CONF-8310229--5

LA-UR--83-3361

DE84 003833

TITLE Plasma Sheet Behavior During Substorms

AUTHOR(S) F.W. Hones, Jr.

[illegible] Proceedings of Chapman Conference on Magnetic Reconnection held in Los Alamos, October 3-7, 1983

MASTER

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

PLASMA SHEET BEHAVIOR DURING SUBSTORMS

Edward W. Hones, Jr.

University of California, Los Alamos National Laboratory

Los Alamos, NM 87545

Abstract

Auroral or magnetic substorms are periods of enhanced auroral and geomagnetic activity lasting one to a few hours that signify increased dissipation of energy from the magnetosphere to the earth. Data acquired during the past decade from satellites in the near-earth sector of the magnetotail have suggested that during a substorm part of the plasma sheet is severed from earth by magnetic reconnection, forming a "plasmoid," i.e., a body of plasma and closed magnetic loops, that flows out of the tail into the solar wind, thus returning plasma and energy that have earlier been accumulated from the solar wind. Very recently this picture has been dramatically confirmed by observations, with the ISEE 3 spacecraft in the magnetotail 220 R_E from earth, of plasmoids passing that location in clear delayed response to substorms. It now appears that plasmoid release is a fundamental process whereby the magnetosphere gives up excess stored energy and plasma, much like comets are seen to do, and that the phenomena of the substorm seen at earth are a by-product of that fundamental process.

Introduction

The solar wind carries energy away from the sun continually in the form of rapidly flowing, fully ionized hydrogen plasma. This is threaded with "frozen in" solar magnetic field which is stretched out by the flowing plasma and which is referred to as the interplanetary magnetic field (IMF). Typical values of solar wind parameters at the orbit of the earth are: density $\approx 10/\text{cm}^3$; flow speed $\approx$ 450 km/sec; magnetic field strength $\approx$ 10 nanoteslas. These constitute a particle flux of $\sim 4.5 \times 10^8/\text{cm}^2$-sec, a kinetic energy flux of roughly 1 erg/cm^2-sec, and a magnetic energy flux of $\sim 10^{-2}$ erg/cm^2-sec. All large-scale objects orbiting the sun encounter this continual flow of matter and energy and, because of the cohesive influence of the IMF, they can restrain, locally, the solar wind's flow and thereby store solar wind plasma and energy in their "magnetospheres." The magnetospheres of those planets having substantial intrinsic magnetic fields (e.g., Mercury, Earth, Jupiter, Saturn) are formed by tangential stresses that the solar wind applies as it gives up momentum to the outer regions of those fields, stretching them downstream to form long comet-like "magnetotails." The magnetospheres of comets and of planets that lack a substantial intrinsic field (e.g., Venus) are formed by the slowing down or "hanging-up" of the IMF by mass loading with cometary or planetary ions or by interaction with their conducting ionospheres.

Storage of energy cannot continue indefinitely and the magnetospheres must, either continually or intermittently, release stored energy and plasma to their parent body or back to the solar wind. In the case of comets, large releases of energy to the solar wind occur intermittently, simply by the comet's discarding part or all of its plasma tail. This process, illustrated in Figure 1, is thought to occur by magnetic reconnection (see the paper by M. B. Niedner, Jr., in this volume). In Figure 1, even as the detached tail of comet Morehouse drifts downstream in the solar wind, a new tail is seen to be forming as lines of the IMF fold around the comet's head. It is reasonable to ask whether the magnetosphere of the earth may also rid itself, intermittently, of excess energy and plasma in this way; and, indeed, there is very good evidence that it does. This evidence, gained during the past decade, largely from satellite measurements of particles, plasmas, and fields in the outer magnetosphere, suggests very strongly that during "substorms" the earth's magnetosphere spontaneously divests itself of a substantial portion of the "plasma sheet" that extends across the midplane of its magnetotail. In fact it now appears that this is the basic underlying physical process in a substorm, i.e., the magnetotail getting rid of stored plasma and energy that it can no longer restrain.

This paper will describe the evidence mentioned above, discussing first that obtained during the past decade from satellites orbiting relatively close to the earth and concluding with a discussion of some remarkable observations, made very recently with the ISEE-3 satellite far out in the magnetotail, of plasmoids, i.e., detached portions of the plasma sheet, flowing out of the magnetotail into the downstream solar wind.

Auroral and Magnetic Substorms

The auroras that regularly light the night skies of the northern and southern polar regions of the earth have been an object of amazement and great interest to man throughout recorded history. Over the centuries, many men of science, famous for their contributions to philosophy, mathematics, chemistry, and physics, have puzzled, also, about the aurora. For example the name, aurora borealis (northern dawn), is said to have been first used by Galileo in 1616. Edmund Halley, in 1716, was the first to suggest some relationship between auroras and the earth's magnetic field. But modern understanding of the auroras began in the late nineteenth and early twentieth centuries with extensive observational and theoretical work such as that of Birkeland and Stormer that showed the auroras to be caused by charged particles, guided by the earth's magnetic field, bombarding the upper atmosphere. (See Eather, 1980, for an excellent description of auroras and the development of our understanding of them from antiquity up to modern times.)

The International Geophysical Year (IGY) of 1957-1958 brought globally-organized research efforts, along with modern rocket and satellite technologies, to bear on geophysics problems, with a strong focus on auroral and magnetospheric research. Widespread networks of all-sky cameras and magnetometers were established to study the large-scale space and time variations of auroras and their associated magnetic signatures. Using data from these, Akasofu (1964) identified a sequence of systematic and characteristic auroral displays which he called an "auroral substorm." Quiet auroras which lie along the auroral oval are intermittently activated. It is at these times that bright, active, and spectacular auroral displays are seen. This activation generally originates near local midnight and rapidly spreads to earlier and later local times and to higher latitudes. The substorm reaches its peak in a rather short time (10-20 minutes) and gradually subsides. The auroral activation is accompanied by substantial (as great as 1 to 2 percent) variations of the local surface geomagnetic field, called "magnetic bays" and thus the name "magnetic substorm" is sometimes applied to these intervals of auroral and magnetic activation. On some days (called "quiet days") there may be only a very small number of substorms (or none) identified. But "active days" are more usual, and then substorms occur every few hours.

The Reconnection Model of Substorms

The advent of scientific spacecraft brought observations of plasmas, particles, and fields in distant space around the earth without which our understanding of substorms could not have gone much beyond simply their identification. The existence and general character of the earth's magnetotail were first fully recognized by Ness (1965) in magnetic data returned by the earth satellite Imp 1. The plasma sheet that carries the cross-tail electric current was discovered by Bame et al. (1967) with a plasma probe on the earth satellite Vela 2B. It was found, soon after these basic structural features were ascertained, that certain variations of the magnetotail and of its plasma and particle populations characteristically accompany substorms. As a result of these latter discoveries, the substorm quickly assumed a central role in magnetospheric physics, as a phenomenon that ordered a wide variety of outer magnetospheric observations and that thus seemed a fundamental part of the magnetosphere's functioning and required a physical explanation. Unfortunately, but perhaps not surprisingly, the complexity of such a global phenomenon and the relatively incomplete observational coverage of it that can be gained from limited numbers of ground stations sometimes make the substorm's identification imprecise. Nevertheless, the studies of magnetospheric dynamics over the past 16 years, with the substorm as a focus, have achieved a quite satisfactory understanding of the macroscopic aspects of the solar wind-magnetosphere interaction in terms of magnetic reconnection, including a reconnection model of substorms.

A full discussion of the reconnection model of substorms and of its

its substorm variations. We shall do so by first examining plasma sheet phenomena observed with Imp 8 satellite during a substorm on October 8, 1974, and then offering an explanation for these phenomera in terms of the reconnection model. The geomagnetic signature of the substorm was the 800 nT magnetic bay shown in the magnetometer record from the near-midnight Russian station, Dixon (Figure 2). Its onset at 18:27 UT was very sharp. It began to recover after its peak at ~19:05 UT and was rapidly recovering by 19:30 UT. This variation of the geomagnetic field was caused by a sudden "turning-on" of an intense westward current (called a westward electrojet) in the ionosphere above Dixon. Examination of records from other near-midnight stations revealed that the electrojet started nearly simultaneously over a several-hour extent in local time along the auroral oval. The electrojet resulted from diversion of part of the magnetotail's dawn-to-dusk cross-tail current along magnetic field lines into the ionosphere (McPherron et al., 1973).

At the time of this substorm Imp 8 satellite was in the magnetotail about 32 R_E from earth, very near local midnight and about 2 R_E below (southward of) the estimated location of the magnetic midplane of the tail. Data from the satellite are shown in Figure 3 where the onset time of the substorm (18:27 UT) is marked by a dashed vertical line. Coincident with the bay onset the plasma began to flow tailward and the energetic electron flux rose suddenly above background. The magnetic field latitude first turned northward and then, at 18:28:45 UT it turned steeply southward. At 18:29:20 UT a dropout of plasma started (indicated by the rapid reduction of plasma electron energy density, U). A particularly important aspect of these data is that the energetic electrons were essentially isotropic when they first appeared at 18:27 UT and for about 4 minutes longer. Then, at 18:31 UT they suddenly began to display a pronounced tailward-streaming distribution, indicating that the satellite became enveloped at that instant by magnetic field lines that opened tailward (Baker and Stone, 1976).

From 18:29 UT until 19:06 UT the field latitude was mostly southward, becoming approximately zero at times when Imp 8 was largely outside the plasma sheet, as indicated by low values of U (e.g., 18:31-18:35 UT and 18:57-19:06 UT). Also, the plasma flow continued to be tailward and the energetic electron flux was low but streaming tailward when measurable. At 19:06 UT, when the bay at Dixon had begun showing rapid recovery, the field latitude became primarily northward, plasma flow turned earthward, and the energetic electron flux became more intense and isotropic.

The interpretation of these data is depicted schematically in Figure 4 where midnight meridian plane projections of the plasma sheet are shown at several sequential times. (A dot represents the Imp 8 location at ~32 R_E from earth.) The processes depicted there do not prevail over the whole width of the plasma sheet but over perhaps the central one-half of its width. A "substorm neutral line" or X-line, N′, forms in the near-earth sector of the plasma sheet at substorm onset (panel 2). Magnetic reconnection occurring there causes fast jetting of plasma earthward and tailward. The earthward jetting plasma flows down field lines to the ionosphere where it creates the auroras. The tailward jetting plasma constitutes the tailward flow sensed by Imp 8 starting at 18:27 UT. The reconnection continuing in panels 3 and 4, creates a structure of closed magnetic loops, and in panel 5 the last closed field line of the pre-substorm plasma sheet is pinched off by reconnection, leaving the plasma sheet magnetically detached from earth. Panels 6 and 7 show this detached plasma sheet, now a free "plasmoid," accelerating tailward under the influence of pre-existing plasma pressure gradients and of lobe field lines (lines 6 and 7) which reconnected after its detachment and are contracting tailward. In panels 6 and 7 the center of the plasmoid, the magnetic O-line, approaches and passes Imp 8 and this causes the change from positive to negative magnetic field latitude seen at 18:28:45 UT. In panels 7 and 8 the trailing edge of the plasmoid approaches and passes Imp 8 and this causes the plasma dropout that begins at 18:29:20 UT and that soon thereafter results in Imp 8's exit from the closed loops of the plasmoid to the later-reconnected field lines that envelop it. The exit from the plasmoid is indicated at 18:31 UT by the appearance of a tailward-streaming population of energetic electrons.

In panel 9 the satellite is shown near a very thin plasma sheet, downstream from the substorm X-line, which has remained at the near-earth location of its initial formation. In this thin downstream plasma sheet one expects to find plasma flowing tailward from the X-line, threaded with open field lines having southward latitude where they cross the midplane. And indeed, these are the conditions found in the Imp 8 data from ~18:35 UT to ~18:56 UT, where frequent neutral sheet crossings are indicated by the fluctuations of field longitude, the field latitude is predominantly southward, tailward plasma flow prevails, and the energetic electrons stream tailward, indicating open field lines.

Panel 10 shows the X-line, N′, at a new distant location N″, and the plasma sheet of closed field lines thickening over the satellite earthward of N″. These are the conditions that were seen in the Imp 8 data starting at ~19:03 UT after an ~11 minute plasma dropout. The field latitude is predominantly northward, the plasma flow is earthward, the energetic electrons become isotropic, indicating closed field lines, and their intensity builds up (because they are now on earth-tied closed field lines and can no longer escape).

The picture that evolves from the above discussion of data from the 18:27 UT substorm on October 8, 1974 is that, starting precisely at the substorm's onset, as observed at earth, the process of magnetic reconnection began at ~15 R_E from earth in the magnetotail. This led, within ~5 minutes, to the severance of a substantial longitudinal sector of the pre-substorm plasma sheet which then flowed rapidly tailward (at speeds approaching 1000 km/sec), presumably to join the solar wind far downstream. After the plasmoid's departure the substorm X-line remained near earth for about a half hour and then, in conjunction with recovery of the auroral zone negative bay, it moved suddenly and rapidly tailward beyond Imp 8, causing the plasma sheet to once more thicken and lengthen, filling with plasma jetting earthward from the retreating neutral line.

Many examples of this sequence were found (e.g., Hones, 1977; Bieber et al., 1982; Bieber, this volume), and the occurrence of plasmoid formation and release and its role in energy dissipation from the magnetosphere were quite well established by these relatively near-earth satellite observations. Just within the past year, data have been obtained from the satellite ISEE 3, as it traversed the magnetotail at ~220 R_E from earth, that provide remarkably detailed confirmation of these near-earth results. Briefly, ISEE 3 found that the plasma sheet at 220 R_E becomes thick, filled with hot plasma flowing rapidly tailward, about 30 minutes after the onset of a substorm at earth. The hot plasma is found to contain closed magnetic loops in a pattern consistent with a large plasmoid. These observations are the subject of the next section.

ISEE 3 Observations of Plasmoids 220 R_E from Earth

From December 1982 to March 1983, ISEE 3 traveled outward along the magnetotail to $X_{SE} \approx -220\ R_E$ and back to earth. (See Bame et al., 1983, for the configuration of the orbit.) Hones et al. (1983) have reported results of a study of data acquired during a 16-day interval in January-February 1983 when the satellite was quite near the center of the magnetotail about 220 R_E from earth. Figure 5 shows geomagnetic records from six auroral zone stations and one mid-latitude station (Rapid City, South Dakota) for January 25, 1983. Periods of enhanced activity are seen at near-midnight stations at ~04:30-06:45 UT (NA, GW, FC. RPC), ~10:00-16:30 UT (RPC, ME, CO), and ~18:00-22:00 UT (AB). Plasma electron data acquired during the same day with a solar wind plasma instrument on ISEE 3 (Bame et al., 1978) are shown in Figure 6. Careful examination of extended periods of data such as these (Bame et al., 1983) and of accompanying magnetic data from the vector helium magnetometer or the satellite (Frandsen et al., 1978; Slavin et al., 1983) permit these authors to identify, with high confidence, intervals when ISEE 3 is in the magnetosheath, the tail lobes, and the plasma sheet. Briefly, the magnetosheath is characterized by the highest densities and lowest temperatures of electrons; the lobes are identified primarily by a nearly constant magnetic field with latitude ~0° and longitude ~0° or ~180°; the plasma sheet is identified primarily by the highest temperatures and, usually, the highest flow speeds (almost always tailward). Using such means, Hones et al. (1983) reached the identifications shown under the Temperature graph of Figure 6. At ~05:00 UT, ~30 minutes after the first interval of enhanced geomagnetic activity began (Figure 5), ISEE 3 crossed from the magnetosheath into the tail lobe, and then into the plasma sheet. About an hour later it went back through the lobe and into the magnetosheath. Again, at ~10:30 UT, about 30 minutes after the onset of the second interval of enhanced geomagnetic activity, ISEE 3 crossed from the magnetosheath into the tail and plasma sheet once more, remaining in the plasma sheet or lobe, this time, throughout essentially that whole extended period of geomagnetic activity. Finally, ISEE 3 was in the plasma sheet again from ~18:30 to ~19:30.

The point to be made from these data is that the magnetotail at 220 R_E appears to swell and envelop ISEE 3 about 30 minutes after the onset of intense geomagnetic activity. ISEE 3 usually encounters the plasma sheet shortly after such tail entries and the implication is that the plasma sheet thickens greatly and is responsible for the tail's swelling.

Figure 7 shows magnetic field data from ISEE 3 for the first tail encounter, ~05:00-07:00 UT. ISEE 3 presence in the plasma sheet is indicated by the reductions of field strength, B, during the interval ~05:25 UT to ~06:12 UT. (The other reductions signify magnetosheath.) The important point here is that the latitude of the field in the plasma sheet is first steeply northward and then steeply and more enduringly southward (top panel). This is the magnetic signature anticipated for the passage of the severed plasma sheet and the body of later reconnecting field lines that follow it.

Figure 8 shows plots of the magnetic field latitude during 14 instances when ISEE 3 made passages from the lobe into the plasma sheet. The beginning of each graph is the time of onset of the corresponding geomagnetic activity enhancement at earth. The time delays (Δt) between substorm onset at earth and entry of ISEE 3 into the plasma sheet are remarkably uniform and average about 30 minutes.

Figure 9 shows the interpretation given these ISEE 3 results by Hones et al. (1983). The plasma sheet is severed by magnetic reconnection near the earth at T = 0 minutes. By T = 30 minutes the plasmoid reaches and envelopes

ISEE 3, having expanded laterally because of reduced lobe magnetic field pressure at greater distances. By T = 50 minutes the plasmoid is well past ISEE 3 which remains for some time, however, in the body of later reconnected field lines contracting behind the plasmoid (and helping to accelerate it tailward).

Remarkably clear verification of important features of this model has been found in measurements of energetic electrons made on ISEE 3 (Scholer et al., 1983; Scholer, this volume). Note that the model predicts that as the plasmoid approaches ISEE 3 the satellite should first be enveloped by open field lines that extend from near the substorm X-line and that were reconnected after the plasmoid's departure. Only after that will ISEE 3 enter the closed-loop structure of the plasmoid itself. Scholer et al. measure electrons (E_e = 75-115 keV) and find that the flux of these is enhanced during substorm-related plasma sheet encounters such as we have discussed above. And, remarkably, they find that the first-appearing electrons arrive before ISEE 3 is deeply enveloped and they stream tailward, indicating open field lines. A few minutes later, as ISEE 3 becomes fully enveloped by the plasma sheet, the electrons become isotropic, indicating a closed magnetic structure. An example of this is shown in Figure 10. A half-hour enhancement of electrons began at ~03:05 UT on 16 February, 1983, some 20 minutes after onset of a very intense substorm at earth. The magnetic field remained lobe-like (i.e., ISEE 3 was not enveloped by high density plasma) and the electrons streamed tailward (open field lines) for about 12 minutes. Then at ~03:17 UT ISEE 3 entered the plasma sheet and the electron flux became isotropic, indicating a closed magnetic configuration. As noted above, such observations as these are in remarkable agreement with the model in Figure 9.

Conclusions

Large bodies orbiting the sun continually accumulate energy and plasma from the ever-flowing magnetized solar wind. This energy cannot build endlessly but must be dissipated somehow. We can see at least one form of this dissipation in comets, where the energy stored in their plasma tails is intermittently returned to the solar wind when the plasma tails are severed, probably by magnetic reconnection.

The auroral or magnetic substorm has been, for nearly two decades, an object of intense scientific research and has been regarded as a process by which energy from earth's magnetosphere is suddenly and rapidly dissipated primarily into the ionosphere. But several years ago data from satellites orbiting in the magnetotail within ~35 R_E of earth were interpreted to mean that during a substorm a sector of the plasma sheet is severed from earth by magnetic reconnection to form a free configuration of magnetized plasma, a plasmoid, that flows out of the magnetotail into the solar wind. Now, ISEE 3 satellite, in the magnetotail 220 R_E from earth, has observed these plasmoids flowing tailward past that location. The discreteness of these plasma releases through the magnetotail and their delayed association, at 220 R_E, with substorm onsets at earth suggest that they are consequences of spontaneous release, probably by magnetic reconnection, of energy and plasma earlier stored in the magnetotail. It is likely that this spontaneous release of energy and plasma to the solar wind, analogous to that observed in comets, is the underlying physical process in substorms, and that the concurrent energy release to the earth, creating the auroral substorm, is simply a by-product of this underlying process.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy.

References

Akasofu, S.-I., The development of the auroral substorm, Planet. Space Sci., 12, 273, 1964.

Baker, D. N. and E. C. Stone, Energetic electron anisotropies in the magnetotail: Identification of open and closed field lines, Geophys. Res. Lett. 3, 557, 1976.

Bame, S. J., J. R. Asbridge, H. E. Felthauser, J. P. Glore, H. L. Hawk, and J. Chavez, ISEE-C solar wind experiment, IEEE Transactions on Geoscience Electronics, GE-16, 160, 1978.

Bame, S. J., R. C. Anderson, J. R. Asbridge, D. N. Baker, W. C. Feldman, J. T. Gosling, E. W. Hones, Jr., D. J. McComas, and R. F. Zwickl, Plasma regimes in the deep geomagnetic tail: ISEE-3, Geophys. Res. Lett. 10, 912, 1983.

Bieber, J. W., E. C. Stone, E. W. Hones, Jr., D. N. Baker, and S. J. Bame, Plasma behavior during energetic electron streaming events: Further evidence for substorm-associated magnetic reconnection, Geophys. Res. Lett. 9, 664, 1982.

Eather, R. H., Majestic Lights, American Geophysical Union, 1980.

Frandsen, A. M. A., B. V. Connor, J. Van Amersfoort, and E. J. Smith, The ISEE-C vector helium magnetometer, IEEE Transactions on Geoscience Electronics, GE-16, 195, 1978.

Hones, E. W., Jr., Substorm processes in the magnetotail: Comments on 'On hot tenuous plasmas, fireballs, and boundary layers in the earth's magnetotail' by L. A. Frank, K. L. Ackerson, and R. P. Lepping, J. Geophys. Res. 82, 5633, 1977.

Hones, E. W., Jr., Transient phenomena in the magnetotail and their relation to substorms, Space Sci. Rev. 23, 393, 1979a.

Hones, E. W., Jr., Plasma flow in the magnetotail and its implications for substorm theories, in Dynamics of the Magnetosphere (S. I. Akasofu, ed.), p. 545, D. Reidel Publ. Co., 1979b.

Hones, E. W., Jr., D. N. Baker, S. J. Bame, W. C. Feldman, J. T. Gosling, D. J. McComas, and R. D. Zwickl, Structure of the magnetotail at 220 R_E and its response to geomagnetic activity, Geophys. Res. Lett., in press, 1983.

McPherron, R. L., C. T. Russell, and M. P. Aubry, Satellite studies of magnetospheric substorms on August 15, 1968. 9. Phenomenological model for substorms, J. Geophys. Res. 78, 3131, 1973.

Ness, N. F., The Earth's Magnetic Tail, J. Geophys. Res. 70, 2989, 1965.

Russell, C. T. and R. L. McPherron, The magnetotail and substorms, Space Sci. Rev. 15, 205, 1973.

Scholer, M., G. Gloeckler, B. Klecker, F. M. Ipavich, and D. Hovestadt, Fast moving plasma structures in the distant magnetotail, J. Geophys. Res., submitted, September 1983.

Slavin, J. A., B. T. Tsurutani, E. J. Smith, D. E. Jones, and D. G. Sibeck, Average configuration of the distant (~220 R_E)) magnetotail: Initial ISEE-3 magnetic field results, Geophys. Res. Lett., in press, 1983.

Figure Captions

Fig. 1. Comet Morehouse (1908 III) on September 30, October 1, and October 2, 1908. This sequence shows the disconnection and drifting away of the plasma tail (Yerkes Observatory photograph).

Fig. 2. Record of the horizontal component (H) of the geomagnetic field measured at Dixon, 17:00-21:00 UT, October 8, 1974. The letter M marks the time when Dixon is at local magnetic midnight. The arrow at right indicates the direction and magnitude of a positive change of H of 200γ, or 200 nanoteslas.

Fig. 3. Various data sets from Imp 8, 18:00-19:30 UT, October 8, 1974. First (top) panel: Longitude (ϕ_{SE}) of the magnetic field. Zero degrees is sunward, 180° is tailward, 90° is duskward. Second panel: Latitude (λ_{SE}) of the magnetic field. Plus 90° is due northward, -90° is due southward. Third panel: Energy density (U) of plasma electrons. Fourth panel: Vectors indicating the direction and magnitude of the bulk flow of plasma, derived from the measured distribution function of plasma protons. Fifth panel: Directional flux of energetic electrons. Sixth panel: Anisotropy parameter, J_{MAX}/J_{MIN}, of energetic electrons. Downward indicates tailward streaming, upward indicates earthward streaming. Numbers at the bottom are the universal time (UT), the satellite geocentric radial distance (r), its longitude (ϕ_{SM}), and its distance from the estimated position of the magnetotail neutral sheet (dZ). The units of r and dZ are earth radii (R_E) and 1 R_E = 6370 km. $\phi_{SM} = 180°$ is in the anti-sunward direction (from Hones, 1979a).

Fig. 4. Schematic representation of changes of the magnetotail plasma sheet that are thought to occur during substorms. These are cuts along the midnight meridian plane of the tail. Earth is at left and a dot near the center of each picture represents a satellite at $r \approx 35\ R_E$ and $dZ \approx +1\ R_E$, Black lines are magnetic field lines and white arrows indicate plasma flow. A distant neutral line, N, is shown at $r \approx 60\ R_E$ and is thought to be a quasi-permanent feature of the magnetotail though its distance is not really known and is probably quite variable. The fine hatching indicates the plasma sheet, which contains closed field lines 1, 2, 3, 4 and is bounded by the "last closed field line," 5. Field lines 6 and 7 are in the lobe, outside the plasma sheet (from Hones, 1979b).

Fig. 5. Magnetograms for January 25, 1983 from Narssarssuaq (NA), Great Whale River (GW), Fort Churchill (FC), Rapid City (RPC), Meanook (ME), College (CO), and Absiko (AB). Magnetic midnight is indicated by M (from Hones et al., 1983).

Fig. 6. Plasma electron parameters. A flow direction (ϕ_{GSE}) of 180° is tailward. ISEE 3 presence in the plasma sheet is indicated by heavy lines under the temperature graph. Magnetosheath intervals are indicated by light lines. The unmarked periods are lobe intervals (from Hones et al., 1983).

Fig. 7. Magnetic field parameters measured by ISEE 3, January 25, 1983. In the latitude (λ_{GSE}) graph 90° is due north, −90° is due south. In the longitude (ϕ_{GSE}) graph 0° is sunward, 180° is tailward. The magnitude (B) is given in nanotesla (from Hones et al., 1983).

Fig. 8. Magnetic field latitude measured by ISEE 3 during plasma sheet encounters. The vertical dashed line marks the time of entry into the plasma sheet, and this time is given at the right of each curve. Horizontal lines with arrowheads mark the durations of substorms at earth. Values of Δt at the right are the number of minutes from substorm onset to plasma sheet entry. Question marks indicate lack of clear substorm onset times. Tic marks on base lines are 10 minutes apart (from Hones et al., 1983).

Fig. 9. Model depicting the severance of (a longitudinal sector of) the plasma sheet at substorm onset (T = 0) and its departure along the tail as a closed magnetic structure, a plasmoid. Black arrows indicate the magnetic field direction and white arrows indicate plasma flow (from Hones et al., 1983).

Fig. 10. Angular distributions of energetic electrons measured by ISEE 3 on February 16, 1983. The azimuthal distribution is measured in eight sectors, and the count rate in the most intense sector is written in that sector. The line at the bottom indicates that the magnetic field was lobe-like (ISEE 3 was not yet deeply embedded in the plasma sheet) until ~03:17 UT (adapted from Scholer et al., 1983).

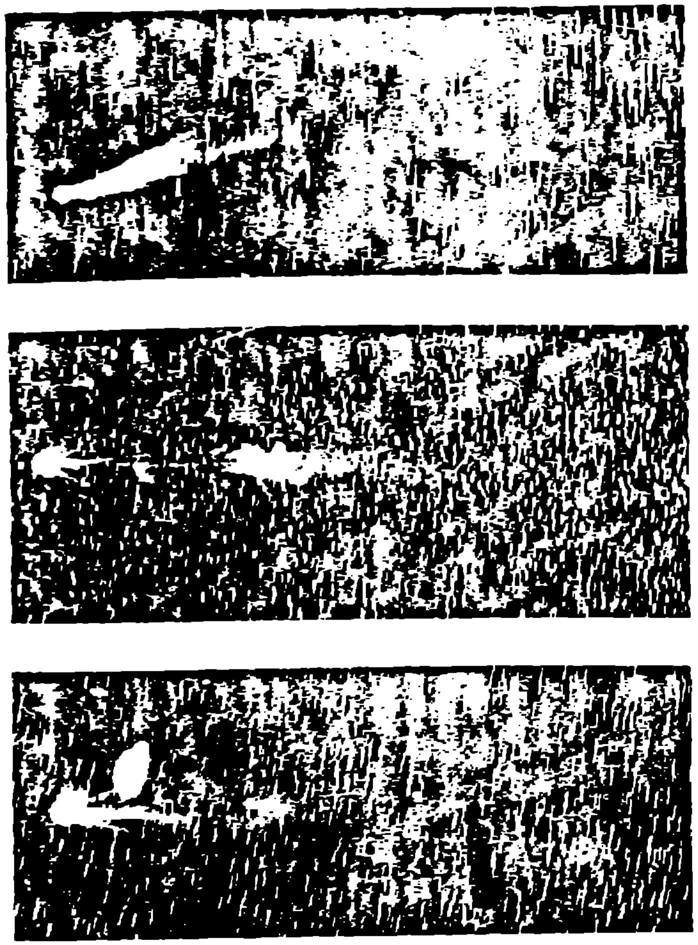
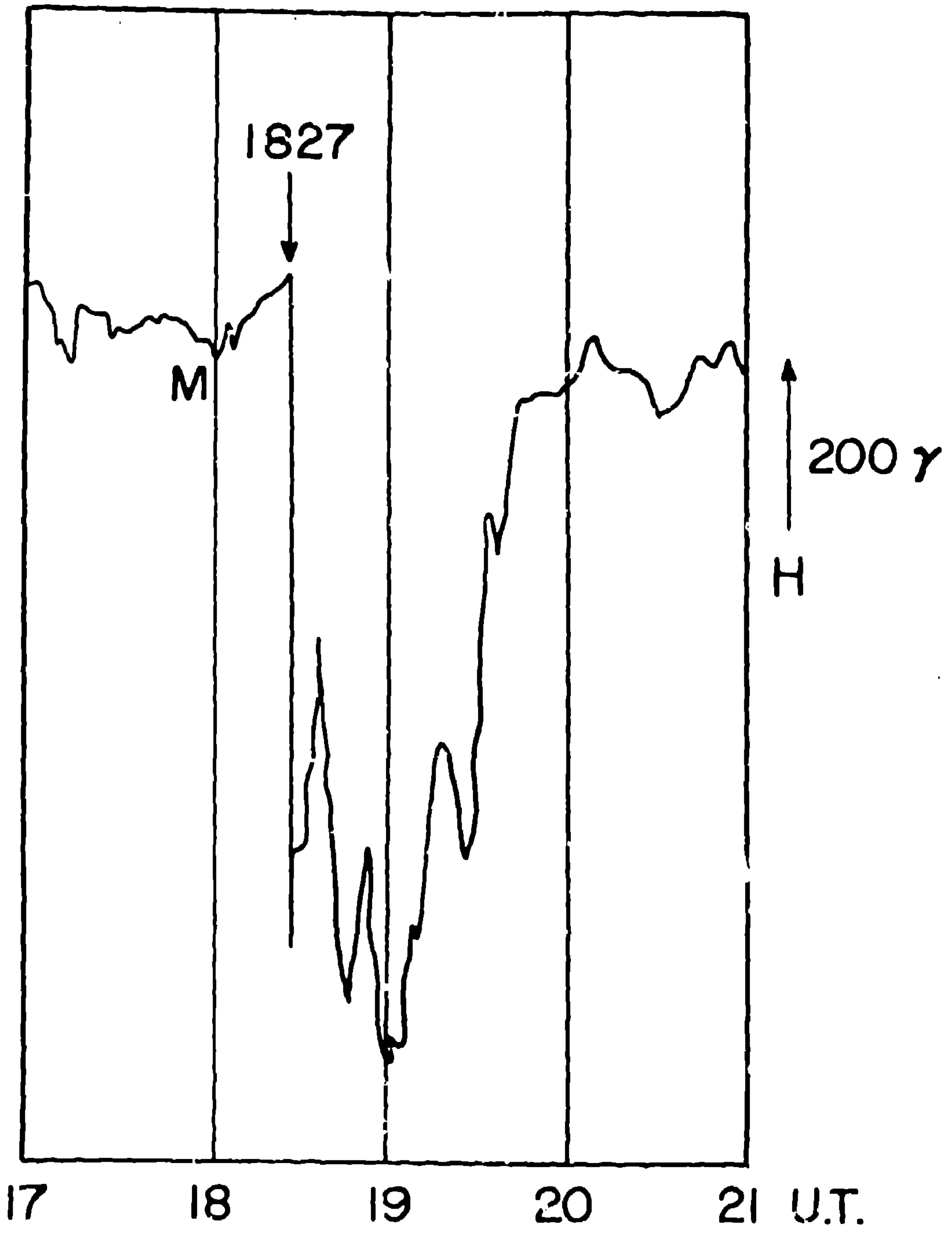


Fig. 1



DIXON ($\lambda = 63°$)

OCTOBER 8, 1974

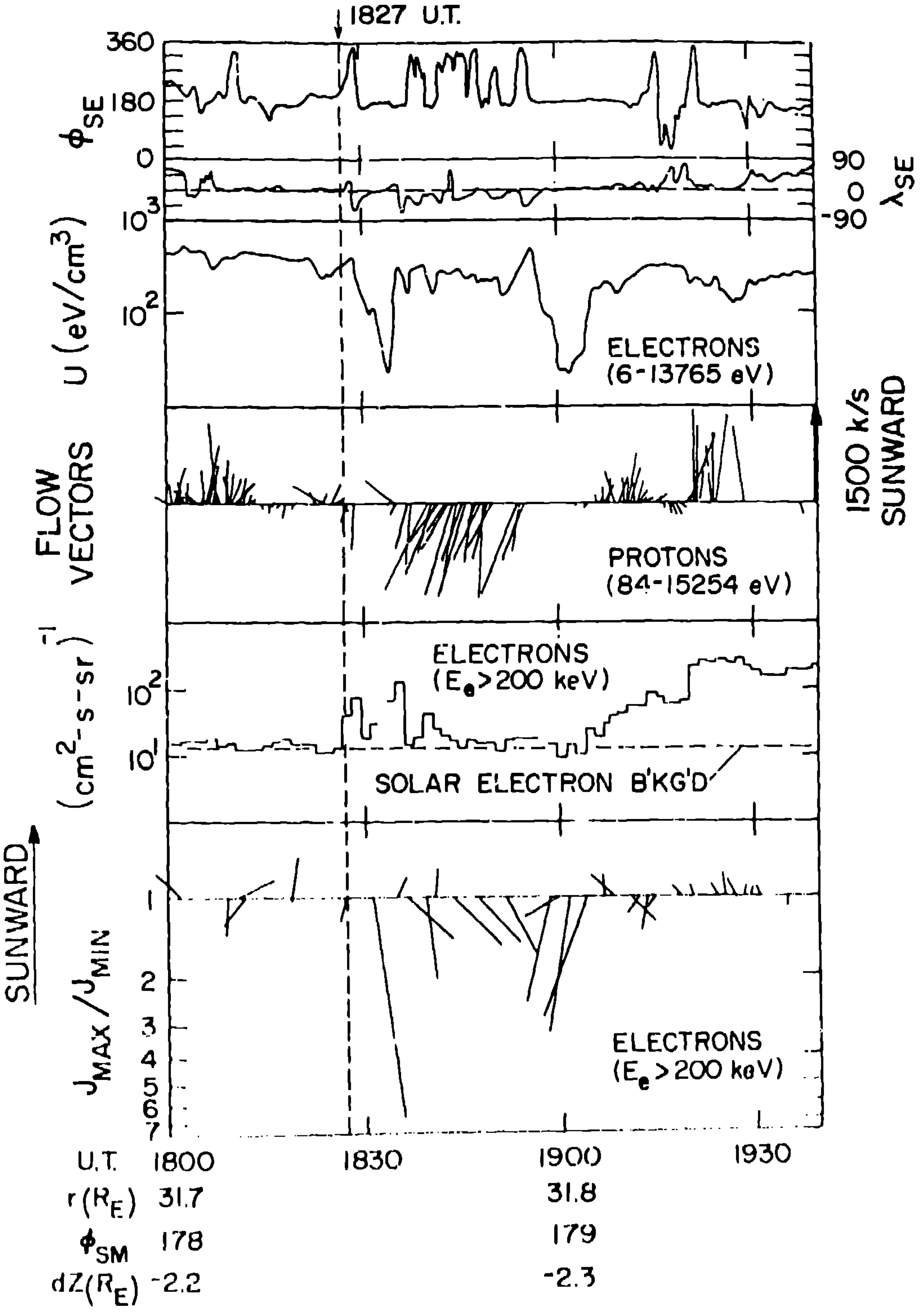

1827 U.T.
360
ϕ_{SE} 180
0
90
0
-90
λ_{SE}
10^3
U (eV/cm^3)
10^2
ELECTRONS
(6-13765 eV)
FLOW VECTORS
1500 k/s SUNWARD
PROTONS
(84-15254 eV)
(cm^2-s-sr)$^{-1}$
ELECTRONS
(E_e>200 keV)
10^2
10^1
SOLAR ELECTRON B'KG'D
SUNWARD
J_{MAX}/J_{MIN}
1
2
3
4
5
6
7
ELECTRONS
(E_e>200 keV)
U.T. 1800 1830 1900 1930
r(R_E) 31.7 31.8
ϕ_{SM} 178 179
dZ(R_E) -2.2 -2.3

Fig. 3

PLASMA SHEET CONFIGURATION CHANGES DURING A SUBSTORM

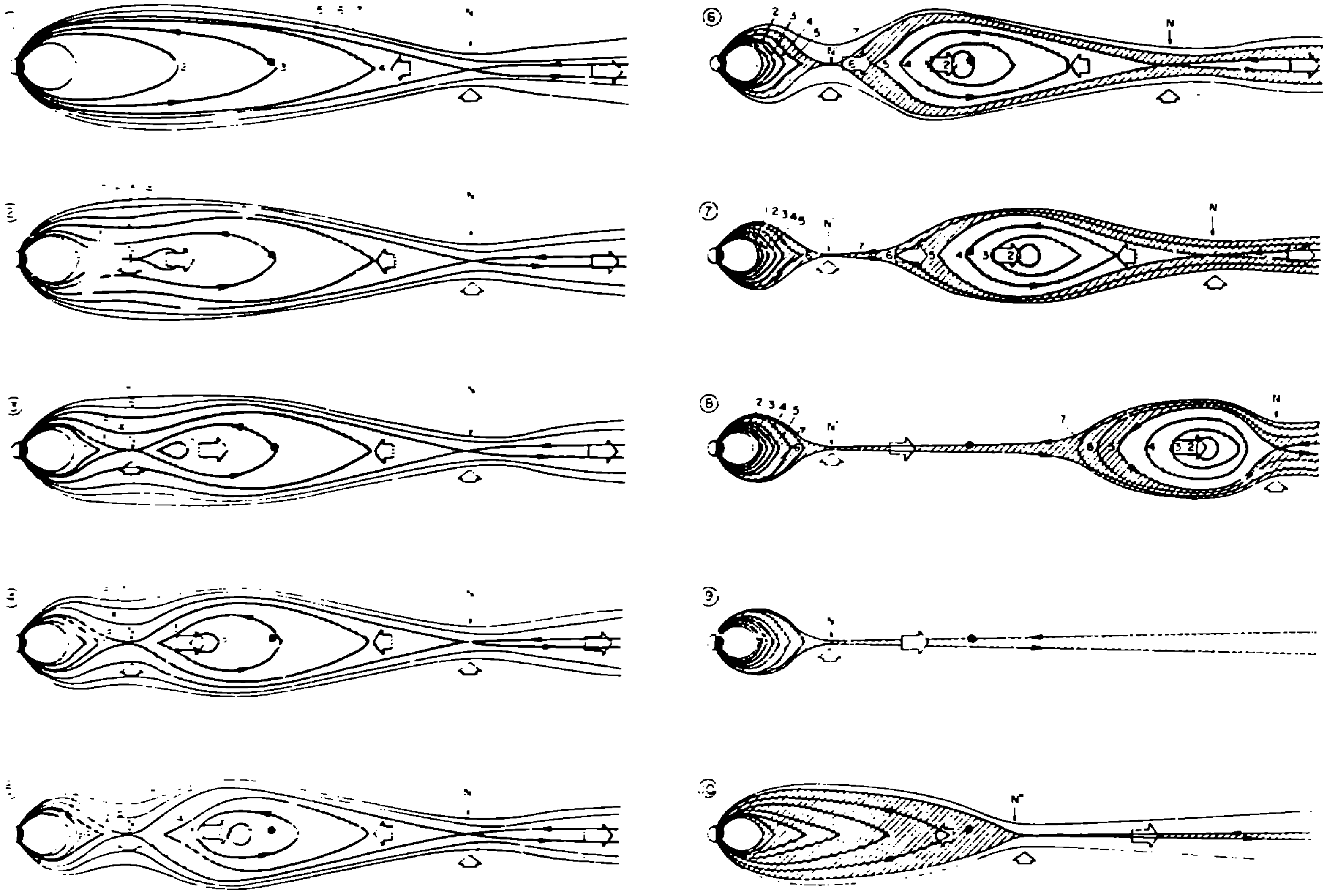


Fig. 4

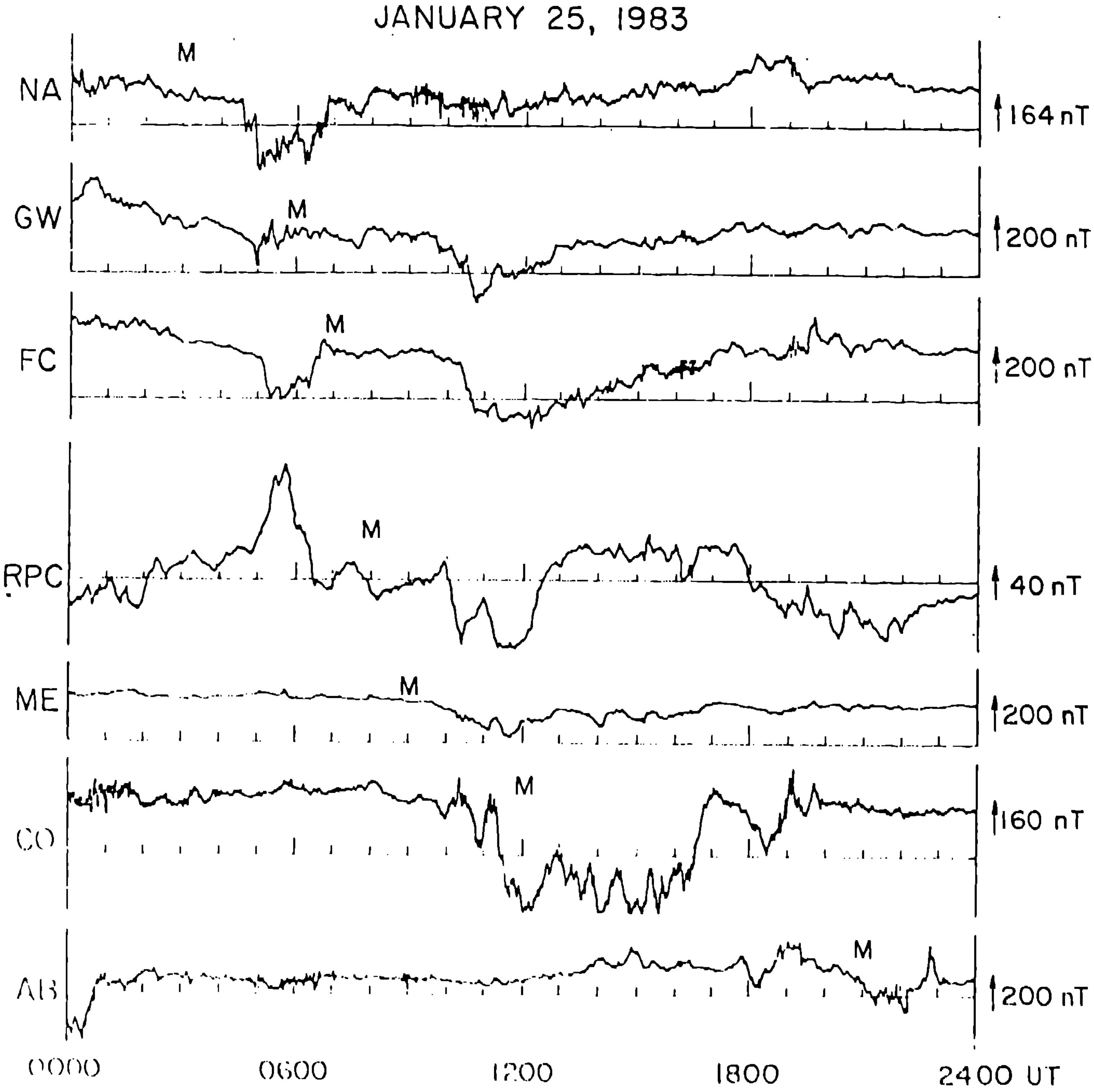

JANUARY 25, 1983
NA
GW
FC
RPC
ME
CO
AB
M
M
M
M
M
M
M
164 nT
200 nT
200 nT
40 nT
200 nT
160 nT
200 nT
0000
0600
1200
1800
2400 UT

Fig. 5

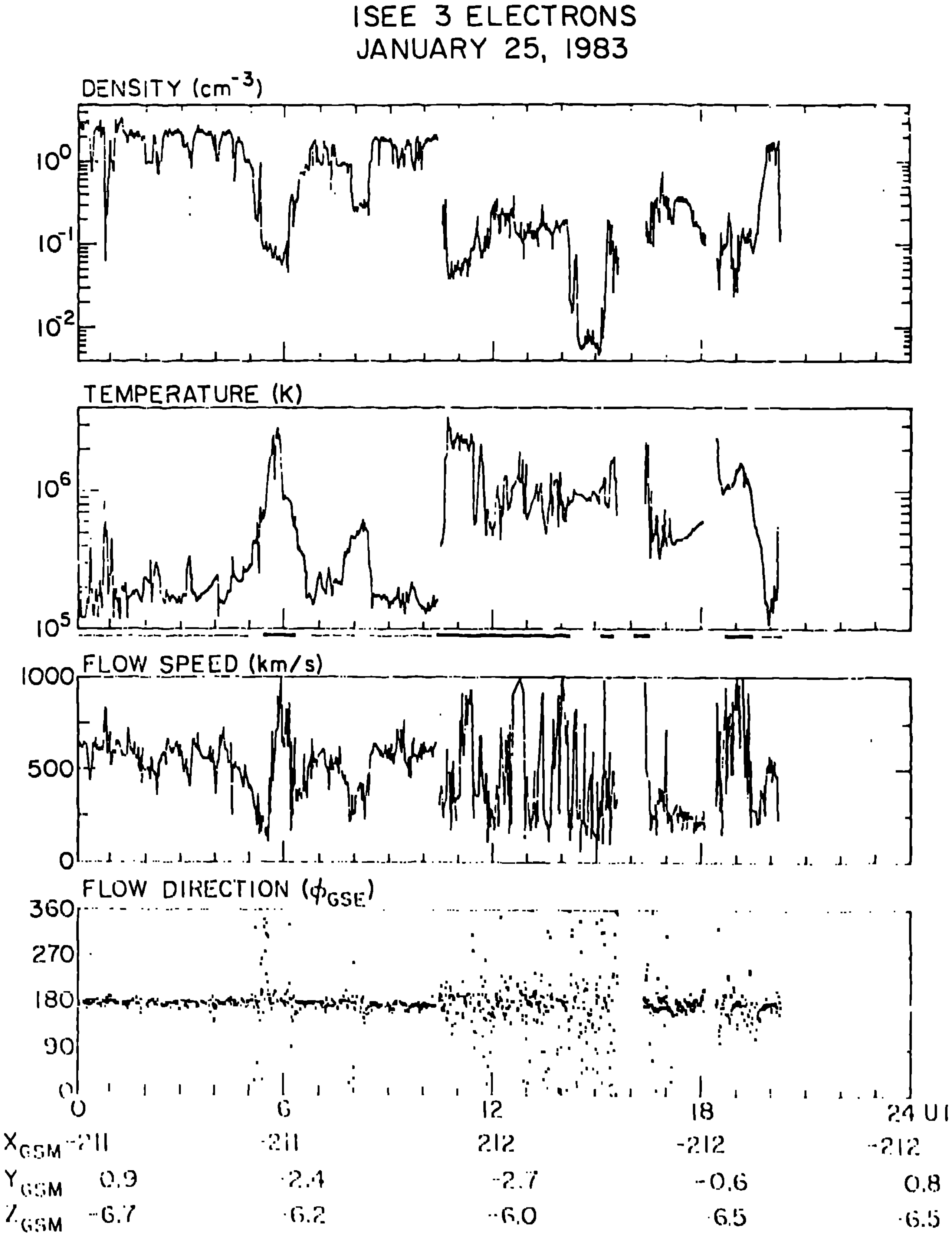

ISEE 3 ELECTRONS
JANUARY 25, 1983
DENSITY (cm^{-3})
10^0
10^{-1}
10^{-2}
TEMPERATURE (K)
10^6
10^5
FLOW SPEED (km/s)
1000
500
0
FLOW DIRECTION (ϕ_{GSE})
360
270
180
90
0
0
6
12
18
24 UT
X_{GSM} -211 -211 -212 -212 -212
Y_{GSM} 0.9 -2.4 -2.7 -0.6 0.8
Z_{GSM} -6.7 -6.2 -6.0 -6.5 -6.5

Fig. 6

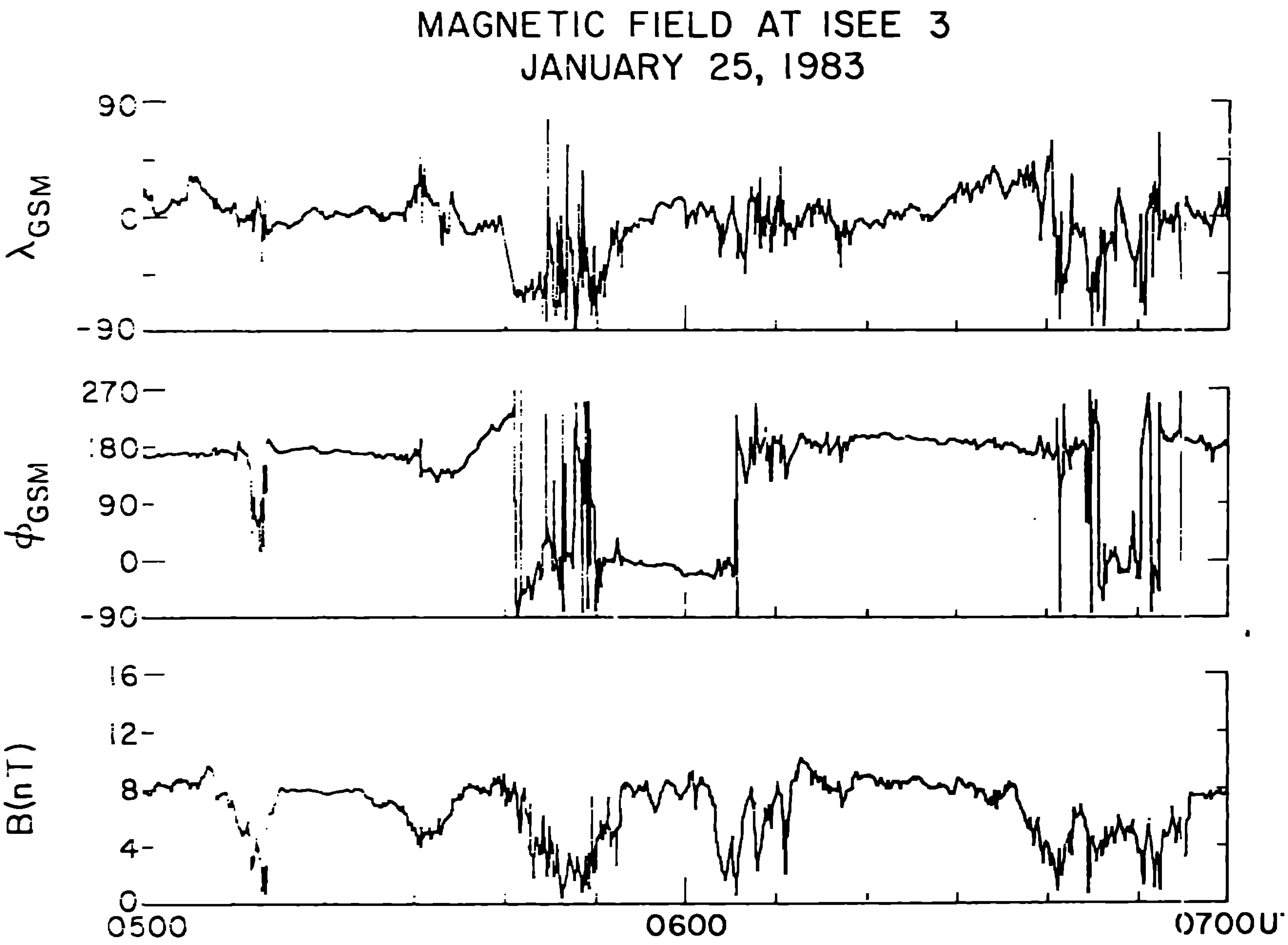

MAGNETIC FIELD AT ISEE 3
JANUARY 25, 1983
90
0
-90
λ_{GSM}
270
180
90
0
-90
ϕ_{GSM}
16
12
8
4
0
B(nT)
0500
0600
0700UT

Fig. 7

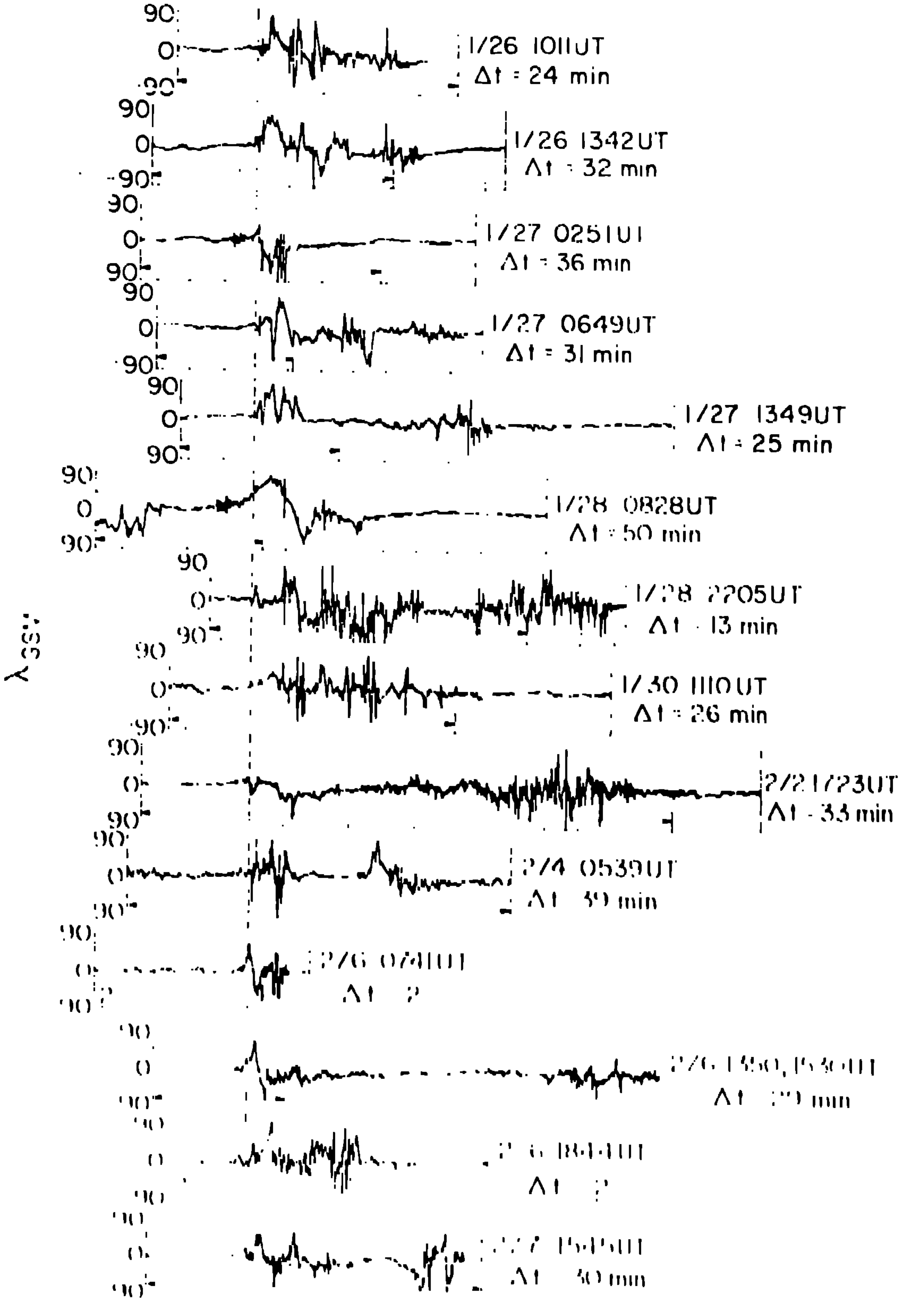

λGSE
90
0
-90
1/26 1011UT
Δt = 24 min
1/26 1342UT
Δt = 32 min
1/27 0251UT
Δt = 36 min
1/27 0649UT
Δt = 31 min
1/27 1349UT
Δt = 25 min
1/28 0828UT
Δt = 50 min
1/28 2205UT
Δt = 13 min
1/30 1110UT
Δt = 26 min
2/2 1723UT
Δt = 33 min
2/4 0539UT
Δt = 39 min
2/6 0741UT
Δt ?
2/6 1450, 1630UT
Δt = 20 min
2/6 1844UT
Δt ?
2/7 1515UT
Δt = 30 min

Fig. 8

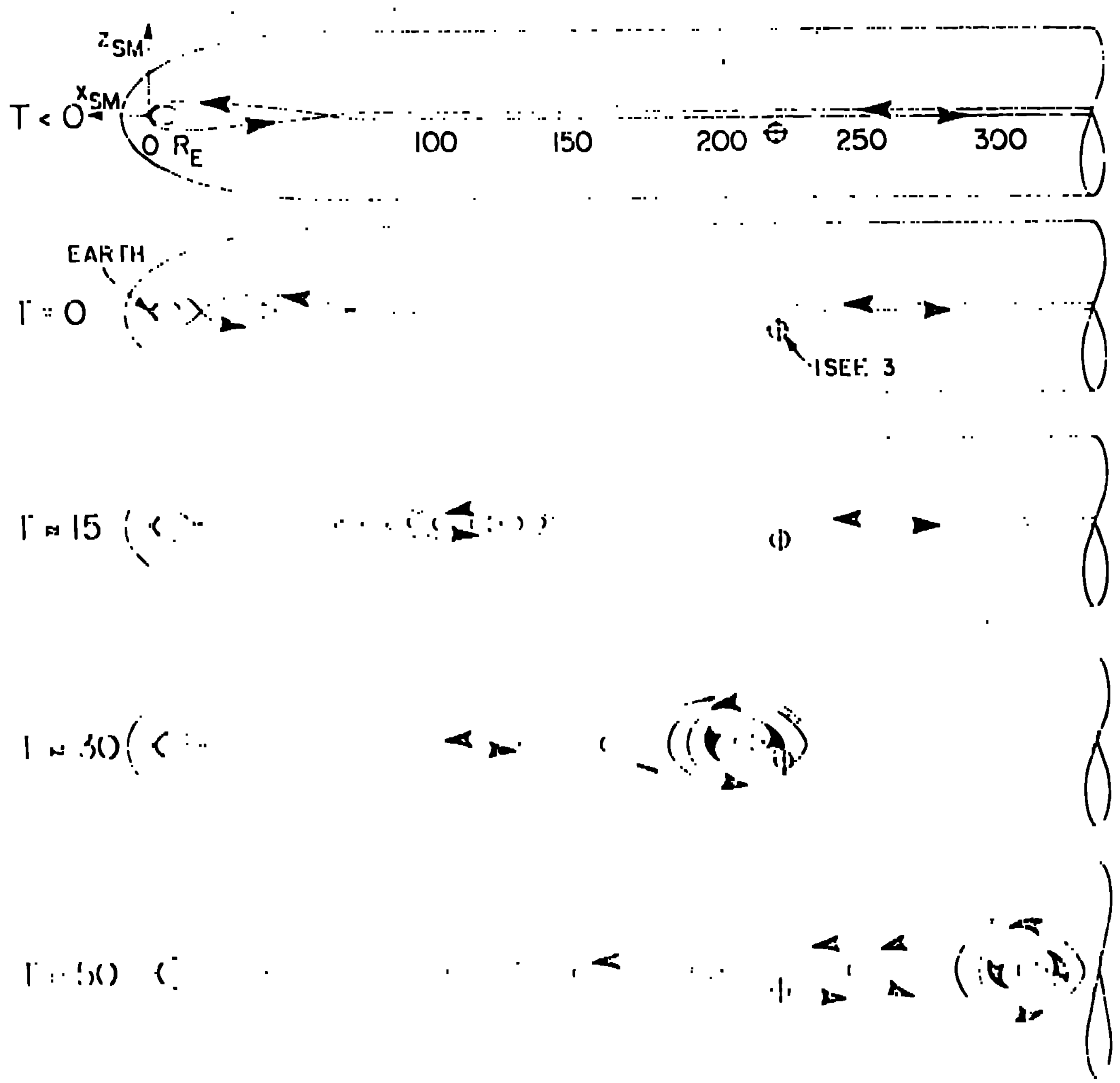


FIG. 9

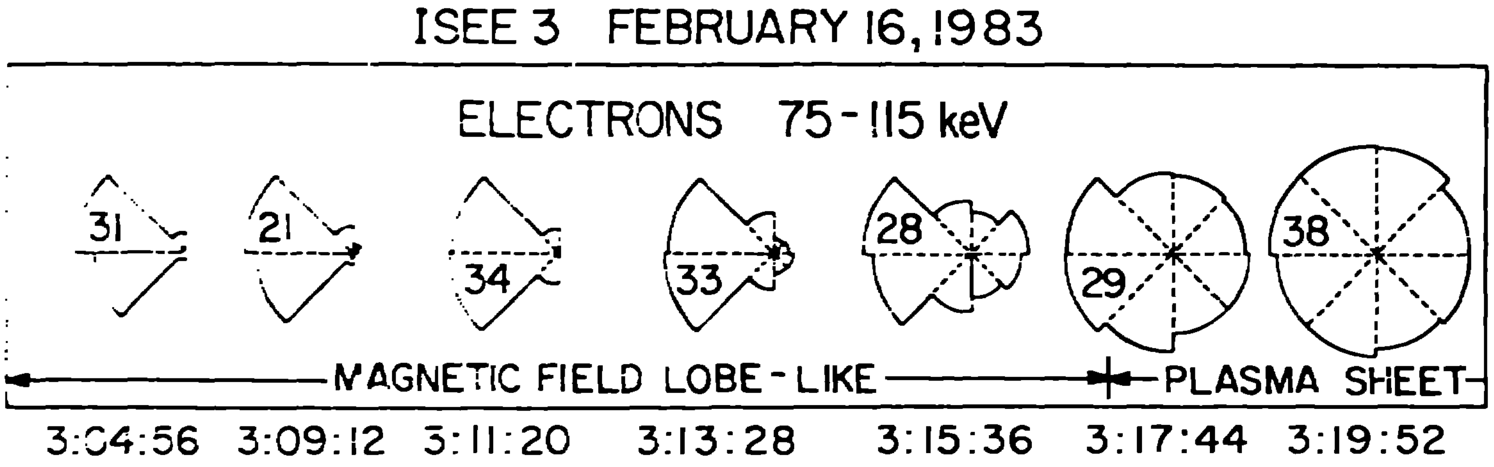

ISEE 3 FEBRUARY 16, 1983
ELECTRONS 75 - 115 keV
31
21
34
33
28
29
38
MAGNETIC FIELD LOBE - LIKE
PLASMA SHEET
3:04:56
3:09:12
3:11:20
3:13:28
3:15:36
3:17:44
3:19:52

Fig. 10