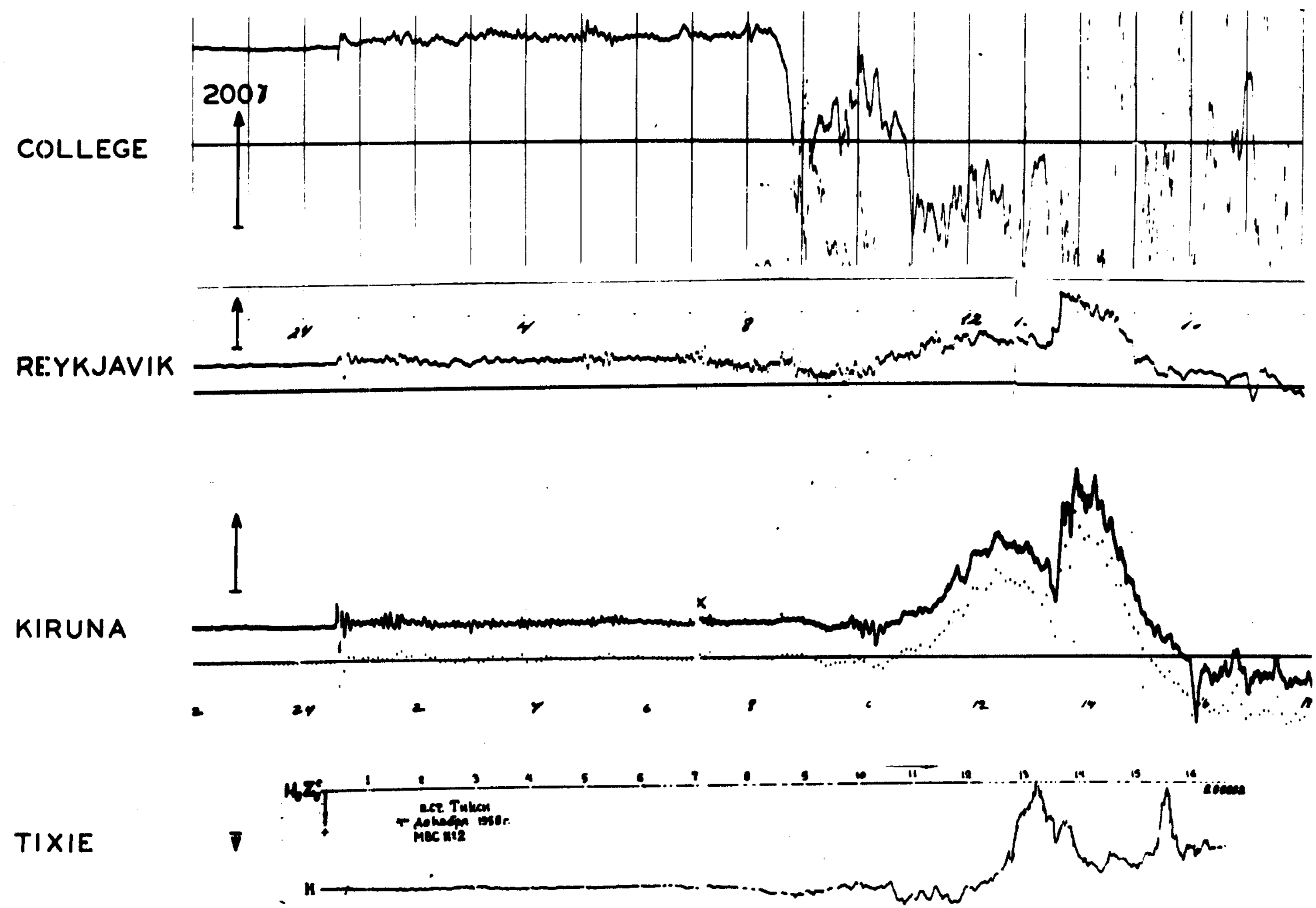


Figure 2.12 (b)

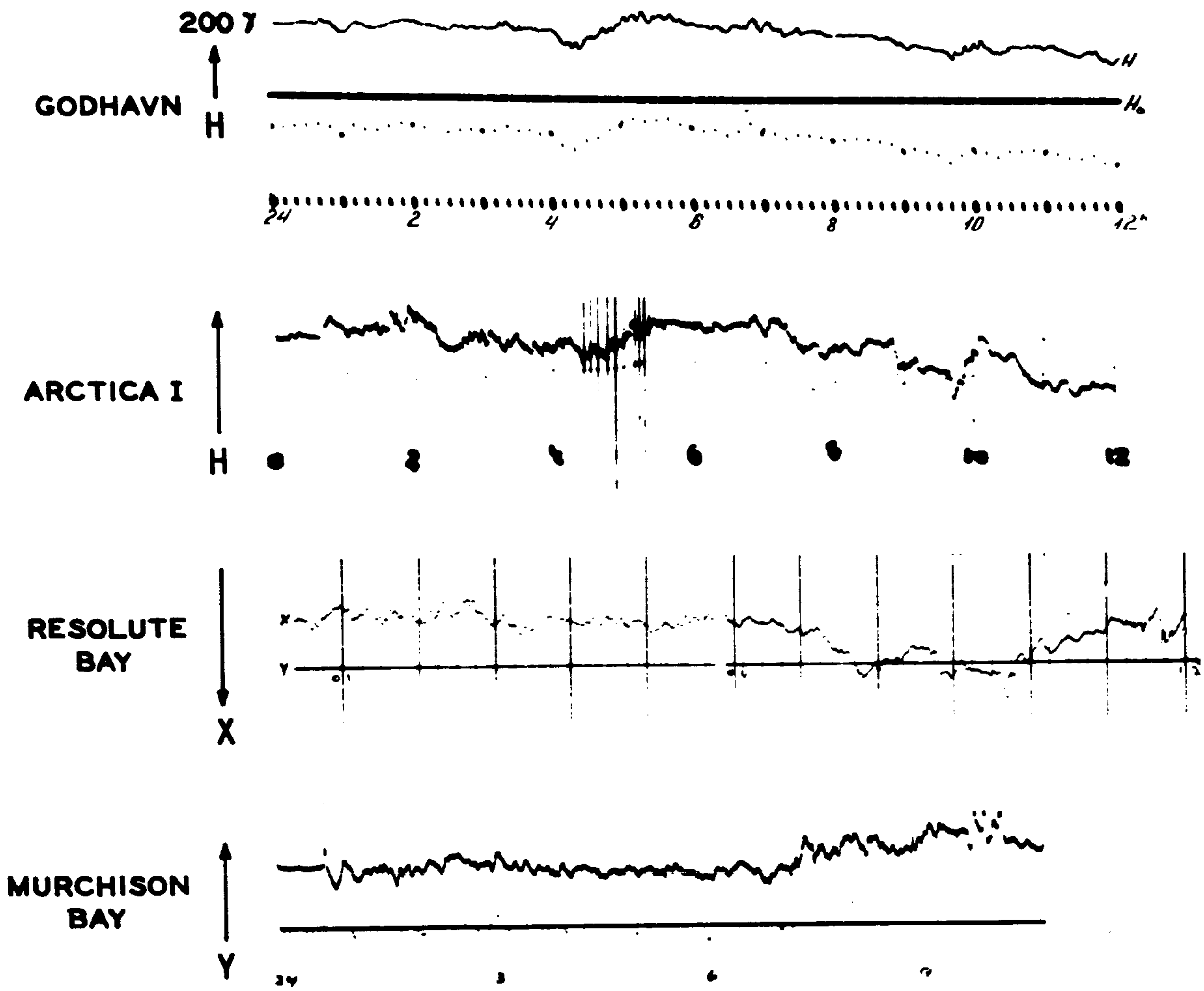
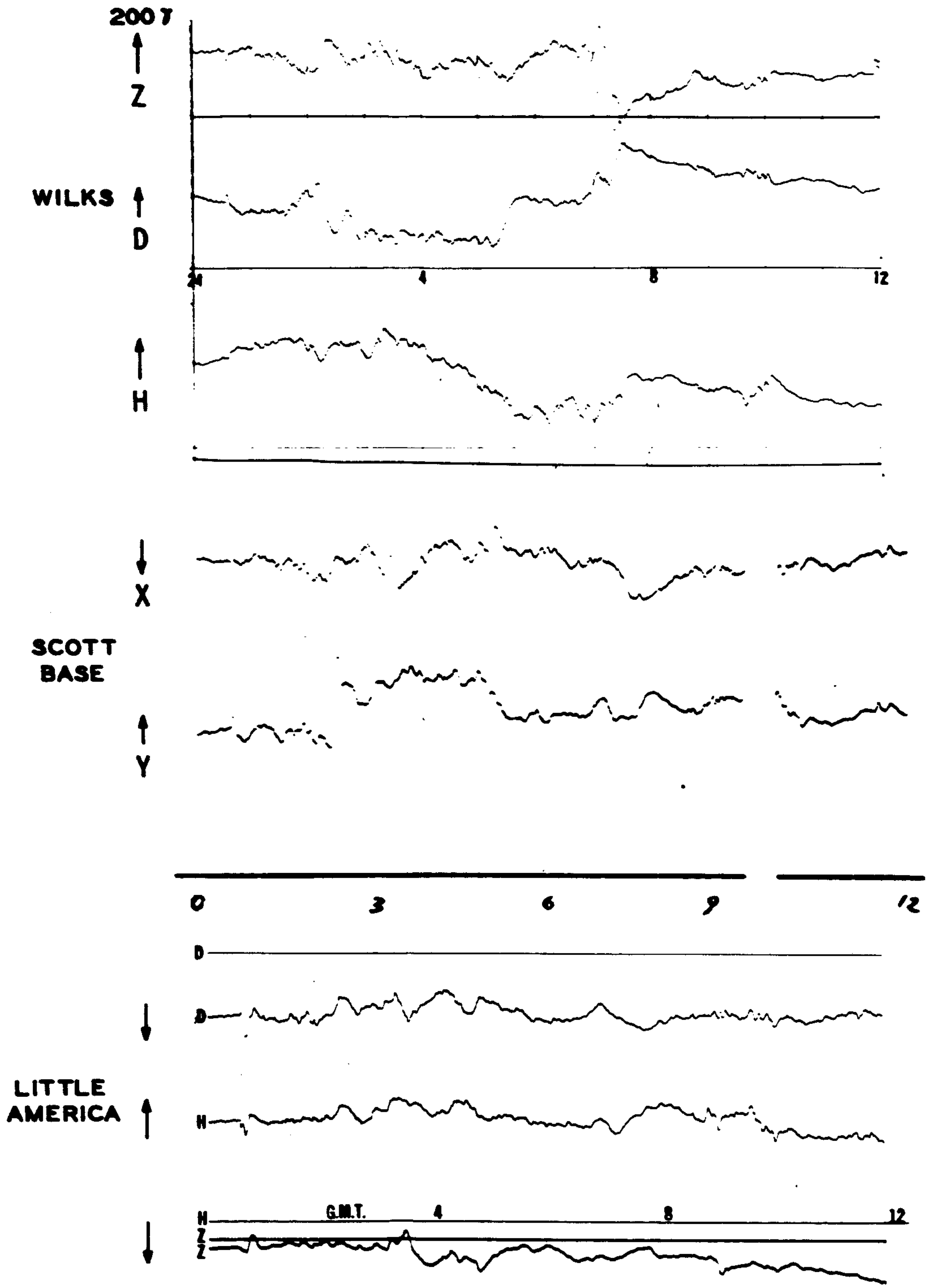

200 γ
GODHAVN
H
H
H_0
24
2
4
6
8
10
12h
ARCTICA I
H
RESOLUTE
BAY
X
MURCHISON
BAY
Y

Figure 2.12 (c)



200 γ
Z
WILKS
D
24
4
8
12
H
X
SCOTT BASE
Y
0
3
6
9
12
D
D
LITTLE AMERICA
H
H
G.M.T.
4
8
12
Z
Z

Figure 2. 12 (d)

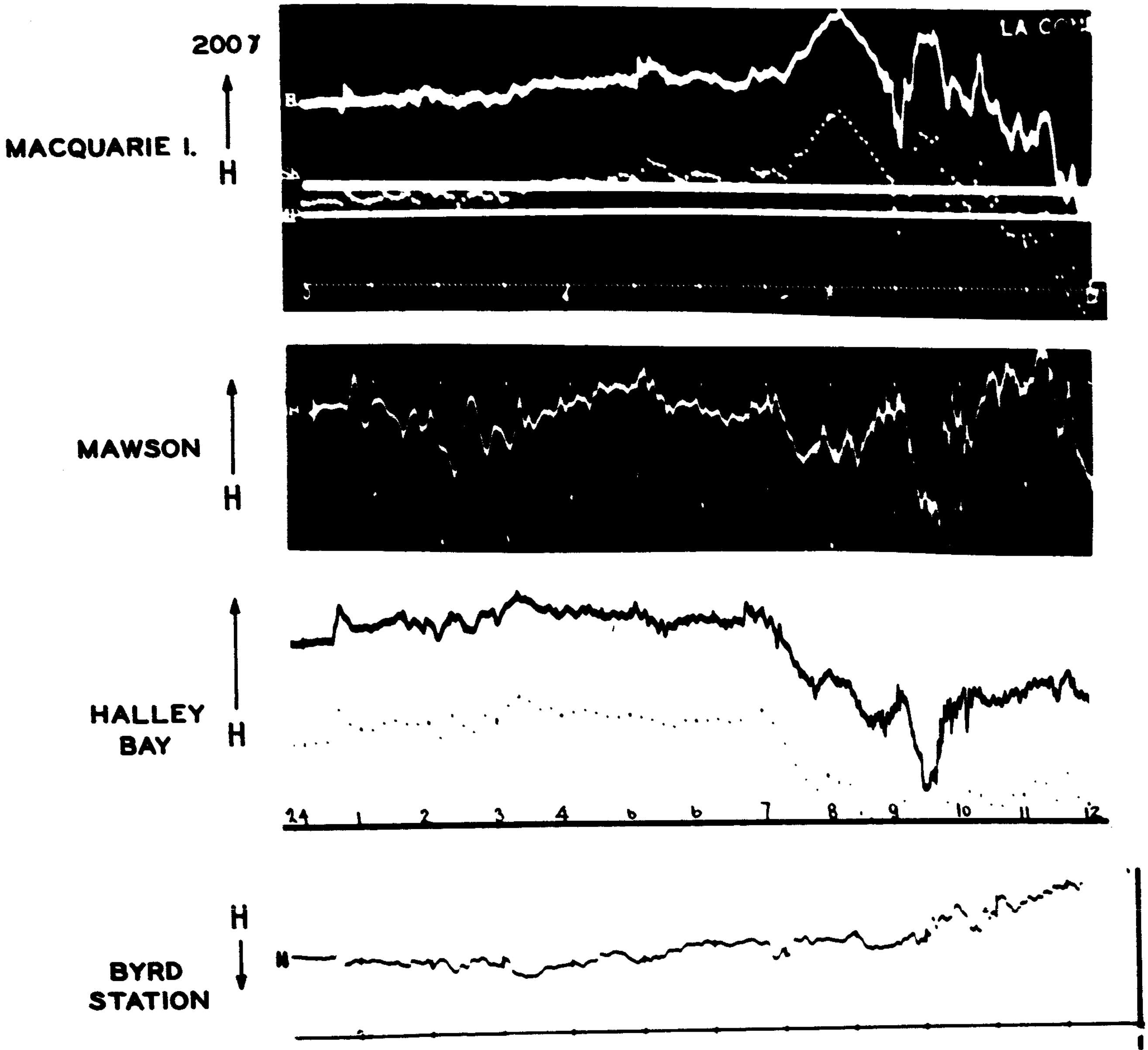

200γ
MACQUARIE I.
H
MAWSON
H
HALLEY
BAY
H
24 1 2 3 4 5 6 7 8 9 10 11 12
H
BYRD
STATION

Figure 2.12 (e)

3. The Main Phase Decrease

3.1 Introduction

A large world-wide decrease of the horizontal component in low latitudes during geomagnetic storms has long been ascribed to a westward electric current encircling the earth. The present concept of its form is due to Singer [1957] who was guided by Alfvén's perturbation treatment of the motion of a charged particle in a dipole field. Later, his study was extended by Dessler and Parker [1959], Akasofu and Chapman [1961], Apel and Singer [1961], Akasofu, Cain, and Chapman [1962], and others. Since the details have already been given in a review paper by Akasofu [1963], we shall confine our attention to recent progresses.

Dessler and Parker [1959] have shown that the magnetic field ($\Delta B_z(0)$) of the ring current at the earth's center is related to the total energy ($\bar{\epsilon}$) of the ring current particles by

$$\Delta B_z(0) = - \frac{2 B_o \bar{\epsilon}}{3 \bar{\epsilon}_m}$$

where $B_o = 3.2 \times 10^4 \gamma$ and $\bar{\epsilon}_m$ is the total energy of the earth's dipole field outside the solid earth.

The azimuthal current intensity i produced by the motions of a group of charged particles in a dipole field is given by

$$i = \frac{1}{B R_c} (p_s - p_n) - \frac{1}{Bh_2} \left(\frac{\partial p_n}{\partial r_c} \right) - \frac{2 \tan \varphi}{h_1} \frac{\partial p_n}{\partial \varphi}^{*} . \tag{1}$$

If the pitch-angle distribution of the particles is given in the form of $\sin^{\alpha+1} \theta$ and if their spatial number density distribution is given by Gaussian's along an equatorial radius, (1) may be rewritten as

$$i = \frac{m n_o w^2 dw}{B_o a} \left\{ (f_o + z)^2 \, d^{-g^2 z^2} \, D(\varphi, \alpha) + 2g^2 z (f_o + z)^3 e^{-g^2 z^2} F(\varphi, \alpha) \right\}$$

where

---

*The last term in (1), $- 2 \tan \varphi / h_1 \, (\partial p_n / \partial \varphi)$, which is missing in (39) in Akasofu [1963] was pointed out by Dr. P. C. Kendall. The equation corresponding to (36) in Akasofu [1963] should read

$$\underline{h} \times \nabla Q = \underline{k} \left(\frac{1}{h^2} \frac{\partial}{\partial r_e} + \frac{2 \tan \varphi}{h_1} \frac{\partial}{\partial \varphi} \right) Q .$$

$$D = P/Q$$

$$P = 3 \left\{1 - 6B\ (\alpha)\right\} \left\{ (\cos \phi)^{5+3\alpha} (1 + \sin^2 \phi)\right\}$$

$$+ 6\alpha\ B\ (\alpha) \sin^2 \phi\ (\cos \phi)^{3\alpha+3} (3 + 5 \sin^2 \phi)$$

$$Q = (1 + 3 \sin^2 \phi)^{2 + \frac{1}{4}\alpha}$$

$$F\ (\phi,\alpha) = \frac{2B\ (\alpha)\ \cos^{3\alpha+3}}{(1 + 3 \sin^2 \phi)^{\frac{1}{4}\alpha}} \quad .$$

As an example, Fig. 3.1 shows the magnetic field ΔB produced by the ring current whose group characteristics are given by the following parameters: (a) The radial distance r_{eo} at which the number density distribution peaks, $r_{eo} = 3a$ (a = the earth's radius); (b) the pitch-angle distribution $F \propto \sin^3 \theta$; (c) the Gaussian parameter g, $g_1 = 2.146$ at $r < r_{eo}$ and $g_2 = 1.517$ at $r > r_{eo}$; (d) the energy density at $r_e = r_{eo} = 3a$, $\epsilon n_o = 6000$ (keV/cm^3). Figure 3.2a shows the distortion of the earth's dipole field by the same belt, but with three different values of ϵn_o, 1000, 4000, and 6000 (keV/cm^3), corresponding respectively to $\Delta B\ (r_e = 0) = -34\ \gamma$, $-136\ \gamma$, and $-204\ \gamma$. Figure 3.2b shows the distorted field line by the same ring current with $\epsilon n_o = 6000$ (keV/cm^3); the equatorial crossing distance of the field line was originally $r_e = 4.0$, but the ring current 'stretches' the crossing distance to $r_e = 5.6$.

Akasofu and Chapman [1961] also developed a semi-analytical method to compute $\Delta B(0)$ for the type of ring current belts which are specified by r_{eo}, g_1, g_2, and α. It is given (after making the correction in the footnotes on p. 62) by

$$\Delta B(0) = 3.86 \times 10^{-30} N\epsilon \text{ (keV)}$$
$$= 2.41 \times 10^{-21} N\epsilon \text{ (ergs)},$$

where ϵ denotes the kinetic energy of ring current particles and N their total number, thus $(N\epsilon)$ the total kinetic energy. As noted by Dessler and Parker [1959] and Sckopke [1966], $\Delta B(0)$ is neither a function of (r_{eo}, g_1, g_2) nor α.

The above computation takes no account of effects of the magnetic field produced by the ring current on the ring current particles; for the second approximation, Akasofu, Cain, and Chapman [1962]. Further, the stability of such a system has not been considered. Kadomtsev and Rokotyan [1960] have shown that when the existence of the ionosphere can be ignored, the stability condition against the convective instability is given by

$$- r_e \frac{dp}{dr_e} < 4\gamma p$$

where p is the plasma pressure, and γ (= 3/5) the adiabatic exponent. This suggests that the convective instability tends to occur in the outer part of the belt where dp/dr_e is negative and large. Kodomtsev and Rokotyan showed also that the existence of the ionosphere tends to check the convection and thus the stability condition becomes

$$-r_e \frac{dp}{dr_e} < \frac{B^2}{8\pi} \left[0.9 + 1.2\left(\frac{a}{r_e}\right)^2 \left(1 - \frac{a}{r_e}\right)^{-1/2}\right] + 4\gamma p \; .$$

3.2 Asymmetric Development of the Ring Current

In the geometrical analysis of the storm field D = Dst + DS, namely

$$D = c_o + \sum_n c_n \sin (n\lambda + \epsilon_n)$$

where

$$Dst = c_o$$

$$DS = \sum_n c_n \sin (n\lambda + \epsilon_n),$$

it has been tacitly assumed that in low latitudes the Dst field is produced by an axial symmetric ring current and the DS field by the return current from a pair of electrojets along the auroral zone

[Chapmand and Bartels, 1950]. However, there has been no detailed study on relationships between the low latitude DS and the growth and decay of the polar electrojet. Recently, Akasofu and Chapman [1964] examined this problem and found that the above tacit assumption must be revised. In the following, we shall review briefly their study.

For this purpose, it is instructive to examine the growth of the main phase decrease for a typical great storm. Figure 3.3 shows the development of the main phase of the September 13, 1957 storm. Approximate iso-intensity contours of D(H), the deviation of the H component from the pre-storm level, are drawn between dp lat $\pm$ 45°. The sudden commencement of the storm occurred at 0046 UT on September 13, so that the first frame (01 UT) shows the contours 14 minutes after the ssc, namely the initial phase. The magnitude of the initial phase seemed to be appreciably greater in the dark sector than in the day sector; both the subsolar and anti-solar points are marked by a rayed circle and dot, respectively. During the next few hours, the main phase began to develop rapidly in the dark sector and also in the afternoon sector (Central Pacific). At 04 UT, the decrease attained a large value of order 200 γ in Central Pacific, but in the far eastern sector the initial phase was still in progress. However, by 05 UT, the main phase decrease spread over the entire longitude. This can be seen also from D(H) curves obtained at two stations separated about 180° (Fig. 3.4). When the main phase decrease began (~ 02 UT), San Juan was in the late evening sector, but Kakioka was located in the late morning sector. Therefore, the decrease was seen much earlier at San Juan than at Kakioka. However, at about the maximum epoch of the main phase, Kakioka was located in the evening sector and observed a greater decrease than that at San Juan.

Because of this non-uniform development of the main phase decrease, a remarkable asymmetry of the main phase decrease grew. The maximum epoch of the main phase was at about 10 UT, and then the decrease began to decay. Although it is not shown here, the asymmetry was noticeable until about 16 UT when the D(H) contours became nearly parallel to the geomagnetic equator. This suggests that the asymmetry disappears during the recovery phase.

In order to study relationships between the observed asymmetry and polar electrojets, we pay particular attention to the period between 08 and 10 UT on September 13.

(i) Period between 0800 and 0813 UT

In high latitudes, this period is characterized by the absence of a significant polar electrojet activity. It is unlikely that the intensity of the jet, if any, was more than 300 γ. In fact, even a quiet arc was seen in the southern sky on the Pullman all-sky camera film (dp lat 53.5° N). A detailed study of relationships between auroral activity and the polar electrojet indicates that the growth of the polar electrojet is associated with the poleward motion of an activated aurora, but not with a quiet arc (sections 4.1 and 4.2). Since the ratio of the intensity of the return current to that of the jet is typically of order 0.035 (section 4.5(b)), the jet of intensity 300 γ may produce a non-uniformity in the low latitude D of magnitude 300 γ x 0.035 $\simeq$ 10 γ. This is negligible compared with the asymmetry observed at 08 UT.

(ii) 1813 UT: Onset of an intense polar electrojet

At 0813 UT, an extremely intense polar magnetic storm began and the quiet arc seen over Pullman broke up only in two minutes. Between 0813 and 0900 UT the jet was intense.

(a) This enhancement of the jet caused negative bays of order 1500 γ in some part along the auroral zone. However, there was no significant positive bay corresponding to such an intense negative bay; such a phenomenon is not uncommon during great storms [see section 4.3 (Fig. 4.8)]. This contradicts with not only the concept of a pair of jets, but also an assumption that the asymmetry ($DS \simeq c_1 \sin(\lambda + \epsilon_1)$) is caused by a pair of jets.

(b) If the asymmetry is caused by the return current from the jet, the time variation of the 'amplitude' of the asymmetry (c_1) should follow closely with the growth and decay of the jet. Assuming that a jet of intensity was as large as 500 γ at 08 UT, there was an increase of factor 3 during the substorm; this factor could be as large as 7. However, there was no such change in the observed value of c_1.

(c) Since the asymmetry is well approximated by DS $\simeq c_1$ sin $(\lambda + \epsilon_1)$, there is the region where DS > 0 and the rest of the region where DS < 0. In Fig. 3.5, this situation is schematically shown by the solid curve which gives D = Dst + DS = -300 γ + 80 (γ) sin $(\lambda + \epsilon)$; λ is expressed in terms of local time and $\epsilon \simeq 0$. If the asymmetry is caused by the return current from a pair of jets, we would observe a positive bay in the region where DS > 0 and a negative bay in the region where DS < 0 and thus an enhancement of the amplitude c_1, because c_1 becomes larger by the enhanced return current; this situation is expressed by a dotted line. Against such an expectation, a positive bay was observed over most of the earth, though its intensity is different at different places (Fig. 3.6). For example, Honolulu was in the region of a large negative DS at 0800 UT (2100 Honolulu time), but it recorded a large positive bay of more than 100 γ during the substorm. Therefore, the actual D curve (dot-line) in Fig. 3.5 was completely different from the expected one. Figure 3.5 shows also two inserts, D(H) as a function of storm time. If a station is located in the morning sector, the observed main phase decrease (upper insert) is much less than that observed in the evening sector (lower insert); however, an enhanced polar jet causes a positive change at both stations, instead of a negative bay in the lower insert.

(d) Therefore, the enhancement of the jet has a tendency of reducing the asymmetry, rather than enhancing it.

(e) The fact that positive bays were observed over most of the earth agrees with the pattern of the polar electrojet current proposed by Akasofu, Chapman, and Meng [1965]. In their proposed pattern, the westward jet flows all along the auroral oval and causes the eastward return current over the extensive part of the earth, except the noon sector; for details of the current pattern, see section 4.2.

Figure 3.7 shows another example of the asymmetric growth of the main phase. The storm of September 29, 1957, began at 0016 UT; but the growth of the main phase was much delayed until as late as

1320 UT. The growth of the decrease was most rapid in the afternoon sector (Jarvis; 14 UT = 03 LT), resulting in a considerable difference of the magnitude of the main phase at the two stations. However, at about the maximum epoch of the main phase, 1540 UT, there was no significant polar electrojet. Thus obviously, the asymmetry cannot be due to the polar jet.

Then, an intense jet began to grow at about 1710 UT. The corresponding positive bays are hatched. Again, positive bays are seen at all the stations. If the early concept of the asymmetry were correct, an intense negative bay would have to be observed at Luanda, corresponding to the lower insert in Fig. 3.5; note that both Chiclayo and Jarvis are located close to the dip equator, so that the positive bays were greatly enhanced there [Akasofu and Chapman, 1963].

The great storm of February 11, 1958, had also a remarkable asymmetry in the main phase decrease. Figure 3.8 shows iso-intensity contours of D(H) at 1000 UT on February 11. The period of between 1000 and 1020 UT was between two intense substorms and was fairly quiet. At 1025 UT, an intense substorm began, and its peak magnitude was as large as 2500 γ in some parts of Alaska. Therefore, even taking a 500 γ jet at 1000 UT, we would expect a considerable increase of the asymmetry, at least by a factor of 5 during the substorm. However, there was no significant enhancement of the asymmetry associated with it. Furthermore, this intense negative bay was not accompanied by the positive bay in the auroral zone.

Another dramatic way of demonstrating this asymmetric growth is to find a pair of observatories which are separated by almost 180°. If storms grow and decay quickly, one of the stations (in the afternoon and evening sectors) observes a large main phase decrease. On the other hand, the other (in the forenoon sector) fails to observe it because the storm subsides substantially before the station comes around to the afternoon sector. Figure 3.9 shows two geomagnetic storms observed at Kakioka and San Juan. The two stations are separated by 11 hours. In both cases, Kakioka was located in the afternoon sector (the local midnight is indicated by an open circle) and thus observed as a large main phase, while San Juan (which was located in the morning sector) could not observe such a large decrease.

It has long been known that a positive bay observed in the afternoon sector of the auroral zone is often associated with a negative change of the H component in middle and low latitudes. Figures 3.10 shows an example from the Big Delta (near College; dp lat 64.3°) and Honolulu. This negative change has been attributed to a westward return current from an eastward electrojet flowing along the auroral zone, which causes the positive bay. However, as shown in section 4.2, the eastward current causing the positive bays along the auroral zone in the afternoon sector is likely to be the return current from the westward current flowing along the auroral oval.

If the negative change is due to the return current, the ratio of the magnitude of the negative change in low latitudes to that of the positive bay in the auroral zone is unreasonably large; it is of order $0.1 \sim 0.5$. This value may be compared with the ratio given in the table in section 4.5 (b). Furthermore, when the positive bay in the auroral zone is intense enough (more than 500 γ), we can see a positive change superposed on the negative change, rather than the enhancement of the negative change.

The negative change is thus unlikely to be the return current from the eastward current along the auroral zone. Instead, the eastward current spreads toward low latitudes when it is intense enough. Further, since the negative change is seen in the afternoon sector, it is very likely to be due to the asymmetric growth of the ring current. The conclusion here reached is quite important. The growth of the polar electrojet is often associated with the simultaneous growth of the asymmetric growth of the ring current.

3.3 Contribution of the Tail Current to the Main Phase Decrease

The magnetospheric tail current may be considered to be a 'partial ring current', since it flows across the tail westward. Therefore, as suggested by Piddington [1963], this current contributes to the main phase decrease. However, since the intensity of the magnetic field produced by the tail current at the earth's surface should not be greater than the intensity in the tail region (which is of order $30 \sim 50\ \gamma$) the contribution of the tail current to the main phase decrease seems to be smaller compared with that of a storm-time ring current.

Simultaneous observations made by the IMP-I satellite and on the ground during the storm of May 10, 1964, seem to support this conclusion. Figure 3.11, constructed by Behannon and Ness [1965], shows both the intensity of the tail field at about 30a away from the earth's center and a number of simultaneous ground magnetic records.

The storm was not a very intense one, so that it is rather difficult to see clearly the growth of the main phase. Let us examine closely the development of the main phase recorded at low latitude stations, Kakioka (dp lat 26.0° N), San Juan (29.9° N), Guam (4.0° N), and Moca (5.7° N). The first clear indication of the growth of the main phase was seen at Moca (8° 40' E geog. long.) which was located in the early afternoon sector. The growth was delayed at San Juan (66° 07' W geog. long.), as we expect from the asymmetric growth discussed in the previous section. Both Kakioka (140° 11' E geog. long.) and Guam (144° 52' E geog. long.) observed the beginning of the growth at about the time when Moca observed. However, since the stations shifted into the morning sector they could not observe the full development of the main phase.

The tail field began to increase a few hours before the beginning of the main phase and became as large as 50 γ early in the UT afternoon hours of May 10. However, when the main phase was growing on the ground, it began to decrease and reached the quiet time value at about 00 UT on May 11, when the main phase was about the maximum epoch. Behannon and Ness [1965] attributed a part of the decrease to the fact that the satellite was approaching toward the neutral sheet.

3.4 Satellite Observations

(a) Early Observations

The earliest satellite observation of the main phase decrease was made by the Vanguard 3 satellite at a 1000 km level and confirmed that the decrease is produced by a current system beyond the ionosphere

[Cain et al., 1962]. The observation made by the Explorer 6 showed a large distinct dip of the geomagnetic field at about 6 earth's radii [Smith, Coleman, Judge, and Sonett, 1960; Sonett, Smith, Judge, and Coleman, 1960; Smith, 1962; Smith, Sonett, and Dungey, 1964].

The direct detection of the ring current particles has not been conclusive. Freeman [1962] found an intense flux of protons (< 100 keV) in the inner radiation belt. The discovery of an extensive proton belt by Davis and Williamson [1963] suggested once that it might be the most plausible belt to be enhanced during geomagnetic storms [Akasofu, Cain, and Chapman, 1962], since it is known to have the larger total kinetic energy $\bar{\epsilon}$. However, after a more detailed satellite data reduction, Hoffman and Bracken [1965] showed that the belt can produce only about a 10 γ decrease during quiet periods and that the storm time enhancement is unlikely to be large.

(b) Recent Studies

The first conclusive evidence of the existence of the ring current was obtained during the observation of the April 17/18, 1965 storm by Explorer 26 by Cahill [1966]. The storm was associated with a large main phase decrease of order 150 γ on the ground.

During the early phase of the main phase, a rapid development of the decrease was observed only in the afternoon and the evening sector of the earth, but not in the forenoon sector. At that time, the satellite was in the forenoon sector and did not observe any significant change of the field. This confirms the conclusion reached by Akasofu and Chapman [1964] that the growth of the ring current is asymmetric.

At about the maximum epoch of the main phase on the ground, the satellite observed a large ΔB of order 217 γ near $r_e = 3a$. During the recovery phase, the asymmetry rapidly disappeared.

The detection of the ring current particles has not been very conclusive yet. Frank [1966] observed an intense flux of particles by a CIS total energy flux detector between L = 2.8 and L = 4.0 during three intense storms encountered by Explorer 12. The growth and decay of the flux followed closely with the PRI part of the main phase decrease [Akasofu, Chapman, and Venkatesan, 1963]. After examining the response of other detectors carried by the same satellite and also the ratio of the kinetic energy density to the magnetic energy density, he concluded that the particles observed by the detector were electrons of energies between 100 eV and 40 keV. Although a more direct observation is needed in the future to confirm such a conjecture, there is no doubt that there occurs a large concentration of the energy deep in the trapping region during the main phase.

3.5 Relationship between the Growth of the Main Phase Decrease and the Polar Magnetic Disturbances

Akasofu and Chapman [1963] found a close relationship between the growth of the main phase decrease and the polar magnetic disturbances. For this purpose, they chose storms which have a prolonged initial phase (about 6 hours or more) and then examined the simultaneous ap indices. This procedure enabled them to examine whether or not the compression of the magnetosphere is directly related to the growth of the main storm phase. Their finding is that a simple enhancement of the plasma pressure is not related in any obvious way to the growth of the main phase. In Fig. 3.12, the initial phase of the storms and the corresponding ap indices are hatched for emphasis.

However, after such a prolonged initial phase, the growth of the main phase decrease and a sudden increase of ap indices occurred simultaneously, suggesting that the energies for the ring current and polar magnetic substorms are introduced into the magnetosphere at about the same time. Another example of this simultaneity was examined in section 1.3.

In Fig. 3.12 it is interesting to note that activity of polar magnetic substorms tends to peak a little earlier than the maximum epoch of the main phase decrease. In other words, activity of polar magnetic substorms is largest when the ring current is rapidly being built up. Fig. 3.13 shows schematically the growth of the main phase decrease in low latitudes and that of the polar electrojet (in γ). Later, this was confirmed by Sugiura [1963] who used a more extensive data during the IGY.

In this connection, it should be noted that in 1952 Chapman [1952] introduced for the first time the concept of the disturbance local-time in equality (DS), and obtained the growth and decay of both Dst and DS as a function of storm time [see also Chapman, 1956]. He found that the low latitude DS component reaches the maximum value about 6 hours earlier than the Dst maximum. From the discussion in section 3.2, however, it is not correct to associate directly the low latitude DS to activity of polar magnetic substorms. Instead, on the basis of the discussion in section 3.2, his results can be interpreted that the ring current tends to be asymmetric during its growing stage; the polar electrojet tends to be also active during this period. Chapman's analysis was later extended by Sugiura and Chapman [1961] who found that the DS tends to peak at about the onset time of the Dst decrease.

3.6 The Ring Current Generation Mechanisms

(a) Introduction

The growth of the ring current can occur without compression [Akasofu, 1965] or after a large sudden negative impulse [Akasofu, 1964] or even before the compression [Akasofu, Chapman, and Yoshida, 1966]. Therefore, there is no obvious casual relationship between the compression of the magnetosphere and the growth of the ring current [Akasofu, 1961; Akasofu and Chapman, 1963; Dessler, 1962].

This inference was recently dramatically demonstrated during the geomagnetic storm of April 17/18, 1965. When the main phase ($\sim$ - 150 γ) of the storm was rapidly growing there was no obvious change in the measurable quantities of the solar plasma, such as the velocity, density, temperature, and composition [Gosling, 1966]. Wilcox and Ness [1966] showed also that the intensity of storms measured by the K_p index has no simple relation to the kinetic energy flux.

Some the basic quantities to be known for the search of possible mechanisms of the generation of the ring current are the total input energy ϵ_T and the rate of injection Q(t) which is a function of storm time. If the loss rate (L(t)) is known, one of the above quantities is enough; note that $L(t) = \bar{\epsilon}(t)/\tau)$ where $\bar{\epsilon}(t)$ denotes the energy contained in the ring current belt at a particular time t, and τ the lifetime of the ring current particles. Unfortunately, none of the above quantities (ϵ_T , Q, L, τ) are known with certainty. The three quantities are related to each other by the following equations

$$\frac{d\,\bar{\epsilon}(t)}{dt} = Q(t) - \frac{\bar{\epsilon}(t)}{\tau}$$

$$\int \bar{\epsilon}(t)dt = \epsilon_T \quad .$$

There has been a tacit assumption that the energy injection ceases at the maximum epoch of the main phase and that the ring current has a free decay after that time. On this basis, the lifetime of the particles τ has been estimated from the duration of the recovery phase of the average storm, namely of order 24 hours [cf. Parker, 1961].

namely

$$\frac{d\bar{\epsilon}(t)}{dt} \simeq - \frac{\bar{\epsilon}(t)}{\tau}$$

or

$$\bar{\epsilon}(t) \simeq \bar{\epsilon}_o e^{-t/c}$$

where $\bar{\epsilon}_o$ denotes the energy contained in the ring current belt at the time of the maximum epoch of the main phase. On the other hand, the injection rate has been inferred from $\bar{\epsilon}_o$, by dividing it by the growth time of the ring current (10 ~ 12 hours), namely by assuming $L(t) = \bar{\epsilon}(t)/\tau = 0$. On this basis, a 100 γ main phase is considered to require the rate of injection of order 3×10^{22} ergs/10 hours ($= 8.8 \times 10^{17}$ ergs/sec)for the growth time of 10 hours.

The above procedure gives only the upper limit of τ and the lower limit of the injection rate. Therefore, there is a possibility that we have grossly underestimated the total energy (ϵ_T). Indeed, Akasofu and Yoshida [1966] have shown that the presently used ϵ_T may have been underestimated by a factor of 10.

Further, in estimating the injection rate, the common practice has been to compute the total energy flux of the solar wind impinging over the whole cross-section of the magnetosphere (taking its radius to be of order $15a \sim 20a$) and compare it with the energy required to produce the main phase. We should recall that the Chapman-Ferraro theory indicates that all the solar wind particles execute an 'elastic' collision on the magnetospheric boundary and thus that none of them enters deep into the magnetosphere. The MHD approximation [Spreiter, Alksne, and Abraham-Shruaner, 1966] suggests also that the solar wind flows around the magnetosphere and does not enter into the magnetosphere. Indeed, the very existence of the magnetospheric boundary indicates that the solar plasma flows around the boundary. Since the above estimate admits the existence of the boundary (to get the cross-section), it is self-contradictory to compute the available energy (to be able to penetrate into the magnetosphere) in such a manner. Therefore, such an estimate gives no answer to our problem.

Obviously, since a few keV protons in the solar plasma cannot directly penetrate deep into the magnetosphere, Dessler, Hanson, and Parker [1961] considered that hydromagnetic waves might be considered as a carrier of the energy from the magnetospheric boundary. Hydromagnetic shock waves generated at the boundary might be dissipated, converting their energy into the kinetic energy of the magnetospheric plasma. However, their mechanism requires $\Delta B/B \sim 1$, so that $\Delta B \sim 1000\ \gamma$ at $r_e \simeq 3a$. It is extremely unlikely that such a violent phenomenon can ever take place in such a deep region of the magnetosphere. The observation by Cahill [1966] also shows that there was only a little fluctuation superposed on ΔB caused by the ring current. Cole [1964] proposed that random electrostatic fields generated in the magnetosphere can change the distribution of the magnetospheric plasma, resulting in the energization. His process depends on the intensity of the random electrostatic fields, which is estimated to be of order $V_A\, b$, where b denotes the amplitude of hydromagnetic waves and V_A its velocity. He estimated this quantity by taking $V_A \simeq 10^8$ cm/sec and $b \simeq 10^{-4}$ gauss in the magnetosphere, namely $\overline{E^2} \simeq 10^8$ emu. However, this electromotive force is not the desired electric field. When the waves penetrate into the lower ionosphere, they may cause a polarization electric field which may have an intensity comparable to $V_A\, b$ in the ionosphere. If this field can be transmitted upward, it will cause the desired result. Therefore, $V_A\, b$ must be estimated by using the ionospheric quantities, but not by the magnetospheric quantities. Certainly, V_A is much less in the lower ionosphere than in the magnetosphere, perhaps by two order of magnitude. Further, as he noted, his value of $\overline{E^2}$ is comparable with the electric field which drives the polar electrojet. Since we know now that the ring current is located at about 3a ~ 5a for a moderate storm, the above value implies the appearance of intense random fluctuations at dp lat 55°, whose magnitude is comparable with that of polar magnetic substorms. This seems to be an over-estimate. Further, at this latitude, most of the geomagnetic changes are the so-called positive bays which are caused by the return current from the polar jet and are thus hardly random noises.

(b) The Requirements of a Model

In the following, the basic requirements for the generation of a ring current model are listed.

1. The total energy injected during a typical growth time of 10 ~ 12 hours must be at least 3×10^{22} ergs for a 100 γ main phase. The minimum injection rate is then of order 8×10^{17} ergs/sec.
2. The energy must be injected to about $2a < r_e < 5a$.
3. The injection must be such as to make the ring current asymmetric during the growing stage.

4. The injection should have no obvious relation to the kinetic energy flux of the solar plasma flow.
5. The formation of the ring current is not a violent phenomenon. Fluctuations superposed on ΔB (ring) are insignificant.
6. The lifetime (τ) of the ring current particles is shorter than 5 hours in the early recovery phase and is then greatly increased after 12 hours or so ($\tau \simeq 60 \sim 90$ hours).

(c) Asymmetric Ring Current

Akasofu and McIlwain [1963] and Akasofu [1964] have suggested that if the solar plasma clouds contain an appreciable amount of neutral hydrogen atoms, they can penetrate directly deep into the magnetosphere without any hindrance to form a ring current belt through reactions, such as

$$H + M \rightarrow H^{+} + e + M$$

where M denotes a terrestrial atom or molecule. Furthermore, since they do not disturb the magnetospheric boundary when they cross it, the lack of the relation between an enhanced ionized component of the plasma and the growth of the main phase can be easily explained, as well as the variety of the development of geomagnetic storms.

As soon as the above reaction takes place, the motion of the resulting proton is controlled by the geomagnetic field. The protons thus produced are trapped, and those that are at levels where collisions are infrequent will form a ring current belt.

Let us consider a very simple situation in which a unidirectional beam of H atoms impinges on the magnetosphere from the direction of the sun. In this case, the reaction occurs all round the morning and evening twilight circle. For simplicity, let us assume that the reaction takes place only there, on the 06 and 18 local time meridian planes. Since the velocity vector $\underline{v}$ of the atom and geomagnetic field vector $\underline{B}$ should be perpendicular, the injection on the formation of the belt is 100%. The geometry of the effective cross sectional area will be of two fan-shaped areas (of outer radius (6370 + 1400) km = 7770 km and inner radius (6370 + 400) km = 6770 km, with the angle subtended at the earth's center $2\pi/3$; the atoms passing an altitude beyond 1400 km will not have the reaction and those passing below 400 km have little contribution to the ring current. The cross-sectioned area thus assumed is of order $5.7 \times 10^{17} cm^2$. If the flux of hydrogen atoms ($\sim$ 10 keV) is of order $10^9/cm^2 sec$, the rate of injection is of order

5.7×10^{17} (cm^2) x 10^9(sec) x 1.6×10^{-8}(ergs) = 9.1×10^{18} ergs/sec

Thus, the total energy introduced in 12 hours is of order 5.9×10^{23} ergs. Akasofu [1964] made a detailed estimate of the total energy injected for hydrogen atoms with an isotropic velocity distribution (namely, injected isotropically into the magnetosphere) and obtained the total energy (converted into the ring current energy in 12 hours) of order 6.9×10^{23} ergs.

The actual case may lie between the above two extreme cases. A possible situation is then a ring current belt with a gap on the nightside. Within the belt there will be electrical neutrality, because protons and electrons are produced there in equal numbers. However, as soon as the protons start to drift westward and the electrons eastward, charge will tend to accumulate at the gap ends, giving a positive charge on the morning end (A in Fig. 3.14a) and a negative charge on the evening end (D). Such an indented ring current was once considered by Fejer [1961] in order to explain the generation of the polar electrojet.

The charges at the ends will be discharged along the field lines towards the ionosphere, resulting in electric currents along the lines of force (from A to B) and in the ionosphere. There, the current will flow westward from B to C on the nightside and eastward on the dayside. At the evening end, the current flows from C to D; this discharge process will be discussed further later. Akasofu and Chapman [1964] have shown that such a model can explain the major feature of the asymmetric main phase.

Brandt and Hunten [1966] argued that it is extremely unlikely that the solar plasma flow contains a high proportion of neutral hydrogen atoms. However, why can some prominence clouds survive more than 30 minutes in the corona, if the lifetime of neutral hydrogen atoms is estimated to be only a few seconds and if the recombination processes can be ignored? An obvious possibility is that each prominence cloud contains a closed magnetic field which can protect H atoms from the bombardment of coronal electrons and which can also trap H atoms to a certain distance from the sun by the charge-exchange process ($H + p \rightleftarrows p + H$) until the free path of H atoms exceeds the dimension of the expanding cloud.

Block [1966] examined in detail the minimum distance reached by the plasma shot toward the earth, say, from the tail region; it is assumed that before the injections the plasma is located inside the magnetospheric boundary and that the moving plasma is associated with an electric field ($\underline{E} = -\underline{v} \times \underline{B}$). Therefore, this is an extension of Alfvén's and Karlson's theory (section 1.2) to a problem inside the magnetosphere. His study follows closely Karlson's approach (which takes into account effects of the space charge), but extends his theory by considering a certain energy spectrum (or a spectr of the magnetic moment). He finds that the forbidden region is sharply bounded and that the dimension corresponding to Alfvén's L is given by

$$60 \left(\frac{\mu M}{eE} \right)^{1/4}$$

which is sixty times greater than Alfvén's. Figure 3.16 shows the relation between the radius of the forbidden region and the electric field associated with the plasma motion at a large distance; the parameters are the energy and number density of the plasma particles.

Therefore, if the plasma motion is caused by an electrostatic field in the magnetosphere (namely, the (E x B) drift or if the plasma can develop an appropriate polarization field by itself), it can attain a rather close distance from the earth for a reasonable value of the kinetic energy of the plasma particles.

Let us consider this problem in some detail. When the plasma is moving across the magnetic field, there is a continual deflection of the plasma particles by the Lorentz force ($e\, \underline{v} \times \underline{B}$). Since the direction of the motion is different for different signs of charges, this causes an electric current. If the lateral dimension of the plasma is limited, this current causes space changes at the boundaries and thus an electric polarization field which drives an electric current directly opposed to the above current. In a steady state situation, there will be no net current and the plasma moves with a velocity $\underline{v} = (\underline{E} \times \underline{B})/B^2$. However, if the space charges are dissipated by some means, the deflection current cannot be cancelled by the polarization current so that there will appear a net current j, resulting in the Lorentz force $(\underline{j} \times \underline{B})$ which tends to decelerate the plasma motion. In his treatment, Block [1966] did not consider in detail the existence of the ionosphere which could short circuit the space charges; for laboratory experiments of the plasma flow across $\underline{B}$, see Sellen and Bernstein [1964, Beckner [1964], and Baker and Hammel [1965].

Alfvén and Falthammar [1961] and Alfvén, Danielson, Falthammer, and Lindberg [1964] question, however, the concept of infinitely conductive field lines and thus an efficient short circuiting effect of the ionosphere. This is becuase in a low density (collisionless) plasma the current intensity is not related to an electric field by

$$i_{\parallel} = \sigma_o E_{\parallel} ,$$

but by

$$i_{\parallel} = \frac{n_e e^2}{m_e} \int E_{\parallel} dt .$$

They demonstrated a possible existence of a potential difference along a field line by considering an injection of electrons at a certain point on the equatorial plane and the reaction of ionospheric ions at the foot of the field line that crosses the equator at the injection point. The potential difference V is given by

$$|e| V = (\gamma - 1) w_{en} - w_{es}$$

where $w_n = m v_n^2/2$ and $w_s = m v_s^2/2$, and v_n and v_s are the velocity component perpendicular and parallel to B, respectively; the value γ is the ratio of the magnetic field intensity at the foot of the field line to that in the equatorial plane. The above equation indicates that unless the injected electrons are accelerated along the field line by the voltage difference (namely, $\gamma w_{en} - w_{es}$ where γ will be of order at least 10^2) and thus the height of their mirror point is reduced, they cannot reach the ionosphere.

The asymmetry of the ring current cannot be simply due to the existence of a cloud of plasma located in the evening sector of the magnetosphere. The cloud of plasma must be accompanied by the electric field mentioned in the above; otherwise, it will drift outward by itself. This is because of the difference of the direction of the motion of positive ions and electrons in the cloud, which will immediately polarize the cloud (Fig. 3.14b). The resulting electrostatic field (E) is directed eastward in the cloud, and thus this causes an outward motion of the cloud; this is a well-known property of plasma, that is, plasma tends to move toward the region of the weakest B. Further, if the space charge is dissipated along the field lines from both the western and eastern end of the cloud, this will induce a current system A D C B in Fig. 3.14b. In a steady state, the condition $\nabla \cdot \underline{j} = 0$ indicates that an extra current flowing along AD due to the plasma cloud (added to the symmetric ring current belt) is exactly equal to the current caused by their drift motion and that this extra current flows along A D C B. Then, since the part CB is closer to AD, the eastward current flowing CB has a greater magnetic effect than the westward current in AD. Furthermore, the extra diamagnetic effect due to the added plasma tends to reduce the effect of the westward current in AD.

Both Piddington [1966] and Axford [1966] suggested that the plasma flow from the neutral sheet is responsible for the ring current. This plasma flow will be discussed in detail in section 4, in connection with the auroral substorm. There, we conclude that if an instability is responsible for the activation of the neutral sheet, it must be the disintegration of the sheet current into a number of filaments (the tearing mode). One of the effects of this instability tends to deflect the plasma flow from the sheet toward the polar cap and thus can explain the explosive phase of the auroral substorm. The main flow of the energy is thus directed along the trapping boundary toward the polar ionosphere. Therefore, the total energy ϵ_T required for the ring current should be less than the energy deposited along the auroral oval. As mentioned earlier, the total energy for the ring current is not well known, because the loss mechanism is not understood. The total energy deposited along the auroral oval cannot also be accurately inferred. A more interesting way of examining the plasma flow from the tail region will be to find the electric field associated with the plasma flow and its ionospheric effects; if electric currents are generated by the field, it should be observable on the ground.

(d) Loss Mechanisms

Since little is known about the exact nature of the particles contributing to the ring current, it is not possible to make any definite conclusion on the loss mechanism. However, it is not difficult to place an upper limit on the energy of both protons and electrons. Protons of energies more than 100 keV are now known to show only a little change during the main phase, so that if protons are mainly responsible for the ring current, their energies must be less than 100 keV. Similarly, the energy of electrons must be less than 40 keV. Further, the gradient of the recovery phase gives us some idea on the lifetime (τ) of the ring current particles.

Protons of energies less than 100 keV are greatly affected by the charge-exchange process with the terrestrial hydrogen atoms ($p + H \rightleftarrows H + p$) [Stuart, 1959; Dessler and Parker, 1959]. At $r_e = 3a$, the lifetime of τ of a 10 keV proton is of order 3×10^4 sec, and at $r_e = 2a$, $\tau \simeq 6 \times 10^3$ sec. If they oscillate along field lines, their lifetime becomes appreciably shorter than the above values [Liemohn, 1961].

Cole [1965] proposed that the ring current particles are degraded in energy by Coulomb collisions with a background magnetospheric plasma. This energy is then conducted downward along the field lines to heat electrons in the F region of the ionosphere to about 3200° K; this temperature is high enough to excite [OI] λ 6300 doublet. He suggested that the so-called 'monochromatic red arc' which is often seen in mid-latitudes during geomagnetic storms is an important sink for the energy of the ring current.

3.4 Changing Auroral Oval

When the sun is very quiet, the auroral oval contracts from its average location to dipole co-latitude 15° or less in the midnight sector and becomes very faint or even invisible. However, even weak geomagnetic activity ($\Sigma K_p \simeq 10$) is associated with the expansion of the oval from its quiet time location to its average location, so that its midnight radius increases to dp co-lat 23° (that of the auroral zone) in the midnight sector [Akasofu, 1964; Stringer, Belon, and Akasofu, 1965].

During an intense geomagnetic storm, the oval exapands greatly, at times as far as dipole co-lat 40° or dp lat 50° during extremely intense storms. Akasofu and Chapman [1963] have shown that the dipole latitude of the midnight portion of the oval depends on the magnitude of the main phase decrease (the Dst values); their diagram is reproduced here as Fig. 3.17. The equatorward shift of the auroral oval is associated with the 'squashing' of the trapping region toward the equatorial plane. A drastic equatorward shift of the outer boundary of the outer radiation belt during intense magnetic storms was first observed by Maehlum and O'Brien [1963]. Since then a large number of observations have been made, particularly by Williams and Palmer [1965] and Ness and Williams [1965]. Williams and Palmer [1965] showed that the day-night asymmetry (the eccentricity) of the outer belt (electrons of energies greater than 40 keV) becomes more obvious as the K_p index is increased.

The internal structure of the magnetosphere is expected to change greatly during geomagnetic storms when both the ring current and the neutral sheet current grow and vary. In this section we show that the growth and decay of the ring current and the neutral sheet current plays an important role in determining the location of the auroral oval in the midnight sector.

During geomagnetic storms, the magnetic field intensity $\underline{B}$ at a point in the magnetosphere can be expressed by the combination of the magnetic field originating in the solid earth (denoted by G) and the magnetic fields generated by the magnetospheric boundary current ($C > 0$), the ring current ($R \gtrless 0$), the neutral sheet current ($N \gtrless 0$), and the polar electrojet ($P \gtrless 0$). We note, however, that $B \simeq G$ on the earth's surface and $B \simeq G + C + R + N$ in the equatorial plane of the magnetosphere [Chapman and Bartels, 1940]. Further, the C field becomes important only when both the R and N fields are small, so that it is not taken into account. The first approximation ($B \simeq G$) gives rise to an error of less than 1% in the following magnetic flux calculation. The consequence of the second approximation will be discussed later.

Consider two equatorial radial lines (OA, OB) separated by longitude $\pm \frac{1}{2}\, d\lambda$ from the sun-earth line in the midnight sector; the earth's center is denoted by O. The two radial lines intersect the boundary of the trapping region at A and B, respectively, and also the earth's surface at A' and B', respectively. Denoting the dipole pole N, consider also a half sectorial area NA'B' on the earth's surface; let A" and B" be the intersection points of the lines NA' and NB' with a dipole latitude circle φ. At a point in the equatorial fan-shaped area (bounded by the two radial lines, the solid earth and the boundary of the trapping region, AA'B'B),

$$B\ (r_e) \simeq G\ (r_e) + R\ (r_e) + N\ (r_e)$$

and the total magnetic flux F_e across the area AA'B'B is given by

$$F_e = \int BdS = \int^{\lambda} \int_{a}^{r_T} B\, r_e\, dr_e\, d\lambda$$

where dS denotes an elementary area and r_T the geocentric distance of the trapping boundary in the midnight sector. For a given set of values of G (r_e), R (r_e), and N (r_e), F_e can be estimated. The latitude φ of the intersection between the ionosphere and the outer boundary of the outer belt can then be determined by using the magnetic conservation theorem [Dessler and Karplus, 1961; Akasofu, 1963] by equating

$$F_s = \int BdS' = \int^{\lambda} \int_{o}^{\varphi} B_r\, a^2 \cos\varphi\, d\varphi d\lambda$$

with F_e, where dS' denotes an elementary area in the half sectorial area NA'B', B_r the radial component of $\underline{B}$ on the earth's surface and F_s the magnetic flux from the area A'B'B"A" on the earth's surface. The latitude thus determined gives the minimum latitude of the field lines which are opened by the growth of both the ring current and the neutral sheet current or the latitude which is exposed to energetic plasma particles from the neutral sheet.

Figure 3.18 shows the latitude φ as a function of the ring current intensity $|R|$, taking the intensity of the neutral sheet current field $|N|$ as the parameter. The function G (r_e) is taken to be a dipole field, namely $B_o/(r_e/a)^3$, with $B_o = 0.32$ gauss. The parameters which specify R (r_e) are given by the geocentric distance of the center line of the ring current belt ($r_{eo} = 1.5a$), the two constants determining the particle distribution inside and outside r_{eo} ($g_1 = 2.990$ and $g_2 = 0.499$, respectively) and the constant determining the pitch-angle distribution of the ring current particles ($\alpha = 2.0$). The kinetic energy density of the ring current is expressed in terms of a measurable quantity R at the equator on the earth's surface ($r_e = a$). The function N (r_e) cannot be determined accurately unless the two dimensional configuration of the neutral sheet is known. Here, N is assumed to be constant; the results are not, however, greatly affected by the functional form of N (r_e) because G (r_e) increases rapidly toward the earth.

Figure 3.18 shows that the neutral sheet of intensity $|N| = 50\ \gamma$ alone can open the field lines beyond dp lat 70° but the growth of the ring current increases considerably the opening efficiency; for the ring current of intensity $|R| = 300\ \gamma$, the field lines beyond dp lat 53° 37' can be opened and thus this latitude can be exposed to the hot plasma from the neutral sheet.

For an extreme case of the ring current intensity $|R| = 300\ \gamma$ and the neutral sheet intensity $|N| = 90\ \gamma$, dp lat 47° 30' can be exposed to the hot plasma from the neutral sheet. This latitude is little less than the minimum dp latitude attained by quiet auroral arcs during the IGY (Fig. 3.17).

Section 3

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Figure Captions

Fig. 3.1 The magnetic field (ΔB) produced by the ring current characterized by $r_{eo} = 3a$, $F \propto \sin^3 \theta$, $g_1 = 2.146$, $g_2 = 1.517$, and $\epsilon n_o = 6000$ keV/cm^3.

Fig. 3.2a The distortion of the earth's dipole field by the belt characterized by $r_{eo} = 3a$, $F \propto \sin^3 \theta$, $g_1 = 2.146$, $g_2 = 1.517$, and $\epsilon n_o = 1000$, 4000, and 6000 keV/cm^3.

Fig. 3.2b The distorted field line by the ring current characterized by $r_{eo} = 3a$, $F \propto \sin^3 \theta$, $g_1 = 2.146$, $g_2 = 1.517$, and $\epsilon n_o = 6000$ keV/cm^3. The original equatorial crossing field line before the distortion is $r_e = 4a$.

Fig. 3.3 The development of the main phase of the September 13, 1957, storm. Approximate iso-intensity contours of D(H) are drawn at each UT hour, between 01 and 12.

Fig. 3.4 The D(H) variation at San Juan (solid) and Kakioka (dotted) during the early phase of the September 13, 1957 storm.

Fig. 3.5 Schematic illustration of the low latitude main phase field (D) as a function of longitude (or local time). The distribution of D during a quiet period in the polar region can be expressed by $D = c_o + c_1 \sin(\lambda) = Dst + DS$ (solid curve). If the DS component is produced by a pair of electrojets, the distribution of the D field during the substorm should be seen as an enhancement of c_1 (dotted curve). However, the actual change (line-dot) is quite different from such an expected one. For the inserts, see the text.

Fig. 3.6 The iso-intensity contours of D(H) during the quiet period in the auroral zone (0800 UT) and the active period (0900 UT). At 0900 UT, intense negative bays were observed at the stations indicated at the top. The actual H component variation at several stations between 0800 and 1000 UT are shown at the bottom.

Fig. 3.7 The H component magnetic records from low latitude stations distributed widely in longitude during the geomagnetic storm of September 29, 1957.
[Akasofu, S.-I., and S. Chapman, J. Geophys. Res., 68, 2375, 1963]

Fig. 3.8 The iso-intensity contours of D(H) at 1000 UT, February 11, 1958. This was at about the maximum epoch of the great magnetic storm.

[Akasofu, S.-I., and S. Chapman, Planet. Space Sci., 12, 607, 1964]

Fig. 3.9 The variation of D(H) at two stations separated by almost 180° in longitude. The large difference in D(H) can be attributed to the asymmetric development of the main phase.

[Akasofu, S.-I., and S. Chapman, Planet. Space Sci., 12, 607, 1964]

Fig. 3.10 The simultaneous magnetic records from Big Delta (near College, Alaska) and Honolulu. The negative change seen at Honolulu had been attributed to the westward return current from an eastward electrojet causing positive bays along the auroral zone.

Fig. 3.11 The simultaneous geomagnetic variations in the tail region of the magnetosphere (upper) and on the ground (lower).

[Behannon and Ness, J. Geophys. Res., 71, 2327, 1966]

Fig. 3.12 The simultaneous growth of the main phase decrease and of the polar electrojet (the ap index).

[Akasofu, S.-I., and S. Chapman, J. Geophys. Res., 68, 3155, 1963]

Fig. 3.13 The schematic diagram to show the development of both the polar electrojet (the polar magnetic substorm) and the ring current (the main phase decrease).

Fig. 3.14 The asymmetric ring current, (a) proposed by Akasofu and Chapman (1964), (b) the ring current with an additional plasma in the late evening sector.

Fig. 3.15 The relationship between the electric field associated with the plasma flow at a large distance and the radius of the forbidden region.

[Block, L. P., J. Geophys. Res., 71, 1966]

Fig. 3.16 The relationship between the souternmost latitude attained by auroral arc and the magnitude of the main phase decrease; $\Delta H'$ is the actually observed Dst value and $\Delta H = (2/3) \times \Delta H'$.

Fig. 3.17 The relation between the minimum open latitude by the interaction of the ring current and the neutral sheet as a function of the intensity of the ring current on the ground (R); the parameter is the intensity of the neutral sheet.

[Akasofu, S.-I., Planet. Space Sci., 14, 1966]

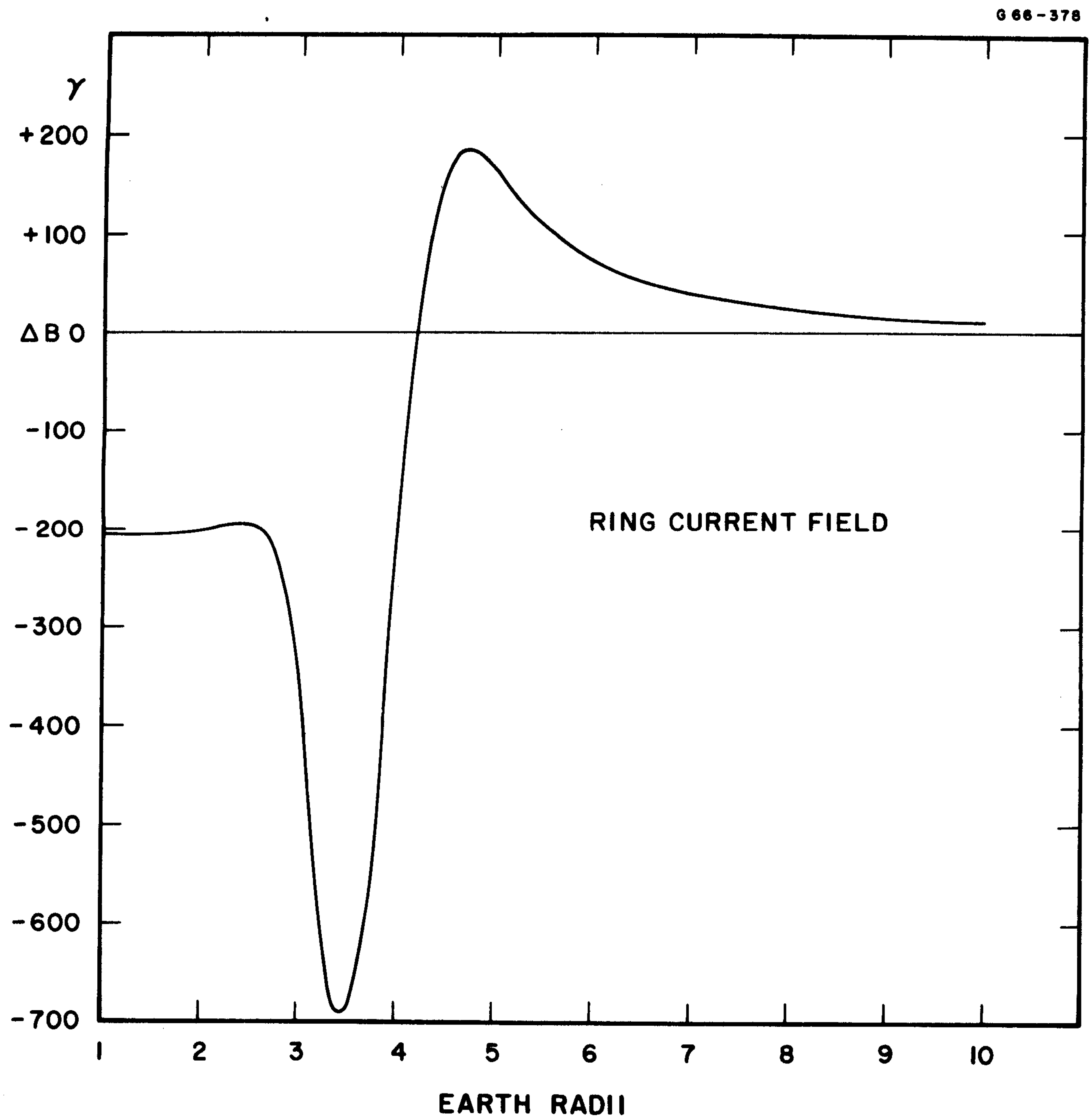

G 66-378
γ
+200
+100
ΔB 0
-100
-200
-300
-400
-500
-600
-700
RING CURRENT FIELD
1
2
3
4
5
6
7
8
9
10
EARTH RADII

Figure 3.1

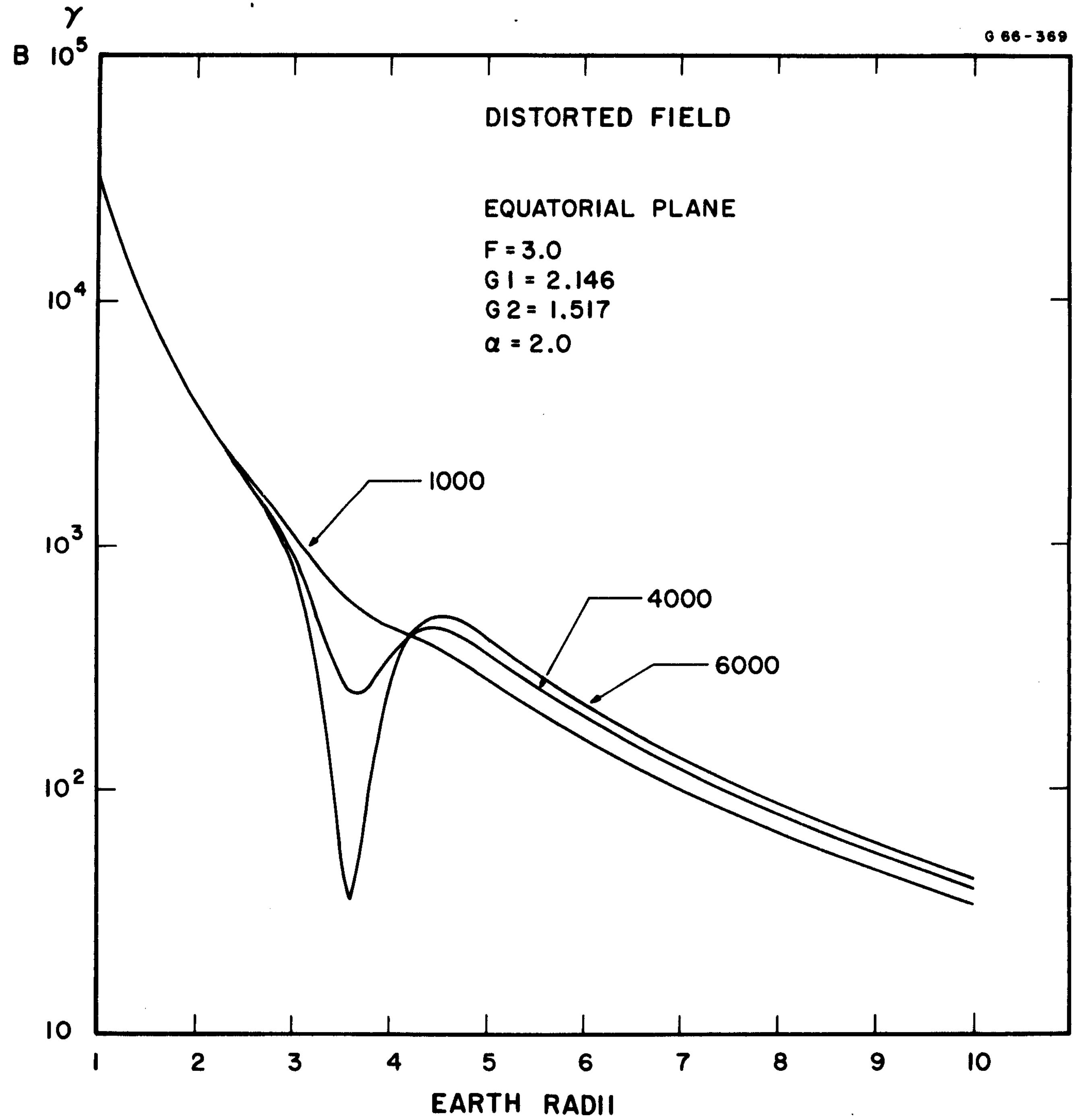
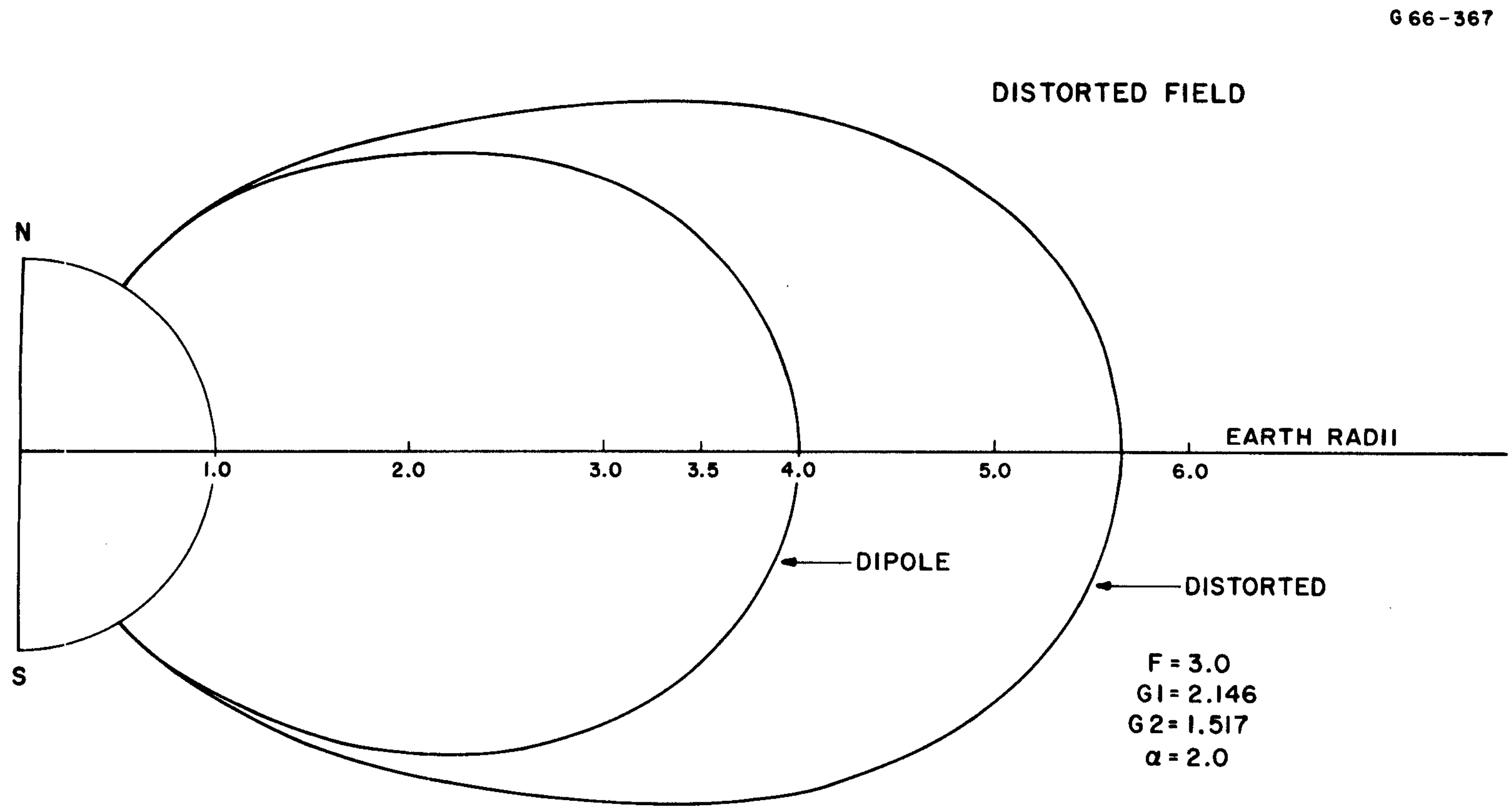

G 66-369
B
γ
10^5
10^4
10^3
10^2
10
DISTORTED FIELD
EQUATORIAL PLANE
F = 3.0
G1 = 2.146
G2 = 1.517
α = 2.0
1000
4000
6000
1
2
3
4
5
6
7
8
9
10
EARTH RADII

Figure 3.2 (a)


G 66-367
DISTORTED FIELD
N
S
1.0
2.0
3.0
3.5
4.0
5.0
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EARTH RADII
DIPOLE
DISTORTED
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G1 = 2.146
G2 = 1.517
α = 2.0

Figure 3.2 (b)

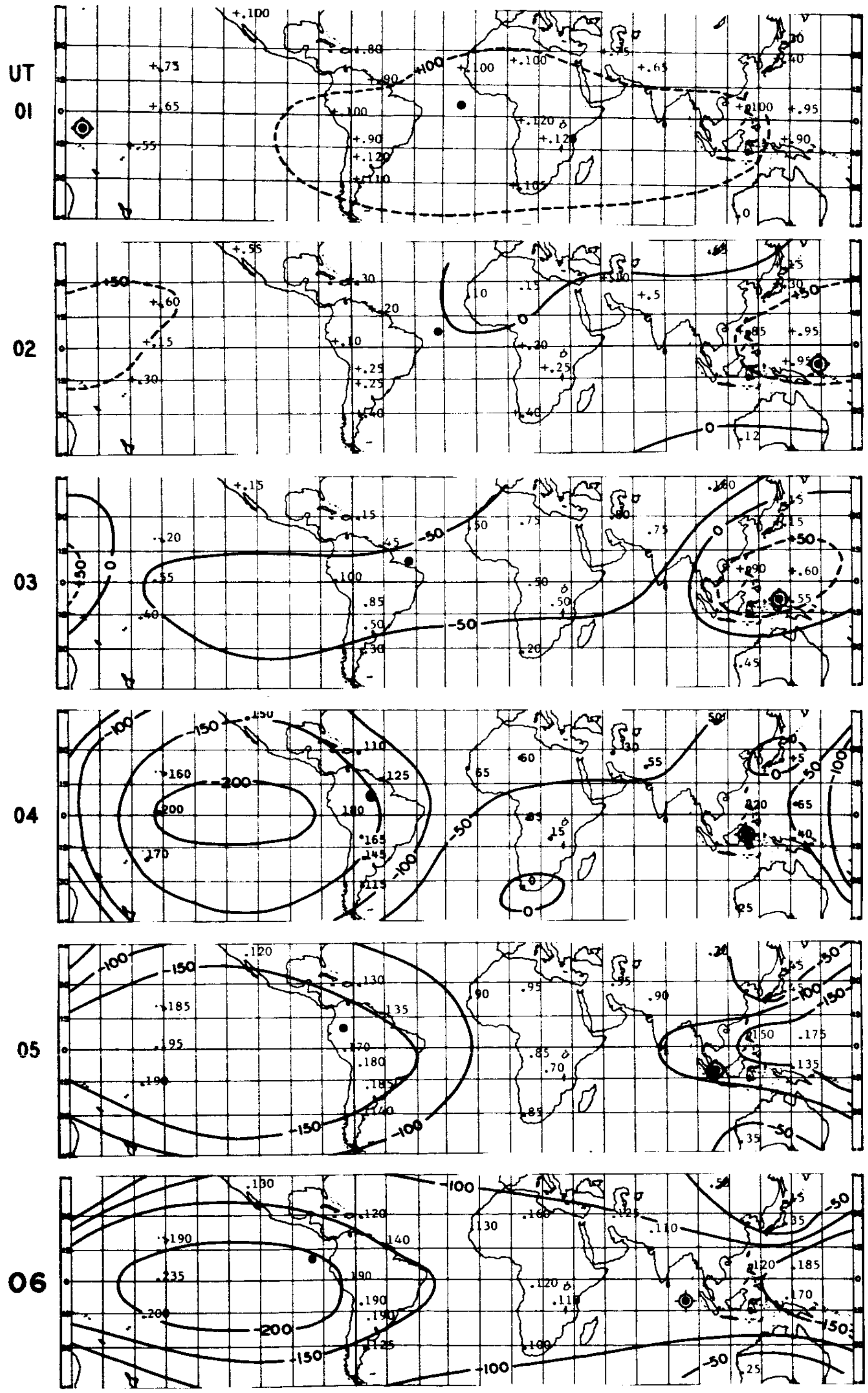


Figure 3.3 (a)

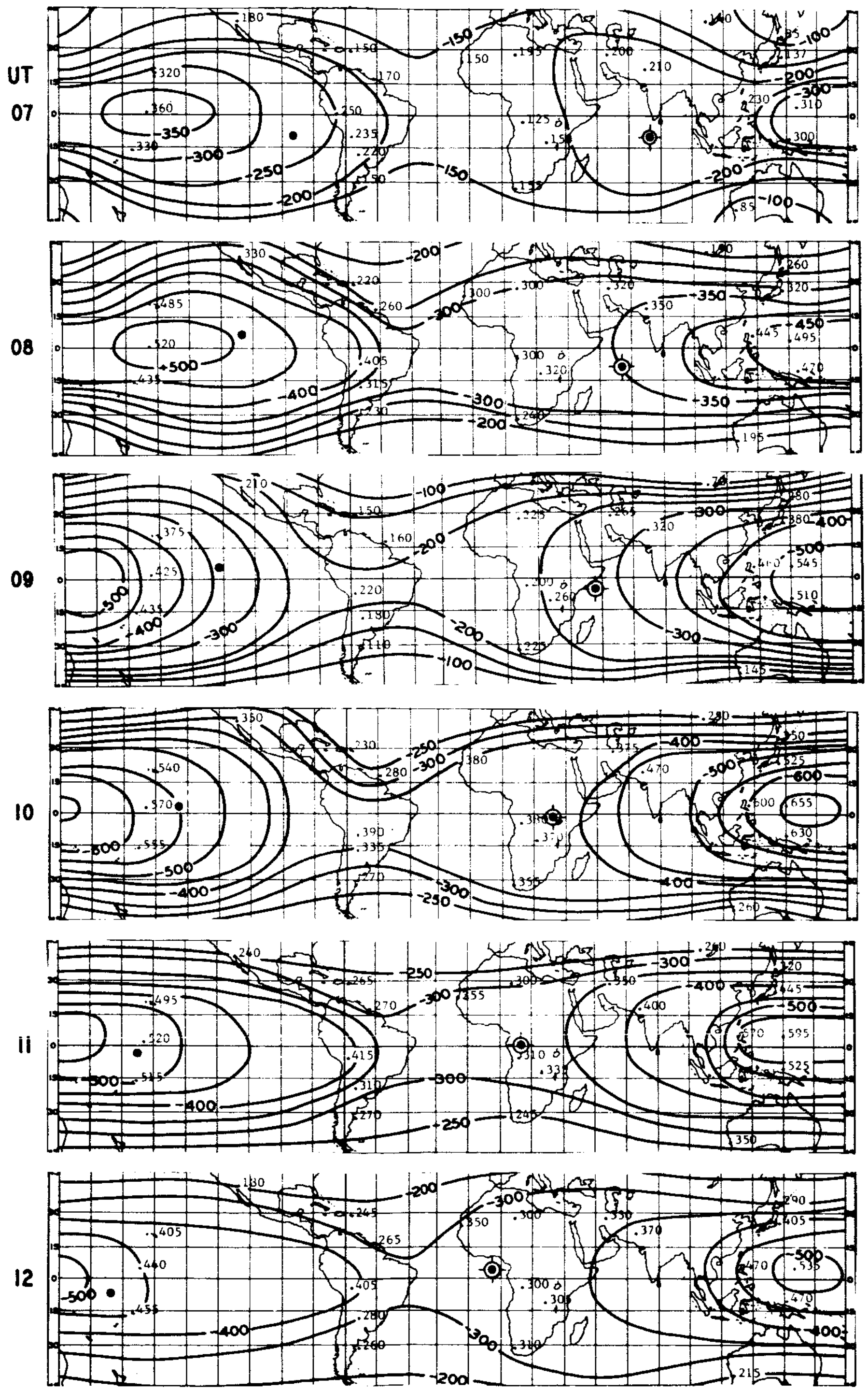


Figure 3.3 (b)

G 66-337

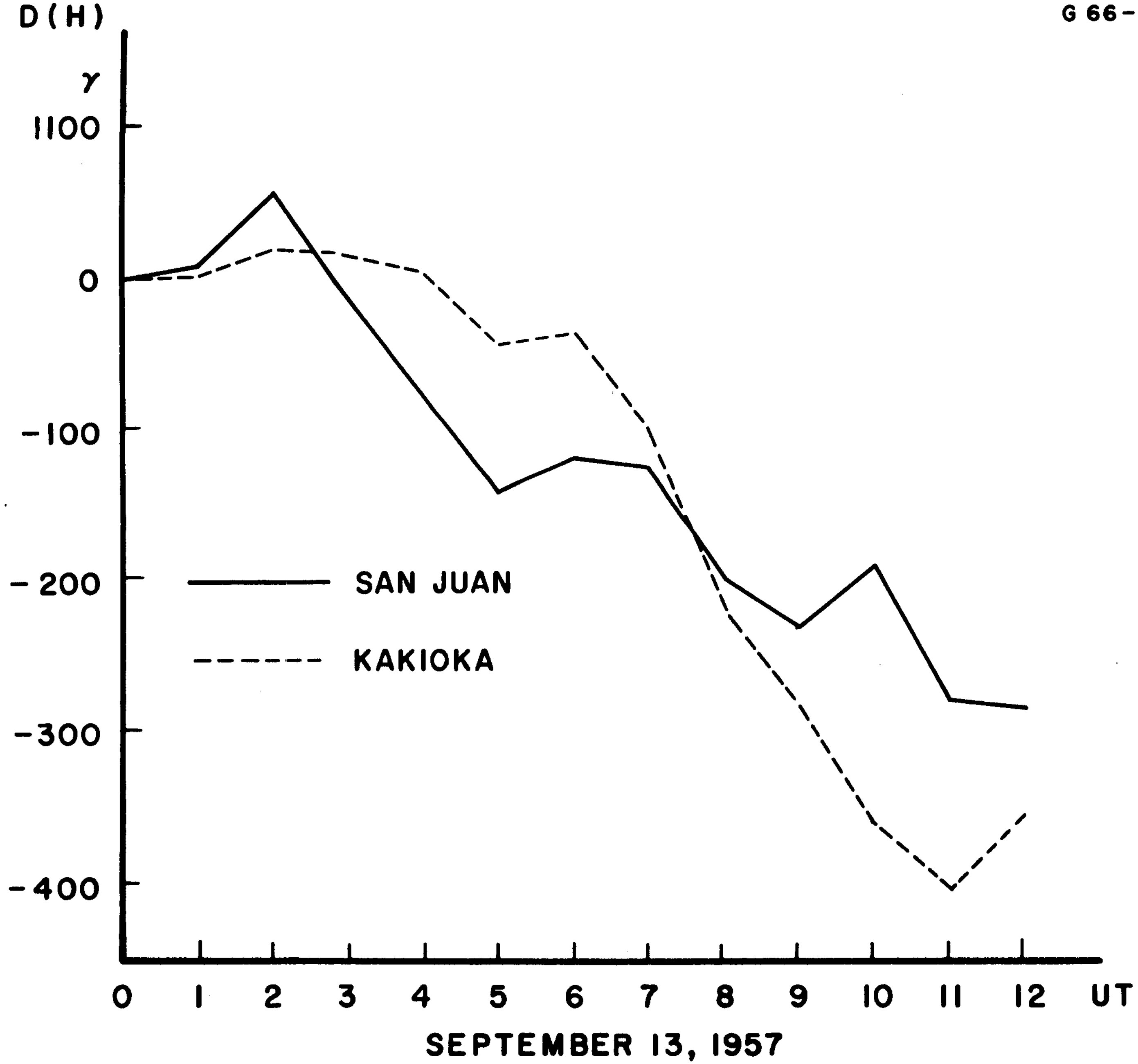


Figure 3.4

G 66-353

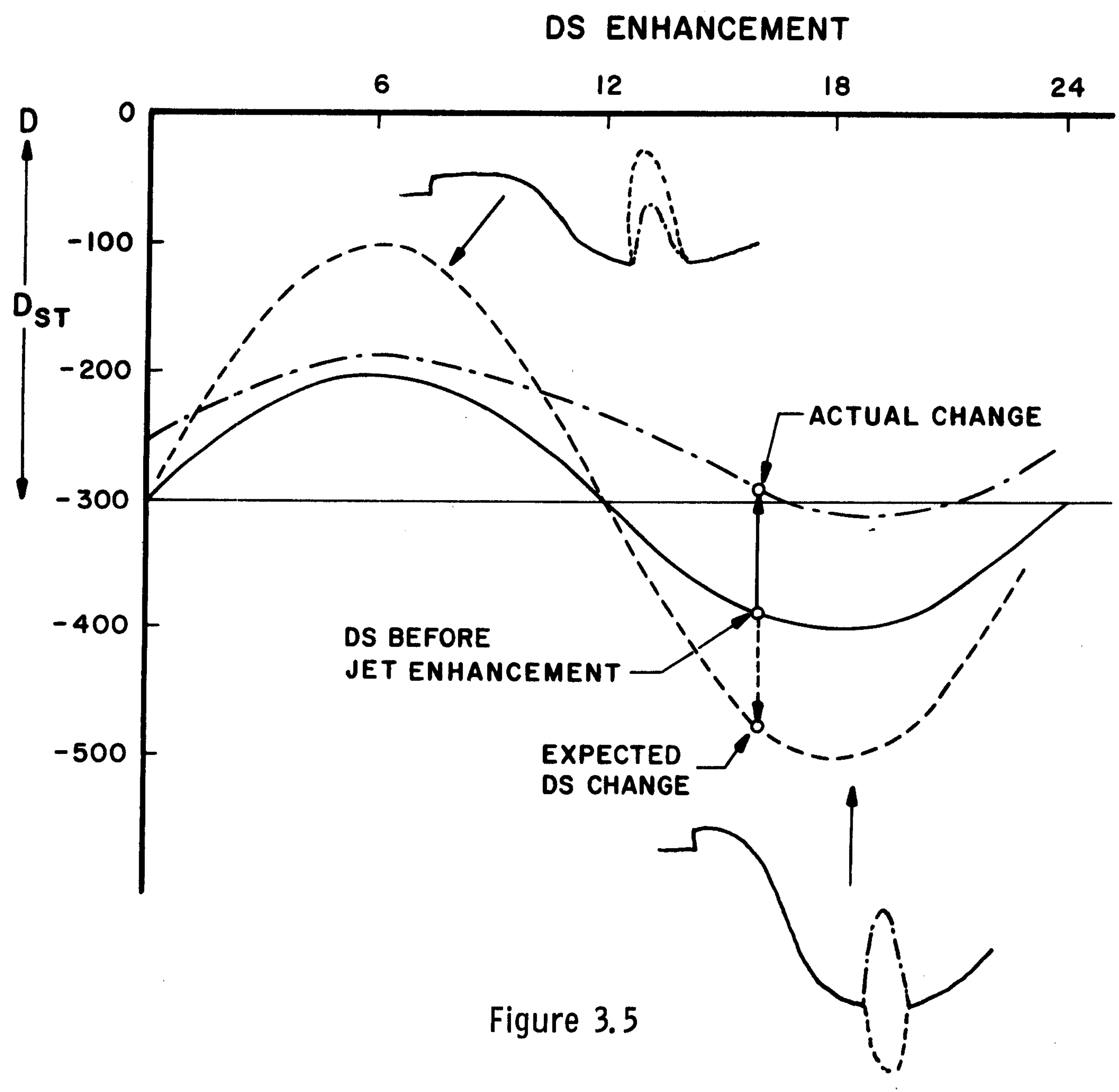


Figure 3.5

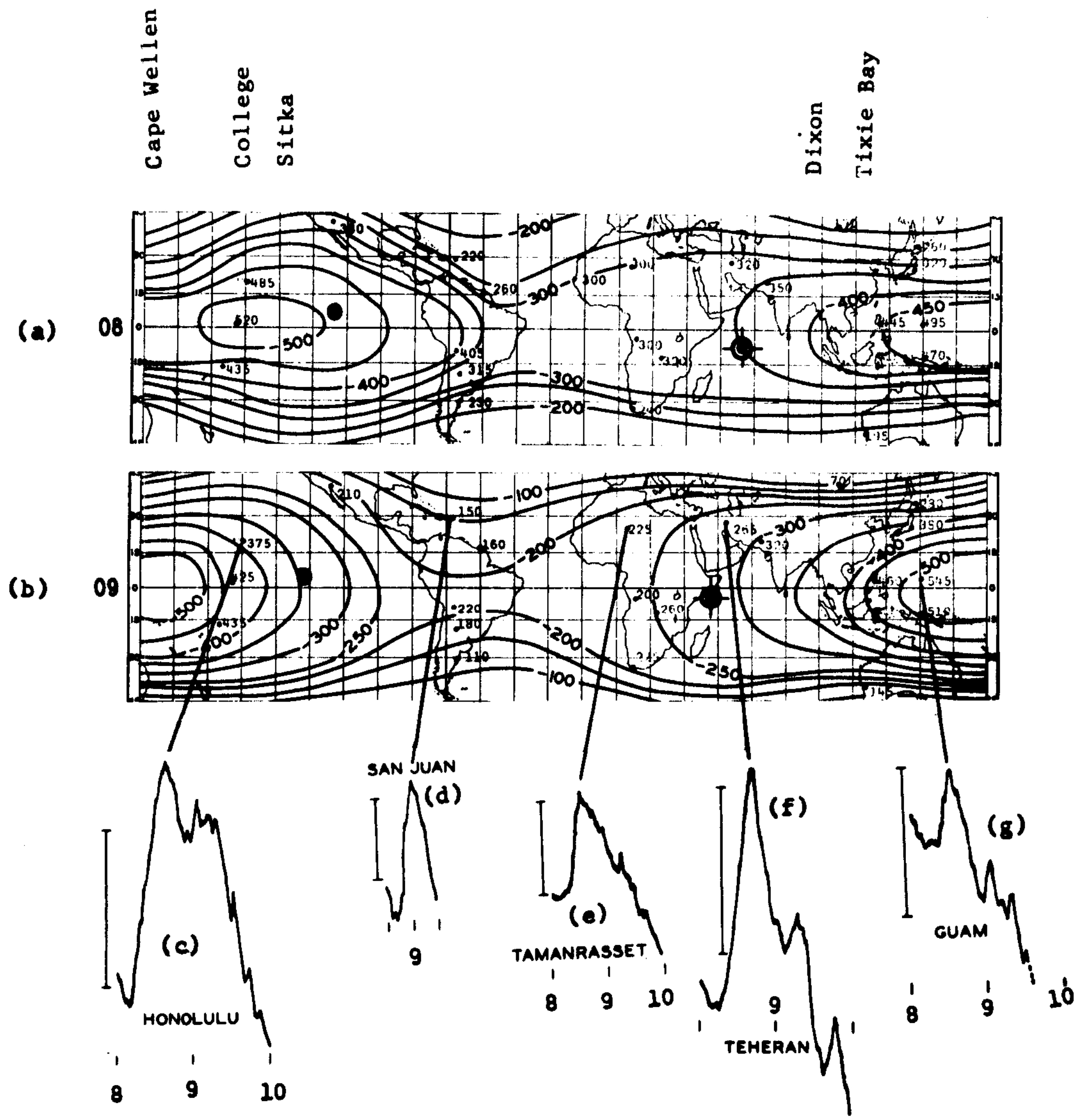

Cape Wellen
College
Sitka
Dixon
Tixie Bay
(a)
08
(b)
09
HONOLULU
(c)
SAN JUAN
(d)
TAMANRASSET
(e)
(f)
TEHERAN
(g)
GUAM
8
9
10

Figure 3.6

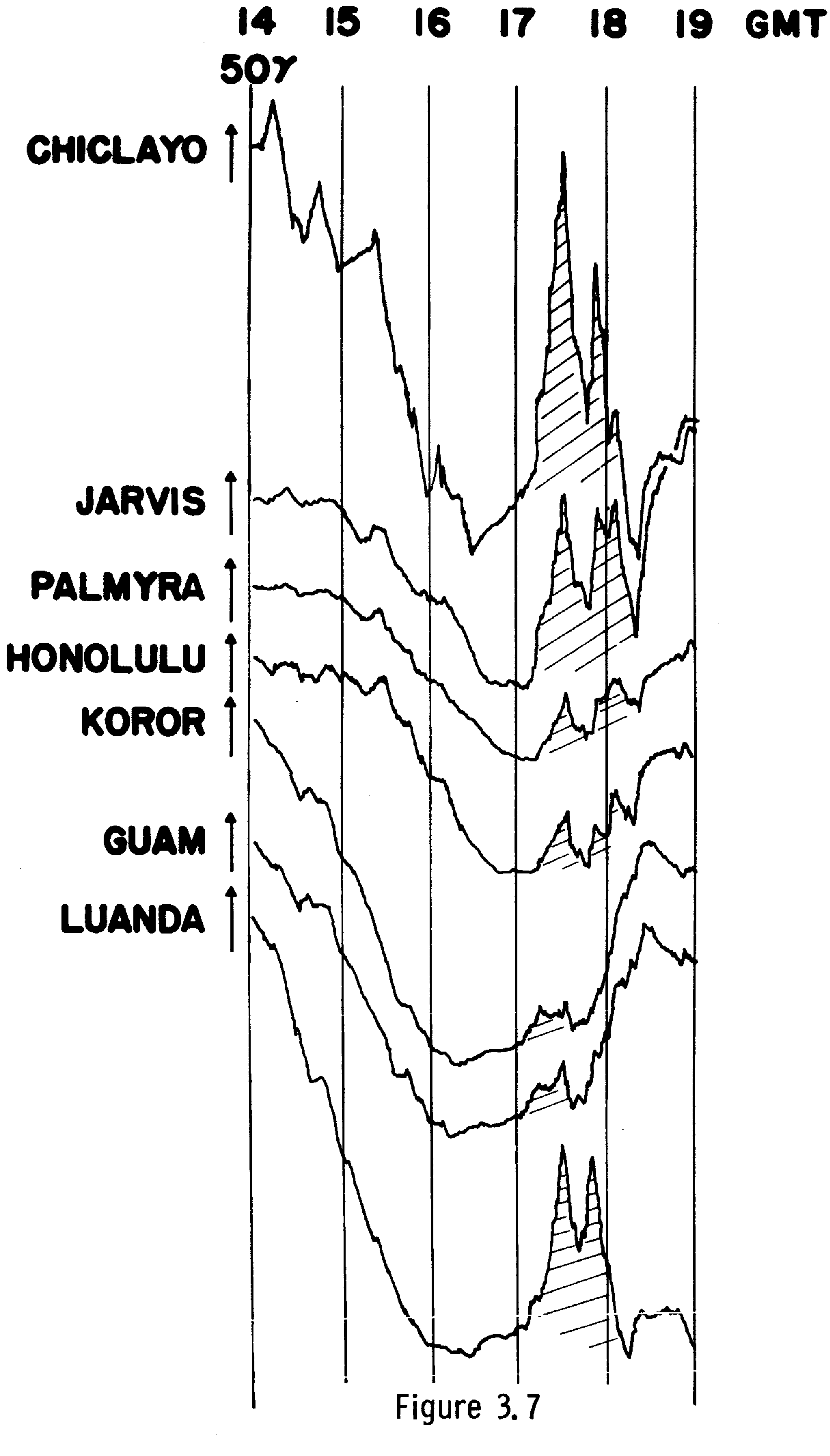
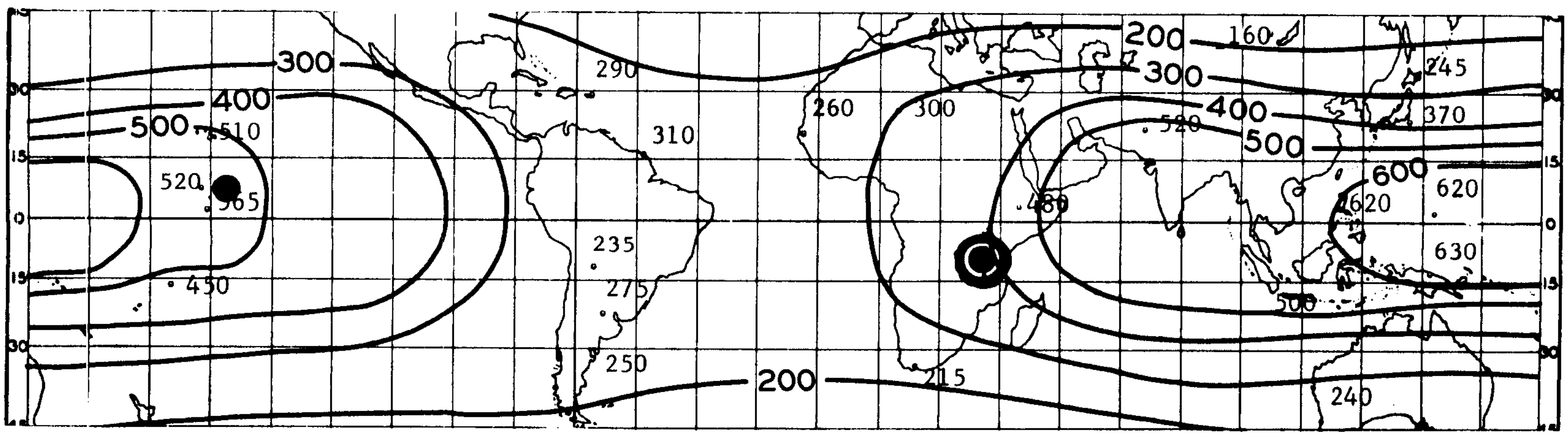
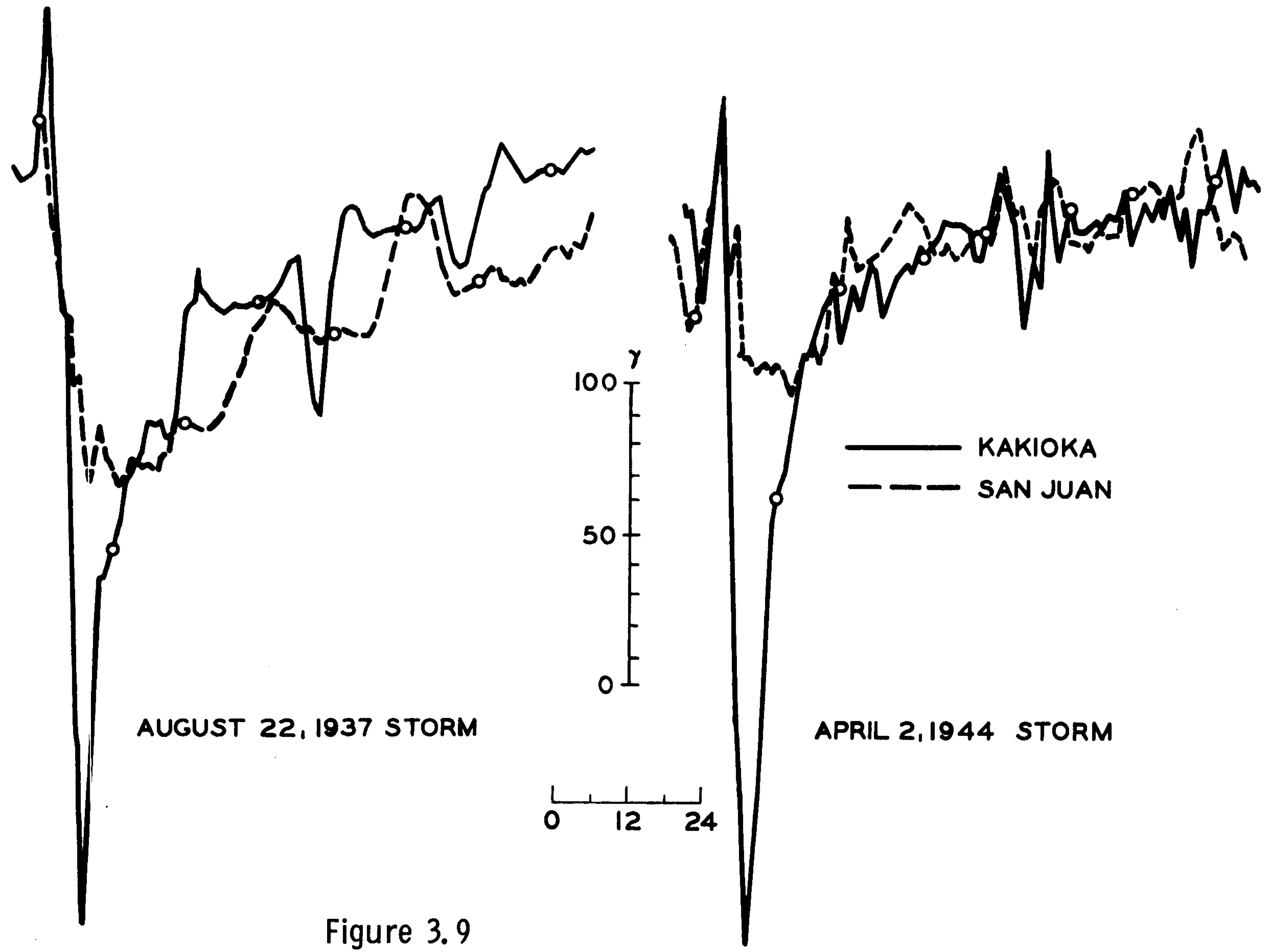

14 15 16 17 18 19 GMT
50γ
CHICLAYO
JARVIS
PALMYRA
HONOLULU
KOROR
GUAM
LUANDA

Figure 3.7



300
400
500
510
520
565
450
290
310
235
275
250
200
260
300
480
215
200
160
300
400
500
520
245
370
600
620
620
630
500
240

Figure 3.8



AUGUST 22, 1937 STORM
APRIL 2, 1944 STORM
KAKIOKA
SAN JUAN
γ
100
50
0
0
12
24

Figure 3.9

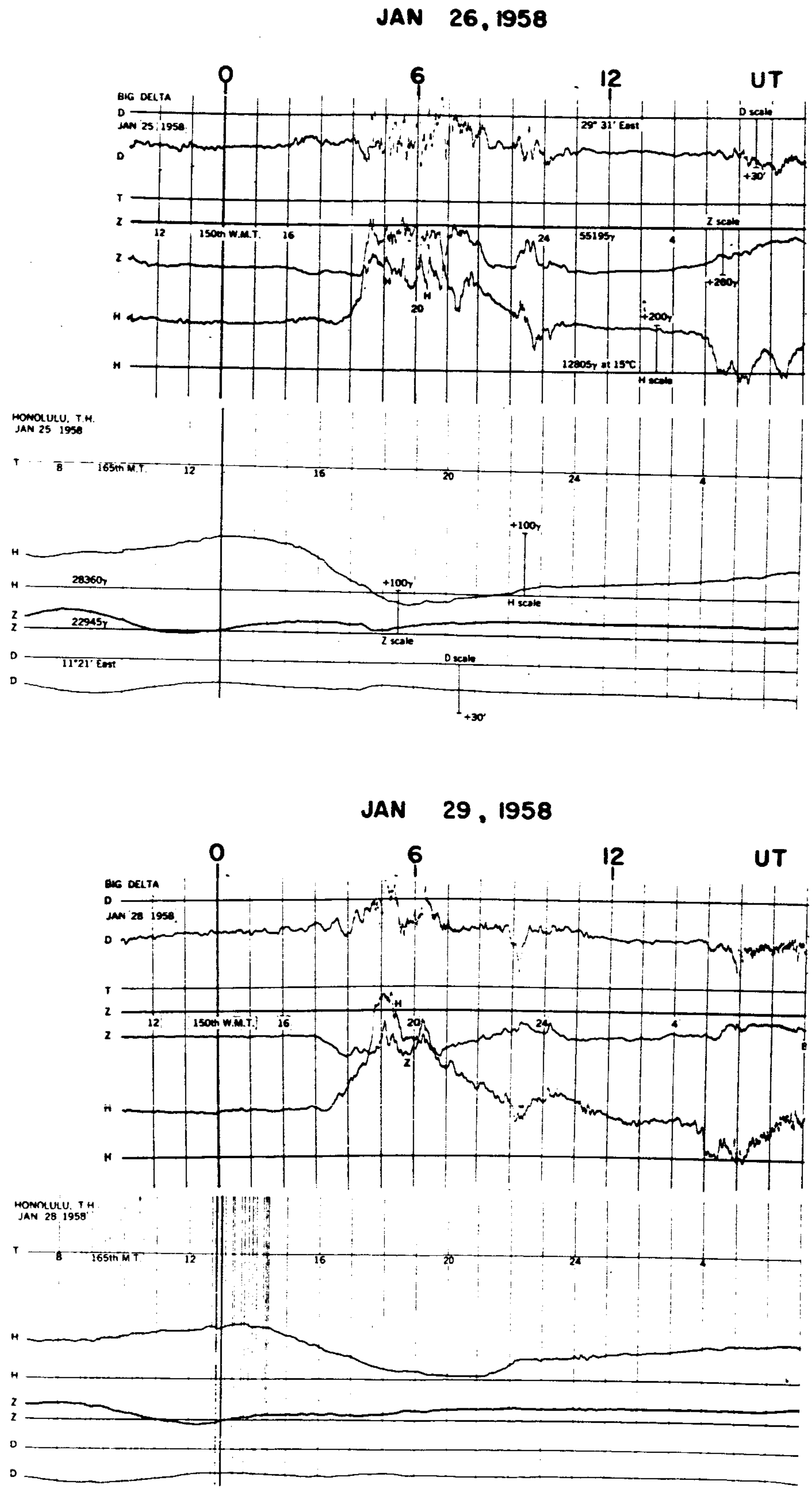
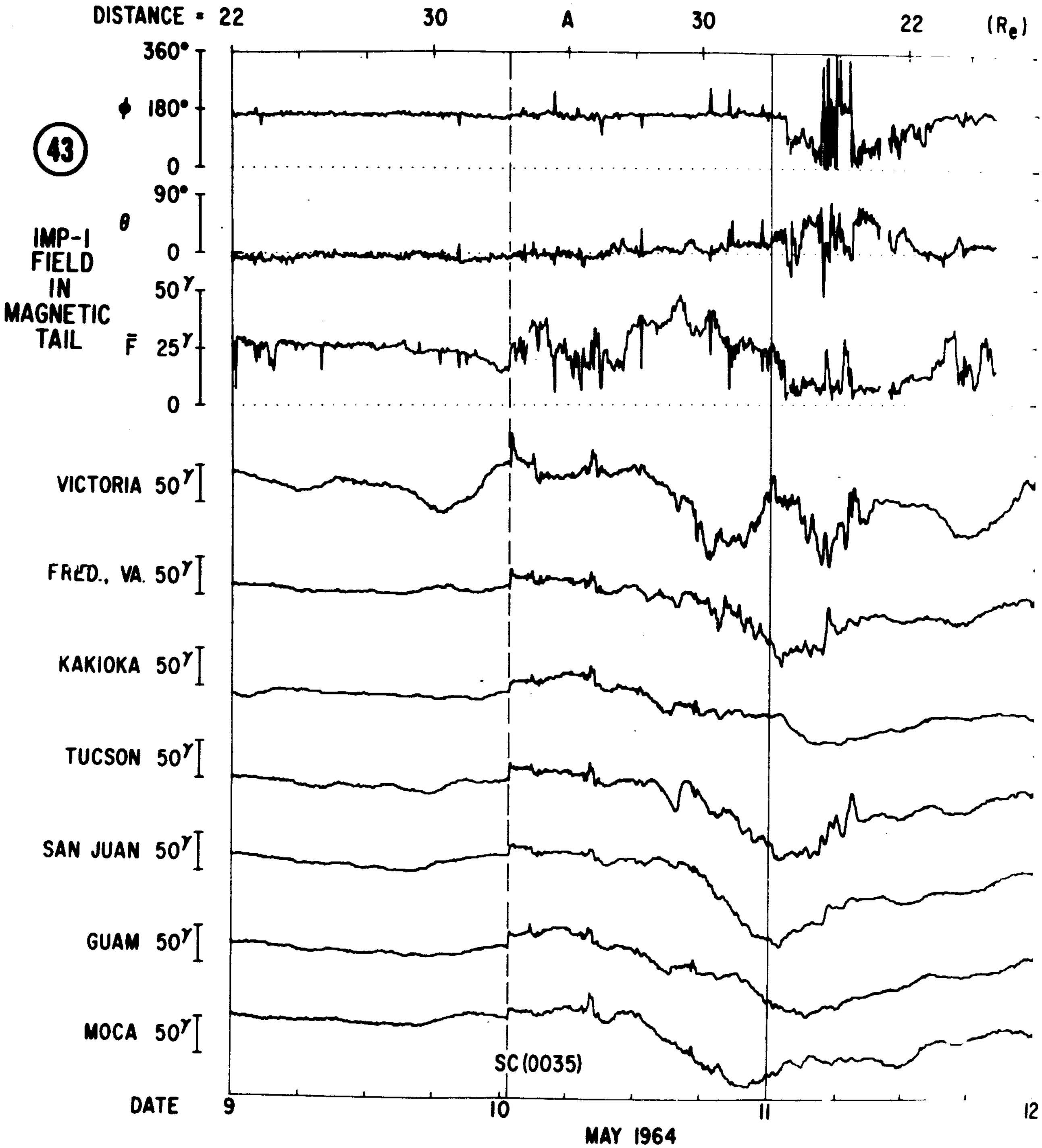

JAN 26, 1958
0
6
12
UT
BIG DELTA
JAN 25, 1958
D
T
Z
H
29° 31' East
D scale
+30'
Z scale
12
150th W.M.T.
16
20
24
4
55195γ
+200γ
12805γ at 15°C
H scale
HONOLULU, T.H.
JAN 25 1958
8
165th M.T.
+100γ
28360γ
22945γ
Z scale
11°21' East
D scale
JAN 29, 1958
BIG DELTA
JAN 28 1958
HONOLULU, T.H.
JAN 28 1958

Figure 3.10



DISTANCE = 22
30
A
30
22
(Re)
360°
φ 180°
0
43
90°
θ
0
IMP-I
FIELD
IN
MAGNETIC
TAIL
50γ
F̄ 25γ
0
VICTORIA 50γ
FRED., VA. 50γ
KAKIOKA 50γ
TUCSON 50γ
SAN JUAN 50γ
GUAM 50γ
MOCA 50γ
SC (0035)
DATE 9
10
11
12
MAY 1964

Figure 3.11

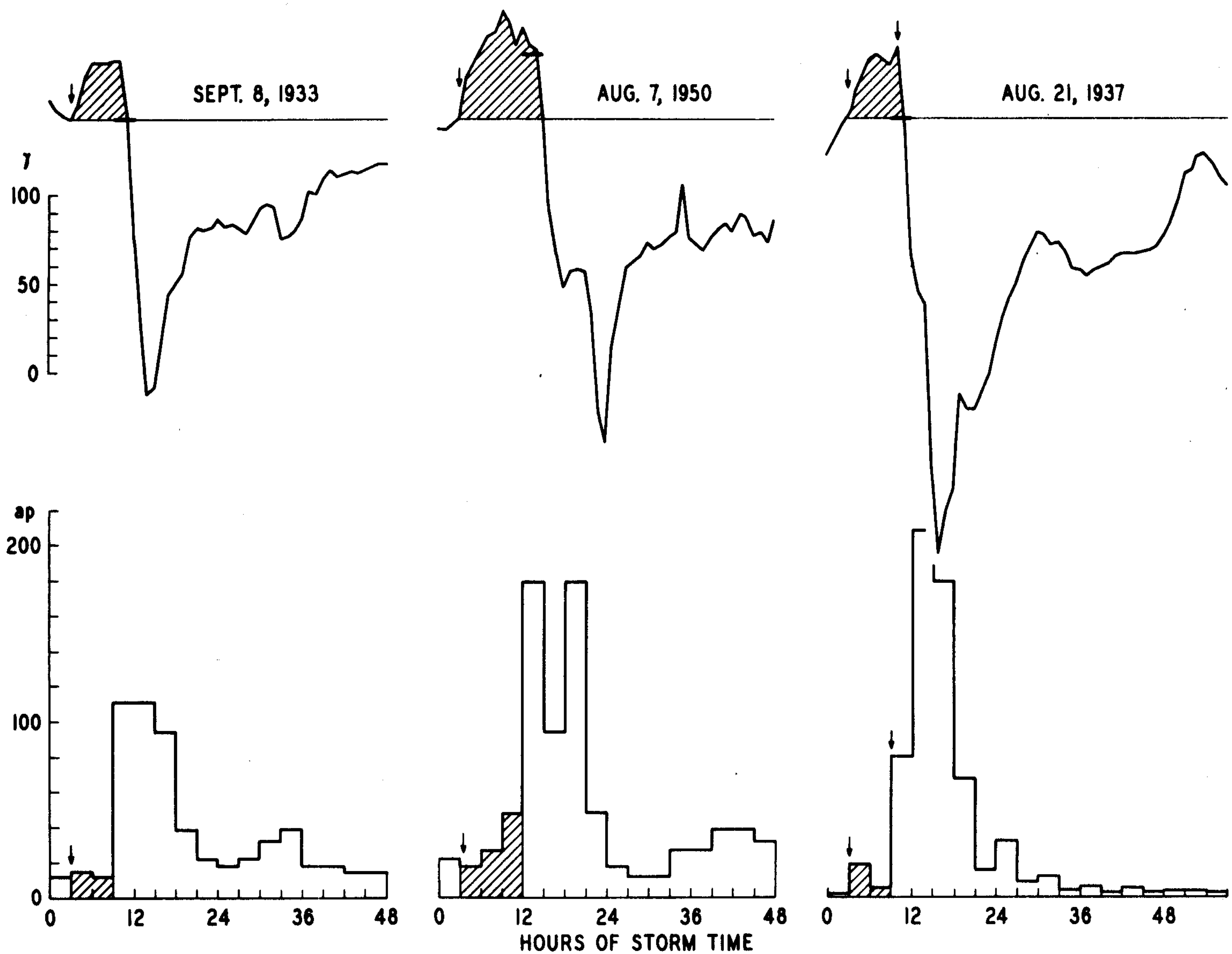

SEPT. 8, 1933
AUG. 7, 1950
AUG. 21, 1937
γ
100
50
0
ap
200
100
0
0
12
24
36
48
HOURS OF STORM TIME

Figure 3.12

G 66-352

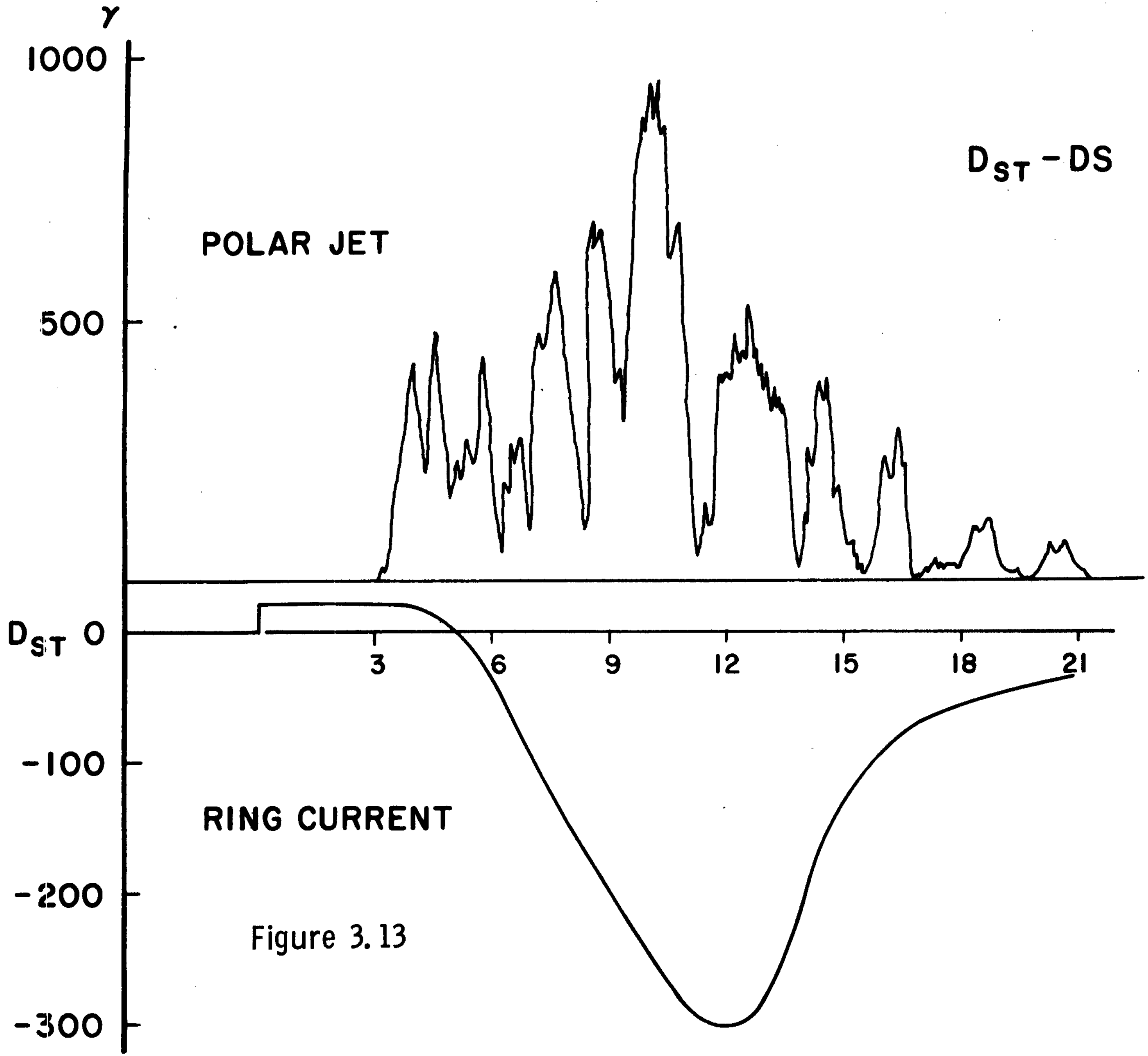


Figure 3.13

G66-359

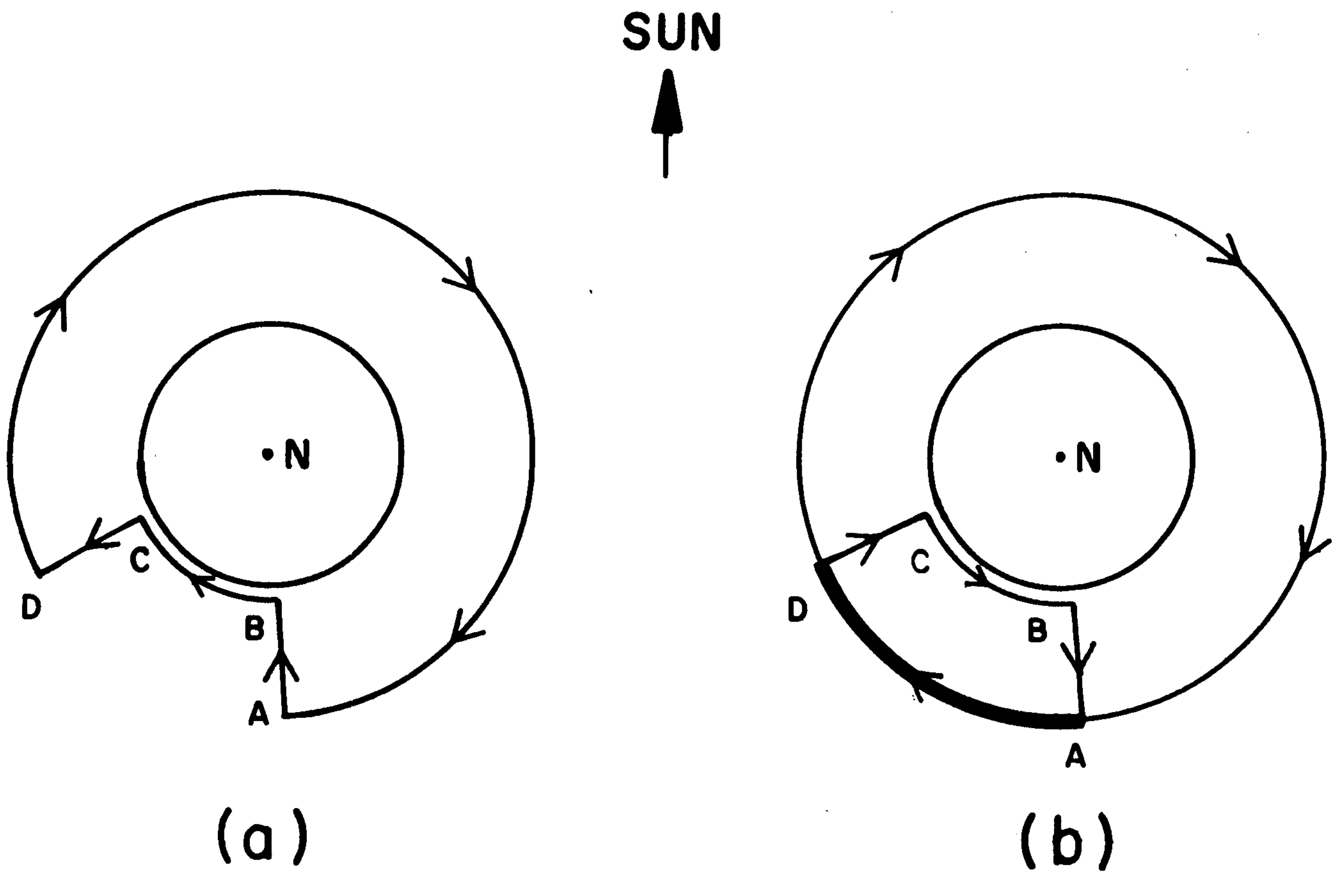
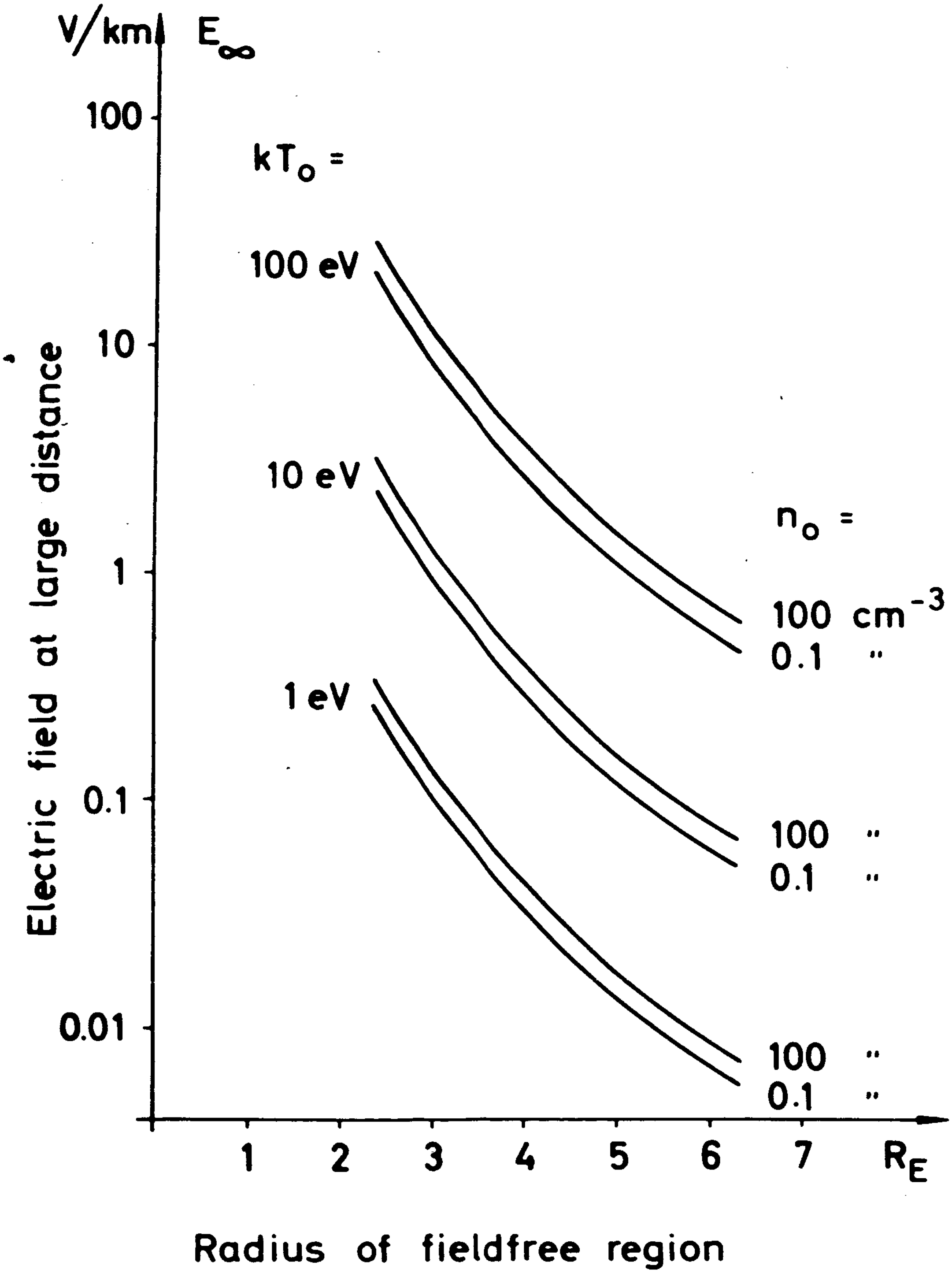


Figure 3.14



V/km
E_∞
100
10
1
0.1
0.01
kT_o =
100 eV
10 eV
1 eV
n_o =
100 cm^{-3}
0.1 "
100 "
0.1 "
100 "
0.1 "
1
2
3
4
5
6
7
R_E
Electric field at large distance
Radius of fieldfree region

Figure 3.15

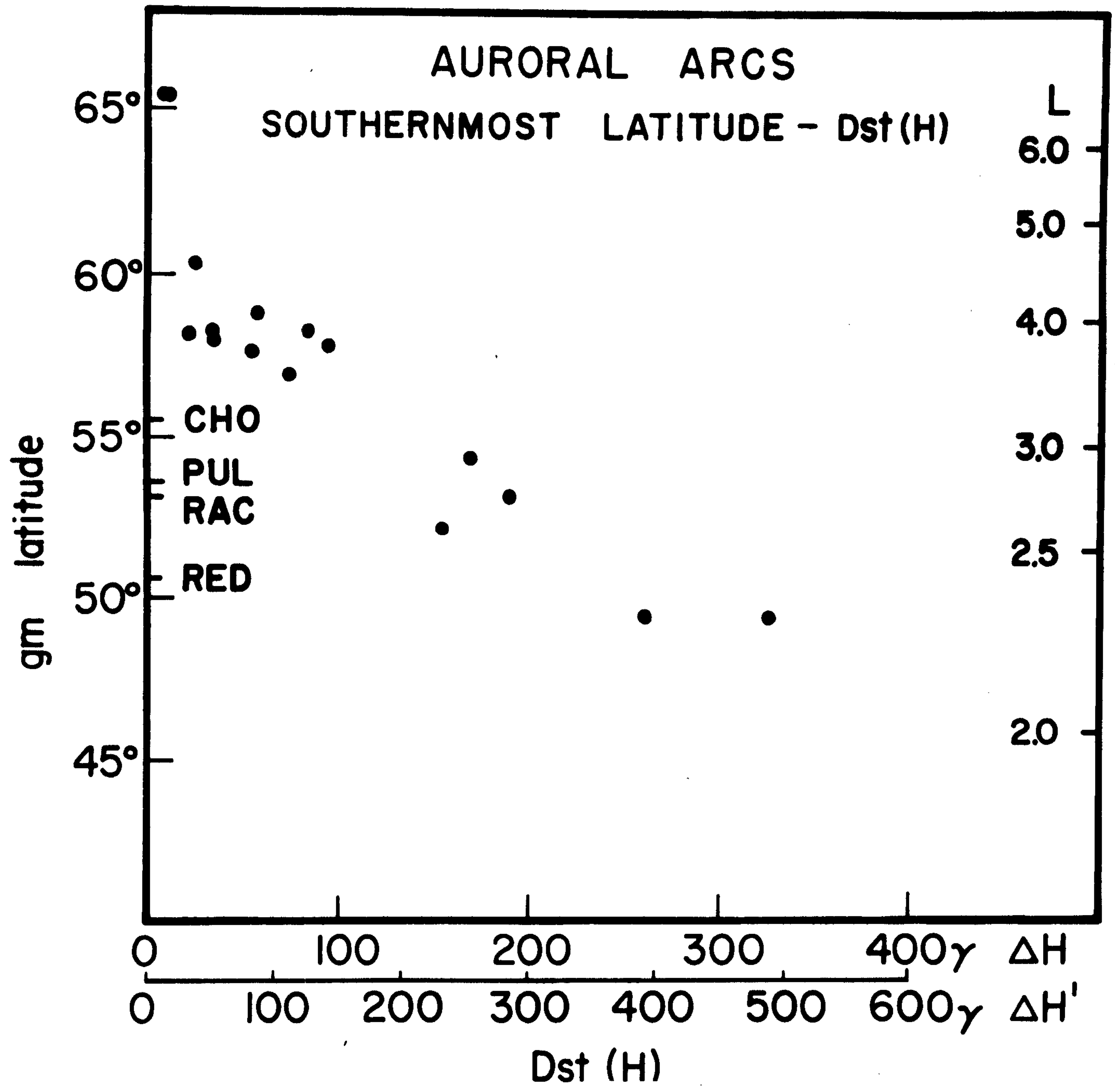

AURORAL ARCS
SOUTHERNMOST LATITUDE - Dst(H)
gm latitude
65°
60°
55°
50°
45°
CHO
PUL
RAC
RED
L
6.0
5.0
4.0
3.0
2.5
2.0
0
100
200
300
400γ ΔH
0
100
200
300
400
500
600γ ΔH'
Dst (H)

Figure 3.16

G 65 — 276

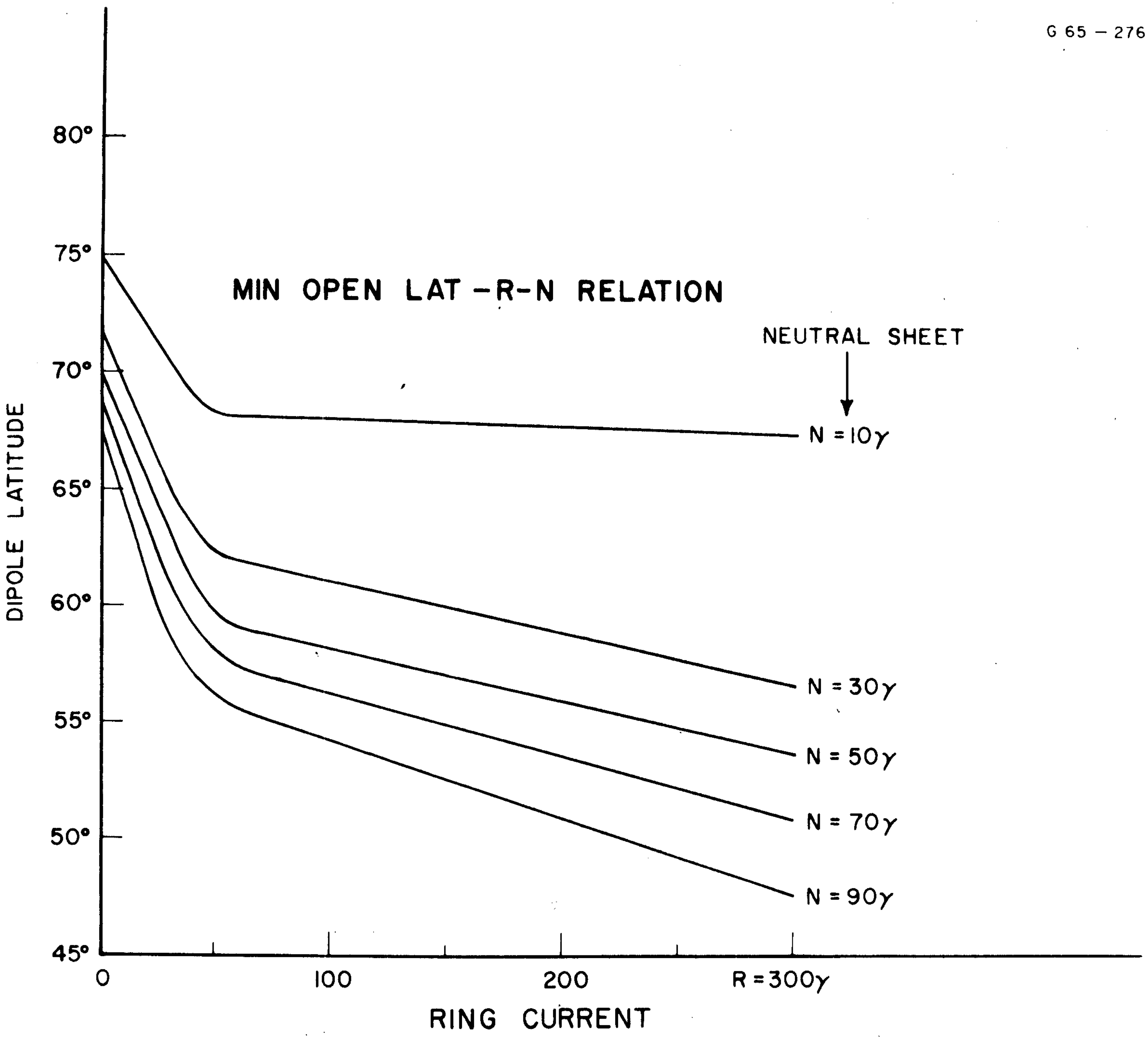


Figure 3.17

4. Auroral and Polar Magnetic Substorms

4.1 Introduction

A close relationship between the auroral displays and polar magnetic substorms has been recognized for many years [Harang, 1946, 1951; Heppner, 1954; Khorosheva, 1961]. It is, however, only recently that large-scale auroral displays over the entire polar region and their detailed individual features have become clear [Akasofu, 1963, 1964]. Such extensive auroral activity as a whole may be regarded as a single event, and is described in terms of the auroral substorm. Since the details of the substorm are described in a summary paper by Akasofu [1965], only a brief description is given here.

The auroral substorm has two characteristic phases: an expansive phase and a recovery phase. During a quiet period (namely, the period between two successive substorms) quiet arcs tend to lie along an oval belt, namely the auroral oval [Feldstein, 1963; Khorosheva, 1962]. This situation is schematically shown in Fig. 4.1 in which the average location of the oval is indicated; the auroral zone is only the locus of the midnight part of the oval where brightest auroras are most frequently seen.

The first indication of the substorm is a sudden brightening of one of the quiet arcs lying in the midnight sector of the oval. In most cases, the brightening of an arc is followed by its rapid poleward motion, resulting in the 'auroral bulge' around the midnight sector. A sharp onset of a negative change in the horizontal component (namely, the so-called 'negative bay') is observed in the region where the brightened arc is located and also in the region swept by its poleward motion, namely in the bulge. In Fig. 4.1b, this region is indicated by the lined shade.

The so-called 'break-up' phenomenon occurs in the bulge, but it is not the whole display. As the auroral substorm progresses, the bulge expands in all directions, so that the region in which the negative bay is observed expands also in all directions. Figure 4.1 shows the successive development of both auroral and polar magnetic substorms.

The activation of aurora associated with the poleward explosive motion spreads rapidly from the midnight sector to the morning sector. The activation is manifested by the development of complicated folds or disintegration of arcs. The disintegration proceeds with a speed of order 10 km/sec and results in 'patches' which drift eastward with a speed of order 300 m/sec. Irregularly folded bands also drift eastward with a similar speed. Therefore, in the morning sky, most of the visible features in all-sky camera films drift eastward with similar velocity vectors. In the region where these eastward motions are seen, a negative bay is observed. The bay has, however, a less sharp onset and is less intense than that in the midnight sector. In general, the patches tend to spread equatorward, so that a negative bay can be observed in an extensive area in both longitude and latitude.

In the evening sector, both auroral and polar magnetic substorms are far more complicated than those in the morning sector. In the evening side of the expanding bulge, there appears a large-scale fold which travels rapidly westward along the pre-existing arcs, namely along the auroral oval. This particular phenomenon is called the westward traveling surge.

When the bulge is expanding, the surge may be considered to be the western leading edge of the bulge. Thus, the fact that the surge travels westward indicates a westward expansion of the region in which a negative bay is observed. At the same time, a positive change in the H component, namely the so-called 'positive bay', is observed to the west of the surge in the equatorial side of the oval. In Fig. 4.1a, the region where a positive bay is observed is indicated by the dotted shade. Therefore, a station located a little to the equatorward side of the path of the surge observes first a positive change in the H component when the surge is seen in the eastern sky, and then a negative change when the surge passes the zenith and goes to the western sky. The speed of the surge is of order 1 km/sec so that the region of the negative bay expands westward with this speed, which is much less than the expansion speed in the morning sector (~ 10 km/sec). This situation is also schematically shown in Fig. 4.2. It shows typical changes in the H component at two stations whose dp lat are 65° and 72°, respectively, at different local times (the first column), indicated in Fig. 4.1a.

A station whose dp lat is about 60° ~ 65°, like College (Alaska) and Kiruna (Sweden), will observe a sharp negative bay when it happens to be located near the midnight meridian (A). When this station is located in the late evening sector (B and C), a positive bay will be observed first when a westward surge appears in the eastern sky, and then a negative bay after the surge advances to the western sky. When the station happens to be located further to the west (in the early evening and afternoon sectors, namely D, E, and F), it will observe, however, only a positive bay. For such locations the surge will be passing too far south to be seen or the sky will be too bright.

Since the surge travels along the pre-existing arcs that lie along the auroral oval, it travels into the region encircled by the auroral zone (or dp lat circle of 67°) in the evening sector, rather than along the auroral zone. It can often reach as far as the afternoon sector of about dp lat 75°. However, since the speed of the surge is only of order 1 km/sec and the typical duration of the expansive phase is of order 30 min or less, the maximum epoch of the auroral substorm (or the expansive phase) in the midnight sector will be over by the time when the surge travels a distance of about 1000 ~ 2000 km along the oval. After this epoch, the surge ceases to be the western leading edge of the bulge and travels as a sort of wave without leading the region of negative bay (Fig. 4.1d). However, such a degenerated surge is still associated with an intense negative bay near its polar boundary and a less intense eastward current in an extensive area to its equatorward side (Fig. 4.2, a 65° station at D, E, and F).

A station whose dp lat is 72° will not observe a sharp negative bay in the midnight sector unless the poleward expansive motion reaches that far. In the evening sector, a surge advances along the oval and thus passes over the station. An intense negative bay will be observed when it is passing directly overhead.

All these complicated geomagnetic disturbances associated with the auroral substorm are regarded as a single event which is called the polar magnetic substorm.

Figure 4.3 shows simultaneous H or X records of a polar magnetic substorm that occurred between 1800 and 2100 UT on December 16, 1957, from a number of stations in the northern polar region. In the midnight sector (Dixon and Tixie Bay) it showed as a negative bay of order 500 γ, most intense at about 1830 UT. In the early morning sector it showed as a less intense negative bay in the auroral zone at Cape Wellen, College, Barrow, and Meanook. In the afternoon sector of the auroral zone, it showed as a positive bay of order 100 γ at Reykjavik, and a combination of a positive bay at Kiruna, indicating that the surge traveled across the Kiruna sky, leading the western boundary of the auroral bulge. At Murchison Bay, there was an intense negative bay of order 300 γ, indicating that the northern boundary of the surge passed there. There was also a delay of almost 30 min in the epoch of its maximum intensity there, as compared with that in the midnight sector.

In the noon sector of the auroral zone (e.g., at Churchill) there was very little systematic variation. However, at Baker Lake the disturbance was strikingly similar to that at Murchison Bay and Tixie Bay. This is an important indication that a part of the westward electrojet which caused the negative bay at Tixie Bay extended that far. This is discussed in more detail in section 4.2. Based on the concept of the auroral and polar magnetic substorms, complicated morphological features of the aurora and major polar magnetic disturbance [cf. Kim and Currie, 1958, 1960; Bhattacharyya, 1960; Meinel and Schulte, 1953; Bullough, Davidson, Keiser and Watkins, 1957; Walker, 1964; Rostoker, 1966] can now be visualized as parts of a single event. Associated phenomena, such as the radio wave absorption, motions of radio auroras, influx of x-rays, will eventually be combined with the concept. For details of the associated events, see Chamberlain [1961], Cole [1963], and Akasofu, Chapman, and Meinel [1966].

In the following the major features of the auroral and polar magnetic substorms are illustrated in detail by using a few examples.

(a) Poleward Motion

Figure 4.4 shows an example of the poleward expansion of the auroral bulge and associated polar magnetic substorm. As mentioned in the above, the poleward expansive motion of the auroral system is seen in the midnight sector and is the most spectacular part of the auroral substorm. At 1130 UT, February 13, 1958, the southernmost band, which had been lying across central Alaska (dp lat 64° N) and the eastern tip of Siberia, began to move poleward. At 1140 UT, ten minutes after the onset of the substorm, the activated southernmost band was rapidly moving poleward, with a speed of order 700 m/sec. The polar magnetic substorm field is expressed in terms of equivalent overhead current. Therefore, the fact that westward currents are seen in the region swept by the activated band is an indication of the onset of a negative bay there. At 1204 UT, 34 minutes after the onset, the expansive motion reached the maximum epoch. The poleward boundary of the bulge reached the Arctic coast of Alaska (dp lat 69° N). This extent of the expansive motion is a typical one for a weak or medium substorm. If the substorm is intense, the northern boundary of the bulge can advance beyond dp lat 75°. [For details of the poleward motion, see Akasofu, Meng, and Kimball, 1966.]

(b) Westward Traveling Surge

In Fig. 4.5, we see a complete sequency of events associated with an intense westward traveling surge which was observed in the evening of October 15, 1958, over Alaska. At 1922, the surge appeared near the eastern horizon at Ft. Yukon and traveled rapidly westward. At 1923, the surge crossed the Alaska-Canada border. At 1926, to the south of the surge (College, Healy, Big Delta, and

Northway), the equivalent overhead current was flowing in the ESE direction, producing a positive change in the H component; however, at Ft. Yukon, where the surge was seen directly overhead at that time, a westward current was detected. Unfortunately, both the Point Barrow all-sky camera and Barter Is. magnetometers were not functioning, but it is reasonable to infer that the surge reached Point Barrow at about 1936. The westward current grew rapidly over Barrow between 1936 and 1944.

The current system over Alaska between 1940 and 1950 suggests a large-scale counter-clockwise current. After 1950, the current over College, Big Delta, and Healy changed to a clockwise direction, and after 2005 the direction was WWS, indicating that these stations observed negative bays. Clearly, the surge was the western leading edge of the expanding bulge. [For details of the westward traveling surge, see Akasofu, Kimball, and Meng, 1965; Akasofu, Meng, and Kimball, 1966.]

(c) Eastward Motion

Figure 4.6 shows an example of the poleward expansion of the auroral bulge in Alaska and the subsequent activation of auroras in Siberia (evening sector) and in Canada (morning sector). At 1130 UT on February 21, 1958, a faint arc lying in central Alaska became suddenly activated and began to move poleward. At that time a faint arc was also seen in Siberia and Canada. At 1206, 36 minutes after the onset, a little before the maximum epoch of the substorm, both Siberian and Canadian auroras were also activated. The surge was propagating along the Siberian Arctic coast, and the disintegration of the arc was in progress over Canada. The disintegration began from the western 'end' of the arc and proceeded rapidly eastward [Akasofu, Kimball, and Meng, 1966]. An intense negative bay was seen over Alaska. At 1212 UT, the surge was beyond the sight of the two Siberian stations. Over the Canadian sky, drifting patches resulting from the disintegration are seen. [For details of the eastward motion, see Akasofu, Meng, and Kimball, 1966.]

(d) Equatorward Shift of the Oval

The schematic diagrams presented in Figs. 4.1 and 4.2 can be taken to be a typical substorm during a medium geomagnetic storm. During geomagnetic storms with an intense main phase, the oval shifts toward the equator, sometimes to dp lat 50°, and the situation will be quite different from the above average condition. Akasofu and Chapman [1963] showed that the equatorward shift is a function of the intensity of the main phase decrease (section 3.7).

Such a great complication can, however, be reduced by taking this changing oval as a natural frame of reference (section 1.2). During a great storm, College (dp lat 64.5° N) becomes temporarily a polar cap station at about dp lat 70° ~ 72°. Thus, westward traveling surges and negative bays can appear abnormally early in the evening, and further around midnight auroras are seen near the southern horizon.

4.2 Polar Magnetic Substorm

In order to study the polar magnetic substorm, two completely independent approaches have been made in the past. The first approach has been to obtain simultaneous geomagnetic disturbance vectors at a number of stations and to infer a current system which could give rise to such a magnetic disturbance. In general, the current is assumed to be located on a spherical shell (the ionosphere). The result thus obtained does not necessarily mean, however, that such a current system exists, and it is simply a means of expressing geomagnetic disturbances. For this reason, it is called the equivalent current system and should not be confused with the actual current system. Further, although the concept of the equivalent current system implies that the current is confined in a spherical shell, it does not exclude the possibility that a part of the actual current flows along the field lines.

(a) The SD Analysis

Chapman [1919, 1935], based on Moos' method, established the so-called SD current system. His analysis is equivalent to a Fourier analysis of the D field

$$S = c_o + \sum_n c_n \sin(n\lambda + \epsilon_n) \qquad (1)$$

where λ denotes dp longitude and ϵ_n the phase angle. The first term indicates the Dst component and the second term, the DS component. Chapman obtained first the SD variaction which is an average of the DS variation over each of the first two storm days. The current system associated with the SD variation is shown in Fig. 4.7.

Later, Vestine [1940], Silsbee and Vestine [1942], Fukushima [1953] have obtained the equivalent current systems or the distribution of the disturbance vectors and confirmed Chapman's result. As we shall see later, this analysis has placed a great emphasis on the geomagnetic latitude circle of 67°, namely the auroral zone, which is now found to have only a statistical meaning. Therefore, it has failed to reveal the eccentric nature of geomagnetic phenomena in the polar region, namely that the major geophysical phenomena occur along the auroral oval and not along the auroral zone. This failure is not, of course, due to incorrectness of the analysis, but is due partly to the fact that the oval system is difficult to be revealed by the analysis based on the dipole coordinate, particularly when a close network of observations over the polar cap is not available.

In the SD or DS analysis, high harmonic terms in (1) have been called Di where the suffix _i_ signifies 'irregular' component [Chapman, 1951].

Thus, (1) may be rewritten as

$$D \simeq Dst + DS_1 + DS_2 + Di$$

where DS_1 denotes the diurnal component of DS and DS_2 the semi-diurnal component. In general $DS_1 >> DS_2$. Now, let us compare $(Dst + DS_1)$ with actual magnetic records in Fig. 4.8. According to Sugiura and Chapman [1960], D is given by

$$D(H) \simeq -60 + 150 \sin(\lambda + 206°)$$

along the auroral zone for a great storm in units of γ. Comparing the actual trace (H) and D(H) at the top, it is immediately clear that although DS_1 indicates the correct signs of changes, the actual trace consists of short-lived impulses whose magnitude is far greater than the amplitude of $DS_1(H)$. Therefore, it may be concluded that Di is not a small and irregular fluctuation superposed on DS, but Di itself is the essential feature of geomagnetic disturbances in the auroral zone and is called the polar magnetic substorm, namely

$$D \simeq \Sigma\ Di \simeq \Sigma \quad \text{(the polar magnetic substorm)}.$$

Here we must realize an important change in our concept of polar magnetic disturbances. The SD analysis implies that the SD current system is fixed with respect to the sun, and the earth rotates under this fixed current system. The SD current intensity is supposed to remain constant for 24 hours. Thus, when it is observed at an auroral zone station, the intensity of the overhead eastward current gradually diminishes as the night progresses and vanishes at about midnight. After midnight, the station advances toward the region of the increasing intensity of the westward current (see Fig. 4.7). On the other hand, our view is that a current system which has some resemblance to the SD system appears intermittently with the lifetime of order 1 ~ 3 hours, almost in an impulsive way or as successive bursts, and the earth rotates under such a situation. The absolute magnitude of the current is much stronger than what we expect from the amplitude of DS.

(b) Spiral Analysis

The other approach is mainly concerned with the range of geomagnetic disturbances (generally, the H component), rather than the disturbance vectors, and also with their daily or seasonal characteristics. This approach was initiated by Stagg [1926, 1935a,b,c] and later extended by Nikolsky [1947], Mayaud [1956], Burdo [1957], and others; see also a review paper by Hope [1961].

Typically, the range of geomagnetic disturbances in high latitudes ($\geq$ dp lat 60°) shows three peaks during the course of a day (Fig. 4.9). For example, at Wrangel Island (dp lat 64.7° N), the first peak appears in the afternoon sector (~ 17 local time), the second in the midnight (00 LT) sector, and the third peak in the morning sector (07 LT); Wrangel Island local time = UT - 12. For this reason, the three peaks are called the A, N, and M peaks.

Nikolsky [1947] found that as one goes from dp lat 60° to the pole, the M peak tends to occur later in the morning sector. Therefore, when the times of the M peak are plotted on a polar map, they tend to line up along a spiral curve, the so-called 'M spiral'. In this paper, we call this type of analysis the spiral analysis. Mayaud [1956] and Burdo [1957] elucidated further the analysis and confirmed three spirals, the A, N, and M spirals.

Later, a number of geophysical phenomena, such as the Hα (or Hβ) emission, the polar blackout, auroral radar echoes, and the sporadic E layer are found to have a tendency to appear along such spirals [Thomas, 1960; Thomas and Piggott, 1960; Montalbetti and McEwen, 1962]. Fig. 4.10 shows the spirals summarized by Nagata [1963].

There have been a number of studies on characteristics of each spiral curve, in particular, the relationship between the M and N spirals. After a detailed review of the early works, Hope [1961] made a strong argument against the conjecture that the N spiral is an extension of the M spiral. Some of the reasons are as follows: (i) The activity of the M and N spirals are poorly correlated. (ii) The N spiral is most active in winter, while the M spiral is most active in summer and equinoctial months.

Based on the present knowledge of the polar geophysical phenomena and the internal structure of the magnetosphere, the (M+N) spiral is essentially the auroral oval. In other words, both M and N spirals are segments of the auroral oval. As we have seen earlier, the westward traveling surge generated in the midnight sector travels westward along the pre-existing arc, and the surge is accompanied by an intense negative bay near the poleward edge. This indicates that the surge travels along the auroral oval (namely the N spiral) and that the westward current flows along the N spiral from the midnight sector during the substorm.

The spiral analysis has been very useful in studying complicated features of geomagnetic disturbances in the polar cap, and has indeed revealed the segments of the auroral oval.

Unfortunately, however, the analysis had relied mainly on the range, and the results have been interpreted in terms of the precipitation pattern of energetic particles, namely the so-called 'Stormer spiral'. Since most visible auroras are known to be caused by electrons of energies of a few kilovolts or less, such an interpretation is a most unlikely one. Now, with the invaluable visible aid of the aurora, there is little doubt that the N spiral is an extension of the M spiral [Akasofu, Chapman, and Meng, 1965; Feldstein, 1966]. Figure 4.11 shows schematically the early concept of the current system and the one proposed by Akasofu, Chapman, and Meng [1965] and Fig. 4.12 a little more detail of the new current system at the maximum epoch of the substorm. Feldstein [1966] has recently reached a similar conclusion (Fig. 4.13). It must be noted, however, that as we can infer from the discussion in section 4.1 the polar jet given in Fig. 4.12 does not appear instantly.

Both the SD analysis and the spiral analysis indicate another type of magnetic disturbance in the afternoon and evening sectors. The SD analysis has suggested that a jet current flows eastward along the auroral zone, namely the so-called eastward electrojet. The A spiral is also an indication of disturbance which is greatly controlled by the season. Akasofu, Chapman, and Meng [1965] have shown that the eastward current is not a part of a pair of jets and that it is likely to be the return current from the westward jet flowing along the oval. The following are the reasons for such an inference; some of the statements are taken from the earlier sections, but it is worthwhile to repeat them for the matter of clarity.

4.3 An Eastward Electrojet

1. Recent studies of the aurora have revealed an important fact that auroras tend to lie in a narrow oval belt encircling the geomagnetic pole (but not along the auroral zone) and that the auroral zone is simply the locus of the midnight part of the oval where intense auroral displays are most frequently seen.

2. Therefore, an auroral zone station (dipole latitude 67°) has no uniqueness in the afternoon and evening hours, since the oval is located well poleward side of the station (or the station is well outside the oval).

This can be recognized by the following facts: At 18 local time at an auroral zone station the sky is dark enough to see overhead auroras in midwinter, but auroras are rarely seen there; in the dusk hours (16 ~ 20 hours), intense auroral activity is seen well poleward side of the station, namely at about dp lat 72°.

As the night progresses, however, auroras appear near the poleward horizon and draw gradually closer to the station, indicating that the station is approaching the oval, since the earth rotates under the eccentric oval (section 1.2). This is a daily event at stations below dp lat 72°; there is no indication that auroras appear in the auroral zone and spread polewards or equatorwards in the dusk hours.

3. The eccentricity of the oval is closely related to the day-night asymmetry of the interval structure of the magnetosphere. The outer radiation belt has a marked asymmetry, and the intersection line between its outer boundary and the ionosphere coincides approximately with the auroral oval [Piddington, 1965; Akasofu, Chapman, and Meng, 1965; Feldstein, 1966]. The concept of the auroral oval has thus a basic foundation, and the oval can be considered to be the natural frame of reference to which major polar geophysical phenomena can be referred. On the other hand, the auroral zone has only a statistical meaning. This latter statement can be easily understood by recalling how the auroral zone is obtained.

4. It is thus difficult to imagine that major geophysical phenomena, such as an eastward electrojet, can occur along the zone which has only a statistical meaning.

5. Westward traveling surges generated in the midnight sector travel along pre-existing auroral arcs, namely along the auroral oval, but not along the zone.

It is at this time when positive bays are observed below dp lat 70° in the same sector; they have been attributed to an eastward electrojet flowing along the auroral zone. Therefore, positive bays, which are seen at an auroral zone station in the dusk hours, are not associated with any overhead auroral activity [Akasofu, Meng, and Kimball, 1966]. This may be contrasted with negative bays in the midnight sector or early morning sector, which are associated with an explosive poleward motion of bright bands or eastward patches.

6. The westward electrojet flows along the oval in the evening sector [Akasofu, Chapman, and Meng, 1965]. It is well known that an auroral zone station is relatively magnetically calm in the noon sector. However, intense negative bays are quite common at about dp lat 75° in the same sector. These negative bays have a striking resemblance with negative bays seen simultaneously in the midnight part of the oval, suggesting that the westward jet does extend along the oval to the noon sector. The SD current system (in which the westward jet current is supposed to be terminated in the late evening hours) must be re-examined based on these new findings.

7. It has been well established that the westward electrojet causes an extensive eastward return current in middle and low latitudes, producing a positive change. Similarly, it has heretofore been believed that an eastward electrojet (causing a positive bay in the auroral zone in the afternoon and evening hours) causes a westward return current and thus a negative change in middle and

low latitudes. Thus, their combined effect (DS) has heretofore been attributed to the asymmetric part of the main phase decrease. However, it has been shown by Akasofu and Chapman [1964] that the asymmetry can be greatly reduced during the period of the enhanced jet current, since intense positive bays are seen in the region where the main phase decrease is largest. This is a direct contradiction to the present concept of the cause of the asymmetry of the main phase decrease and also to the concept of a pair of jets. For details, see section 3.2. In fact, this asymmetric growth is now confirmed by a recent satellite observation [Cahill, 1966].

8. It is well known that as magnetic activity increases, the (local) time of the first appearance of negative bays advances from midnight toward earlier hours. During intense magnetic storms, it is common to see negative bays at as early as 19 ~ 20 local time at an auroral zone station like College. At this time, positive bays are most common during a medium disturbance. The result is a decrease of the period of the appearance of positive bays. Figure 4.8 shows a collection of College magnetic records for different storm intensities. The top one is the most common daily variation and the bottom one during an intense geomagnetic storm. As the storm intensity increases, the time of the first appearance

of negative bay advances toward dusk hours from midnight and also toward late morning hours from the early morning hour. During most intense storms, positive bays sometimes disappear almost completely from all along the auroral zone, though intense negative bays of magnitude as large as 2000 γ may be seen [Akasofu and Chapman, 1964]. This suggests also a fundamental difference of the nature between positive and negative bays.

This drastic change can well be understood in terms of the equatorward shift (section 3.7)and intermittent bulging (in the midnight sector) of the oval. The equatorward shift of the oval places the oval at the auroral zone latitude in the dusk hours, resulting in an abnormally early appearance of auroras, westward traveling surges, and thus negative bays. On the other hand, the appearance of negative bays in the midnight sector is due to an intense bulging.

9. It is also well known that the development of positive bays is different from that of negative bays. The onset of negative bays is, in general, much more sharply defined than that of positive bays. Negative bays are, in general, more intense than positive bays. Further, activity of positive bays is known to depend on the daylight.

10. Thus the nature of positive bays (an eastward current) is fundamentally different from that of negative bays (the westward jet), and the difference is not a matter of the direction of the current. Furthermore, there are a number of reasons to believe that the eastward current is a return (or leakage) current from the westward electrojet flowing along the auroral oval, although the existence of an eastward current may not be completely denied.

4.4 Aurora and Polar Electrojet at Geomagnetically Conjugate Points

It has been realized that polar magnetic substorms at geomagnetically conjugate points show a striking similarity [Nagata and Kokubun, 1960; Wescott, 1962; Bryunelli, 1962; Ondoh and Maeda, 1962/3; Boyd, 1963; Bobrov, 1963; Yudovich, 1963; Wescott and Mather, 1965 a,b,c,d]. This suggests that the polar electrojets at the geomagnetically conjugate points are driven by the common electric field, suggesting that the auroral field lines are, as a first approximation, equipotential. Figure 4.14 shows some examples of the H component magnetic records from Kotzebue (dp lat 63.7° N) and Macquarie Island (dp lat 61.1° S) [Wescott and Mather, 1965a]. Although details are somewhat different, the major changes are very similar. Wescott and Mather [1965a] showed, however, that positive bays are less well correlated than negative bays; positive bays are seen more in summer months than in winter. This evidence may be added to the discussion in the previous section to indicate that positive bays are fundamentally different than negative bays.

DeWitt [1962] has shown that the auroras seen from Farewell (dp lat 61.4° N) and Campbell Island (dp lat 57.3° S), conjugate pairs, have similar forms and motions. Further, the conjugate auroras undergo similar variations in brightness and the break-up, simultaneously. Other geophysical phenomena at conjugate points have recently been extensively studied [Hook, 1962; Leinbach and Basler, 1963; Brown, Anderson, Anger, and Evans, 1962; Brown et al., 1965; Yanagihara, 1963; Wright and Lokken, 1965].

Such a good correlation becomes increasingly poorer when one examines higher latitude conjugate pairs inside the auroral oval. Figure 4.15 shows some examples from the Shephard Bay-Scott Bay conjugate pair; both negative bays and the daytime agitation (section 4.11(b)) are not correlated.

4.5 Nature of the Polar Electrojet

(a) The Hall Current

The exact nature of the polar electrojet is not yet understood. Here, we review briefly an interesting work by Boström [1964]. He assumes that the polar electrojet flows in the auroral arc which is assumed to be a thin slab of thickness 10 km. In the slab, the electron density n_e varies with height, with a peak at about 120 km level, where $n_e = 10^6/cm^3$. This slab is embedded in a horizontally uniform ionosphere with $n_e \simeq 2 \times 10^3/cm^3$ at about 120 km. The conductivity of the slab and the surrounding ionosphere as a function of height is then computed, based on a certain model atmosphere. The height integrated Pedersen (Σ_1) and Hall (Σ_2) conductivities are

$$\Sigma_1 = 0.56 \text{ mho} = 5.6 \times 10^{-10} \text{ emu}$$

$$\Sigma_2 = 0.19 \text{ mho} = 1.9 \times 10^{-10} \text{ emu}$$

for the surrounding ionosphere and

$$\Sigma_1 = 36 \text{ mho} = 3.6 \times 10^{-8} \text{ emu}$$

$$\Sigma_2 = 56 \text{ mho} = 5.6 \times 10^{-8} \text{ emu}$$

in the arc. This indicates that according to his model the Pedersen conductivity Σ_1 is quite important and comparable to the Hall current [see also Kim and Kim, 1963].

Boström [1964] examined two different conditions by using the above equations. In the first case, any charge accumulation near the boundary of the thin arc cannot leak away beyond the upper part of the ionosphere, so that the height integrated current density has zero divergence. He showed that in this situation an appreciable current can be obtained only when an electric field is applied parallel to the arc. The Hall current (which flows perpendicular to the arc) tends to polarize the arc and the resulting electric field gives rise to an additional current along the direction of the arc. Thus, within the arc, the apparent conductivity along the arc tends toward the Cowling conductivity.

The current thus produced in the arc flows from one end of the arc to the magnetosphere along the field line and flows into the ionosphere from the magnetosphere from the other end (Fig. 4.16a).

In the second case, any charge accumulated at the boundary of the arc is assumed to be able to escape into the magnetosphere along the field lines. Therefore, the field lines are equipotential, and the magnetospheric plasma moves with a speed $\underline{v} = \underline{E} \times \underline{B}/B^2$. Since this motion can be identified with that of the aurora (see below), E should be of order 0.05 volt/cm for a reasonable value of $v \simeq 1000$ m/sec [Nichols, 1959; Akasofu, 1960; Cole, 1963] and drives a westward current of order 3 amp/m or 3×10^4 amperes in the arc; this current is the Hall current.

Another way of understanding this process is to examine interactions between the magnetospheric plasma (which is moving with $\underline{v} = \underline{E} \times \underline{B}/B^2$) and the neutral gas underneath. This (E x B) drift can occur only when the plasma particles are essentially gyro-free, namely they can execute many gyrations between collisions with neutral particles. This gyro-free situation holds even in the F2 region of the ionosphere, so that the upper ionspheric plasma can participate in the (E x B) drift motion of the magnetospheric plasma. However, this motion meets a resistance in the E region. There, positive ions are no longer gyro-free and cannot participate in the motion, since collisions between the positive ions and neutral particles are frequent enough to disrupt their complete gyration. On the other hand, the electrons in the E region are still essentially gyro-free, because of their high gyro-frequency (~ 1 Mc/sec). As a result, only electrons participate in the (E x B) drift along the arc. This is the Hall current. Boström showed, however, that the Pedersen current flows across the arc and then forms sheet currents, because the charges do not accumulate at the arc surface (Fig. 4.16b).

Zmuda, Martin, and Heuring [1966] did not observe magnetic disturbances by a satellite at about 1000 km level in the midnight sector when ground magnetic records below the satellite recorded intense disturbances. One possibility is that the Pedersen conductivity is not as large as what Boström computed. It is quite important to know whether or not the current is divergence free in a rather spherical shell (the ionosphere), or whether or not a substantial current flows along the field lines. Further extensive satellite studies are needed for a better understanding of this problem. This is also an important problem to be solved for the solar quiet day daily variation (sq) [cf. Dougherty, 1963; Wescott, DeWitt, and Akasofu, 1963].

Boström's assumption may be a good assumption during a very early stage of the explosive phase. However, when the arc is sufficiently activated, folds of various scales appear on the surface of the arc, so that it can be hardly a uniform slab. Further, rayed arcs have a thickness of order one kilometer or even less [Akasofu, 1961]. Therefore, it is not certain whether or not an extremely concentrated current can flow in such a thin and non-uniform slab. Indeed, a large negative bay is observed within the auroral 'bulge' where we can hardly expect any simple arc structure; the bulge is covered by patches or very irregular bands. The (E x B) drift motion of the electrons in the E region (Boström's surrounding region) may have a greater contribution to the integrated current intensity than that in the slab.

(a) The Return Current

When an intense electrojet grows along the oval, a positive change of the H component is observed over an extensive area of the dark side in the middle and low latitudes (Fig. 4.17); if the jet is very intense, the positive change is observed almost over the entire middle-low latitude belt. This positive change, the so-called 'positive bay', has been interpreted as an indication of the return current from the jet current. This is quite likely to occur, because the jet is strong only in a limited region and thus it will produce space charges, a positive charge at the western end and a negative one at the eastern end, resulting in an electric dipole-type polarization field over the entire ionosphere [Fukushima, 1953].

A great fluctuation of the equatorial electrojet during the substorm [Akasofu and Chapman, 1963] is an important indication of the existence of such an electric field, since the driving power of the equatorial electrojet is the ionospheric polarization field. The upper ionosphere in middle latitudes is known to move upward during the substorm [Becker, 1960, 1962], and this is likely to be due to the upward component of the (E x B) drift of the electrons in the F2 region. Therefore, there is little doubt that a large-scale polarization appears over the entire ionosphere during the substorm, resulting in an eastward current in middle and low latitudes and thus a positive bay (see Fig. 4.11(b).

The following table gives the ratio of the magnitude of positive bays observed at Honolulu (dp lat 21° N) to that of corresponding negative bays observed at College (dp lat 64.5° N) for 22 well-defined bays; both stations are located approximately in the same sector.

Ratio Ho/Co	No. of Cases
0.010 ~ 0.015	0
0.016 ~ 0.020	2
0.021 ~ 0.025	2
0.026 ~ 0.030	5
0.031 ~ 0.035	8
0.036 ~ 0.040	4
0.041 ~ 0.045	1
0.046 ~ 0.050	0

The table indicates that a negative bay of 100 γ at College is most commonly associated with a positive bay of 3.5 γ at Honolulu.

4.6 Review of Substorm Theories

The auroral and polar magnetic substorm theories proposed so far can be classified into the following nine groups. In this section, the first seven groups are critically discussed under the title 'the early conjectures'. Then, we review briefly the presently available important evidences and extract the proposed fundamental features. This process leads us to explain the substorm in terms of a plasma instability.

(a) Early Conjectures

(1) Discharge from an extra-terrestrial source by Birkeland [1908, 1913], Alfvén [1950, 1955], Karlson [1962, 1963], Block [1966].

(2) Diamagnetism
by Maris and Hulburt [1929]

(3) Polarization of the radiation belts
by Martyn [1951], Shaw [1959], Chamberlain [1961], Kern [1962], Kern and Vestine [1961], Fejer [1961, 1963, 1964].

(4) Dynamo action

by Fukushima and Oguti [1953], Obayashi and Jacobs [1957], Cole [1960, 1962], Swift [1963].

(5) Convection

by Piddington [1962 a,b, 1963, 1966] Axford and Hines [1961], Hines [1964].

(6) Neutral point discharge

by Dungey [1961, 1963].

(7) Neutral line discharge

Akasofu and Chapman [1961].

(b) Plasma Instabilities

(8) Neutral sheet instability

Petschek [1964], Piddington [1966], Akasofu [1966].

(9) Interchange instability

Swift [1966].

(1) Discharge from an Extra-terrestrial Source

Birkeland's study [1908, 1913] was based on an extensive analysis of magnetic records collected during the First International Polar Year. He correctly revealed the essential feature of the polar geomagnetic disturbances, recognizing that they consist of a successive appearance of impulsive disturbances, namely what he called the polar elementary storms. They are called here the polar magnetic substorms.

He proposed that the polar magnetic substorms are caused by a beam of electrons from the sun which flow along the auroral zone and escapes into interplanetary space. The interaction between the electrons and the upper atmosphere was thought to cause the aurora. He demonstrated his idea by using the first model experiment, terrella.

Alfvén proposed that any space charge at the boundary of his forbidden region (section 1.2) will be immediately discharged along the field lines toward the auroral zone. The discharge causes a current flow from the dayside boundary of the forbidden region to the nightside boundary along the field lines, and then along the dawn and dusk sides of the auroral zone and again along the field lines. He associated these currents to be the polar jets. As mentioned in section 1.2, contrary to Alfvén's assumption, there occurs a considerable change of the earth's magnetic field due to the plasma flow (namely, the compression). However, this theory seems to have an important application in understanding the formation of the ring current belt (see section 3.6).

(2) Diamagnetism

Maris and Hulbert [1929] proposed that a high concentration of a plasma sheet, with its bottom cross-section A in the auroral latitude, causes a diamagnetic distortion of the earth's field and that such a distortion would have essentially the same characteristics of the polar magnetic substorms (Fig. 4.18). Since each plasma particle has the magnetic moment $\mu = (w_{\perp}/B)$, the magnetic moment of the plasma sheet is given by $A\, n\mu = A\, n\, \kappa\, T/B$ [see Alfvén, 1950, p. 59], and thus the pole magnetic strength $A\, n\, \kappa\, T/4\pi B$.

The theory suggests that the H component disturbance field should change the sign just under the east-west center line of the bottom of the plasma sheet, a negative charge to the poleward side of the line and a positive charge to the equatorward side. However, observations indicate that a negative bay is observed in the whole region of the auroral bulge.

(3) Polarization of the Radiation Belts

A possible polarization of the radiation belts and its consequences have been studied by a number of workers. Martyn [1951] proposed that a radial electric polarization field associated with the ring current (proposed by Chapman and Ferraro [1933]) will repel some of the charged particles toward the auroral zone; this will transmit the polarization field into the auroral ionosphere and will generate the auroral electrojet. He suggested that the potential difference between the inner and outer edges of the proposed ring current will be of order 10^5 volts, and thus taking into account geometrical convergence of the two field lines from the two edges, a poleward electric field of more than 10^{-3} volts/cm can be introduced into the polar ionosphere. Martyn assumed that positive ions will drift faster than negative ions (the Hall current), so that a westward current flows in the dawn sector and an eastward current in the dusk sector. We know, however, that in the E region of the ionosphere the Hall current is mainly carried by electrons so that his current system must be reversed.

After the discovery of the outer radiation belts, its possible axial asymmetry and the resulting polarization electric field have been extensively studied. Both Chamberlain [1961] and Kern [1962] proposed that a longitudinal gradient of the magnetic field (∇B) will be produced by an inhomogeneous plasma distribution and also by compression of the magnetosphere and that ∇B is directed towards the midnight meridian on both the evening side and morning side. The direction of the drift motion associated with ∇B is opposite for opposite charges, resulting in thin layers of space charges and thus an outward polarization field in the evening sector and inward field in the morning sector. The electric fields thus produced will be transmitted to the polar ionosphere, causing an eastward current in the evening sector and a westward current in the morning sector. Chamberlain [1961] proposed further that each thin layer of the space charges (positive or negative) could accelerate charged particles of the same sign, predicting a separation of auroras produced by electrons and protons. This idea was criticized by Cole [1962]. It is well known that auroras caused mainly by electrons are well separated from a diffuse luminous band caused by the proton bombardment, but also that this separation has little to do with geomagnetic disturbances [Montalbetti and Jones, 1957; Romick and Elvey, 1958; Galperin, 1959, 1963; Rees, Belon, and Romick, 1961; Stoffregen and Derblom, 1962; Yevlashin, 1961, 1963]. Therefore, it is quite doubtful if the above separation carries an electric field into the auroral ionosphere.

The polarization of a radiation belt and its consequences was most extensively studied by Fejer [1964]. His basic assumption is that the energetic proton belt, a positive space charge, is embedded in the low energy magnetospheric plasma. Ignoring the inertia ($m d\underline{v}/dt$), a charged particle in the magnetosphere drift with the velocity $\underline{v}_G$

$$\underline{v}_G = \left(\underline{E} - \frac{\mu \nabla}{e} \underline{B}\right) \times \underline{B}/B^2 .$$

For the low energy plasma, the above equation is simplified, since the ∇B drift will be negligible compared with the daily rotation with the earth, namely

$$\underline{v}_G = \underline{E} \times \underline{B}/B^2$$

where $\underline{E}$ is given [cf. Hines, 1964] by

$$\underline{E} = \underline{\Omega} \times \underline{r} \times \underline{B}$$

where $\underline{\Omega}$ denotes the rotational velocity, $\underline{r}$ the radius vector measured from the axis of rotation.

On the other hand, for a very energetic particle, the rotation of the earth has a negligible effect and drifts with velocity

$$\underline{v}_G \simeq -\frac{\mu}{e} \frac{\nabla \underline{B} \times B}{B^2} .$$

Therefore, in a non-axial symmetric field (such as the magnetosphere compressed by the solar wind), the paths of the energetic protons and the low ene gy plasma are different, giving rise to a tendency of a large space charge. Charge neutrality can, however, be nearly restored by currents along the geomagnetic field lines and also currents in the ionosphere.

Suppose a tube of magnetic force carves out an area of 1 cm^2 from the ionosphere which is assumed to be a spherical shell. Any electrostatic field E causes a motion of tube of force, together with the low energy plasma filling it. The foot of the tube of force moves with velocity v_D with respect to the earth's rotation. Thus, if Q denotes half the space charge of the low energy plasma, the current density associated with the motion of the foot is given by $Q\underline{v}_D$. Space charge (-Q) of the energetic particles seen from an observer on the earth, will produce a current $(-Q)(-\underline{v}_R) = Q\underline{v}_R$, where $\underline{v}_R$ denotes the velocity of the rotation of the earth.

Recalling that the equations for the dynamo theory by the tidal wind system s given by Chapman and Bartels [1940] is equivalent to

$$\nabla \cdot \underline{J} = \nabla \cdot [-(\int \sigma \ dz) \ \nabla \varphi + \int \sigma \cdot (\underline{v} \times \underline{B}) \ dz] = 0,$$

our new situation is simply expressed by

$$\nabla \cdot (\underline{J} + Q \ \underline{v}_R + Q \ \underline{v}_D) = 0$$

where φ denotes the electrostatic potential. The above differential equation may be rewritten as a differential equation of φ, from which $E = - \nabla\varphi$ and thus J can be obtained. Fig. 4.19 shows an example of his calculation; the integrated Hall conductivity along the auroral zone is taken to be 45 mho (= $45. \times 10^{-8}$ emu), which is about twice the midday conductivity at medium latitudes. According to his calculation, the magnetic field produced by the above mechanism is of order 80 γ. If there is a great enhancement of the proton belt and of conductivity along the auroral zone during geomagnetic storms it would be somewhat enhanced. Nevertheless, this mechanism is unlikely to be the explanation of the polar magnetic substorm, since the magnitude of the polar magnetic substorm can be as large as 1000 γ or more. In addition to such a difficulty, contrary to the prediction of the theory, an increased axial asymmetry (produced by an intense impact of the shock wave on the magnetosphere which is seen as storm sudden commencements or sudden impulses) does not necessarily initiate the polar substorms. This could be due to some defect in his original assumption of the space charge.

(4) Dynamo Action

The success of the dynamo theory for the solar quiet day daily variation has led some people to speculate that the dynamo action ($\underline{v} \times \underline{B}$) in the ionosphere is also responsible for auroral electrojets.

The dynamo theory of polar magnetic storms assumes a highly conductive belt (one in each hemisphere) along the auroral zone, so that an extra current system is induced by the dynamo action, in addition to the Sq current system.

Fukushima and Oguchi [1953] and Obayashi and Jacobs [1957] made illustrative calculations for the ionosphere with anisotropic conductivity. The differential equation for the current intensity J is the same as that for the dynamo theory of Sq

$$\frac{\partial}{\partial\lambda}\left(\frac{\partial J}{\sin\theta\partial\lambda}\right) + \frac{\partial}{\partial\theta}\left(\sin\frac{\theta\partial}{\partial\theta}\right) = 2G\,\Sigma_3\left[\cot\frac{\theta\partial^2\Psi}{\partial\lambda^2} + \frac{\partial}{\partial\theta}\left(\sin\theta\cos\theta\frac{\partial\Psi}{\partial\theta}\right)\right]$$

Here, $J = J_q + J_d$ (where J_q denotes the current intensity for the Sq variation and J_d the additional current intensity due to the increased conductivity (the Cowling conductivity $\Sigma_3 = \int \sigma_3 \, dh$) along the auroral zones); the wind velocity is assumed to have the velocity potential

$$\Psi = k_1^1 P_1^1 (\cos\theta) \sin(n\lambda + \pi/2).$$

The conductivity along the auroral zones of width 5° is assumed to be b times larger than the rest of the ionosphere. Fig. 4.20 shows an example of their calculation; the factor k denotes the ratio $\int \sigma_2 \, dh / \int \sigma_1 \, dh$.

Fukushima and Oguichi [1953] found that the wind system responsible for the Sq variation cannot explain the orientation of the current system with respect to the sun. Further, the current intensity is much weaker than the observed one. To overcome these difficulties, the air motion in high latitudes must differ in phase by about 100° ~ 150° with respect to the Sq wind system, and the wind speed or the conductivity along the auroral zone must also be greater than the values they assumed. These difficulties were also pointed out by Maeda [1957].

The most serious difficulty of the theory is, however, the fact that at geomagnetically conjugate points the Sq variation is quite different (indicating that the wind system in the northern and southern hemisphere may differ greatly from each other), while the polar magnetic substorms are, in general, strikingly similar [Boyd, 1963; Wescott, DeWitt, and Akasofu, 1963].

Both Cold [1960] and Swift [1963] considered the dynamo action in a little different way. Assuming a highly conductive and narrow slab, they examined effects of a uniform wind blowing across it. The wind tends to carry positive ions along its direction more closely than electrons, resulting in a polarization electric field across the high conductive slab and thus an intense Hall current along it. Again, their proposed mechanism depends greatly on the direction of the ionospheric wind, so that criticism given in the above may also be applied here. Further, their model is independent of height, but the proposed mechanism should occur only in the E region of the ionosphere where the collision frequency of positive ions with neutral particles is high enough. Therefore, if the space charge is discharged vertically along the field lines, their effect will be considerably diminished.

(5) Convection

Piddington [1960, 1964], Axford and Hines [1961], and Hines [1964] proposed that a 'friction' (by the former author) or a 'viscous-like interaction' (by the latter authors) between the solar wind and the magnetosphere could cause a large-scale 'convective motion' in the magnetosphere. Here, the convective motion is limited to the motions (of velocity $\underline{v}$) which satisfy

$$\underline{E} + \underline{v} \times \underline{B} = 0 \tag{1}$$

where the electric field $\underline{E}$ is given by the gradient of a scalar function φ

$$\underline{E} = - \nabla \varphi \tag{2}$$

so that

$$\underline{v} \times \underline{B} = \nabla \varphi \,. \tag{3}$$

This type of motion has been called the interchange of magnetic tubes of force [Gold, 1959]; plasma which occupies a tube of force at a particular time migrates with the tube at all times. Since both $\underline{v}$ and $\underline{B}$ should be perpendicular to $\nabla\varphi$, they should lie on the surfaces of φ = const., the equipotential surfaces. Consider the equatorial cross-section of the equipotential surfaces in a dipolar field. The intersection lines should then be the equipotential lines and those equipotential lines should coincide with the flow lines of the plasma (or the flow lines of the equatorial crossings point of a thin tube of force).

Instead of obtaining the generated convective flow pattern from the proposed interaction between the plasma flow and the magnetosphere, Axford and Hines [1961] set up an ad hoc flow pattern which consists of two closed systems (Fig. 4.21a), and its projection onto the ionospheric level coincides with the trace of the foot of convecting geomagnetic field lines. In the E region of the ionosphere, however, positive ions can no longer be attached to the field lines by frequent collisions with neutral particles during their gyration. The result is a flow of electrons along the convective flow path and thus the Hall current which has the opposite direction to the electron flow (see section 4.5).

Axford and Hines [1961] inferred that based on (1) and (3) there must be a positive space charge near the dawn boundary of the magnetosphere (A) and a negative space charge near the dusk boundary (B). Thus, they projected these space charges onto the polar cap. Then, instead of driving theoretically the potential difference across the two centers, they took radar observations of the motions of auroral ionization [see Axford, 1964, p. 48]

$v \sim 1$ km/sec to obtain the electric field $E = vB \simeq 5 \times 10^{-4}$ volts/cm across the auroral zone. Assuming then the width of the auroral zone to be 200 km the potential drop across the polar cap is claimed to be 2×200 km $\times E \sim 2 \times 10^{4}$ volts.

However, this does not seem to be a correct procedure. They must compute first their flow pattern, based on their proposed mechanism. If its projection onto the solar cap agrees well with the polar current pattern (except the direction), they could then claim that their proposed convection is indeed responsible for the polar current. Secondly, the potential drop across the polar cap must be theoretically predicted; if it agrees with the observed one, they can then claim that the proposed convection is indeed powerful enough to drive the polar jet. In their theory, it is difficult to distinguish their theoretical predictions and their interpretations of corresponding observations. The polar current system does suggest a large-scale convective system suggested by Axford and Hines [1961]. However, it is not self-evident that the existence of the SD current system is proof of the convective pattern generated by their proposed mechanism. We shall show in section 4.10 that the convection is likely to be a secondary phenomenon generated by an instability in the magnetosphere. We note also that the SD current pattern must be re-examined (section 4.2).

Further, their projection of the equatorial flow pattern to the polar cap was not done with a specific model so that the distribution of the charges in the vicinity of the center of the oval may not necessarily be accurate. In fact, since the proposed space charge should occur near the viscous boundary layer, Dewitt [1963] shows that the points A and B in Fig. 4.21b could lie within a radius of a few hundred kilometers, centered at the point P, the foot of the field line from the neutral point (Fig. 4.21b). Axford took the thickness of the boundary layer to be of order 400 km. This boundary layer can be considered to be the outer shell of the magnetospheric tail. Let us calculate the total magnetic flux contained in the shell, taking the radius of the cross-section of the magnetospheric tail to be 20a. Since the cross-sectional area of the cylindrical shell is of order 3.20×10^{18} cm^2 and $B \simeq 30\,\gamma = 3 \times 10^{-4}\,\Gamma$, the total flux is $9.6 \times 10^{14}\,\Gamma$ cm^2. The flux must originate from an area which contains the foot of the field line from the neutral point. Taking $B = 5.5 \times 10^{-1}\,\Gamma$ in the area and assuming that the area consists of two circles (one in each hemisphere), its radius is only of order 170 km. There is no *a priori* reason to assume that the space charge is distributed in the way suggested by Axford [1964]. It may well be a circle of radius less than 200 km. For the latter case, the space charges should be distributed near the fringe of the circle of radius of only 200 km, rather than near the fringe of the entire polar cap.

Further, they claimed that their predicted flow pattern agrees with Davis' alignment of auroral arcs over the polar cap [Davis, 1962]. Axford and Hines [1963] indicated that the process is analogous to that displayed in a cup of coffee after it is stirred and a drop of cream is deposited in it. The cream quickly forms into an elongated arc which traces out the convective flow pattern. However, it is found later that Davis' pattern is not an instantaneous one [Davis, 1963]; when auroras in the oval are active, there may be no polar cap auroras. Bullough's study [1961] of radio auroras in the polar cap is also not very conclusive as supporting evidence of their convective motion. Piddington [1965] suggested also that the predominant equatorward motion of auroras in the midnight sector [Davis, 1961] is an indication of the flow of the flux tubes; however, this equatorward motion occurs <u>after</u> the poleward explosive motion, namely during the slow recovery phase. There is also no visible indication that auroras drift from the day sector to the night sector across the polar cap.

It is very unfortunate that such an important concept must rely, at present, on observations which are considered to be not conclusive. Further, since the SD current system (from which they inferred the equatorial convective pattern) must be revised (section 4.2), it becomes more urgent to compute the convective pattern based on their theory. This is particularly so because the interaction between the solar wind and the magnetospheric boundary is closely related to one of important unsolved problems, the formation of the magnetospheric tail.

Their proposed convection and thus the potential drop across the polar cap must exist even during a quiet period. So far, this potential difference has been claimed to be found by ground observation indirectly by magnetic variations over the polar cap, namely the S_q^p [Nagata and Kokubun, 1962; Nagata, 1964]. However, since their data were obtained during an active period of the sun, a contamination caused by a weak polar electrojet may be inevitable. A more reliable pattern may be obtained by using records obtained during periods of quiet sun. Since geomagnetic disturbances are one of the few evidences of inferring a large-scale electrostatic field within the magnetosphere, the extension of the study by Nagata and Kokubun is urgently needed.

In section 4.6 (3), we noted that if there exists an electrostatic field (perpendicular to $\underline{B}$) in the magnetosphere, the thermal plasma tends to drift on equi-potential surfaces ($\underline{E} = - \nabla\varphi$). However, if the particles are energetic enough to be unaffected by the electric field, they move on the L surfaces. Particles of an intermediate energy will thus move on the surfaces which are neither the equipotential surfaces nor the L surfaces. In Fig. 4.22, consider the intersection lines between the equipotential surfaces $(\varphi_1, \varphi_2, \varphi_3, \ldots)$ and the ionosphere and also the intersection lines between a L shell and the ionosphere. Suppose then that both the thermal particle and a very energetic particle start from the point A. The projections of their paths are given by $\varphi = \varphi_2$ and L, respectively. Particles of an intermediate energy will move on a path which lies between φ_2 and L. If the equipotential surfaces are asymmetric with respect to the dipole axis, particles of different energies will have different degrees of asymmetric distribution. The most energetic particles have the least degree of asymmetry. Therefore, if the degree of the asymmetry as a function of the energy of particles can be determined instantaneously, this will become a powerful tool to examine the existence of the electric field. Taylor and Hones [1965] and Taylor [1966] have shown that the electrostatic field associated with the polar electrojet is intense enough to produce a large asymmetry of the outer radiation belts (electron $\simeq$ 40 keV).

It should be noted finally that convective motions of magnetic tubes of force could also be set up by an electrostatic field which is generated by some internal processes within the magnetosphere or the ionosphere. Hines [1964], Maeda [1964], DeWitt and Akasofu [1964], and DeWitt [1965] showed that a large-scale convective motion of the magnetospheric plasma can be generated by the electrostatic field produced by the dynamo action in the ionosphere. [For the transmission of the ionospheric electrostatic fields see Farley, 1960; Spreiter and Briggs, 1961.]

(6) Neutral Point Discharge

Dungey's theory predicts a large-scale convection of the magnetospheric plasma similar to that proposed by Piddington and Axford and Hines. The difference is the driving mechanism of the convection. Instead of a friction or a viscous-like interaction, he proposes that an interaction between a southward oriented interplanetary magnetic field and the earth's dipolar field plays an important role. The interaction results in an X-type neutral point at the apex and rear of the magnetosphere. Then, the combined effect of the solar wind and the plasma flow in the vicinity of the

X-type neutral point [cf. Dungey, 1958] causes a convective motion of the field lines [see also Levy, Petschek, and Siscoe, 1964]. Dungey inferred that the projection of the convection pattern onto the ionosphere has a resemblance to the SD variation. In Fig. 4.23, the successive motions of the convected field lines are shown. The motions corresponding to the sequence 1 to 8 should cause a motion of the foot of the field line across the polar cap along the noon-midnight meridian. Fairfield and Cahill [1966] have recently found a good correlation between the southward directed field just outside the magnetospheric boundary and the occurrence of polar magnetic substorms, supporting Dungey's mechanism. A further extensive observation would be needed to confirm such an observation.

(7) Neutral Line Discharge

Akasofu and Chapman [1962] considered that a ribbon-like structure of the aurora is one of the most vital points in any theory of the aurora. They propose that there must be a specific structure (whatever it may be) in the magnetosphere to generate thin sheet beams of energetic auroral electrons. They inferred that the structure must be closely related to a deformation of the earth's magnetic field since the dipolar field itself has no characteristic region qualified to be a source of such a sheet beam. Further, since the ribbon-like structure has a planetary scale, the scale of the deformation must have also a large scale. Based on such a consideration, they inferred that the ring current seems to be one of the qualified causes of the deformation that satisfies the above requirements. The diamagnetic effect of the ring current tends to cause a 'dip' in the dipole field so that an enhanced ring current may reduce the dipole field and produce a line on which the field intensity may become null ($B = 0$) or very small, although this requires a very large β ($= n \kappa T/(B^2/8\pi)$) value. They inferred also that a further enhancement of the belt might result in a reversal of the original magnetic field, forming the X and O type neutral lines. This point has, however, been criticized by several workers. Parker [1962] states that there is no reason to believe that the over-inflation can generate new lines of force with a reversed direction.

The discovery of the neutral sheet in the tail region of the magnetosphere suggests the existence of a current system which may be considered to be a partial ring current across the tail [cf. Axford, Petschek, and Siscoe, 1965; Speiser and Ness, 1966]. Coppi, Laval, and Pellat [1965] suggested that since it is confined in a thin sheet, an enhancement of the current may cause a pinch effect, disintegrating the sheet current into a number of filaments. Each filament will have closed magnetic fields so that a small scale reversal of the field could occur. In fact, this is a common instability which has been experienced in a thermonuclear device. We shall discuss this problem in more detail later (section 4.10).

4.7 Review of Observations

Most of the theories discussed in the previous section have been put forward to try to explain one or more auroral phenomena, but all are inevitably far from complete. This is party due to a great complexity of auroral phenomena and thus to the difficulty of obtaining the correct morphological features. This, together with the fact that auroral phenomena are unfamiliar to most, make it difficult to single out the fundamental features to be most seriously considered. Therefore, we review briefly the major features of auroral phenomena in the following.

1. A homogeneous ribbon-like structure (namely, the homogeneous arc) is the fundamental structure of the aurora; other forms have active features (such as rays and folds of various scales) which are added to the homogeneous arc.

2. The ribbon-like structure has an east-west length of at least several thousand kilometers, with an extremely small thickness of order a few hundred kilometers.

3. The ribbon-like structure appears commonly in multiple, with the most common separation distance of $30 \sim 40$ km.

4. The ribbon-like auroras tend to lie in a narrow oval band encircling the dipole pole, the auroral oval, not the auroral zone.

5. During the main phase of geomagnetic storms, the auroral oval shifts toward the equator. The magnitude of the shift is closely related to the magnitude of the main phase decrease (or the intensity of the ring current).

6. The ribbon-like structure is mainly caused by electrons of energy of a few kilovolts or less [Meredith et al., 1958; McIlwain, 1960; Rees, 1963; Sharp et al., 1964, 1965].

It is commonly assumed that in electron bombardment, about one ionization in 50 leads to the emission of a λ 3914 photon [Chamberlain, 1961]. If in a weak arc the intensity of the λ 3914 emission is 10 kR (= an apparent emission of 10^{10} photons $(cm^2 sec)$), the ion production rate must be of order $50 \times 10^{10} = 5 \times 10^{11}$ (ions/cm^{2}sec). The associated total energy injection rate is 5×10^{11} (ions/cm^{2}sec) x 35 (eV) = 1.75×10^{13} eV/cm^{2}sec = 28 ergs/cm^{2}sec. If this energy is carried by 5 keV electrons, the flux must be of order 3.5×10^9 electrons/cm^{2}sec. During an intense display, the λ 3914 emission may be as high as 1000 kR, corresponding to an electron flux of 3.5×10^{11}/cm^{2}sec.

7. Auroral substorm: In the midnight sector, the southernmost arc* (in the northern hemisphere) becomes bright first. The brightening occurs over a considerable part of the arc (~ a few thousand kilometers) in a few minutes and moves poleward with a speed of order 500 m ~ 1000 m/sec. This poleward motion causes the auroral 'bulge' in the midnight sector. The period during which the bulge is expanding is called the expansive or explosive phase and lasts typically 5 to 30 minutes. [* Any one of the multiple arcs can become activated, but except the case of the southernmost one, it is, in general, the only arc which becomes active and others may remain fairly quiet (the so-called pseudo break-up). However, if the southernmost one becomes activated first, the development of the substorm is most intense.]

8. This activation of the midnight arc is then propagated westward and eastward. The bulge produces a large-scale fold which travels along pre-existing arcs, namely along the auroral oval. This traveling fold is called the westward traveling surge; its speed is of order 400 m/sec ~ a few kilometers per second. In the morning sector, the disintegration of arcs proceeds from their western end toward the eastern end (from the midnight end to the dawn end) with a speed of order 10 km/sec. The resulting 'patches' spread equatorward and drift eastward with a speed of order 300 m/sec. Some arcs become folded and also drift eastward approximately with the same speed.

9. When the poleward boundary of the expanding bulge attains the highest latitude (dp lat 70° ~ 75°), the expansive phase ends. Then, the arcs and bands begin to move equatorwards, with a speed of order 200 m/sec or less. This is the beginning of the recovery phase. During this period, many arcs are formed in the shrinking bulge and fade away. Eventually, a few arcs will be seen at approximately the same location where the first brightening of the arc at the onset of the substorm took place. The recovery phase proceeds much more slowly than the expansive phase and lasts typically 1 ~ 3 hours.

10. The substorm occurs intermittently, with a typical lifetime of order 1 ~ 3 hours. During geomagnetic storms, new substorms may appear one after another, before previous ones subside completely.

11. In the auroral bulge, a sharply defined 'negative bay' is observed, indicating a sudden decrease of the horizontal component of the geomagnetic field; its magnitude can be as large as 2000 γ. A less intense, but a well-defined negative bay is also observed near the northern boundary of the westward traveling surge, and a positive bay in the region south of the pass of the surge. In the morning sector, a less intense and less well-defined negative bay is also observed in the region where eastward drifting bands or patches are observed.

12. The auroral substorm is associated with other polar geophysical phenomena, such as radio wave absorption and x-ray emissions (indicating the penetration of energetic particles as low as 50 km), various types of VLF emissions, ionospheric disturbances, and a heating of the upper atmosphere [Winckler et al., 1958; Winckler et al., 1959; Brown, 1961; Brown and Bareus, 1963; Barcus, 1965; Parthasarathy and

Berkey, 1965; Morozumi, 1965; Obayashi, 1964; Jacchia and Slowley, 1964; Maeda, 1963, 1964].

13. The auroral substorm is a phenomenon which occurs in the auroral oval. There is no visible indication that its onset is preceded by motions of the aurora elsewhere (for example, across the polar cap from the noon sector to the midnight sector).

14. There is no indication that the auroral substorm is initiated directly by a sudden enhancement of the solar plasma flow. Satellite observations show also that the kinetic energy flux of the solar plasma has no obvious relation to the K_p index.

15. Both auroral and polar magnetic substorms are very similar at geomagnetically conjugate points.

4.8 Requirements of a Model

The auroral and polar magnetic substorms are a manifestation of interactions between the magnetospheric plasma near the outer boundary of the trapping region and the neutral atmosphere underneath. Two kinds of interaction dynamical and atomic, occur in a narrow belt along the intersecting line between the outer boundary of the trapping region and the ionosphere, the auroral oval.

Both interactions occur most violently in the E region of the ionosphere which is a rather thin transition region between the magnetospheric plasma and the neutral atmosphere. The dynamical interaction is a frictional interaction between the plasma and the neutral atmosphere and causes an intense polar electrojet. The atomic interaction is collisional excitation or ionizations which result in the auroral light.

1. The ribbon-like form of the aurora suggests a thin electron (or plasma) sheet beam injected from outside the polar ionosphere.

2. Thin plasma sheet beams should lie approximately along the intersecting line between the ionosphere and the outer boundary of the outer radiation belt (or the trapping region).

The mechanism that causes the sheet beams is multiple in nature, rather than singular, so as to produce several arcs, with the most common separation distance of order 30 ~ 40 km.

3. The mechanism must be able to supply a very weak plasma sheet beam into the polar ionosphere (10 ergs/cm^2 sec) and should not spontaneously be activated by itself (or there is an accompanying mechanism that tends to check the spontaneous activation to a certain extent), since homogeneous arcs can remain fairly quiet for a few hours. However, when it is activated, it should increase the output (particle flux) at least by two orders of magnitude over a wide range of energies (less than 500 eV to perhaps more than 100 keV).

4. The activation of the mechanism (namely, the onset of the auroral substorm) must occur suddenly, within several minutes. The center of the activation is located in the midnight sector. Since there is no visible indication that the substorm is preceded by any auroral motion and since an enhanced solar plasma does not initiate the substorm, the substorm is most likely to be an <u>internal process within the magnetosphere</u> [Akasofu, 1964].

5. Since the auroral substorm has a sudden onset, an explosive energy release (the explosive phase) and a slow relaxation

(the recovery phase), the activation must be caused by an instability.

6. The activation of the mechanism must be associated with the poleward shift of the plasma sheet beams.

7. During the substorm, an intense Hall current flows along the auroral oval.

8. Both auroral and polar magnetic substorms cannot be a local ionospheric phenomenon. Polar magnetic substorms at geomagnetically conjugate points are driven by the common electric field.

4.9 Requirements of the Instability

From the studies made in the previous section, we are now led to conclude that the auroral substorm is most likely to be due to a plasma instability. In this section, we try to specify characteristics of the instability.

1. The instability must occur in a confined region of the magnetosphere.

2. The confined region must be stable against the instability to a certain extent, in order to give rise to a stable homogeneous arc.

3. The growth rate of the instability must be rapid, the e-folding time being of order $10^2 \sim 5 \times 10^2$ sec.

4. The instability should be non-linear and explosive in the sense described by Sturrock and Coppi [1966] in their discussion of mechanisms of solar flares. This is because a stable homogeneous arc, which can remain inactive for hours, becomes activated in a matter of a few minutes, so that the non-linear process must promote the instability.

5. The instability must be such as to cause a rapid poleward shift of the plasma sheet beams.

6. Dynamical processes associated with the instability must cause an intense eastward motion of the heated plasma whose interaction with the neutral atmosphere causes the westward Hall current.

4.10 Possible Mechanisms

The specification of the characteristics given in the above section limits greatly a number of possible candidates for the required instabilities. So far, two kinds of instabilities have been examined as possible mechanisms. The first is an instability which takes place in the neutral sheet and the other an interchange instability which takes place in the vicinity of the outer boundary of the ring current.

(a) The Neutral Sheet Instability

The principal feature of this mechanism is to extract the necessary energy for the substorm by the fusion or annihilation of the magnetic field near the neutral sheet. The exact mechanism for the fusion is, however, a matter of controversy.

Since the fusion problem was extensively studied in the past for a similar magnetic configuration in connection with searches for the energy source of solar flares [Sweet, 1958; Parker, 1957; Dungey, 1958; Petschek, 1964], the same or similar arguments have been applied to this problem [cf. Axford, Petschek, and Siscoe, 1965; see also Axford, 1966].

In particular, Petschek's theory [1964] predicts that magnetic field lines in the tail region drift toward the neutral sheet in the equatorial plane with a speed of approximately one-tenth of the Alfvén wave speed, namely 0.1 V_A ($= B/\sqrt{4\pi\rho}$), which must be the same as the local (E x B) drift speed, namely,

$$E/B = 0.1\, B/\sqrt{4\pi\rho}\ .$$

These fusing field lines were originally located in the day-side, but after the reconnection with interplanetary field lines in a manner discussed in section 1.2, they have been transported toward the tail region. The foot of these field lines moves thus along passes parallel to the noon-midnight meridian line. Therefore, the above drift motion toward the sheet must be related to the speed of the foot of the field lines moving in the polar cap. Let ϕ be the pontential across the polar cap along the dawn-dusk meridian (see section 4.6). Then,

$$\frac{E}{B} = \frac{0.1 \ B}{\sqrt{4\pi \rho}} = \frac{\phi}{LB}$$

where L is approximately the width of the magnetospheric tail. Therefore, ϕ is given by

$$\phi = \frac{0.1 \ B^2 \ L}{\sqrt{4\pi \rho}} \quad .$$

The above equation predicts the magnitude of B for a given ϕ and also predicts ϕ for a given value of B (provided that L and ρ are known).

Axford, Petschek, and Siscoe [1964] showed that taking $L = 2 \times 10^5$ km, $\rho = 2 \times 10^{-24}$ g/cm^3, $B \simeq 10\ \gamma$ for $\phi = 30$ kV .

As pointed out by Sturrock and Coppi [1966], Petschek's mechanism (as well as Sweet's and Dungey's) is not an instability mechanism and is concerned with the steady-state dynamical behavior of the plasma and magnetic field configuration in the vicinity of the neutral sheet. Therefore, the above discussion does not seem to apply for the auroral substorm.

The neutral sheet could have three kinds of instabilities, the rippling mode, tearing mode, and gravitational mode. They have been extensively studied by Marty [1961], Furth [1961, 1964], Furth, Killeen, and Rosenbluth [1963], Johnson, Greene, and Coppi [1963] and others under the name of finite-resistivity instability. Our particular interest is concerned with the tearing mode. This is essentially a disintegration of a sheet current into a number of filaments by the pinch effect. Further, since the medium has a finite resistance, a de-coupling between the field lines and plasma occurs, and the field energy can be converted into the thermal energy by Ohmic heating mechanism. The existence of this type of instability is also experimentally proved by Bodin [1963] and Eberhagen and Glaser [1964]. Furth [1964] studied also the growth of the tearing instability in a collisionless plasma, since effects of collisions (leading to the resistivity) can be replaced by electron inertia. He examined the stability of the neutral sheet configuration obtained by Harris [1962] for a perturbation (exp ($\omega t + ikz$)) and showed that the stability condition can be written in a form

$$\frac{1}{2} A\, n_o\, r_c \left(\frac{v_s}{v}\right)^2 > 1$$

where

$$A = 8\pi/k\,(h + k)$$

$$r_c = e^2/mc^2$$

$$h^2 = 2\pi\, n_o\, r_c\, v_s/v^2 \simeq (\text{the sheet-pinch thickness})^2$$

v_s = the directed particle velocity .

The above condition is analogous to the Bennett pinch condition

$$I^2 > 2\, A_s\, n\, m\, v^2$$

$$\left(\text{or } \frac{1}{2} A_s\, n\, r_c \left(\frac{v_s}{v}\right)^2 > 1\right)$$

where I denotes the current of a cylindrical particle stream, A_s its area. Furth suggests thus that the area A_s of each first-order pinch to be identified with A, which is roughly the product of the sheet-pinch thickness 2/h and the instability wave-length $2\pi/k$. Therefore, $k = h$ represents marginal stability and $k < h$ represents instability. For the growth rate, Furth noted that in a special case the hydromagnetic and Vlasov-equation approaches to this problem give essentially the same result.

A more detailed examination of the growth rate by using the Vlasov-equation approach has been made by Laval and Pellat [1964], based on Harris' solution of the plasma-magnetic field configuration in the vicinity of the neutral sheet. The application of their results to auroral phenomena was discussed by Coppi, Laval, and Pellat [1965]. Their study shows that the growth time τ of the instability is given by

$$\tau = \frac{1}{1/2} \left(\frac{2\lambda}{R_{Le}} \right)^{3/2} \frac{\lambda}{v_{th}} \frac{\Theta_e}{\Theta_e + \Theta_i}$$

where λ denotes the sheet thickness, R_{Le} the gyro-radius of electrons; v_{th} the electron thermal velocity, and Θ_e and Θ_i are κT_e and κT_i, respectively. Taking $2\lambda \simeq 600$ km,
$B \simeq 1.6 \times 10^{-4}$ gauss, $\Theta_i \simeq 1$ keV,

$$\tau \simeq 15 \text{ sec} \quad \text{if} \quad \Theta_e \simeq 10 \text{ keV}$$

$$\tau \simeq 5 \text{ sec} \quad \text{if} \quad \Theta_e \simeq 1 \text{ keV} .$$

As mentioned earlier, the tearing mode is essentially the pinch of a sheet current, resulting in the disintegration of the sheet current into a number of filamentary currents. Each filament produces its own magnetic field around it. Figure 4.24 shows schematically the situations before and during the instability. Piddington [1966] has discussed this instability as a candidate for the substorm and considered its consequences.

One of the important features of this instability is that some of the field lines which had been 'opened' by the tail current before the onset of the instability tend to close. This closure forces the hot plasma produced by the instability to flow toward higher latitude. This may be identified with the expansive phase of the auroral substorm.

Since one of the basic processes of this particular instability is the conversion of the magnetic energy to the thermal energy of the plasma, a transient decrease of the magnetic field in the tail is inevitable. In fact, Behannon and Ness [1965] observed such a transient decrease by Imp 1. Akasofu [1966] computed the minimum open latitude ϕ (namely, the latitude of the intersection between the ionosphere and the outer boundary of the outer belt) as a function of the ring current intensity R, taking the intensity of the neutral sheet current field N as the parameter (Fig. 3.18).

Suppose that the intensity of the neutral sheet is suddenly decreased. As is clear from Fig. 3.18, a decrease of the intensity of the neutral sheet must indicate an increase of the minimum open latitude ϕ. For the ring current intensity R = 100 γ, a decrease of the neutral sheet intensity from N = 50 γ to 10 γ can cause the closure of the field lines which anchor between dp lat 57° to 68°. During geomagnetic storms of a medium intensity $R \simeq 100 \sim 150$ γ, the auroral oval descends from its average location (dp lat 67°) to about 57° ~ 60°; then during auroral substorms, the poleward boundary of the oval moves rapidly to about dp lat 70°. Brightest auroral bands are seen at the advancing boundary, and the region swept by such bands is covered by irregular bands or patches.

An extremely intense substorm observed at about 1030 UT on February 11, 1958 could be explained if the intensity of the neutral sheet decreased from N = 90 γ to N = 10 γ if the intensity of the ring just prior to the substorm was of order 300 γ. This will result in a temporal widening of the oval, extending from about dp lat 50° to dp lat 70°. This agrees well with the extent of the poleward motion observed during an extremely intense substorm which occurred about 1030 UT on February 11, 1958 (Fir. 4.25). In fact, such a drastic substorm occurs only during geomagnetic storms with a large main phase decrease.

One important problem to be examined in this connection is whether or not the transportation of the fusing field lines from the dayside to the nightside occurs. If this is the case, what are the firm evidences to support such a conjecture? So far, although different mechanisms have been proposed by different authors, it seems to be that the SD current system is the basis of their conjecture [Dungey, 1966; Piddington, 1966; Axford, Petschek, and Siscoe, 1965].

We should not forget the great contribution made by the SD current system to the field of geomagnetism. It was, however, based on rather limited amounts of material. Since there is now much more abundant material available, it is worthwhile to re-examine and improve it, if necessary. Our new analysis in section 4.2 shows that there is no indication that the westward jet is terminated in the midnight sector or late evening sector, as the SD current system suggests. Instead, the jet flows westward along the auroral oval and constitutes a closed current system.

If the westward jet is entirely due to the Hall current, it must be generated by an eastward motion of the plasma shell whose bottom coincides with the auroral oval. Figure 4.26 shows schematically this situation. The interaction between the neutral atmosphere and the plasma shell causes the motion of electrons along the oval. The thickness of the plasma shell is largest in the midnight sector, so that the current leaks away from the main flow into both the polar cap and the middle-low latitude belt; the Hall current is divergenceless.

One of the possible causes of the eastward motion of the plasma shell may be simply due to the fact that the plasma (which is originally located in the neutral sheet and is rotating with the earth) tends to acquire an additional eastward velocity relative to the rotating earth when it is ejected to a region of smaller radial distance and of higher latitude, namely the conservation of the absolute angular momentum. At present, it is not known whether or not the plasma in the neutral sheet is rotating with the earth during quiet periods. However, the fact that fairly quiet auroral forms or isolated auroral rays (which are simply a bright portion or folded portion of a very faint arc) do not seem to show any significant differential motion with respect to the earth may be taken to be important evidence for the co-rotation.

Another important problem is what controls the substorm activity and thus the instability of the sheet current. The pinch depends on the geometry of the sheet current and the current intensity. What characteristics of the solar plasma control these factors? We have now confirmed that the kinetic energy flux of the solar plasma is not related directly to the substorm activity. Fairfield and Cahill [1966] have shown that a southward directed magnetic field outside the magnetospheric boundary is closely related to the substorm activity; this supports Dungey's prediction.

(b) Interchange Instability

Swift [1965] suggested that the auroral substorm results from a fluting instability on the outer boundary of the ring current belt. Thus, the necessary energy is first accumulated in the ring current belt as an internal energy and is then converted into the dynamical energy by the fluting (in a manner analogous to the conversion of thermal to kinetic energy of air motion when an automobile tire has a blowout). Swift considers that the electrostatic field associated with the asymmetric growth of the ring current tends to steepen the gradient of the ring current particle distribution in the midnight sector. The auroral substorm is thus considered to be a relaxation process for such a stress. This can explain the fact that the substorms tend to occur when the asymmetric ring current is rapidly growing. A quiet and homogeneous arc may be explained as an effect of discharge from a thin surface boundary layer of the ring current belt. However, if the steepening of the gradient exceeds a certain value, the flute instability tends to grow, but it is checked by the ionosphere underneath [cf. Cole, 1963]. Swift pointed out, however, that an electric current associated with this checking flows along the field lines. If this current becomes intense enough, ion acoustic waves can develop, and interaction between the waves and the current particles cause a sudden increase in the longitudinal resistance. (The field lines were originally highly conductive and equipotential.) However, the increased resistance will free the magnetospheric plasma from a close tie with the ionosphere and allow the flute instability to grow rapidly. At the same time, the ion acoustic wave energizes electrons. He estimated that the growth rate of the instability will then be of order of a few seconds. Suddenly enhanced VLF emissions at the time of the onset of the substorm are considered to be an indication of the growth of ion acoustic waves. Although it is not clear how the surface instability is related to a large-scale bodily movement of the plasma (implied in theory to account for the poleward motion), a number of basic morphological features are seriously considered in Swift's theory.

4.11 Polar Geomagnetic Variations other Than the Polar Magnetic Substorms

(a) S_q^p

Nagata and Kokubun [1962] showed that the daily magnetic variation over the polar cap consists of two parts, the daily variation caused by the dynamo action (denoted by S_q^o) and an SD like variation (denoted by S_q^p). Thus,

$$S_q = S_q^o + S_q^p .$$

The current for the S_q^o variation is a fairly uniform one, flowing from the dusk sector to the dawn sector across the sunlit polar cap. Like the SD current, the S_q^p current system consists of two ovals (Fig. 4.27). Its intensity is of order 15 x 10^4 amperes in local summer and 5 x 10^4 amperes or less in local winter.

(b) Daytime Agitations

It has been realized that a considerable geomagnetic disturbance exists in the polar cap region, particularly in the sunlit cap, even during periods of very low K_p indices. Figure 4.28 shows a collection of magnetic records from nine stations distributed between dp lat 63° and 83° on August 24, 1957 [Bobrov, 1960]. The corresponding K_p indices are shown at the bottom. At Churchill (dp lat 68.7° N) and below, there is no indication of the existence of polar magnetic substorms. However, both Resolute and Baker Lake stations indicate considerable disturbances. This particular type of magnetic disturbance has been called the daytime agitation and been studied by a number of workers [Mayaud, 1955, 1956; Fukushima, 1962; Yudovich, 1962; Bobrov, Koroleva, and Novikova, 1964]. The disturbances tend to be rather irregular, and their vectors do not seem to have any preferential direction. Therefore, they have been studied in terms of the range, or local Q and K indices.

One of their most important characteristics is that their activity is controlled by sunlight. Nagata and Kokubun [1962] showed this by using two contrasting pairs of magnetic records from Resolute Bay (dp lat 83° N) and Mirny (dp lat 77° S).

Figure 4.29 shows the daily variation of the agitation for different seasons (b-spring, c-summer, d-autumn, e-winter, a-all) at Heiss Isle (dp lat 71.3° N), Mirny (77.0° S), Gothavn (79.9° N), and Resolute (83.0° N). The daylight control of the activity is quite obvious.

A more detailed study by Lebeau [1965] shows, however, that the geomagnetic time is also an important factor. He obtained the following empirical relation among the magnetic noon (M), the local noon (L), and the time of maximum activity (H).

$$H - L \simeq \frac{1}{2} (M - L) .$$

He suggested that the activity of the daytime agitation is controlled by two factors, namely an "excitation factor" which tends to generate a maximum at magnetic noon and a "modulation factor" which is essentially the conductivity of the E region, which tends to peak at local noon.

Wescott and Mather [1965] examined the controlling factor of the daytime agitation by using the Shepherd Bay (Canada) --Scott Base (Antarctica) conjugate pair; the two stations are separated by 6 hr 40 min in local time. They demonstrated that the daytime agitation tends to peak when the longitude of the field line connecting the two stations at its furthest point from the earth surface agrees with the noon meridian. This time (denoted by FLN) differs from the local noon by about 6 hours at Scott base. There, the activity peaks clearly about FLN, but not at local noon.

Another important characteristic is that their activity is only slightly controlled by the sunspot cycle. Bobrov, Koroleva, and Novikova [1964] suggest that the daytime agitation can be considered to be a good indicator of the permanent solar wind. If there were a polar cap observatory contributing to the K_p index, there would be a very few days when the index is zero.

The daytime agitation is rather poorly correlated at geomagnetically conjugate points [Yudovich, 1963; Wescott and Mather, 1965].

The cause of the daytime agitation is not well understood. There are at least two obvious possibilities. The one is an intrusion of the solar plasma through the neutral point, and the other is hydromagnetic waves traveling down along the field line from the neutral point after they are generated on the magnetospheric boundary surface. Bobrov, Koroleva, and Novikova [1964] considered that it is difficult to interpret a great seasonal difference in the agitation in terms of attenuation of hydromagnetic waves and propose that the agitation is caused by the direct injection of solar plasma from the sunlit neutral point. On the other hand, Axford [1962] suggested that the agitation results from instability of the magnetospheric surface. It is true that a pure Alfvén wave will have little attenuation along most of the path and that the winter ionosphere is even more transparent than the summer ionosphere. We note, however, some other types of hydromagnetic disturbances can be recognized on the ground only when they generate the Hall current in the ionosphere. For example, the detection of Piddington's twist wave (section 2.4) is greatly affected by the Hall conductivity in the E region.

It is quite important to examine outer geophysical phenomena associated with the daytime agitation. Lebeau [1965] showed that the agitation is closely related to the disappearance of the F region in ionograms; it is caused by an abnormal ionization and the consequent attenuation of the sounding radio wave. Bryunelli and Sandulenko [1961] and Bullough [1962] noted a particular type of radar echoes associated with the daytime agitation. Both observations may be considered to be an important evidence that the agitation is associated with energetic (perhaps auroral) particles.

(c) Geomagnetic Disturbances at the Dipole Poles

The equivalent current systems proposed so far suggest a fairly uniform current flowing across the polar cap from the evening sector to the forenoon sector. Therefore, we would expect that the magnitude of the disturbance vector should be approximately constant. Extensive studies made by Feldstein [1961, 1962], Nikolsky [1961], and Yudovich [1962] suggest that such an inference is incorrect. Figure 4.30 shows the daily variation of the Q index obtained by Yudovich [1962] for Vostok (dp lat 89.2° S) and Thule (dp lat 89.0° N) for different seasons, a-summer, b-equinoxes, c-winter, The magnitude (Q) varies greatly during the course of a day, and the maximum occurs at about local noon.

Section 4

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Figure Captions

Fig. 4.1 The schematic diagram to show the development of both the auroral and polar magnetic substorms, from (a) a quiet situation (upper left), (b) an early epoch of the expansive phase (upper right), (c) the maximum epoch of the substorm (lower left) to (d) an early epoch of the recovery phase (lower right). The region where a negative bay is observed is indicated by the lined shade, and the region of a positive bay by the dotted shade.

[Akasofu, S.-I., C.-I. Meng, and D. S. Kimball, J. Atmosph. Terr. Phys., 1966]

Fig. 4.2 The typical H-component variations at different longitudes along the dp lat circles of 65° and 72°. For the first column (local time) and the second column (A, B, C,...), see Fig. 1(a).

[Akasofu, S.-I., C.-I. Meng, and D. S. Kimball, J. Atmosph. Terr. Phys., 1966]

Fig. 4.3 The simultaneous magnetic records between 1600 and 2100 UT on 16 December 1957 from a number of stations in the northern hemisphere; view from above dp north pole;

Fig. 4.3 (Cont'd)

the direction of the sun at 1600, 1800, and 2100 UT is indicated, and also the local time at each station at 1800 UT; scale = 200 γ.

[Akasofu, S.-I., S. Chapman, and C.-Il Meng, J. Atmosph. Terr. Phys., 27, 1275, 1965]

Fig. 4.4 An example of the poleward motion of activated bands during the explosive phase of the auroral substorm.

Fig. 4.5 An example of intense westward traveling surge.

Fig. 4.6 An example of the formation of patches in the morning sector, associated with the onset of the auroral substorm in the midnight sector.

Fig. 4.7 The SD current system.

[Chapman, S., and J. Bartels, Geomegnetism, Vol. I]

Fig. 4.8 The College (Alaska) magnetic records (H), illustrating the appearance of negative bays (hatched) for different degrees of disturbances. The top record shows more or less the normal time of the onset of negative bays and the bottom one during an intense storm. At the top of the diagram, the SD curve for great storms obtained by Sugiura and Chapman [1961] is also shown.

Fig. 4.9 The range of geomagnetic disturbances (H) as a function of UT. There are three distinct peaks, denoted by M, N, and A. The local midnight in each station is marked on the curves.

[Nikolski, A. P.; see Hope, E. R., J. Geophys. Res., 66, 747, 1961]

Fig. 4.10 The loci of the maximum geomagnetic disturbances (M, N, A), maximum auroral appearance, maximum intensity of hydrogen emission, maximum occurrence of ionospheric Es and the polar blackout.

[Nagata, T., Planet. Space Sci., 11, 1395, 1963]

Fig. 4.11 (a) Earlier model current system (schematic) for polar magnetic substorm; view from above dp north pole; the direction of the sun is indicated.

(b) New model current system (schematic) proposed by Akasofu, Chapman and Meng.

[Akasofu, S.-I., S. Chapman, and C.-I. Meng, J. Atmosph. Terr. Phys., 27, 1275, 1965]

Fig. 4.12 A new model current system for an intense polar magnetic substorm; view from above dp north pole.

[Akasofu, S.-I., S. Chapman, and C.-I. Meng, J. Atmosph. Terr. Phys., 27, 1275, 1965]

Fig. 4.13 A new model current system proposed by Feldstein.

[Feldstein, Y. I., Planet. Space Sci., 14, 121, 1966]

Fig. 4.14 Comparisons of magnetic records (H) from the Kotzebue (K) and Macquarie Is. (MI) geomagnetic conjugate pair station.

[Wescott, E. M., and K. B. Mather, J. Geophys. Res., 70, 29, 1965a]

Fig. 4.15 Comparisons of magnetic records from the Shepherd Bay and Scott Base geomagnetic conjugate pair station in the polar cap.

[Wescott, E. M., and K. B. Mather, Planet. Space Sci., 13, 303, 1965d]

Fig. 4.16 Two model current system for the polar electrojet and associated current systems.

[Boström, R., J. Geophys. Res., 69, 4983, 1964]

Fig. 4.17 The horizontal component magnetic records from the Honolulu and College stations (from 2300, 5 December to 0500, 6 December 1958; 150° WMT); two positive changes (positive bays) in the H-component at Honolulu, 2355 and 0315 (150° WMT), are produced by return currents from auroral electrojets which caused two polar magnetic substorms at College. Positive

Fig. 4.17 (Cont'd)

bays are not the DCF-field because they are observed only in a limited region of the earth. In the above example, there was no corresponding positive change at San Juan.

[Akasofu, S.-I., Planet. Space Sci., 12, 801, 1964]

Fig. 4.18 The diamagnetic effect of the plasma sheet

[Maris, H. B., and E. O. Hulburt, Phys. Rev., 33, 413, 1929]

Fig. 4.19 The Hall current system computed on the basis of the polarization of the magnetosphere.

[Fejer, J. A., J. Geophys. Res., 69, 123, 1964]

Fig. 4.20 The current system produced by the dynamo action of the ionosphere. The auroral zone is supposed to be a highly conductive belt encircling the pole.

[Fukushima, N., and T. Oguti, Rep. Ionosphere and Space Res. Japan, 7, 137, 1953]

Fig. 4.21 (a) The sketch of the equatorial section of the earth's magnetosphere looking from above the north pole. Streamlines of the solar wind are shown on the exterior, and the internal streamlines refer to the circulation. The internal streamlines are also equipotentials of an

Fig. 4.21 (Cont'd)

associated electric field which may be recorded as being due to accumulations of positive and negative changes as indicated at A and B.

(b) The sketch of the circulation corresponding to (a) at ionospheric levels in the north polar cap.

[Axford, W. I., Planet. Space Sci., 12, 45, 1964]

Fig. 4.22 The intersection lines between the equipoential surfaces (φ_1, φ_2,...), a L surface, and the ionosphere (see the text).

Fig. 4.23 The interaction between interplanetary and the geomagnetic field and the resulting motions of the plasma (open arrows) proposed by Dungey. Numbers indicate the motion of individual field lines with the motion progressing toward higher numbers.

[Levy, R. H., H. E. Petschek, and G. L. Siscoe, AIAA Journal, 2, 2065, 1964]

Fig. 4.24 The tearing mode instability of the neutral sheet proposed by Coppi, Lard, and Pellat [1965].

Fig. 4.25 The explosive phase of the auroral substorm which began at 1020 UT, February 11, 1958.

[Akasofu, S.-I., and S. Chapman, J. Atmosph. Terr. Phys., 24, 735, 1962]

Fig. 4.26 The schematic diagram to show the relationships between the motion of the magnetospheric plasma shell ($\underline{V}_\lambda$), the associated electric field ($\underline{E}$), and geomagnetic field ($\underline{B}$).

Fig. 4.27 The S_q^p current system in the northern polar cap: upper, the local summer and lower, the local winter.
[Nagata, T., and S. Kokubun, Rep. Ionosphere and Space Res. Japan, 16, 256, 1962]

Fig. 4.28 Collection of magnetic records (H or X) from both auroral zone and polar cap stations during a very quiet day (August 24, 1957). The K_p indices are shown at the bottom.
[Bobrov, M. S., Soviet Astronomy, 4, 392, 1960]

Fig. 4.29 The magnitude of geomagnetic disturbances from high polar cap stations (a) all year, (b) spring, (c) summer, (d) autumn, (e) winter.
[Bobrov, M. S., N. F. Koroleva, and R. M. Novikova, Geomagnetism and Aeronomy, 4, 259, 1964]

Fig. 4.30 The daily variation of the Q index Vostok (curve 1) and Thule (curve 2).
[Yudovich, L. A., Geomagnetism and Aeronomy, 2, 922, 1962]

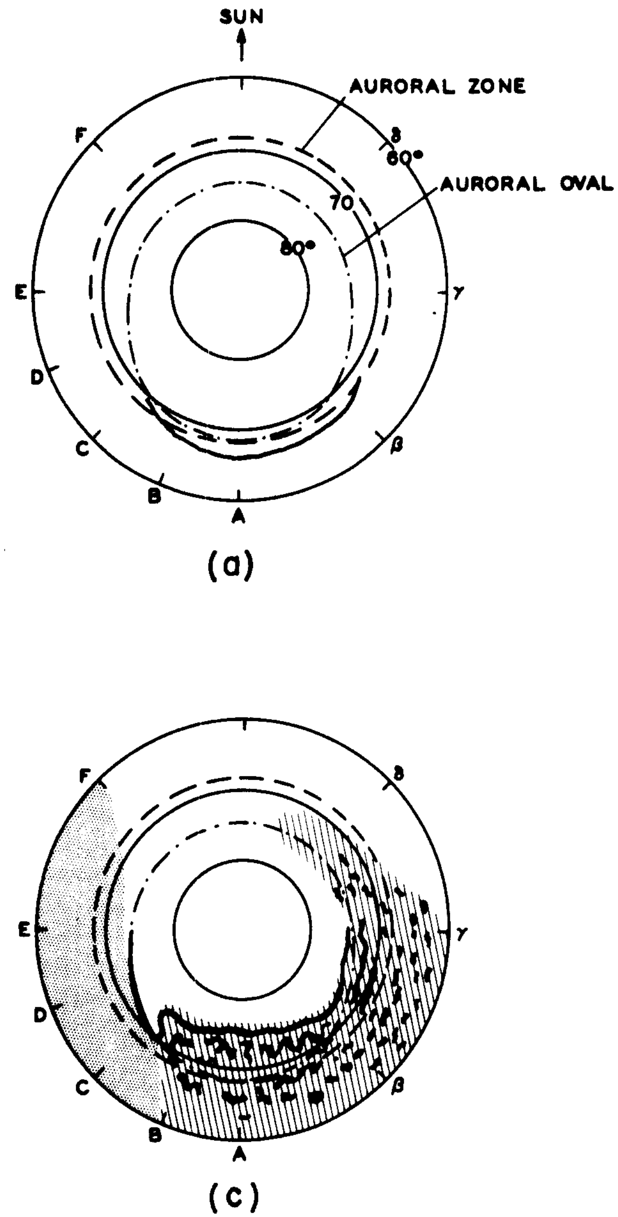
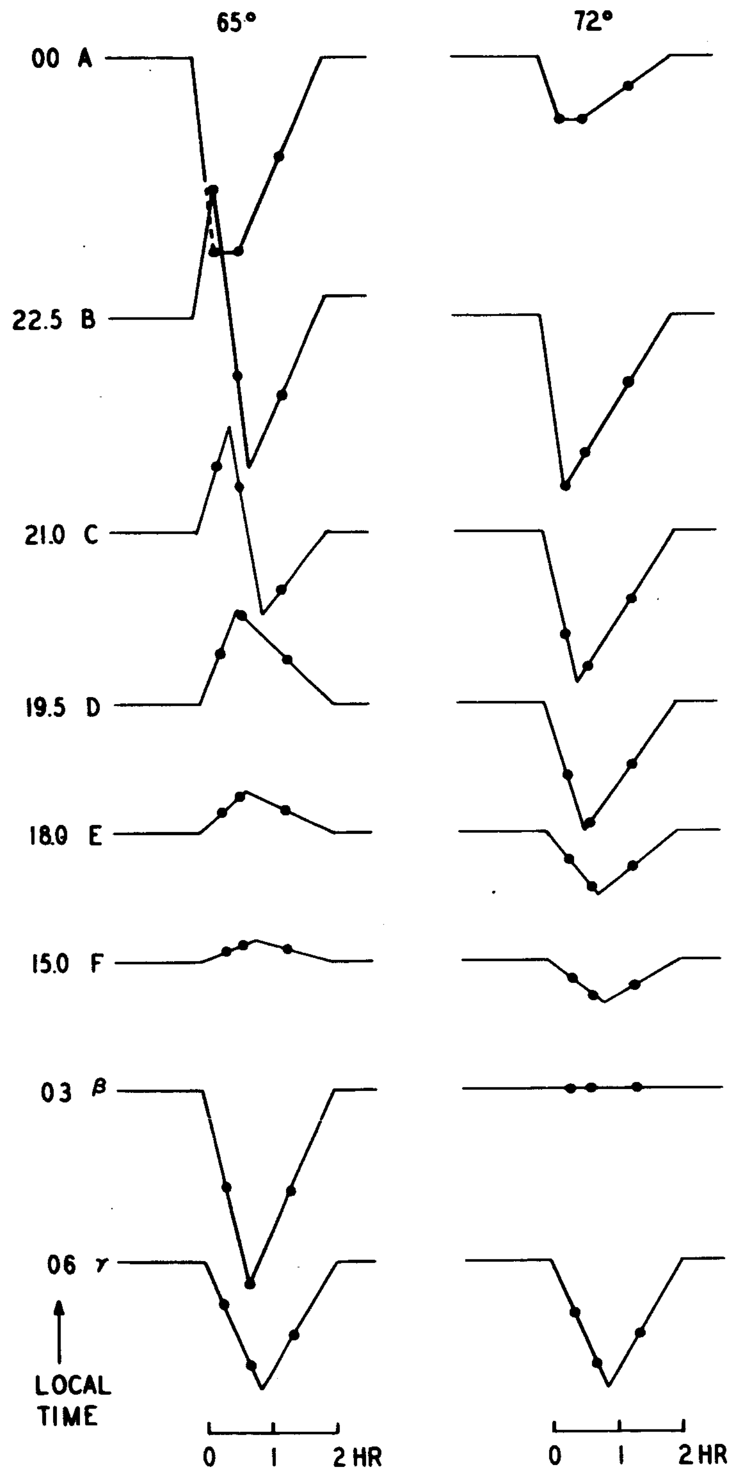
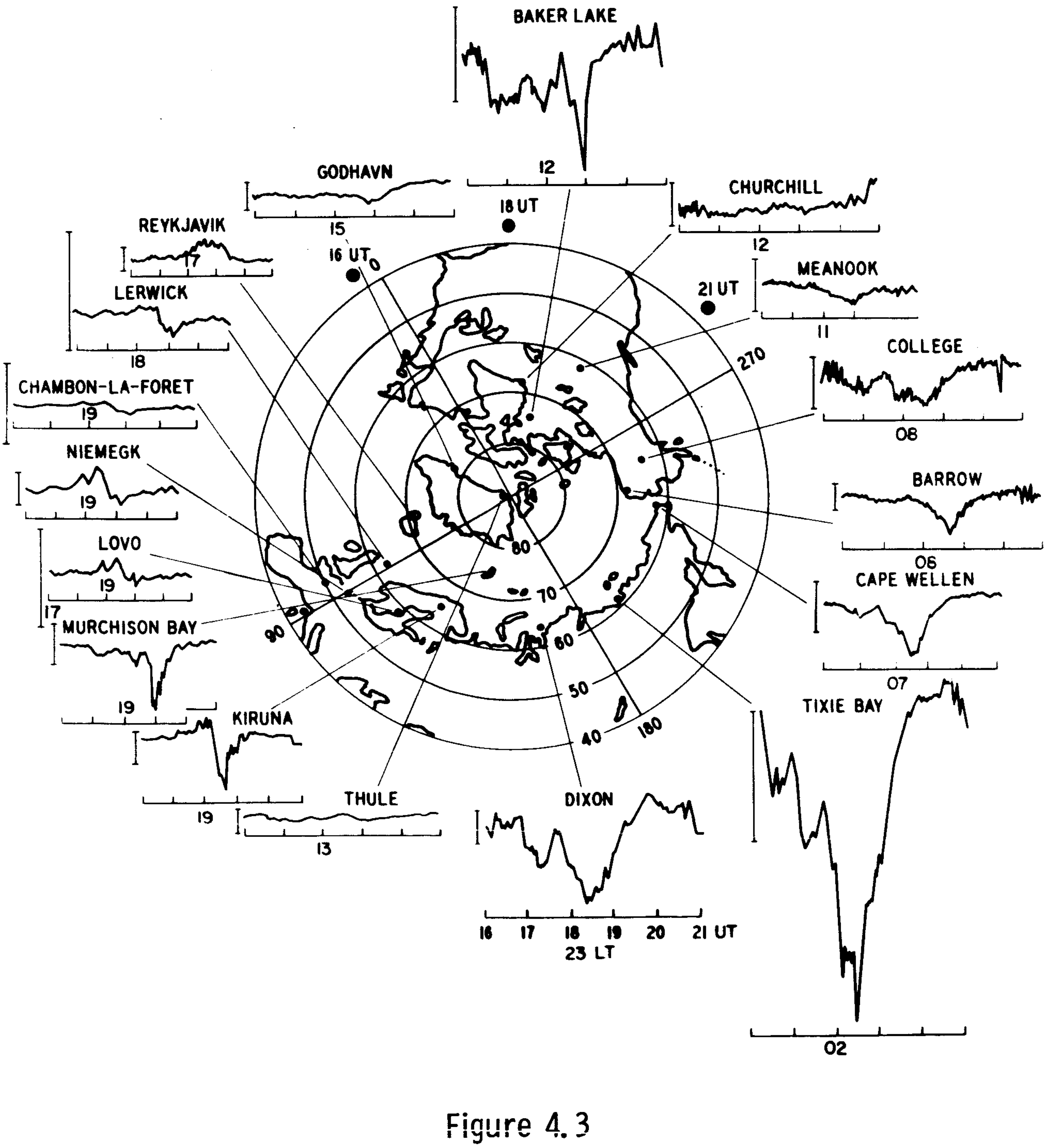


Figure 4.1



65°
72°
00 A
22.5 B
21.0 C
19.5 D
18.0 E
15.0 F
03 β
06 γ
LOCAL
TIME
0
1
2 HR
0
1
2 HR

Figure 4.2



BAKER LAKE
12
GODHAVN
15
18 UT
CHURCHILL
12
REYKJAVIK
17
16 UT
0
LERWICK
18
MEANOOK
21 UT
11
COLLEGE
08
CHAMBON-LA-FORET
19
270
NIEMEGK
19
BARROW
06
LOVO
19
80
CAPE WELLEN
07
17
MURCHISON BAY
70
90
60
19
50
KIRUNA
TIXIE BAY
40
180
19
THULE
13
DIXON
16 17 18 19 20 21 UT
23 LT
02

Figure 4.3

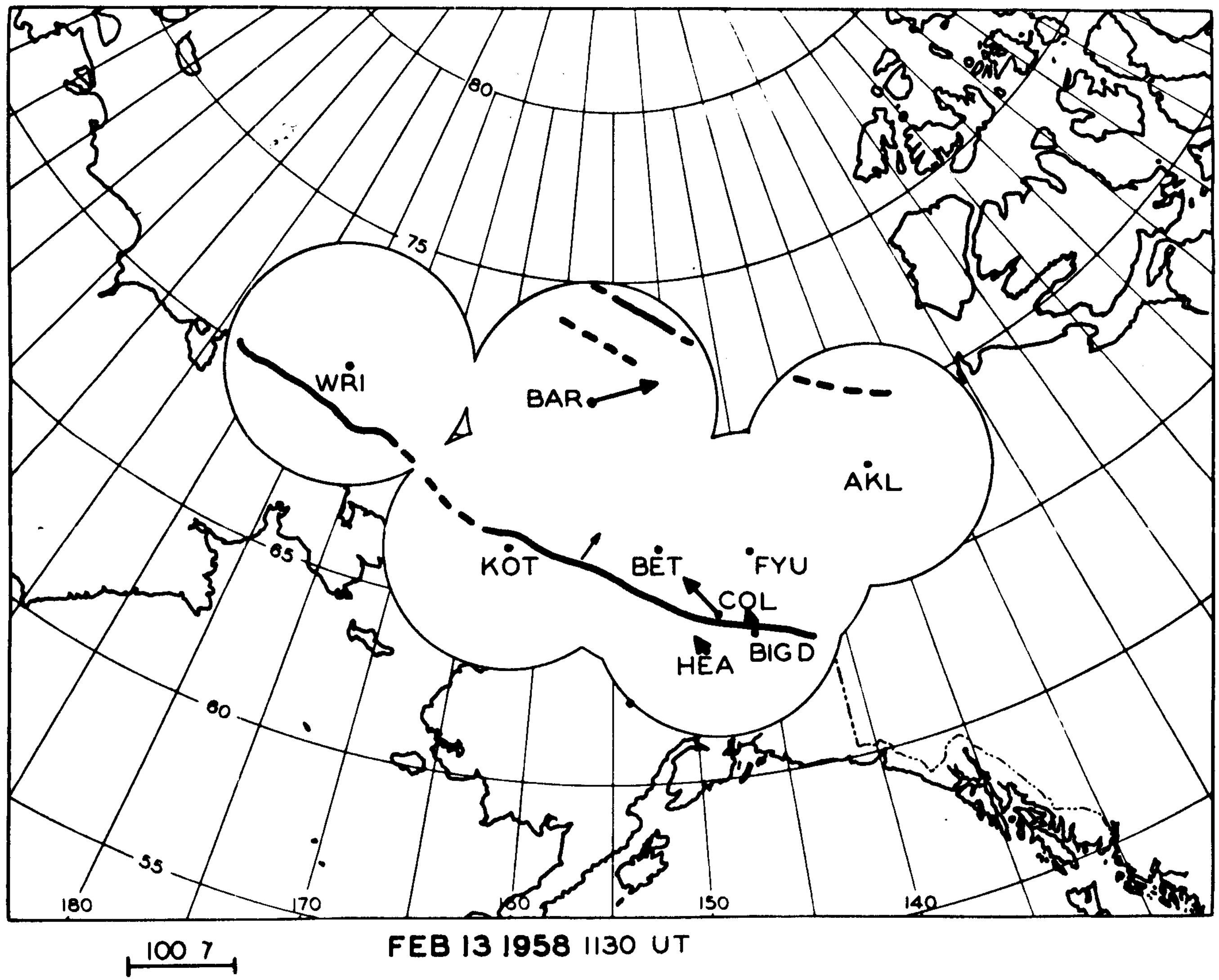
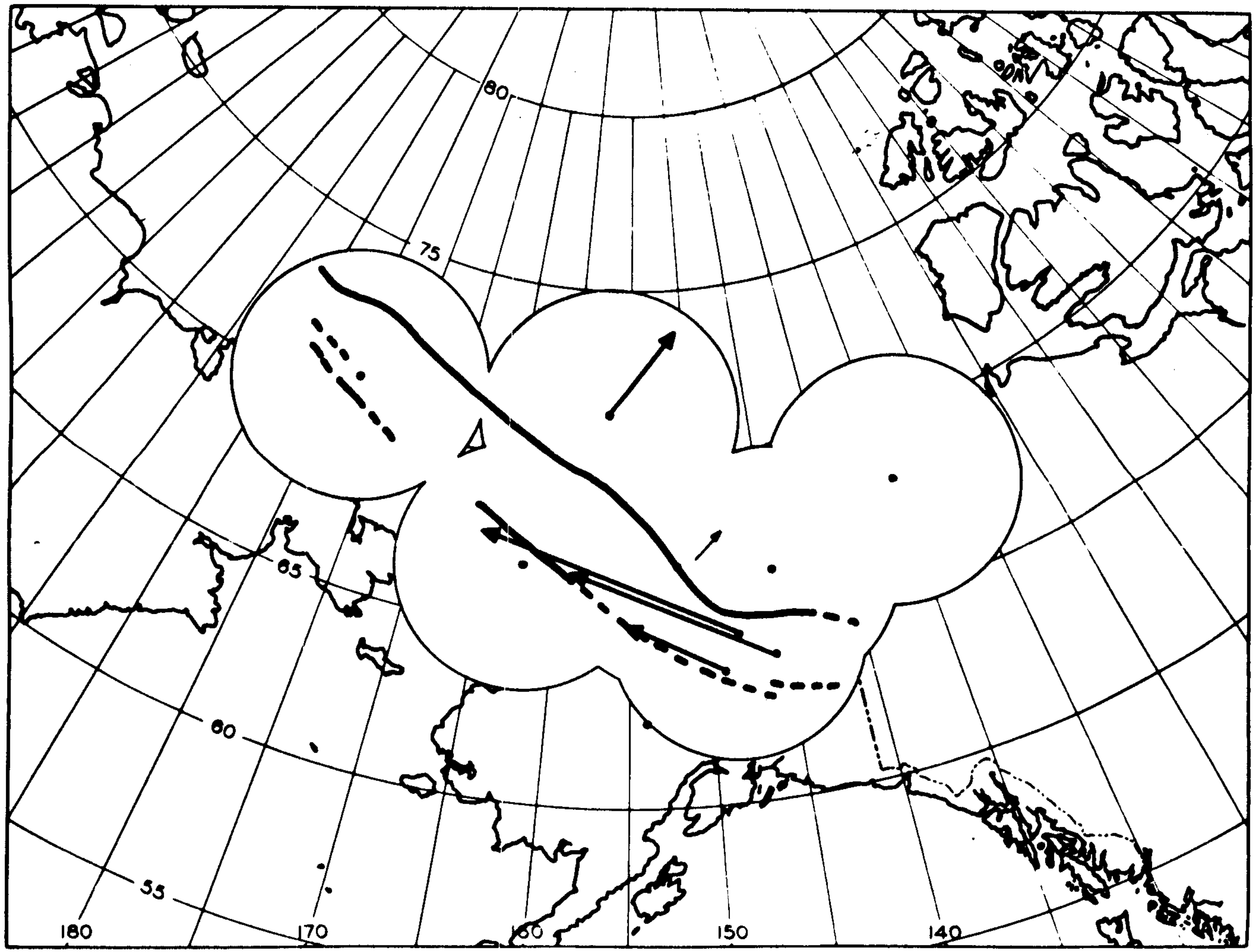
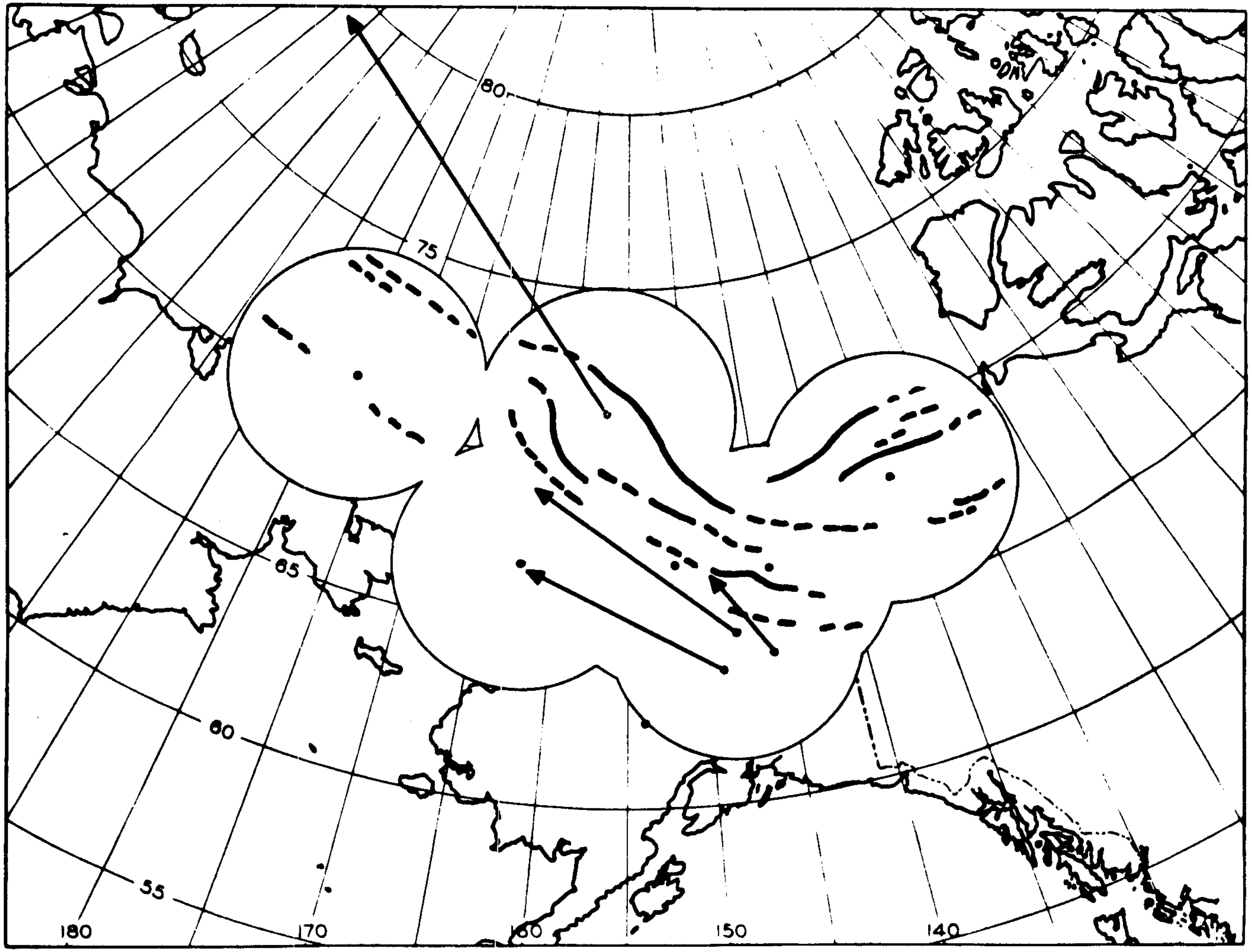

WRI
BAR
AKL
KOT
BET
FYU
COL
HEA
BIG D
80
75
65
60
55
180
170
160
150
140
100 7
FEB 13 1958 1130 UT

Figure 4.4 (a)



1140 UT FEB 13 1958

Figure 4.4 (b)



FEB 13 1958 1204 UT

Figure 4.4 (c)

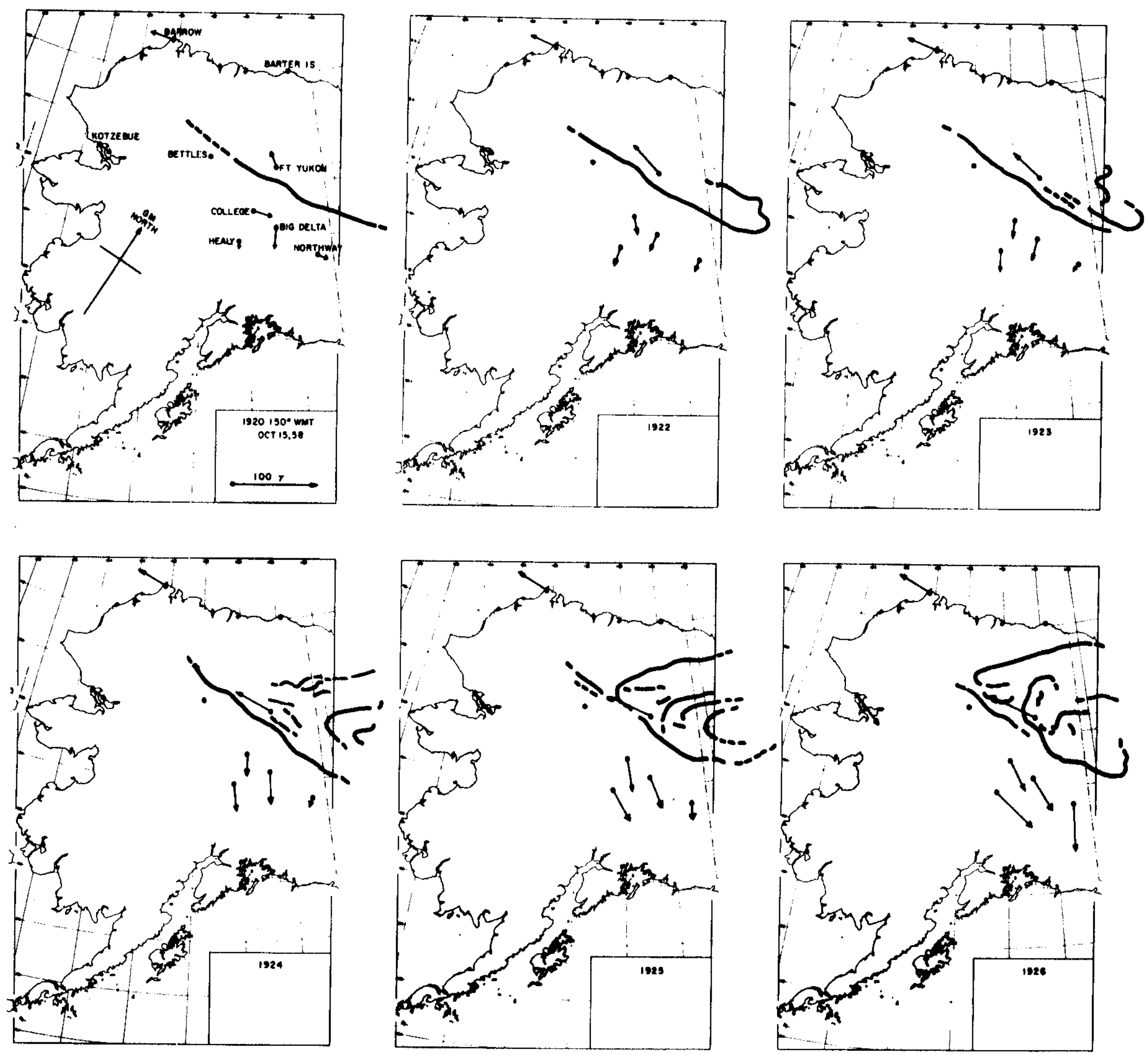

BARROW
BARTER IS
KOTZEBUE
BETTLES
FT YUKON
COLLEGE
BIG DELTA
HEALY
NORTHWAY
GM NORTH
1920 150° WMT
OCT 15,58
100 γ
1922
1923
1924
1925
1926

Figure 4.5 (a)

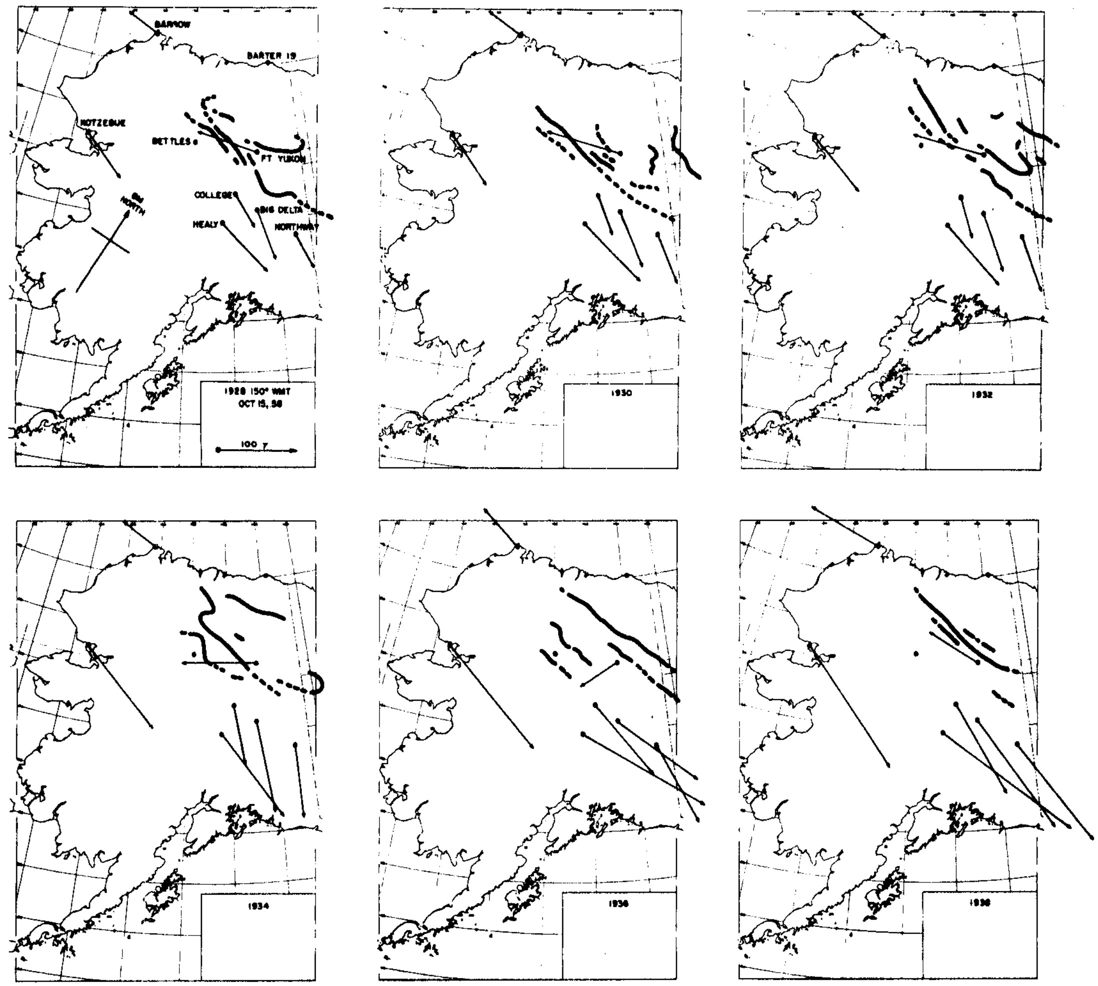

BARROW
BARTER IS
KOTZEBUE
BETTLES
FT YUKON
COLLEGE
BIG DELTA
NORTHWAY
HEALY
1928 150° WMT
OCT 15, 58
100 γ
1930
1932
1934
1936
1938

Figure 4.5 (b)

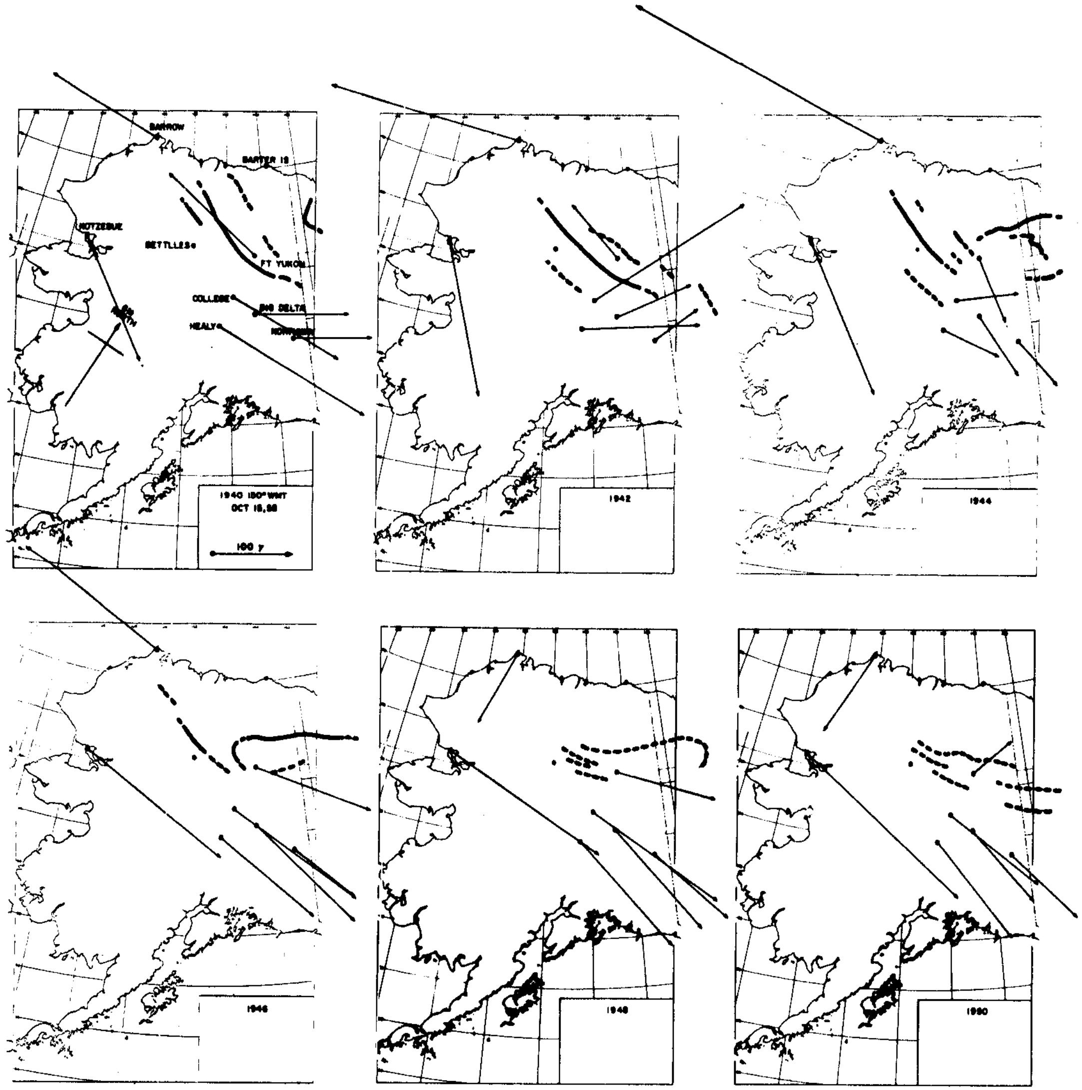
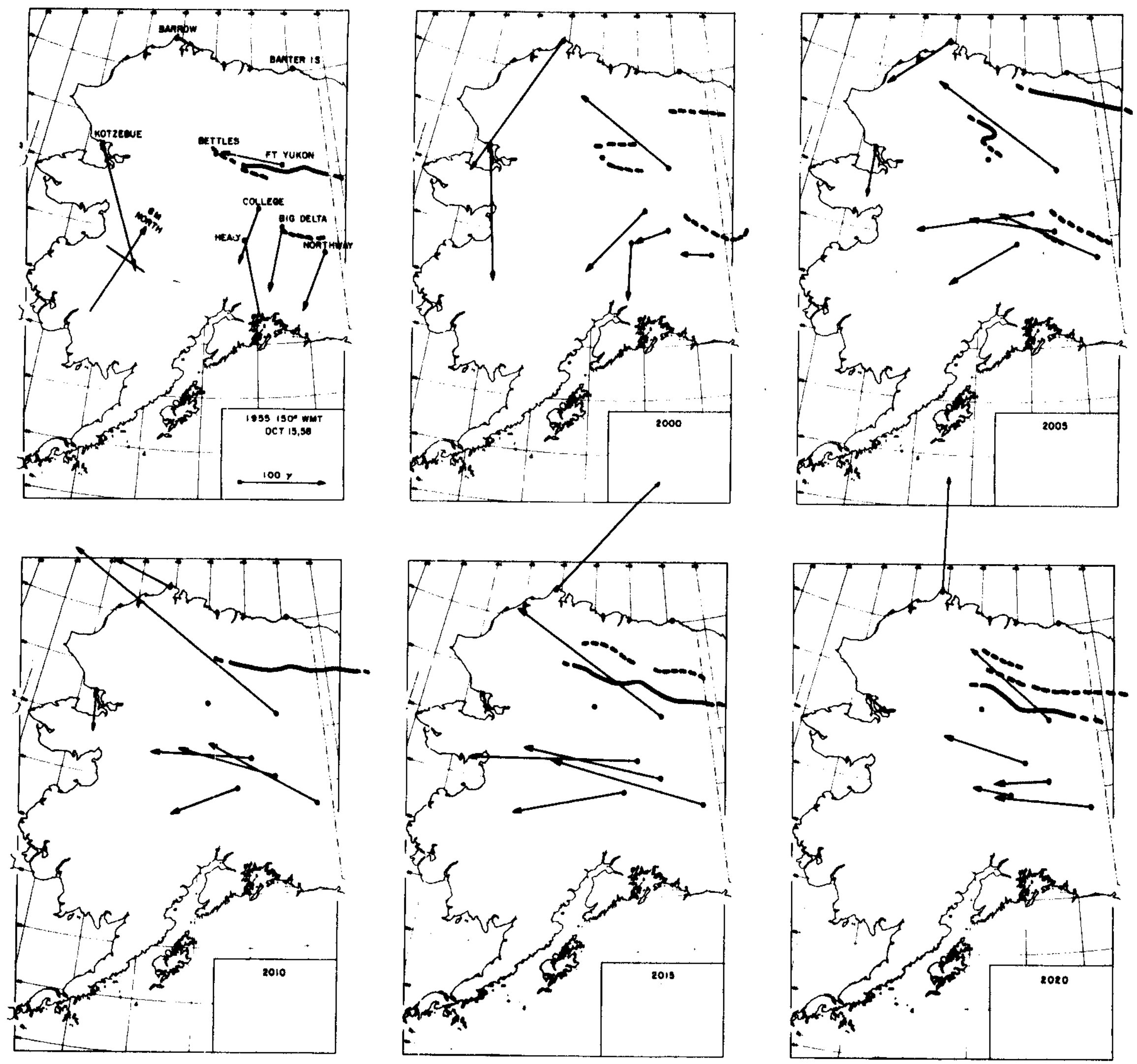

BARROW
BARTER IS
KOTZEBUE
BETTLES
FT YUKON
COLLEGE
BIG DELTA
HEALY
1940 150°WMT
OCT 18,58
100 γ
1942
1944
1946
1948
1950

Figure 4.5 (c)



BARROW
BARTER IS
KOTZEBUE
BETTLES
FT YUKON
COLLEGE
BIG DELTA
HEALY
NORTHWAY
1955 150° WMT
OCT 15,58
100 γ
2000
2005
2010
2015
2020

Figure 4.5 (d)

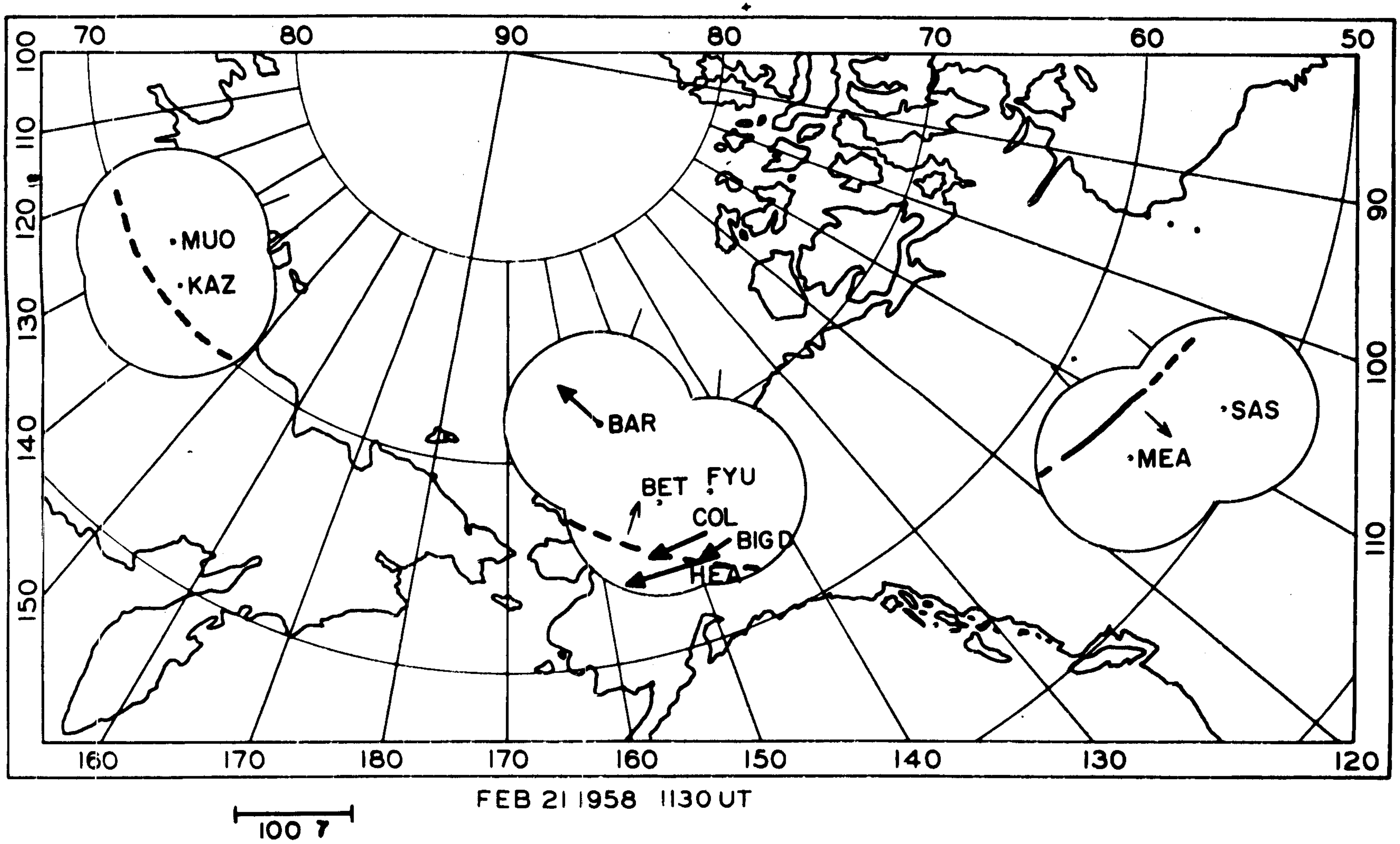

MUO
KAZ
BAR
BET
FYU
COL
BIG D
HEA
SAS
MEA
FEB 21 1958 1130 UT
100 γ

Figure 4.6 (a)

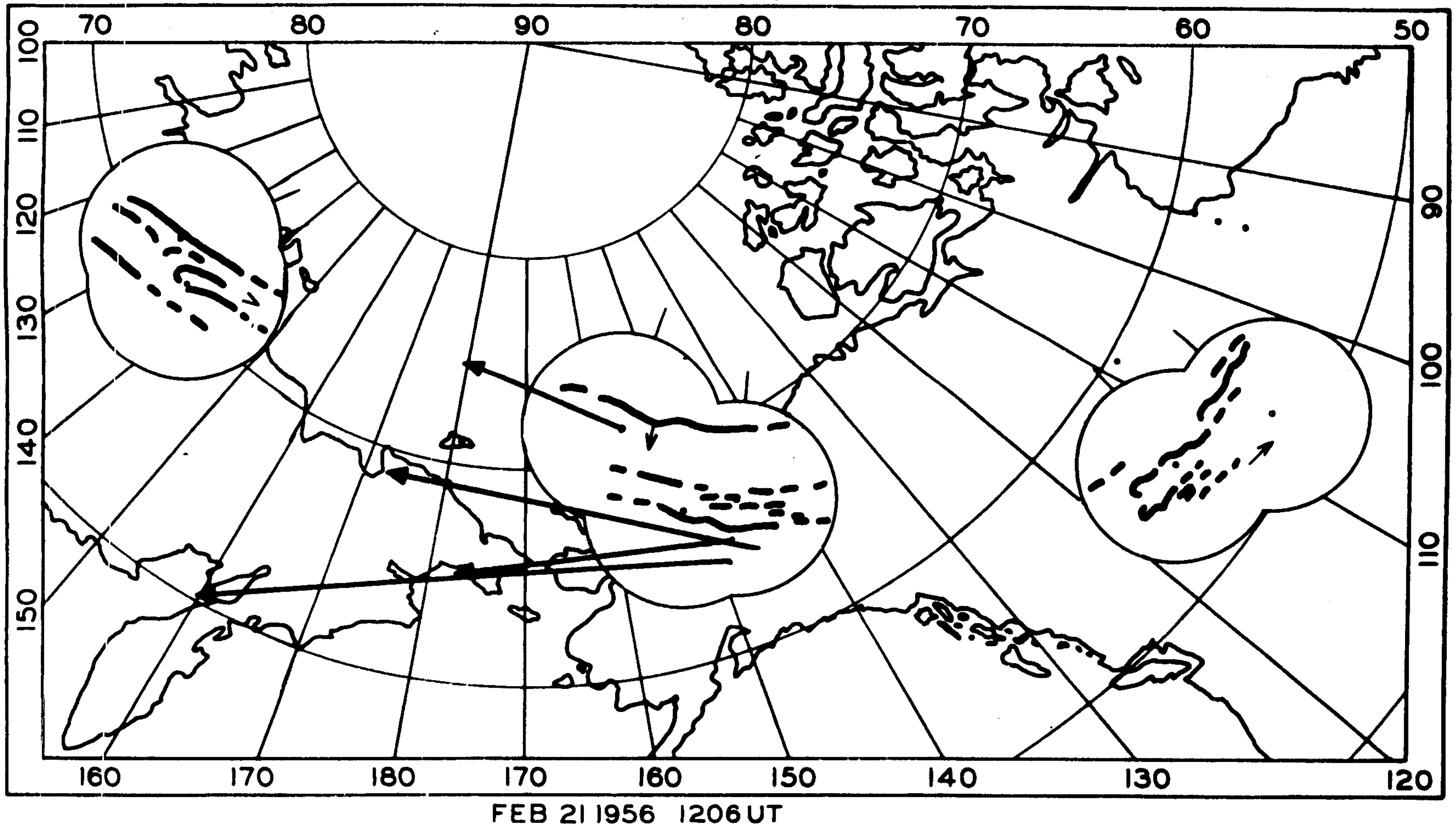
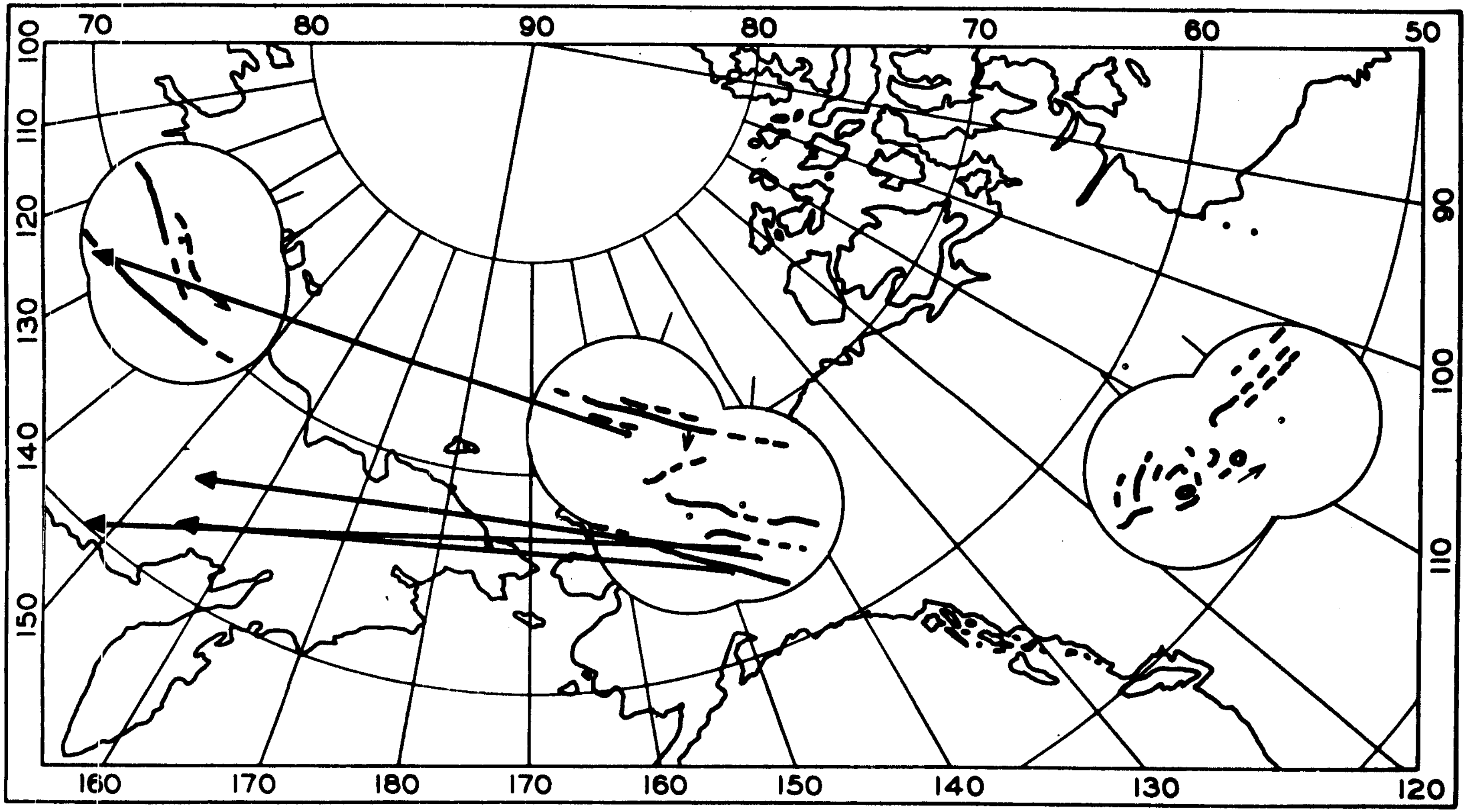

70
80
90
80
70
60
50
100
110
120
130
140
150
90
100
110
160
170
180
170
160
150
140
130
120
FEB 21 1956 1206 UT

Figure 4.6 (b)



FEB 21 1958 1212 UT

Figure 4.6 (c)

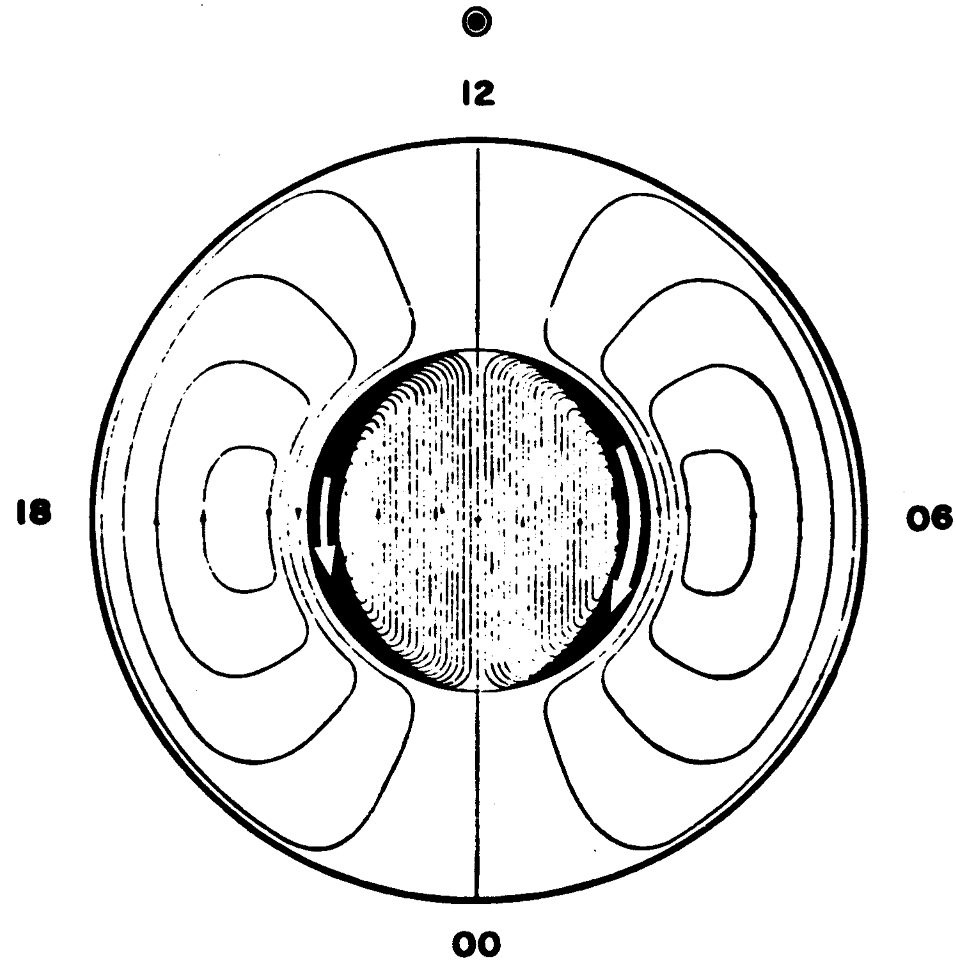
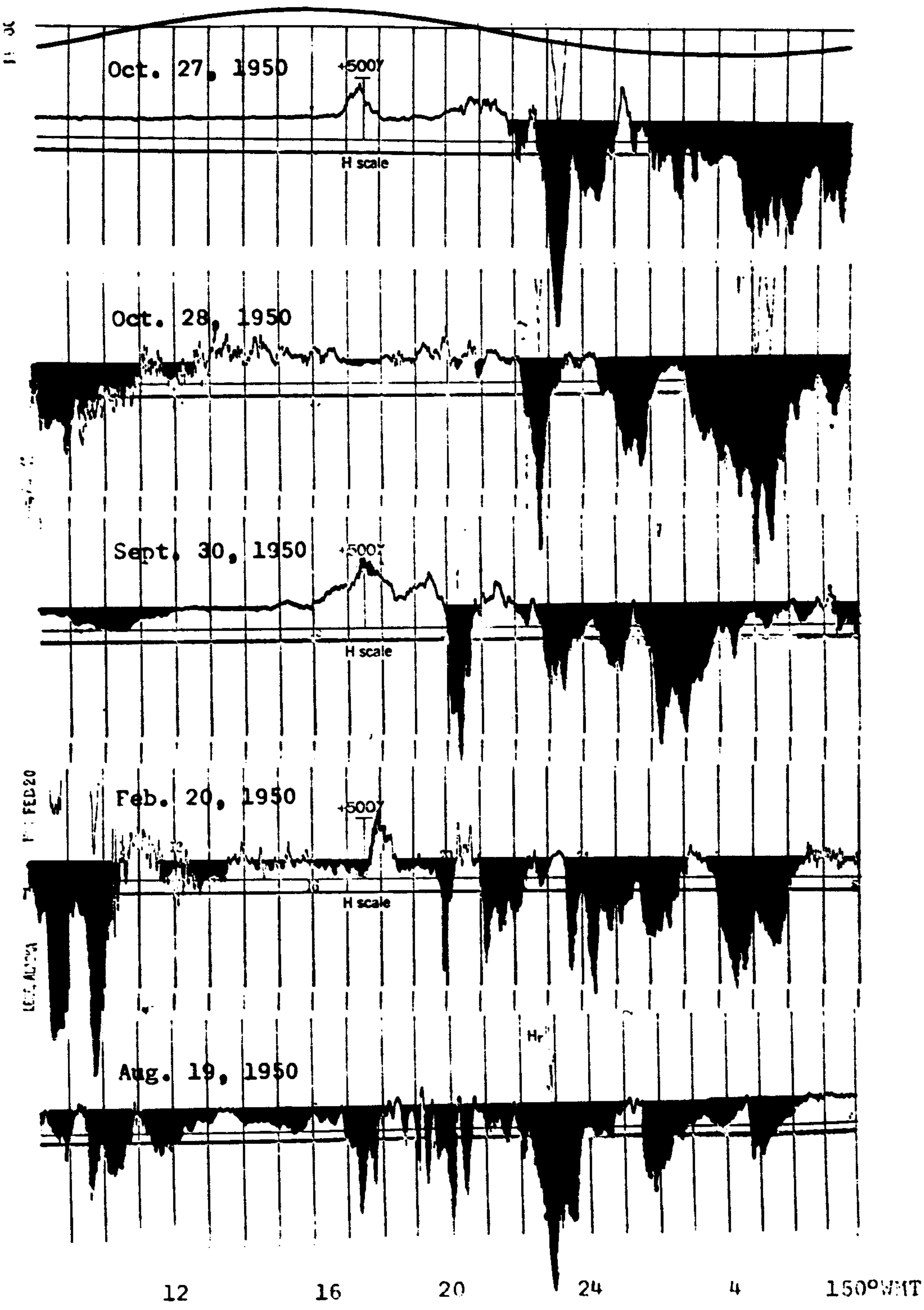


Figure 4.7



Oct. 27, 1950
+500γ
H scale
Oct. 28, 1950
Sept. 30, 1950
+500γ
H scale
Feb. 20, 1950
+500γ
H scale
Aug. 19, 1950
12
16
20
24
4
150°WMT

Figure 4.8

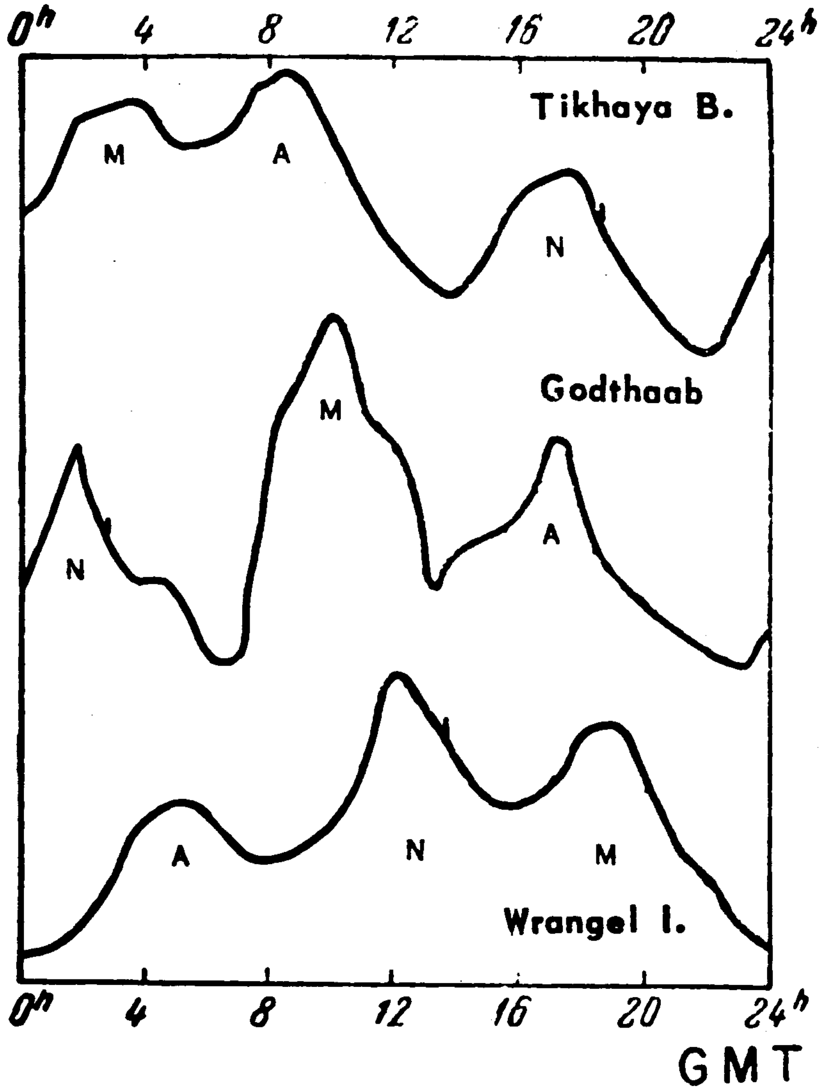

0h
4
8
12
16
20
24h
Tikhaya B.
M
A
N
Godthaab
M
N
A
A
N
M
Wrangel I.
0h
4
8
12
16
20
24h
GMT

Figure 4.9

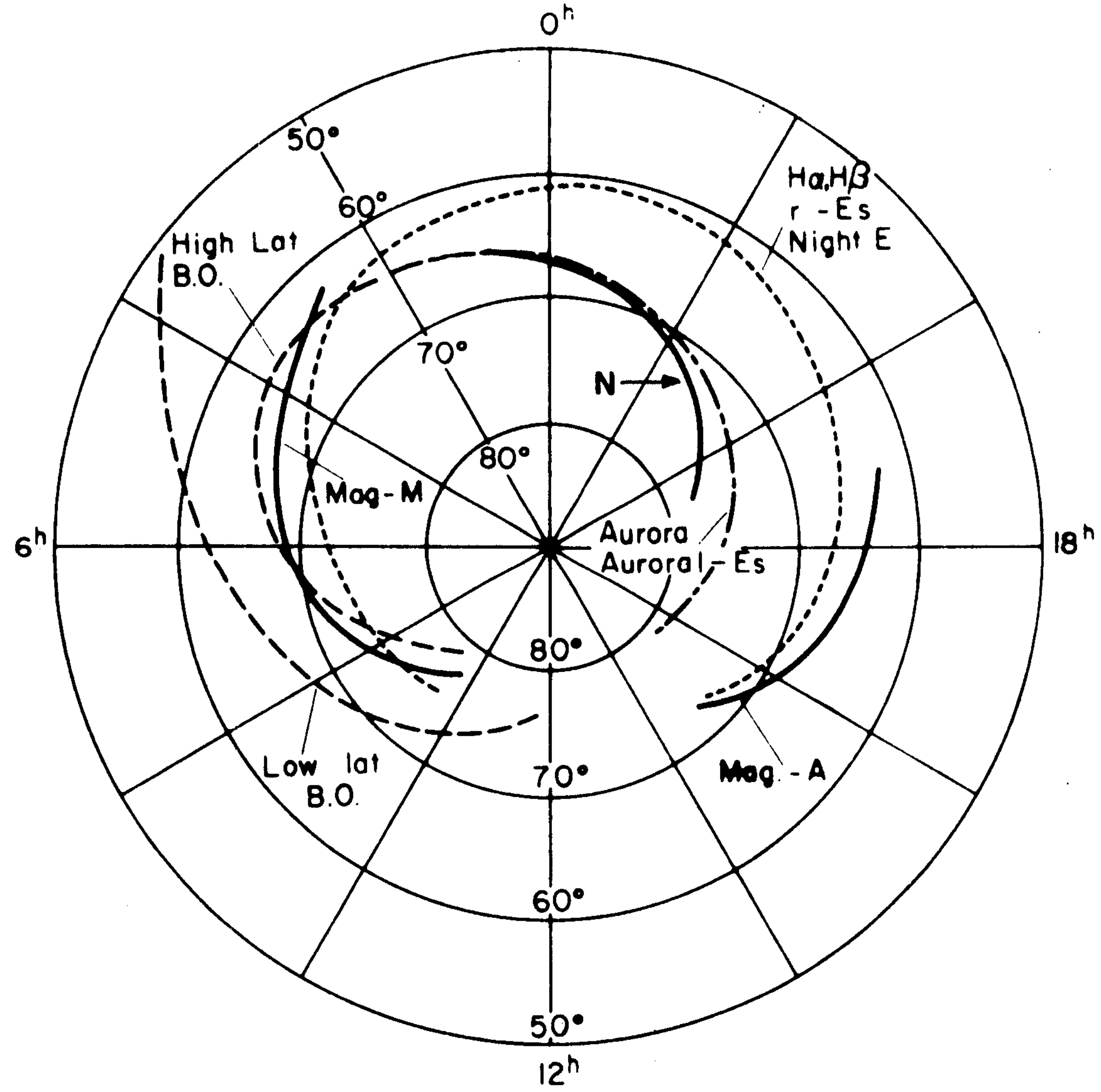

0h
6h
18h
12h
50°
60°
70°
80°
High Lat
B.O.
Mag-M
Low lat
B.O.
Hα,Hβ
r -Es
Night E
N
Aurora
Auroral-Es
Mag. - A

Figure 4.10

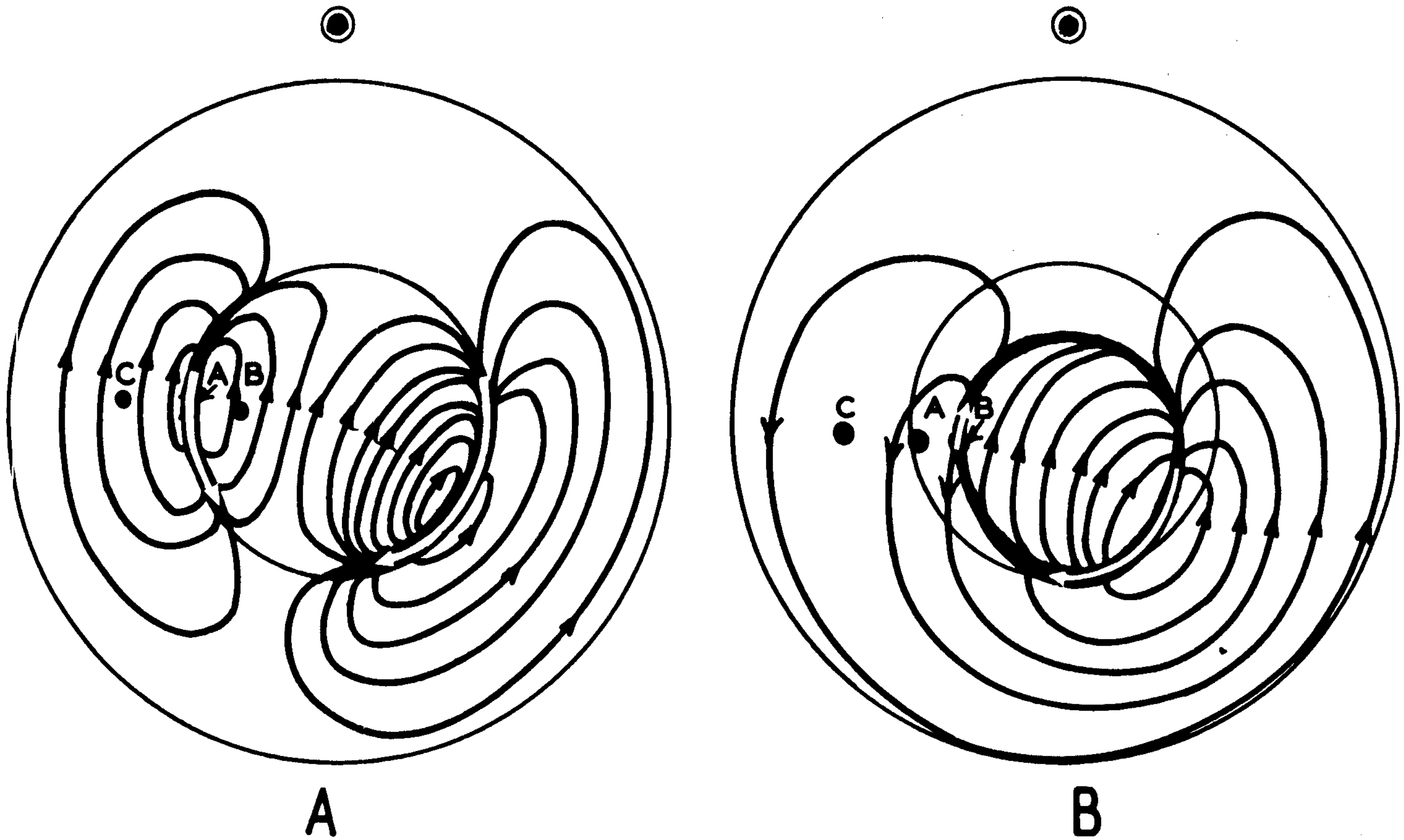


Figure 4.11

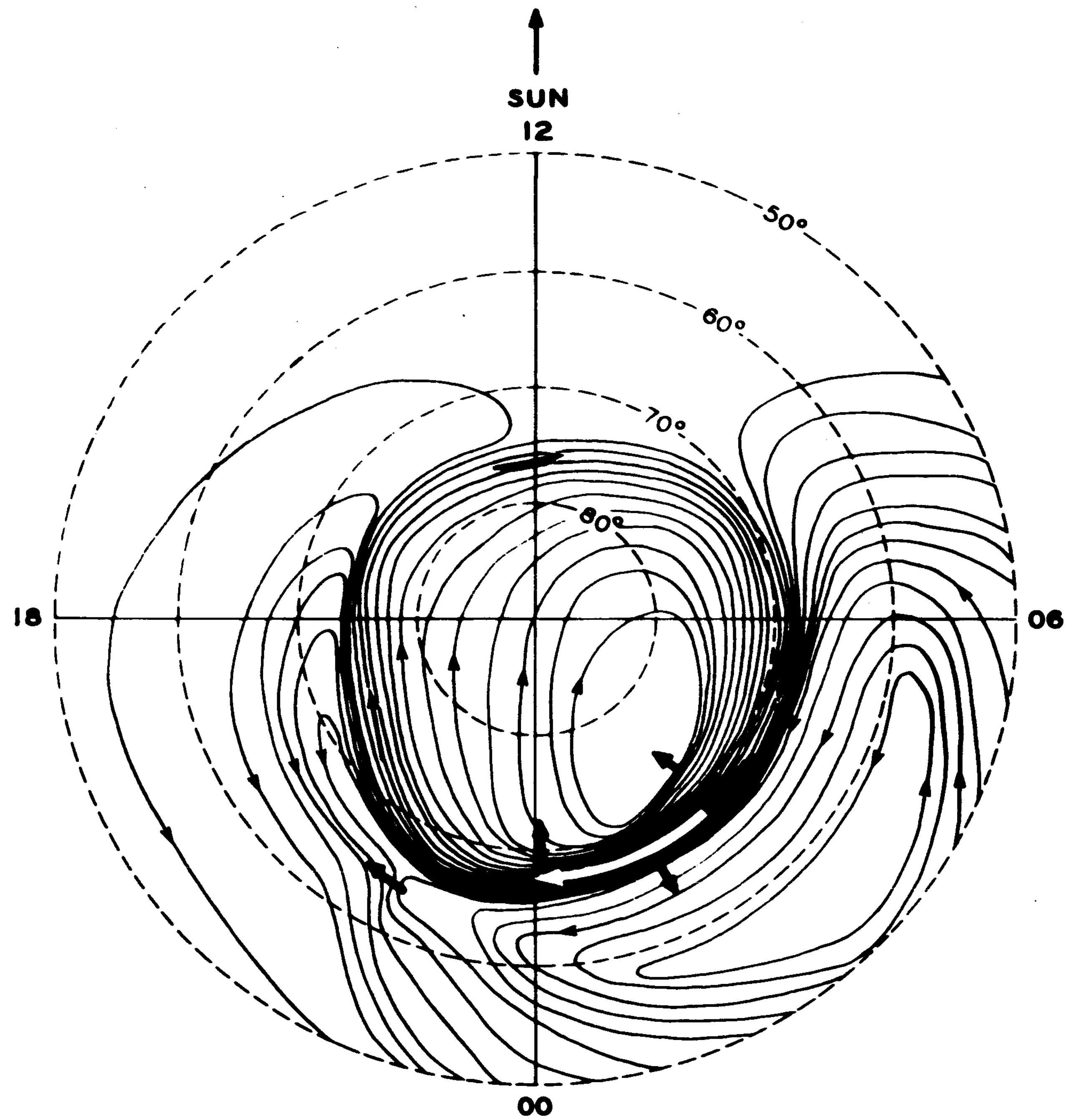


Figure 4.12

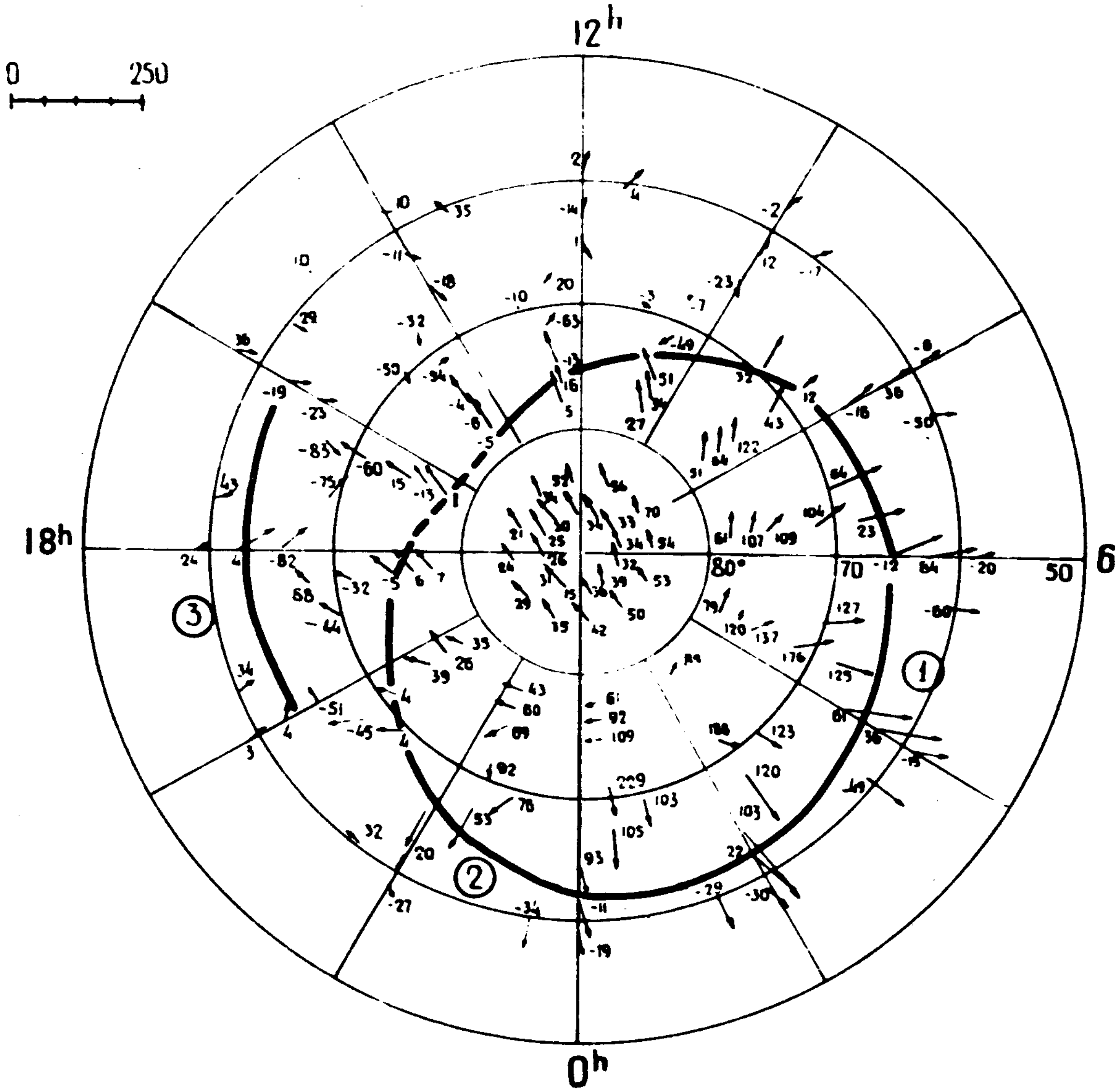


Figure 4.13

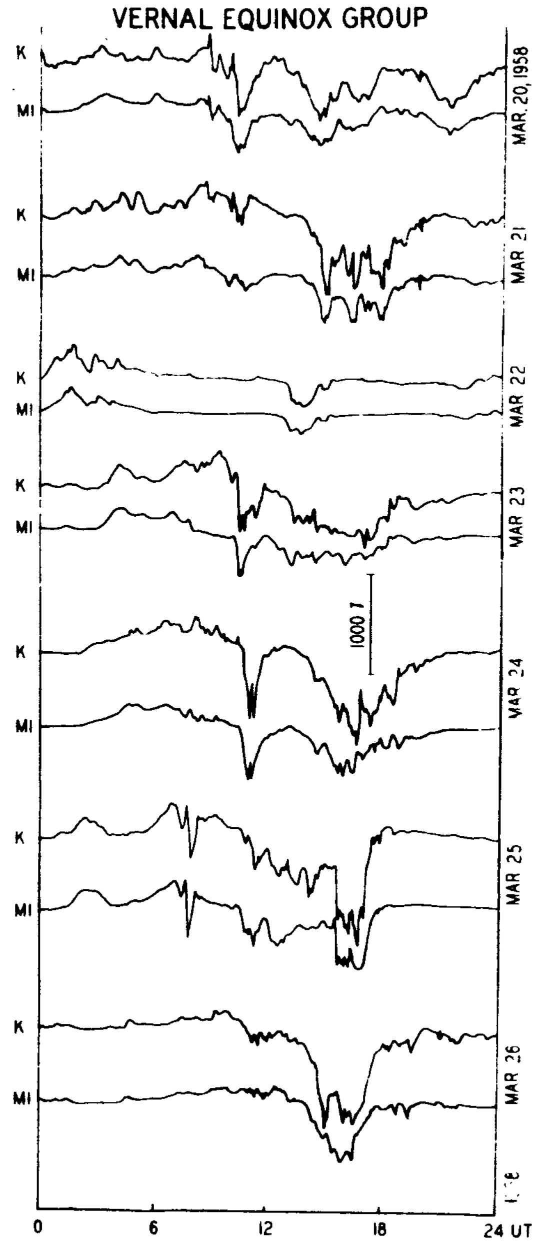

VERNAL EQUINOX GROUP
K
MI
MAR. 20, 1958
MAR 21
MAR 22
MAR 23
MAR 24
MAR 25
MAR 26
1000 γ
0
6
12
18
24 UT

Figure 4. 14

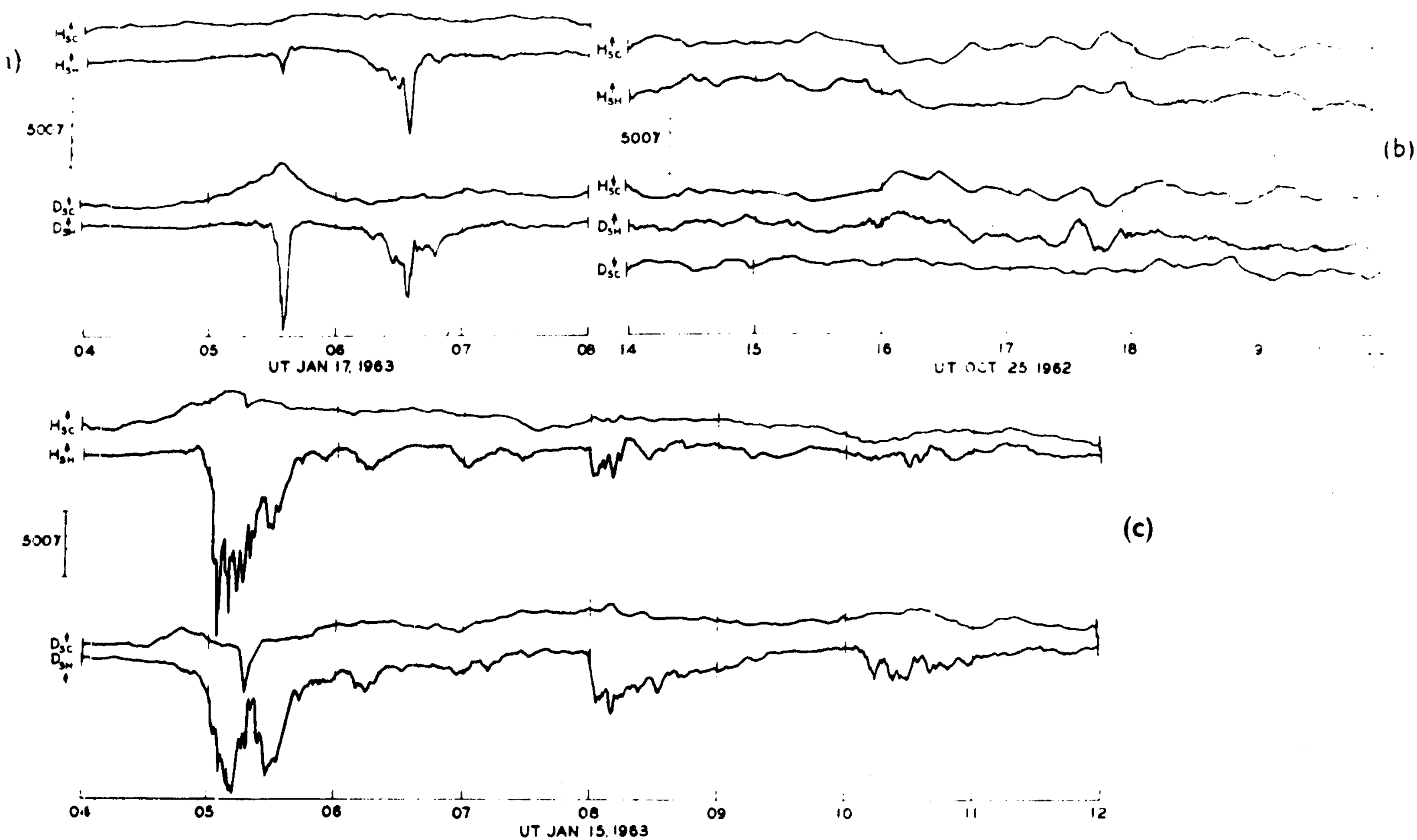


Figure 4.15

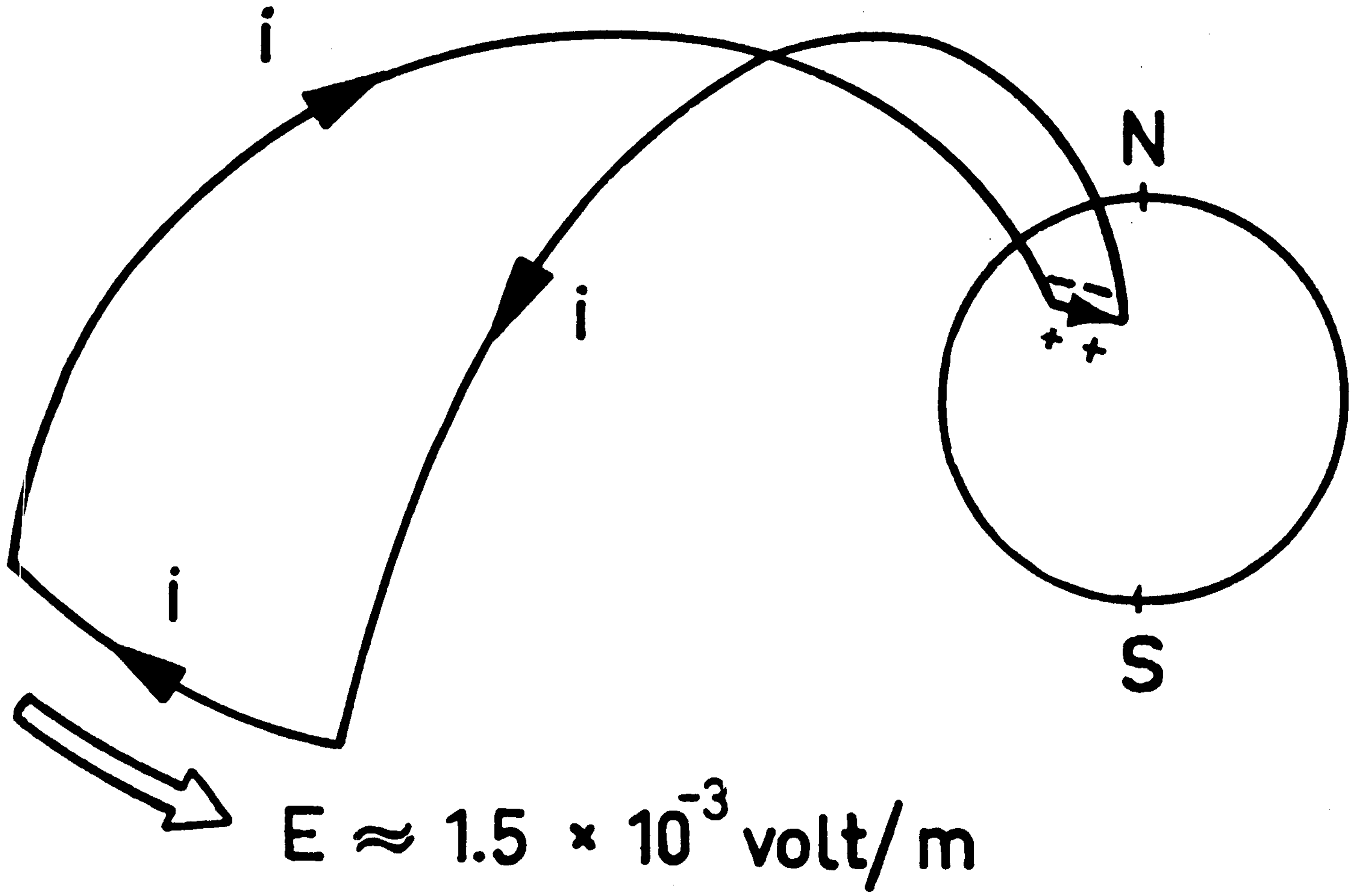


Figure 4. 16 (a)

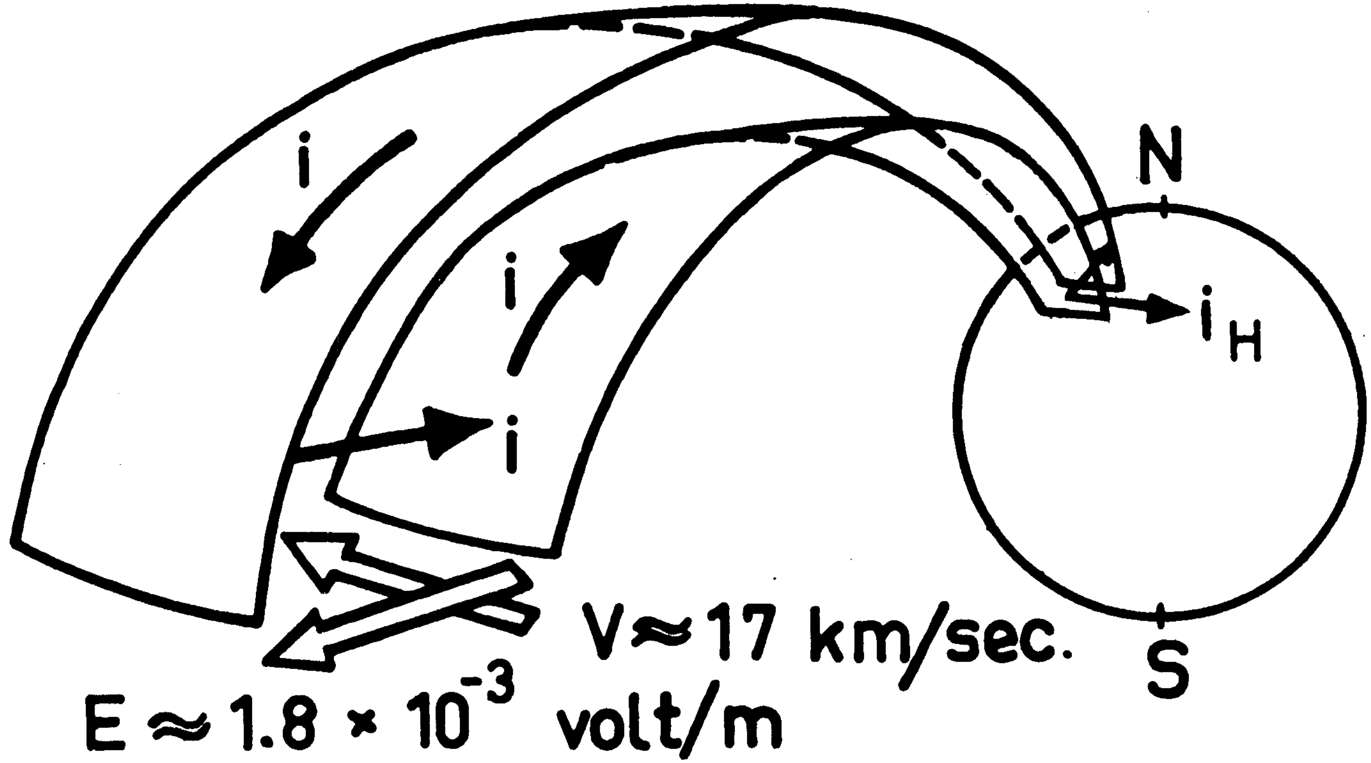


Figure 4.16 (b)

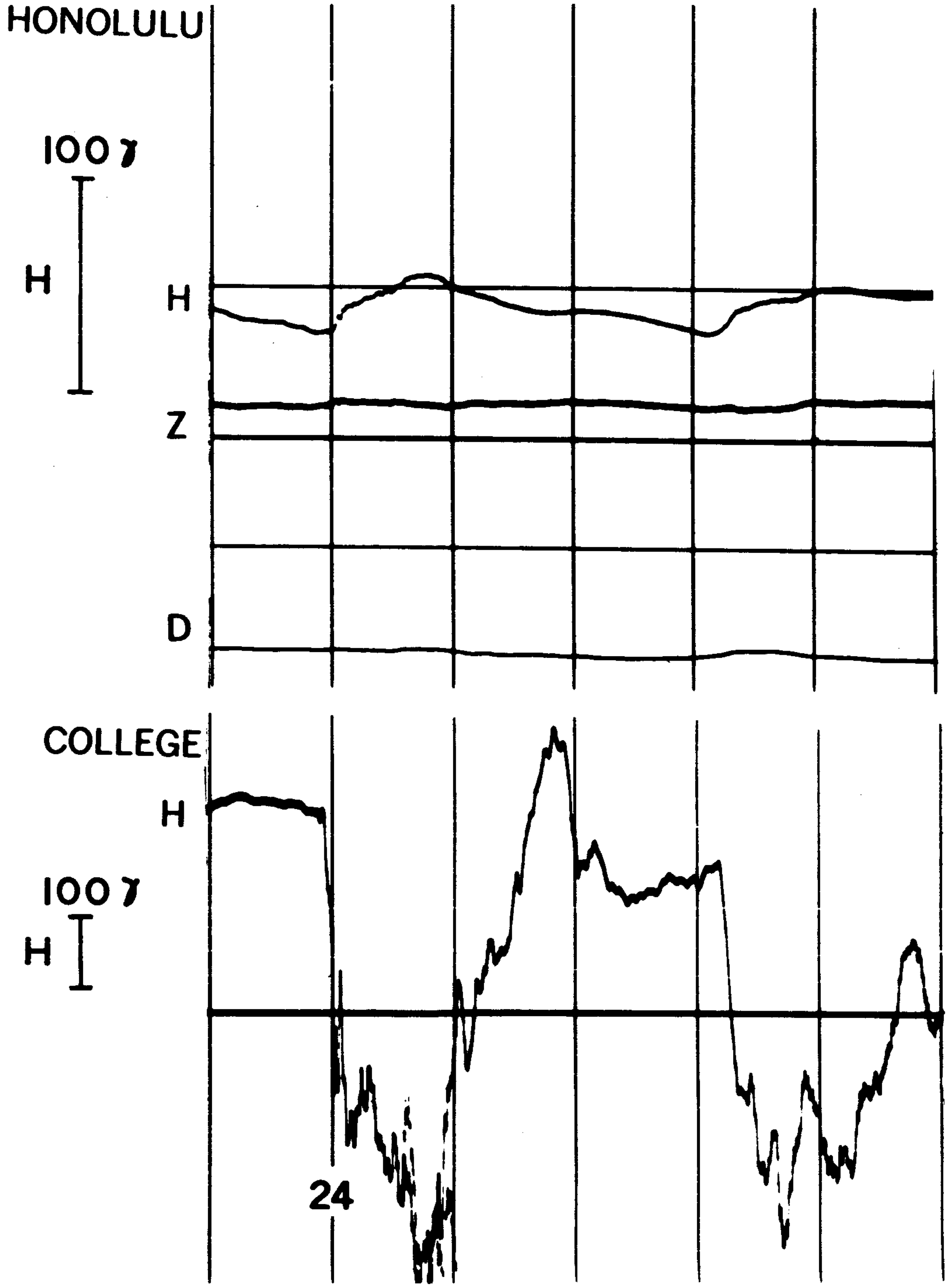


Figure 4.17

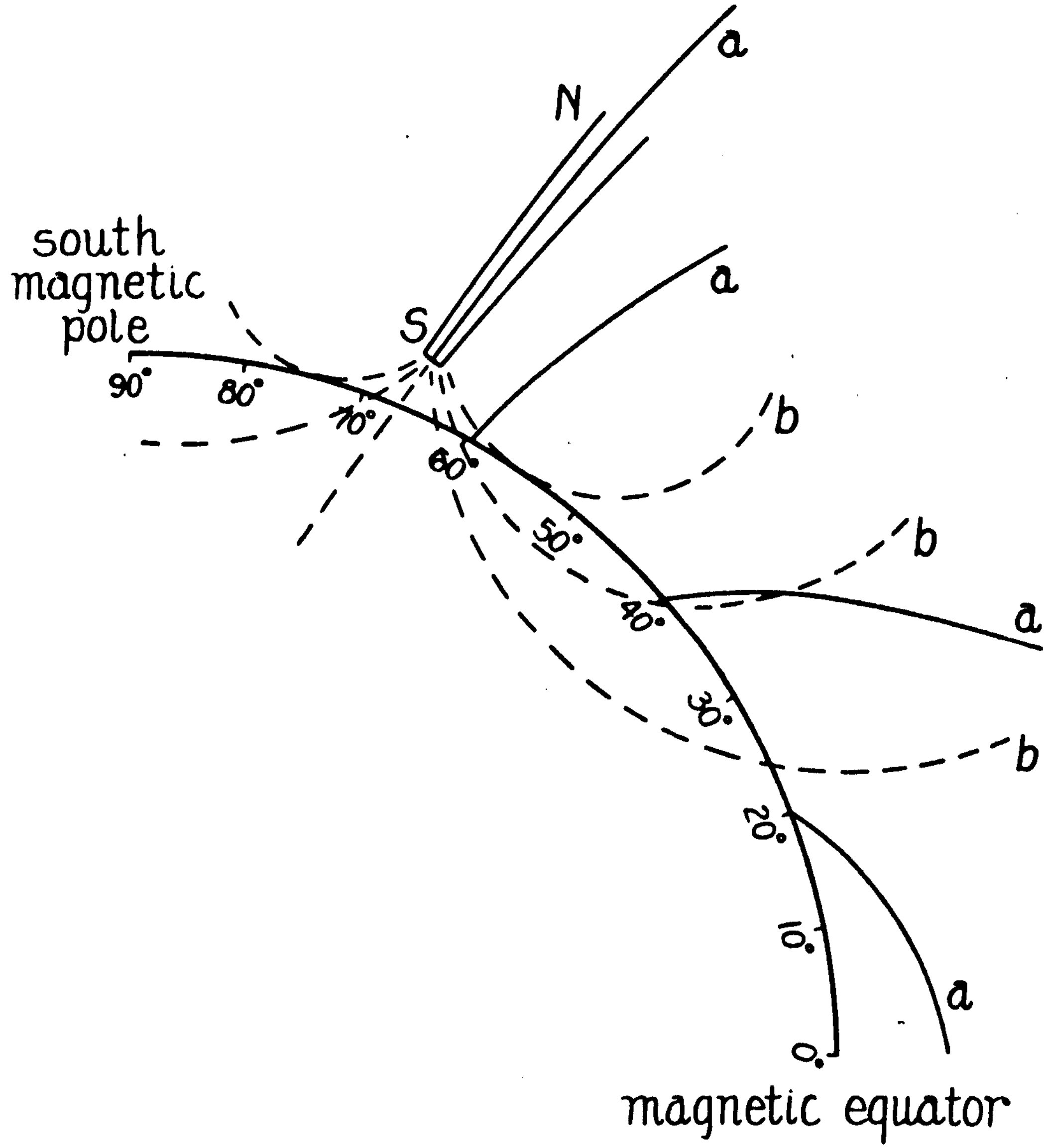

south magnetic pole
N
S
a
a
a
a
b
b
b
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
magnetic equator

Figure 4.18

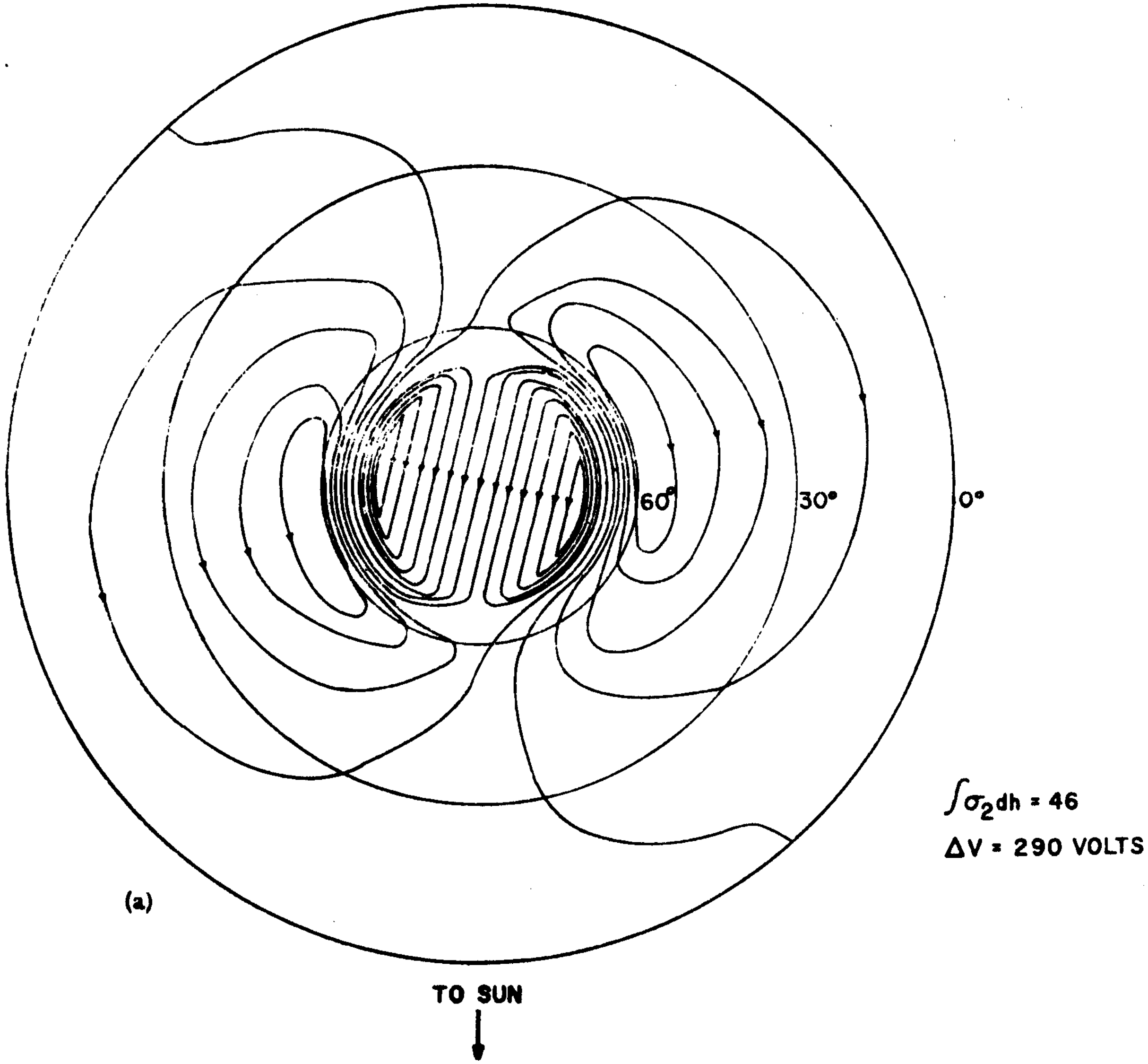


Figure 4.19

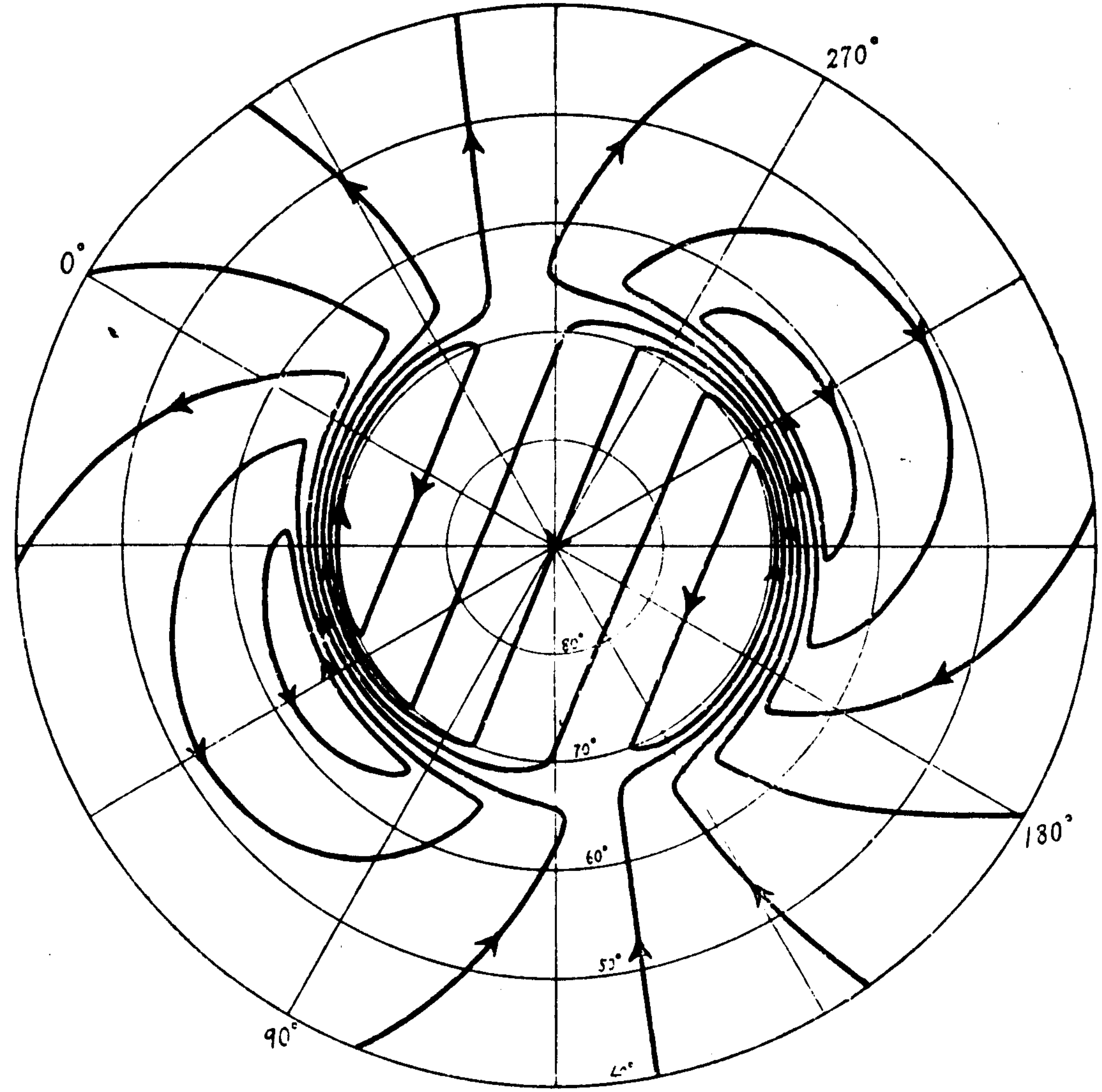


Figure 4.20

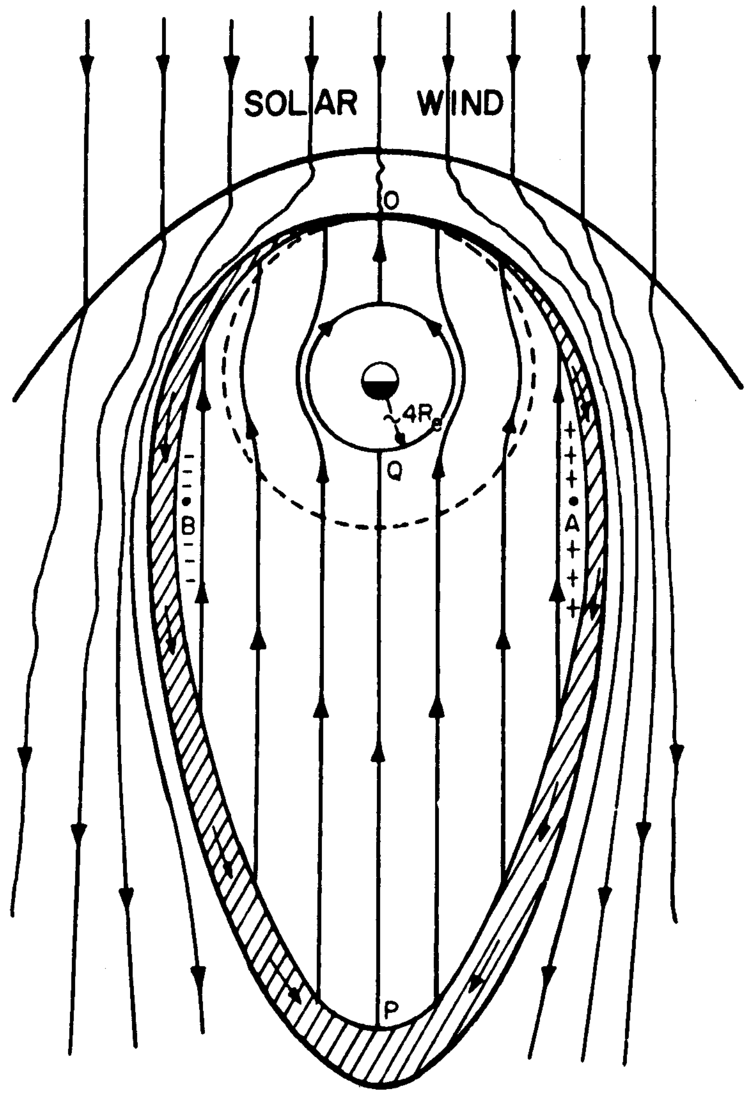


Figure 4.21 (a)

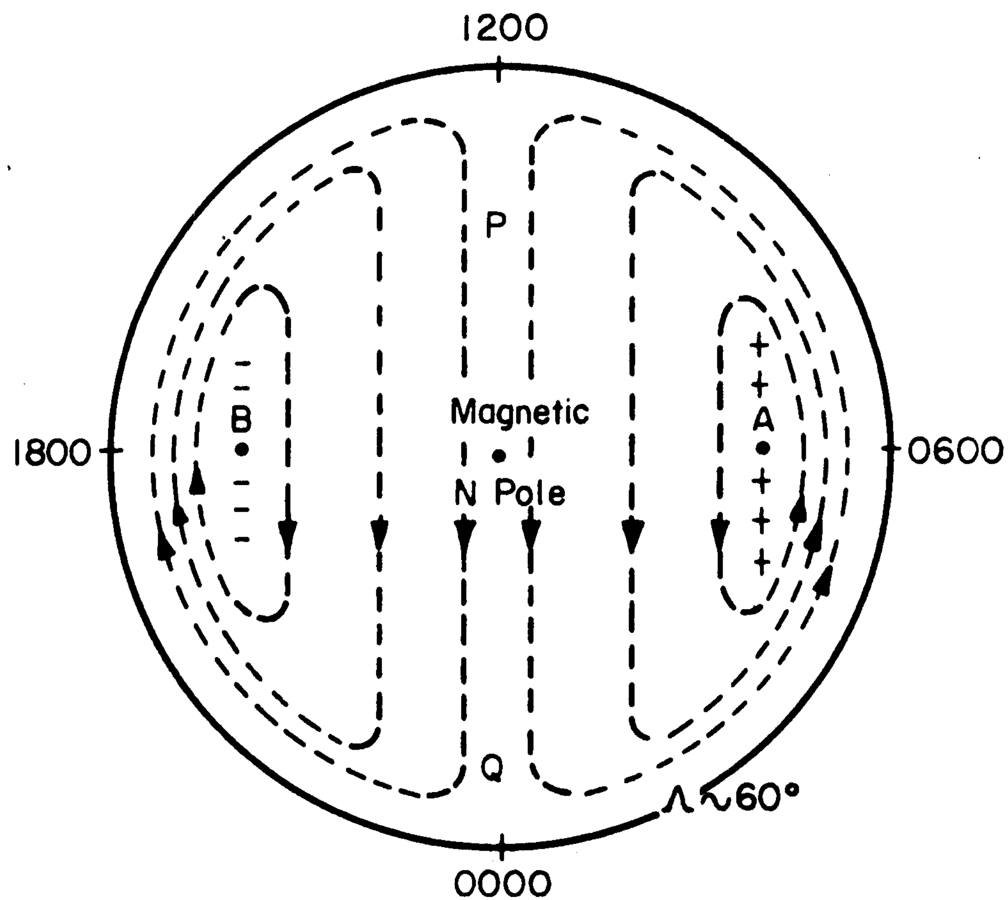


Figure 4.21 (b)

G 66-358

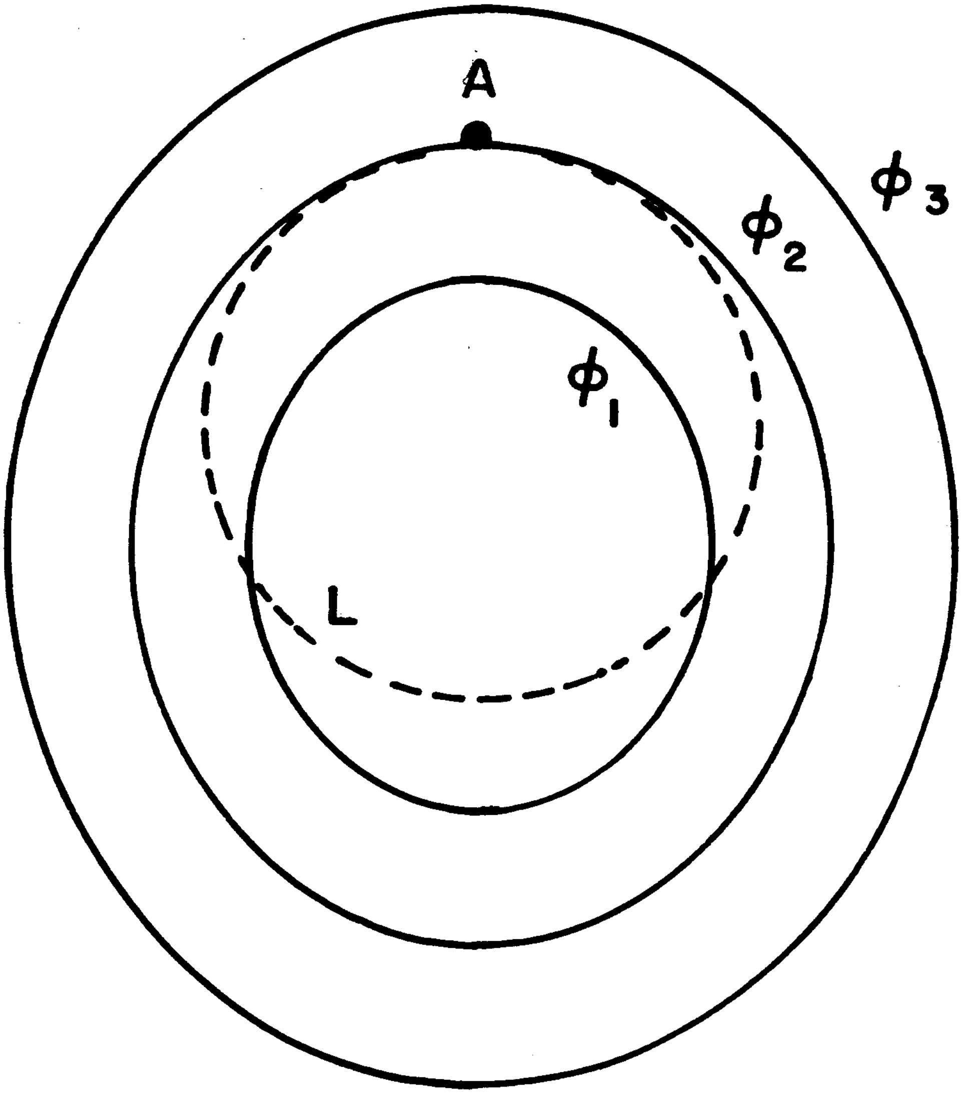


Figure 4.22

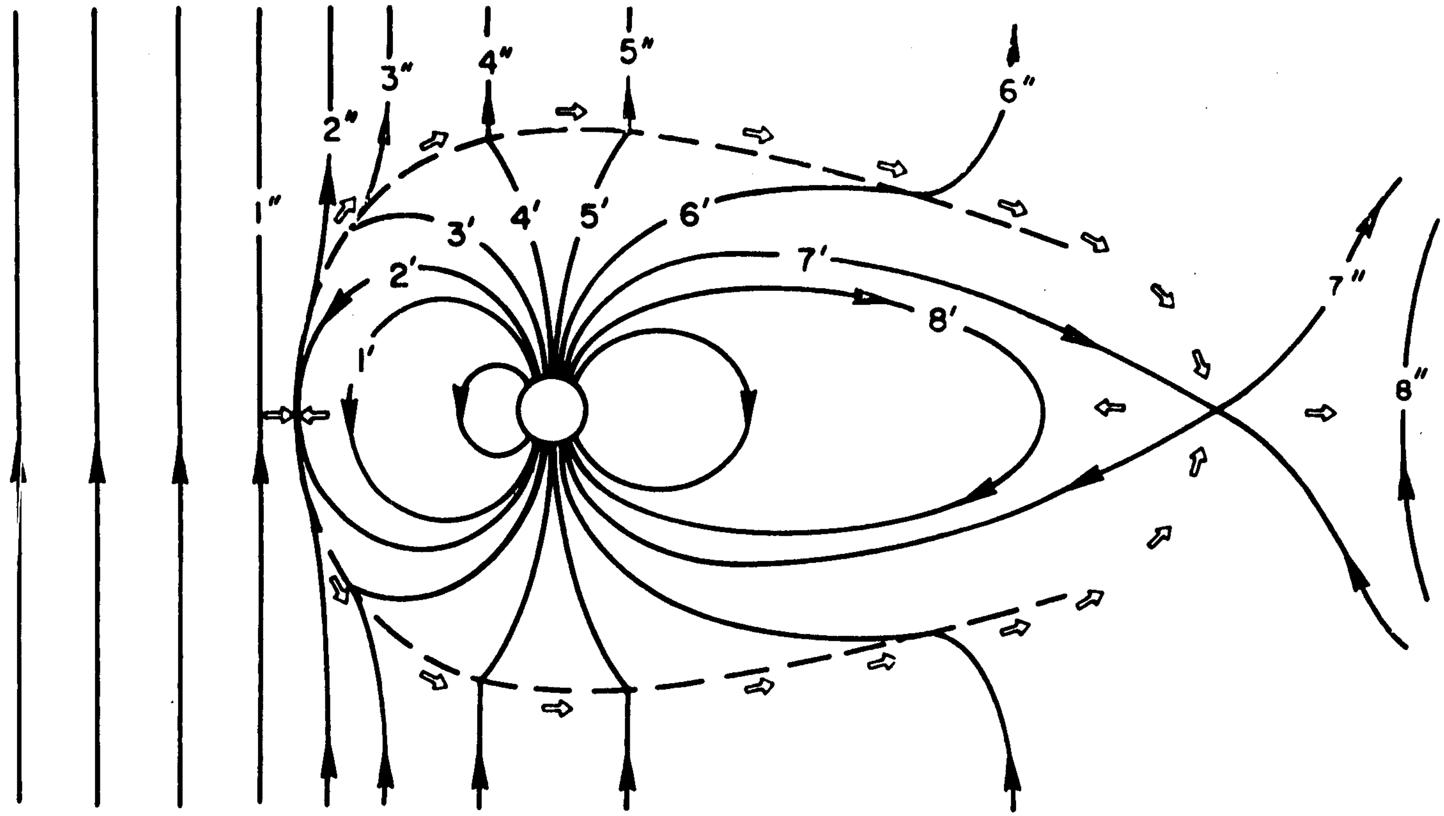


Figure 4.23

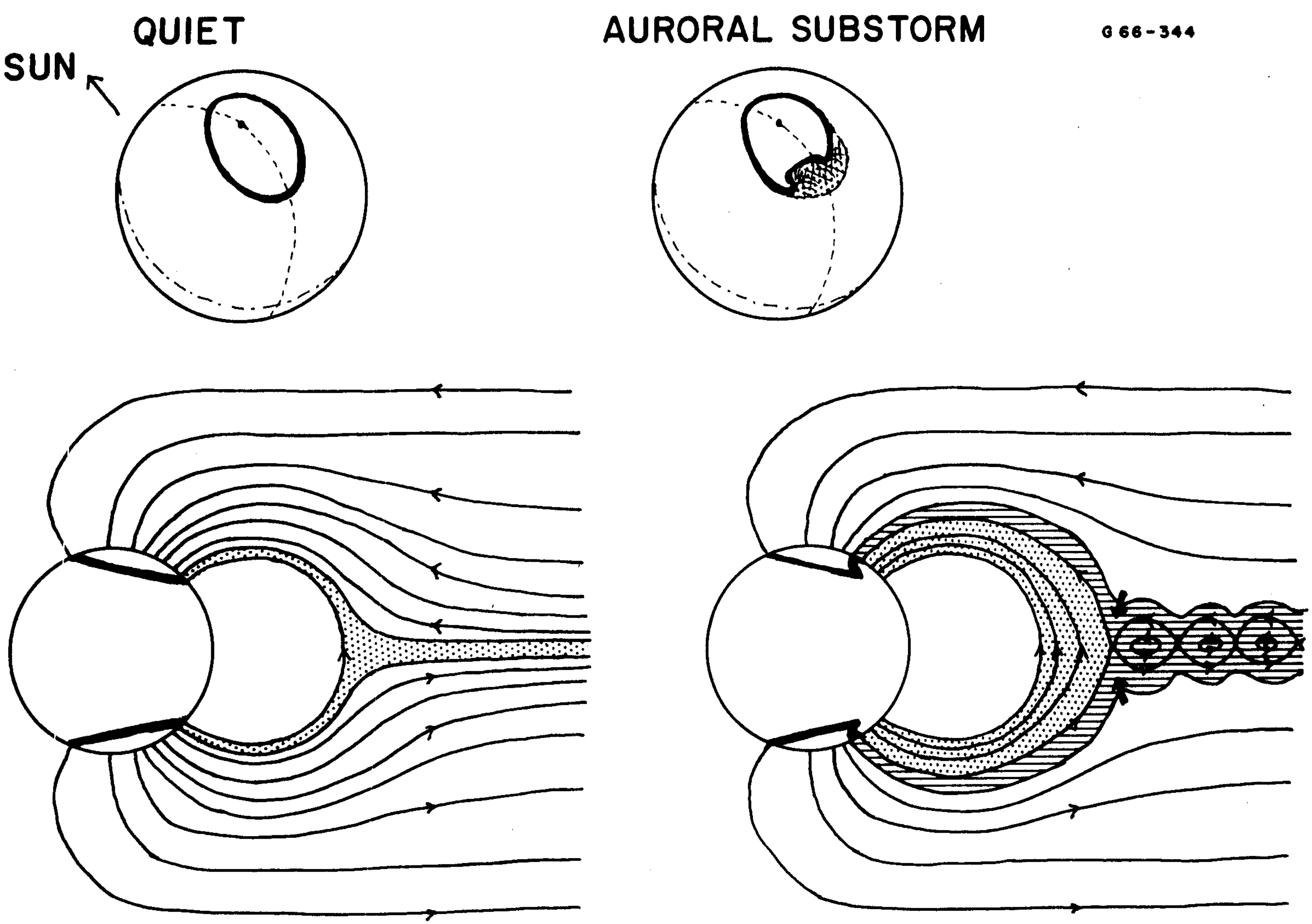


Figure 4.24

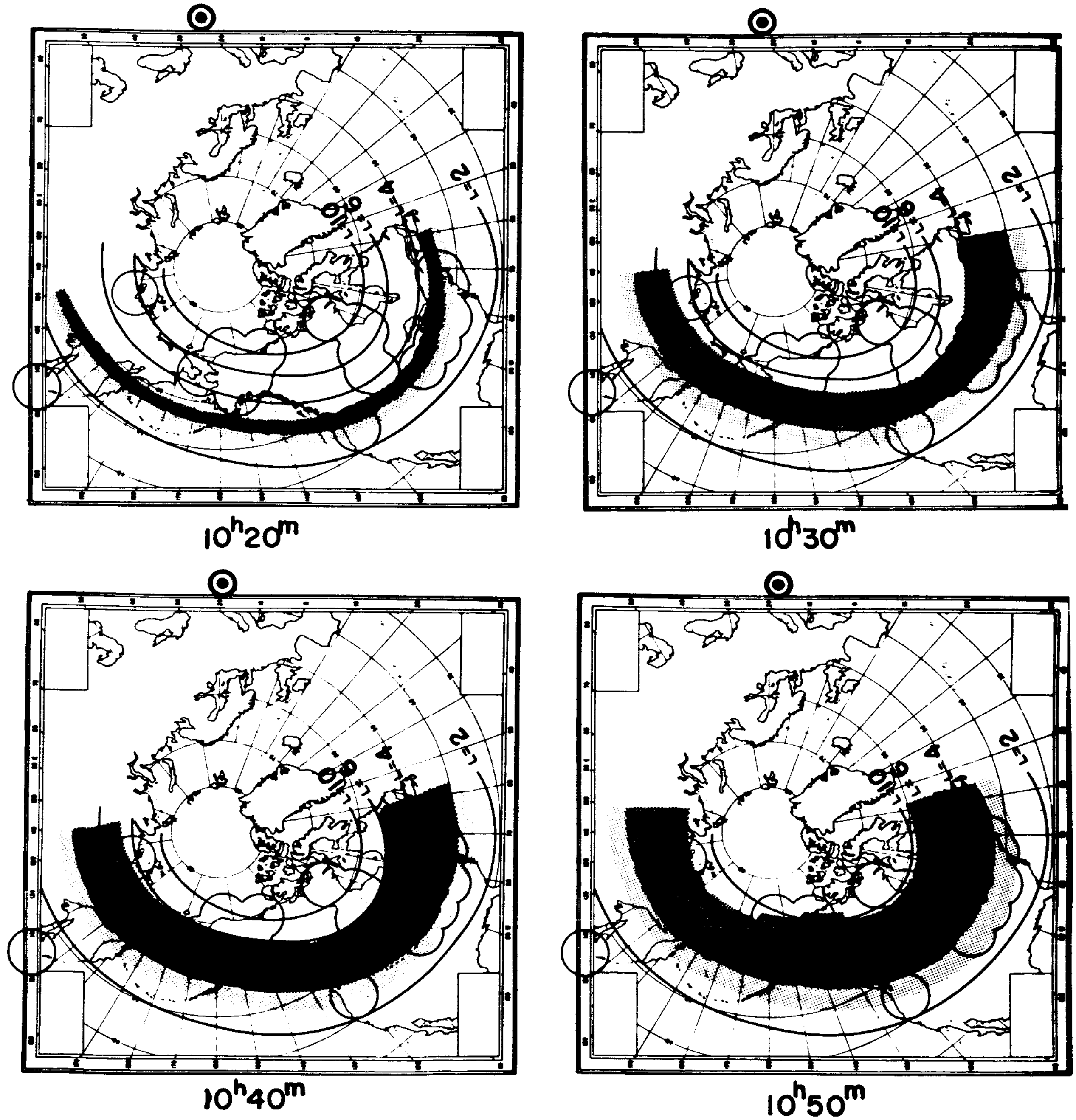


Figure 4.25

G 66-336

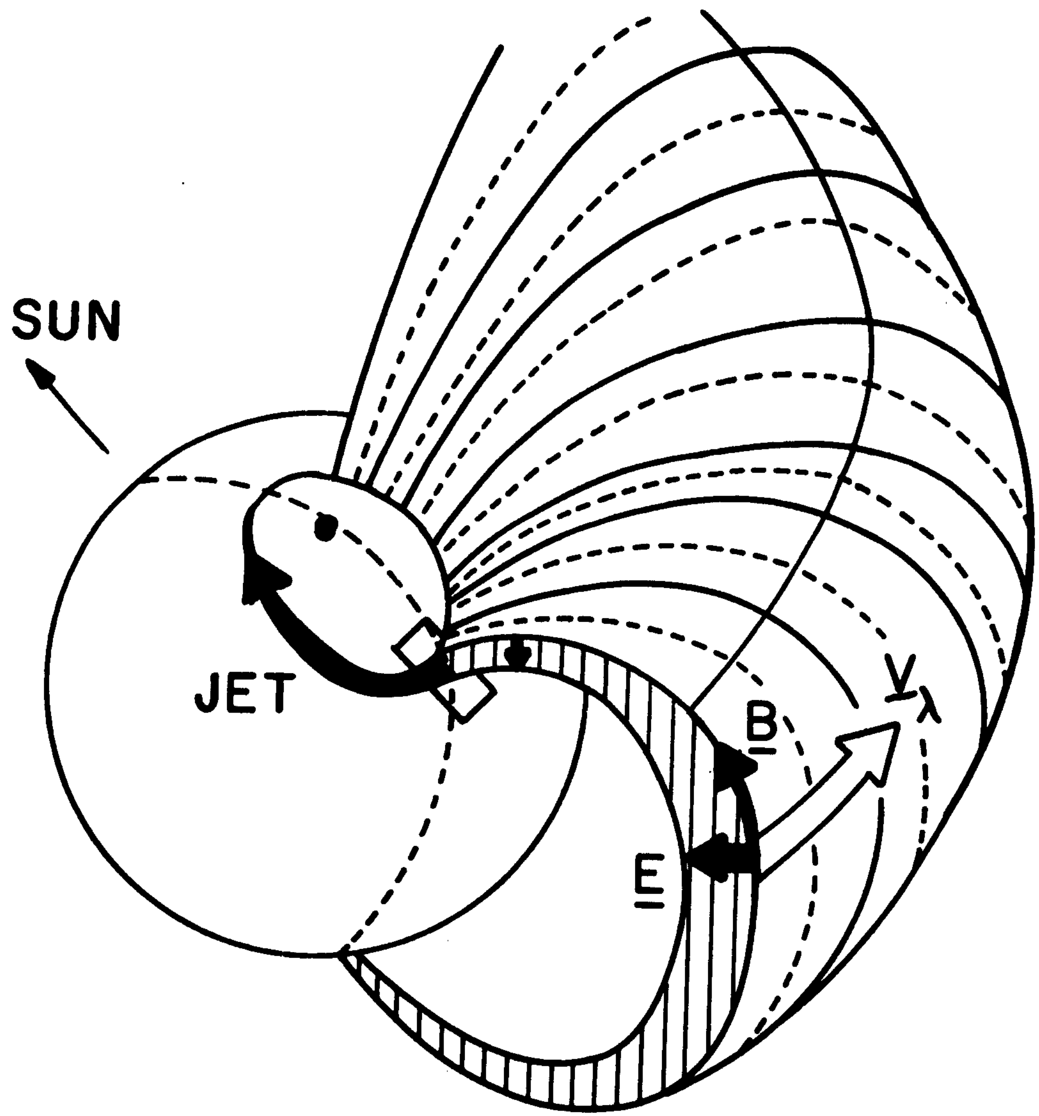


Figure 4.26

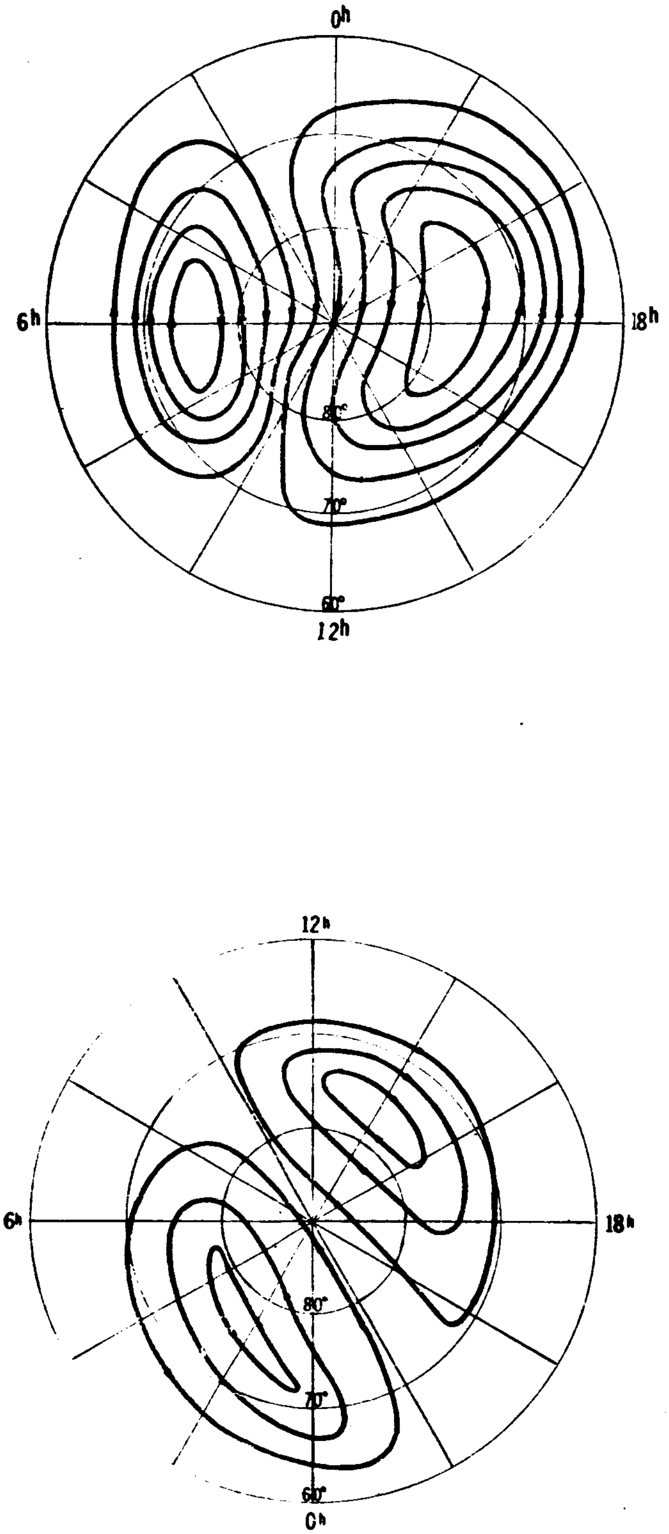


Figure 4.27

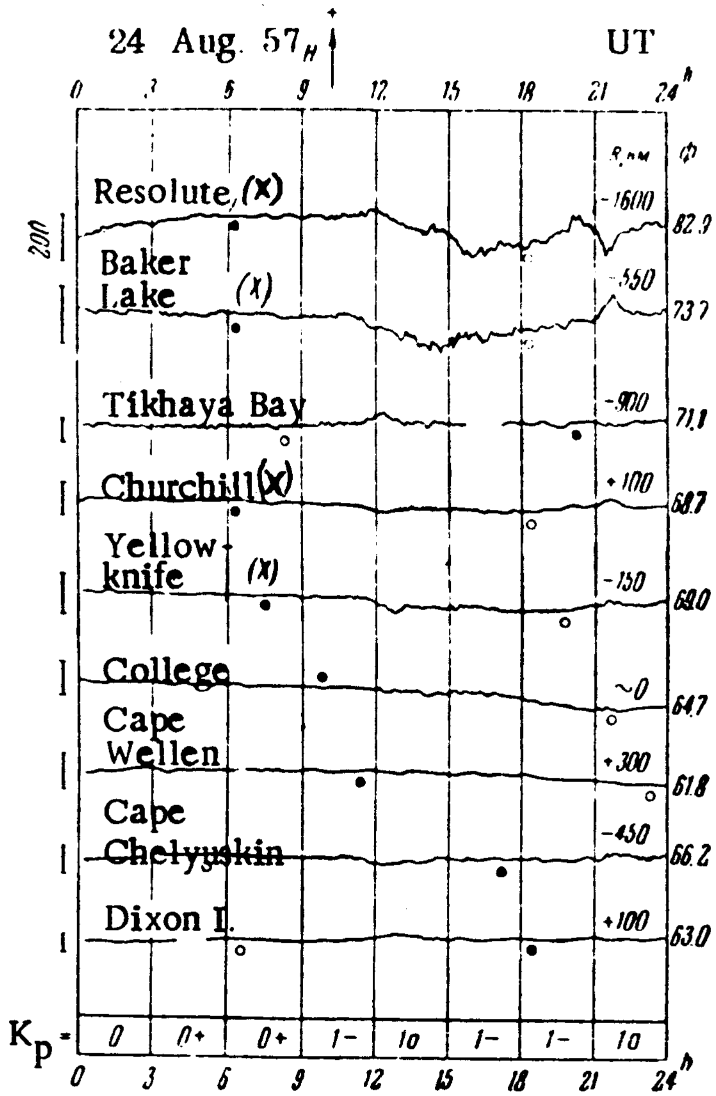
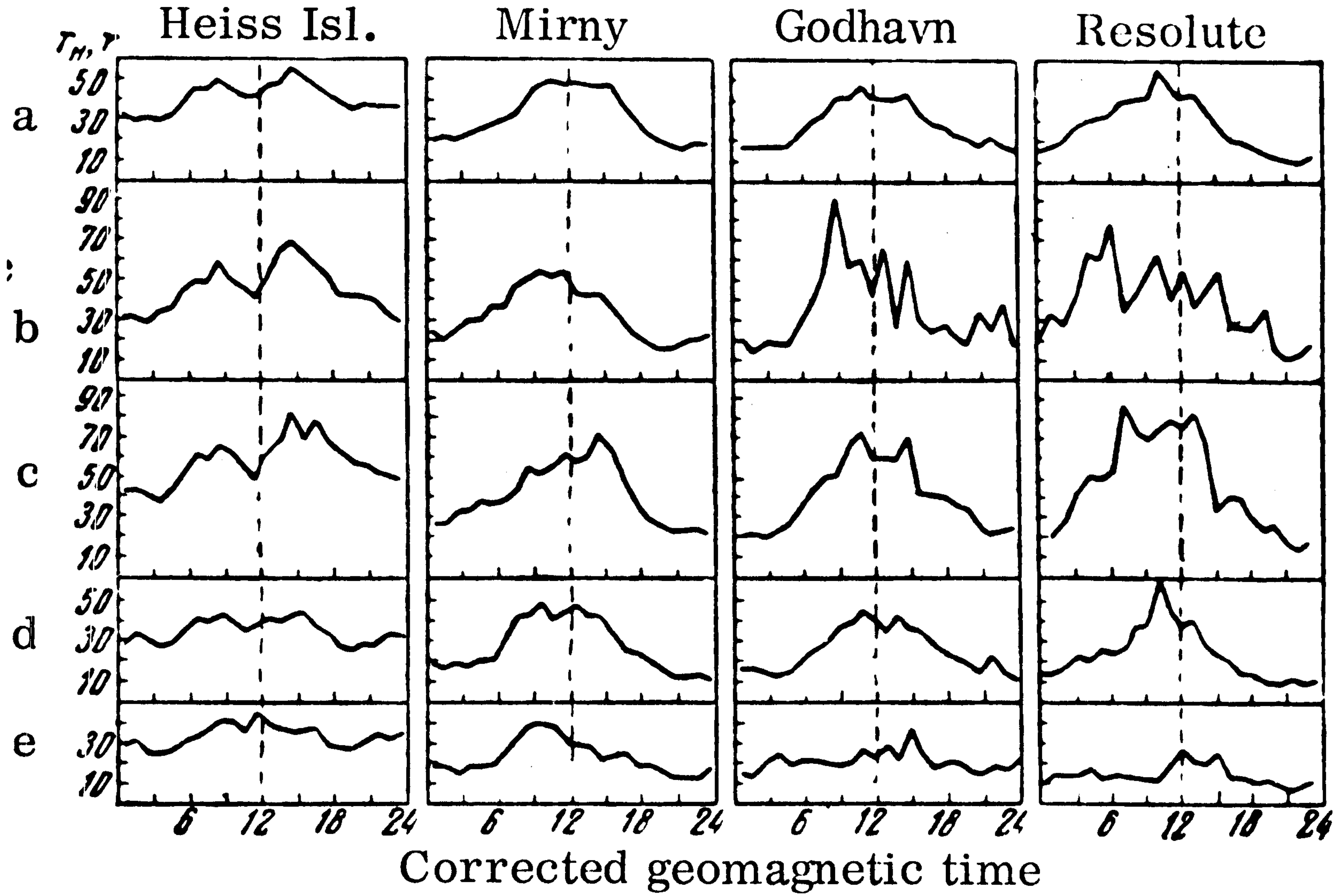

24 Aug. 57
UT
0 3 6 9 12 15 18 21 24
Resolute (X)
-1600
82.9
Baker Lake (X)
-550
73.7
Tikhaya Bay
-900
71.1
Churchill (X)
+100
68.7
Yellowknife (X)
-150
69.0
College
~0
64.7
Cape Wellen
+300
61.8
Cape Chelyuskin
-450
66.2
Dixon I.
+100
63.0
Kp =
0
0+
0+
1-
1o
1-
1-
1o
0 3 6 9 12 15 18 21 24

Figure 4.28



Heiss Isl.
Mirny
Godhavn
Resolute
T_H, γ
a
b
c
d
e
50
30
10
90
70
6
12
18
24
Corrected geomagnetic time

Figure 4.29

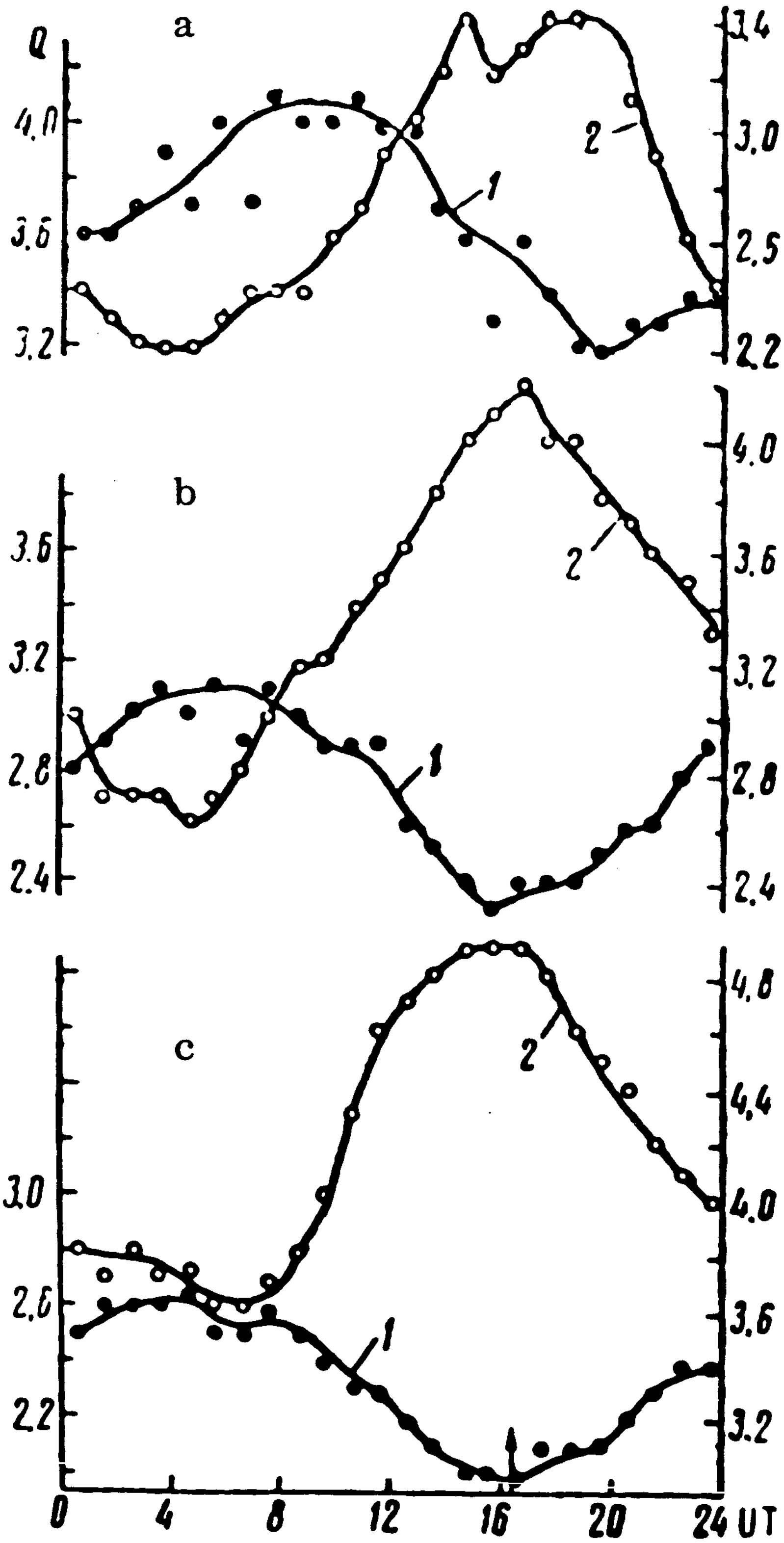

a
b
c
Q
4.0
3.6
3.2
3.4
3.0
2.5
2.2
1
2
3.6
3.2
2.8
2.4
4.0
3.6
3.2
2.8
2.4
3.0
2.6
2.2
4.8
4.4
4.0
3.6
3.2
0
4
8
12
16
20
24 UT

Figure 4.30

ACKNOWLEDGEMENT

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