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MAGNETOSPHERIC AND AURORAL PLASMAS: A SHORT SURVEY OF PROGRESS, 1971 - 1975*+

by

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Abstract

Important milestones in our researches of auroral and magnetospheric plasmas for the past quadrennium 1971 - 1975 are reviewed. Many exciting findings, including those of the polar cusp, the polar wind, the explosive disruptions of the magnetotail, the interactions of hot plasmas with the plasmapause, the auroral field-aligned currents, and the striking 'inverted-V' electron precipitation events, were reported during this period. Solutions to major questions concerning the origins and acceleration of these plasmas appear possible in the near future. A comprehensive bibliography of current research is appended to this brief survey of auroral and magnetospheric plasmas.

I. PROLEGOMENON

During the quadrennium preceding 1971 much of the groundwork, both experimental and theoretical, was established for the exciting and decisive surveys of auroral and magnetospheric plasmas of the past several years. From the experimental point of view, instrumentation suitable for measurements of the plasmas in planetary magnetospheres was developed and successfully employed in the terrestrial magnetosphere -- instruments with great dynamic ranges in energy, $\sim$ 1 eV to 50 keV, and with sufficient sensitivities to adequately cope with these quasi-isotropic, hot plasmas. Equally important was the introduction of the so-called 'energy-time' spectrograms which allow a candid, three-dimensional display of the remarkably large and complex body of plasma measurements acquired with the new-generation plasma instrumentation. Simultaneously with these innovations detectors capable of measuring the low-density, thermal plasmas in the magnetosphere and the species compositions of the hot plasmas were being perfected. On the theoretical side, a mechanism for a 'polar wind', analogous in spirit to the principles of the well-known solar wind had been suggested. Various possible acceleration schemes for the modification of distant magnetospheric plasmas to yield the dynamic, complex precipitation encountered at auroral altitudes were introduced. Such plausible schemes included quasi-static electric fields aligned parallel to the geomagnetic field and rapid pitch-angle scattering of plasmas into the atmospheric loss cone by various plasma wave-particle interactions. During this period was also witnessed the enthusiastic development of magnetospheric dynamical models assuming the merging of geomagnetic field lines with those of the interplanetary medium -- and the implications of these ideas concerning the overall characters of the auroral and magnetotail plasmas. Concurrently with these studies the nature of the striking relationships among the earthward termination of the magnetotail plasma sheet, the ring-current 'torus', and the plasmasphere demanded that more comprehensive observations were needed to resolve the participating mechanisms. Drifts of large bodies of plasmas in the geomagnetic and geoelectric fields were already established as a fundamental reality for much of the magnetospheric domain.

The author has been charged with writing a brief account of our progress in understanding magnetospheric plasmas, and their 'foot-prints' as auroral precipitation, for the quadrennium 1971 - 1975. Only the major advances will be discussed, and these from a point of view not necessarily directed toward those vigorously participating in this research, but a view more appropriate for researchers in the host of related fields. In the pre-1971 era the proton distributions comprising the ring current encircling the earth at geocentric radial distances of about 4 to 8 earth radii had already been detected, and their intimate connection with geomagnetic storms established. Earthward and approximately contiguous to this ring current the high-density, thermal plasma region known as the plasmasphere was also found to respond with changes in size and geometry to the occurrence of geomagnetic activity. At greater distances within the ring current the plasma sheet on the nightside of earth displayed a conspicuous termination of electron intensities with a rapid decrease of average electron energy with decreasing geocentric radial distances. At still greater distances in the plasma sheet in the magnetotail a magnetic 'neutral sheet' was discovered, but the mechanism for solar plasma entry into the earth's magnetosphere remained unresolved. At low altitudes of approximately one to several thousand kilometers the auroral plasmas were found to share at least two common features with those of the distant magnetosphere -- complex spatial structure and great temporal variability. Zones of 'hard' electron and proton precipitation into the atmosphere, with energies in the tens of keV range, were found early as well as less energetic, or 'softer', precipitation regions. These measurements were gained with both rocket- and satellite-borne instrumentation. Hints of a poleward zone of magnetosheath plasmas directly impinging upon the upper atmosphere were evident in several of these observations, particularly with retrospection. It was apparent that dedicated studies of both the auroral and magnetospheric domains with simultaneous plasma-wave, electric and magnetic field, energetic particle and plasma measurements were required in order to gain substantial knowledge of the cornucopia of phenomena lying above the earth's atmosphere. Much of the promise of this period was fulfilled by the advances of the past several years. Needless to say, these advances have given birth to many exciting problems still unresolved.

It is my intent to discuss here several of the major advances in our knowledge of magnetospheric and auroral plasmas of the past several years. This brief survey begins at auroral altitudes and ends with the vast plasma regimes of the distant magnetosphere. In terms of the most probable primal source of most of these plasmas, the solar wind, this chronological order of the text perhaps appears out of sequence. However, it is my belief that our observational knowledge of the auroral plasmas has advanced significantly beyond that of their counterparts in the distant magnetosphere, and thus a presentation first of auroral findings provides the most effective starting point. A comprehensive bibliography is appended to this brief review in order to placate my colleagues and fellow enthusiasts.

II. THE LOW-ALTITUDE PLASMAS

We begin our discussion of major advances in plasma researches of the past few years with the meridional summary of major plasma regimes encountered at low altitudes as portrayed in Figure 1. By 'low-altitude plasmas' we imply here all of the diverse plasmas encountered at altitudes of several hundreds to a few thousands of kilometers above the earth's surface, which have been studied with rocket- and satellite-borne instruments. These plasmas are thus not only those associated with the classical auroral oval, but those of the polar cap and of equatorial latitudes.

One of the more striking, observational finds at low-altitudes is that of 'inverted-V' electron precipitation events at auroral latitudes. An example is given in Figure 2. The display is a three-dimensional coding necessary for the proper presentation of the immense quantities of observations of plasmas currently being gained throughout the earth's magnetosphere. This form of data presentation is also extensively used by Heikkila and Winningham and by McIlwain and DeForest, examples of which will be given here. The ordinate scale of Figure 2 is electron energy in units of electron volts and the abscissa is universal time. The detector responses are color coded from blue to red (low to high responses) at each point in the E-t plane. A color calibration strip for the $\log_{10}$ of the detector response in counts $(\sec)^{-1}$ is provided at the right-hand side of the graph. Often this calibration strip in these E-t spectrograms is gray coded. Magnetic invariant latitude (Λ), magnetic-field magnitude (B) at the satellite position, and corresponding magnetic local time (MLT) are given at the bottom of the spectrogram. There are three 'inverted-V' precipitation events evident in the spectrogram of Figure 2 at 0147:50 to 0148:20 U.T., 0148:20 to 0149:00 U.T., and 0149:40 to 0150:10 U.T. These electron precipitation events are usually characterized by electron average energies which increase to a maximum energy and subsequently decrease as the satellite passes through these regions [Frank and Ackerson, 1972]. The overall features of these precipitation events, together with the observational facts that low-energy protons are not observed simultaneously and similar electron structures have not yet been found in the distant magnetosphere, suggest electron acceleration via quasi-static electric fields directed parallel to the geomagnetic field at low or intermediate altitudes. Various mechanisms for the possible development of these potential drops along geomagnetic tubes of force have been investigated, notably those by Kindel and Kennel [1971] and Block [1972a]. There are currently no decisive measurements which provide an assessment of the scale length of such potential drops -- possibly hundreds of meters to thousands of kilometers. Until recently it was thought that the major features of 'inverted-V' events, which precluded a direct interpretation in terms of parallel electric fields, were the presence of large electron intensities perpendicular to the geomagnetic field ('trapped fluxes') and a large low-energy component well below the average energies of the primary spectrum. However, Evans [1974] has calculated the expected pitch angle distributions and energy spectrums for electron intensities accelerated under such conditions and has included the secondary electron intensities expected from a reasonable atmospheric model. His results for an 'inverted-V' spectrum are shown in Figure 3. These results add further plausibility to interpretations of this electron precipitation in terms of parallel electric fields [see also the review by Paulikas, 1971].

The anticipated findings of the direct entry of magnetospheric plasmas into the dayside polar ionosphere were reported by Heikkila and Winningham [1971] and Frank and Ackerson [1971]. This region and its distant polar magnetospheric counterpart are known as the dayside (or polar) cusp. The term 'dayside magnetospheric cleft' is also used in the current literature. An example of E-t spectrograms of electron and proton intensities for a polar cusp traversal at low altitudes is given here as Figure 4. The satellite, ISIS 2, is moving poleward as a function of Universal Time (see also left-hand side of Figure 1). The magnetospheric plasmas are first encountered at 0015:40 U.T. and are evidenced by the dramatic increases of low energy electrons in the electron (top) spectrogram. Low energy protons are also present in this region (bottom spectrogram). The more energetic electron and proton intensities observed prior to entry into the polar cusp are typical of precipitation of the large regime of such plasma trapped within the earth's magnetosphere. The polar cusp plasma is believed to be positioned on geomagnetic field lines which are open, or connected, to those of the interplanetary field in the distant polar magnetosheath. The width of the polar cusp at these altitudes has been the subject of some controversy. The width inferred from the spectrograms of Figure 4 would be at least 5° in invariant latitude (see also Heikkila and Winningham, 1971). Plasma and convection electric field observations with Injun 5 at similar altitudes seem to indicate a typical width of 2° or 3° [Frank and Ackerson, 1972; Gurnett and Frank, 1973]. This apparent discrepancy may be intimately related to the recent discovery of a further plasma regime in the distant polar magnetosphere known as the 'plasma mantle' and also populated with particles of direct magnetosheat origins [Rosenbauer _et al_., 1974].

The spatial configuration of the above two plasma regions, 'inverted-V' events and polar cusp, as projected onto the earth's ionosphere is both complex and heatedly controversial. Intimately involved are the correct identification of the ionospheric 'footprint' of plasma regions in the distant magnetosphere, the configurations of the convection electric fields and of the distant geomagnetic fields, and the character of energetic electron and proton intensities with E > 50 keV in the various plasma regions. An attempt at such a polar projection is given in Figure 5 which is a further interpretive summary of Figure 1. Comprehensive plasma measurements appear to reveal the clear signature of at least two distinct, but contiguous plasma regimes -- a high latitude zone of polar cusp plasmas and 'inverted-V' bands and a lower-latitude zone of plasma sheet and ring-current intensities [Frank and Ackerson, 1972]. Convection is anti-sunward in the poleward region and sunward at lower latitudes. Approximately coincident with the reversal of the convection electric fields and with the common boundary of these two major plasma regions is located the 'trapping boundary' for more energetic electrons (E > 45 keV). An example of the relationships among 'inverted-V' events, plasma sheet precipitation, convection electric fields, trapping boundary and plasmapause near local midnight is shown in Figure 6 [Gurnett and Frank, 1973]. The overall character of these electric fields within the two plasma regimes are notably different -- greatly fluctuating within the 'inverted-V' bands and relatively quiescent in the equatorward plasma sheet precipitation. The magnetic field topology is such that geomagnetic field lines poleward of the trapping boundary are assumed 'open' to those of the interplanetary medium. This boundary should be used reservedly in defining the demarcation between closed and opened field lines since substantial energetic electron intensities are often encountered on open field lines as determined with simultaneous electric field and plasma measurements.

The simplified interpretive diagram of Figure 5 touches on many of the currently active researches of auroral and polar plasmas. First the question as to whether or not the geomagnetic field topology is partially open or entirely closed to the interplanetary medium is not wholly resolved. In addition Heppner [1972a, 1972b] has concluded that a more typical picture of convection fields over the polar cap is one of relatively strong anti-sunward flow via an analysis of OGO-6 electric field observations. Heikkila [1974] has proposed that the high-latitude precipitation zones on the nightside of the earth are not the relatively simple convective extensions of the dayside polar cusp as shown in the lower left-hand panel of Figure 5. Moreover, the 'plasma void' centered over the polar cap has been shown convincingly to be filled with weak intensities of low-energy electrons which become intense and highly structured during periods of geomagnetic activity [Winningham and Heikkila, 1974]. These electron intensities give rise to an interpretive problem in that these polar-cap field lines have been often assumed to correspond to those of the lobes of the magnetotail, regions which are notably empty of measurable plasmas. Despite the many disparate interpretations of the large body of available plasma observations in terms of magnetospheric topology, of plasma entry into the magnetosphere, and of electron acceleration there have been great strides in gaining relatively consistent surveys of electron and proton precipitation over the auroral zones and polar caps.

Our knowledge of the overall temporal behavior of these precipitation regions has been advanced with a comprehensive study of OGO-4 plasma measurements by Hoffman and Burch [1973]. Their results are summarized in Figure 7 for various phases of polar magnetic substorms. Quiet magnetic conditions are characterized by the persistent presence of polar cusp and plasma sheet intensities. As the interplanetary field turns southward, the auroral plasmas respond with an equatorward motion of the dayside polar cusp and increased precipitation from the plasma sheet in the local evening sector. During the expansion phase of the substorm intense precipitation features are encountered over the nightside aurora. Then, as the recovery of the substorm activity accompanies the northward turning of the interplanetary field, plasma sheet and polar cusp precipitation returns to the more polar positions typical of quiescent periods and a broad electron precipitation zone, 'the mantle aurora', spreads through the local morning sector. More such plasma studies, including simultaneous surveys of convection patterns, VLF emissions and energetic particles, need be available in the literature before convincing assessments of the origins and acceleration mechanisms can be achieved. This particular study is an excellent beginning for further comprehensive treatment of observations of auroral plasmas.

Important new findings concerning the character of the field-aligned, or Birkeland, currents originally detected with low-altitude satellite magnetometer measurements by Zmuda and his coworkers have added great impetus to analyses of this phenomenon which is central to the issue of ionosphere-magnetosphere coupling. Simultaneous observations with rocket-borne magnetometers and plasma analyzers have provided much of our new insight [Choy *et al.*, 1971, Cloutier *et al.*, 1973]. Generally speaking, the magnetic perturbations associated with these currents are of the order of several hundreds of gammas, and typical currents are some tens of microamperes per square meter. An example of rocket-borne measurements of field-aligned currents in the vicinity of an auroral arc is given in Figure 8. Electron intensities precipitating into the atmosphere are sufficient to account for the upward flowing field-aligned current. The particles comprising the downward current, low-energy ions or electrons with energies less than tens of electron volts, have remarkably eluded detection by both rocket- and satellite-borne plasma analyzers. The positions of field-aligned currents in 'inverted-V' precipitation events are worthy of note. For example, such currents are found either at the boundaries of the 'inverted-V' events, or interspersed throughout these precipitation regions as indicated by the anisotropies summarized in Figure 9 for the events of Figure 2 [cf. Berko, 1973]. These currents appear to be located adjacent to, rather than directly within, the maxima of precipitation (or bright arcs). However, magnetometer measurements were not gained simultaneously with these plasma observations. The study of field-aligned currents is still severely limited by the present unavailability of simultaneous magnetic field and plasma observations from low-altitude satellites.

Are the primal origins of the magnetospheric and auroral plasmas the solar wind or the terrestrial ionosphere? It is difficult to neglect the fact that the earth is surrounded by a great sheath of turbulent plasma -- its magnetosheath. The plasma densities and particle energies encountered in the plasma sheet, the polar cusp and other environs of the distant magnetosphere continually guide us to an often unconscious conclusion that the particle source, distinct from the power supply, is the solar wind. Recent low-altitude observations of the composition of positive ions precipitating into the auroral zone suggest that at least part of these plasmas can be attributed to the ionosphere. Shelley, Sharp and Johnson [1972] have reported the convincing discovery of large intensities of energetic oxygen ions during geomagnetic storms. A exemplary set of observations is given in Figure 10. These oxygen ions are found well equatorward of the 'trapping boundary', and hence populate closed field lines. The peak differential intensities at

$L \approx 3$ to 4 are nontrivial in terms of intensities of ions found at the equator -- in fact these intensities are comparable to those of the ring current at these energies. Perhaps the occasional findings of large intensities of low-energy protons (ions) and electrons at yet lower latitudes are also intimately related to this as yet largely unexplorered ionospheric participation [cf. Heikkila, 1971]. It is a matter of obvious importance that such measurements be gained in the immense plasma reservoirs near the equator in order to quantitatively access the ionosphere's contributions to these plasmas. Accordingly, we must not lose sight of the fact that the bulk of our present observations of auroral and magnetospheric ion intensities have been gained with energy-per-unit-charge analyzers which require a minimum of satellite resources and are capable of comprehensive and rapid energy scans but do not identify unambiguously the ion species.

Banks and Holzer [1968] investigated the consequences of open magnetic field lines over the earth's polar cap with regard to hydrogen and oxygen ions of the ionosphere. The results of these calculations showed that there should be an outward flow of hydrogen ions along these field lines, which is strikingly similar in many respects to the expansion of the solar corona and subsequent development of the solar wind. Appropriately Axford [1968] referred to this flow of ions from the polar ionosphere as 'the polar wind'. *In situ* measurements of such flow are more difficult than those of the solar wind -- ion energies are in the electron-volt range and the signature of upward flow of hydrogen ions relative to the oxygen ions must be resolved. J. Hoffman and his coworkers [1974] have recently confirmed the existence of this polar wind with measurements with an ion mass spectrometer on ISIS 2. An example of these observations is given in Figure 11. The viewing geometry for the ion mass spectrometer is shown at the top of Figure 11, and the corresponding responses of the instrument to hydrogen ions and singly-ionized oxygen atoms are summarized in the lower panel. The clear displacement of the hydrogen and oxygen ion peaks as functions of the spin phase of the satellite can be interpreted in a relatively straightforward manner as an upward expansion, or wind, from the polar ionosphere. These measurements are of great interest not only from the viewpoint of loss of ions from the terrestrial ionosphere, but also in terms of the supply of thermal ionospheric plasmas into the hot plasmas of the distant magnetosphere and the implications concerning magnetospheric topology. Comprehensive surveys of this polar wind at auroral and polar latitudes are awaited with anticipation of their contributions to discerning the dynamics of the ionosphere and distant magnetosphere.

There is a recent instrumental advance which should significantly aid our interpretations of auroral plasmas in the next few years -- auroral imaging from orbiting satellites. Such imaging will allow comprehensive, simultaneous monitoring of all, or a major fraction of, the auroral and polar auroras while single-point analyses of plasmas are gained along the trajectory of the satellite. Thus temporal and spatial variations observed along the spacecraft orbit may be resolved without the prohibitive use of a large, multi-satellite mission. The feasibility of such global auroral imaging has been amptly demonstrated with auroral imaging devices on ISIS 2 and a defense satellite [cf. Lui et al., 1973; Shepherd et al., 1973; Pike and Whalen, 1974].

III. THE MAGNETOSPHERIC PLASMAS

The distant magnetosphere is awesome in size and temporal variability in terms of discerning magnetospheric dynamics with a single, though well-equipped satellite. Significant topological changes of the magnetosphere are known to occur on the time scale of minutes; yet the typical periods of satellite orbits through these regions are measured in days. Irregardless of this unavoidable disadvantage, substantial progress has been gained toward understanding the origins and dynamics of the immense plasma domains of the terrestrial magnetosphere. A summary of one possible magnetospheric topology which is consistent with most of our current knowledge of these plasmas is offered in Figure 12. The principal features of this topological model are (1) merging of geomagnetic and interplanetary magnetic field lines in the vicinity of the dayside polar cusp, (2) convection of these field lines with their plasmas along the flanks of the magnetosphere into the distant plasma sheet, (3) reconnection of magnetic field lines along a 'neutral line' in the magnetotail accompanied by injection of plasma onto these newly closed field lines in the plasma sheet and (4) subsequent convection of plasma towards earth and adiabatic motion of plasmas in the geomagnetic and geoelectric fields as the plasmapause is approached.

This model is suggested here as a viable alternative to that proposed by Heikkila [1974]. Both models are similar in many respects. The primary disparity lies in the role of the polar cusp in magnetospheric dynamics. In Heikkila's model, the polar cusp is severely limited to the dayside polar magnetosphere: plasma entry into the distant magnetosphere is accomplished by diffusion through the boundaries of the polar cusp. Analyses of recent observations in the earth's polar magnetosphere will soon probably resolve this crucial issue.

The long anticipated discovery of the direct entry of solar plasmas into the earth's magnetosphere in the vicinity of the dayside, high-latitude neutral points was accomplished by the satellite IMP 5 which enjoyed very fortuitous crossings of the polar magnetosphere on the inbound portions of its highly elliptical orbit. The geometry of the dayside polar cusp as deduced from these early observations for periods of relative magnetic quiescence is summarized in Figure 13. The position of the polar cusp is responsive to the occurrence of magnetic storms and moves rapidly equatorward at the onset of magnetic activity (cf. Russell _et al_. [1971] and Figure 7 of present review). The polar cusp is a persistent feature of the polar magnetosphere [Frank, 1971] and appears to be rich in plasma wave phenonema [Fredricks et al., 1972]. Recently a new plasma region was found with a polar orbiting satellite, HEOS 2, at latitudes beyond the capabilities of the IMP-5 orbit. This region, also endowed with magnetosheath plasmas, is located inside the polar magnetopause and downstream from the dayside polar cusp. It is appropriately called 'the mantle' [Rosenbauer et al., 1974]. These plasmas have not been included in the summary of Figure 12, as their relationships with the magnetotail are still unclear.

In the early years of exploration of the plasma sheet in the magnetotail, we viewed this great plasma reservoir as a relatively placid, persistent feature. Comprehensive plasma measurements in this region over the past several years have shown that this is a grossly incorrect impression. Hones and his coworkers have mounted an extensive analysis of the temporal behavior of the plasma sheet during magnetic storms at approximately 18 R_E (R_E, earth radii) with plasma instrumentation on the Vela satellites [cf. Hones et al., 1973; Hones 1972a,b]. A summary of these findings is given in Figure 14. At the onset of the expansion phase of the substorm the plasma sheet thickness decreases dramatically. Plasma flow at the satellite position (V) is directed tailward. This tailward flow continues through the expansive phase of the substorm. Then, at the beginning of the recovery phase, the plasma sheet thickens and the plasma flow is now earthwards -- strongly suggesting that plasma is also being injected deep into the magnetosphere. These observations are interpreted in terms of a line of reconnection lying between earth and the spacecraft during the expansion phase and rapidly moving beyond the satellite to a position further in the magnetotail during recovery. This valuable contribution to our knowledge of the dynamics of the magnetotail would be greatly amplified if simultaneous measurements of magnetic fields were available. The above conclusions advanced by Hones are supported at least in part with measurements of plasma flows with other satellites in the magnetotail. An example of simultaneous determinations of plasma flow at two positions in the plasma sheet with IMP's 6 and 7 is shown in Figure 15. IMP 6 was positioned at 25 to 30 R_E geocentric radial distances in the local evening sector of the plasma sheet; IMP 7 moved slowly through the dawn sector at about 34 R_E during this period of observations. During periods of relative magnetic quiescence, plasma flows are typically 10 to 100 kilometers $(sec)^{-1}$ and directed more or less randomly (V_x is earthward; V_y toward local dawn). At the onset of the substorm at about 2200 U.T. the plasma sheet abruptly disappears at the position of the

IMP-6 satellite which is several earth radii above the expected position of the neutral sheet, and explosive tailward jetting of plasma at speeds ranging from 100 to 200 kilometers $(sec)^{-1}$ is observed at IMP 7. Formation of a line of reconnection or the triggering of a large-scale instability at radial distances less than 20 R_E? Further detailed studies of such plasma flows with simultaneous measurements of the magnetic fields must be employed to resolve this fundamental issue.

The plasma which flows earthward during the violent disruptions of the magnetotail accompanying magnetic substorms penetrates to and beyond geostationary satellite positions at 6.6 R_E in the ring current. At the geostationary orbit of ATS 5 McIlwain has employed electrostatic analyzers to gain comprehensive measurements of the motions of these ions and electrons in the geomagnetic and geoelectric fields [McIlwain, 1972; 1974]. E-t spectrograms of electron and proton intensities encountered for a 48-hour period are presented in Figure 16. The pitch angles sampled in this spectrogram range from 10° to 30°. (Note here that white denotes high intensities and black, low intensities, and that the energy scales are proportional to $(E + 3\ keV)^{-1}$.) The satellite's daily encounter with the electron edge of the nightside plasma sheet is clearly evident at about 0400 to 0500 U.T. in these spectrograms. McIlwain concludes that these plasma structures are reformed with each substorm and employs their charge and energy dependences to construct models of the geoelectric field in the vicinity of the satellite, an advantage not enjoyed in the magnetotail due to the variability of those much weaker magnetic fields. Such observations of plasmas at the geocentric orbit are also essential for critical analyses of the growth and decay of the 'classical' ring current. Analysis of these measurements has proceeded in scope to the identification of times for plasma injections during large magnetic substorms with an accuracy of about 10 minutes [Kamide and McIlwain, 1974].

Contiguous to these hot plasmas of the ring current and plasma sheet within the nightside magnetosphere lie the high-density thermal plasmas of the plasmasphere. Our early concept of the outer surface of the plasmasphere, the plasmapause, was one of a relatively smooth surface with an outward extension, or bulge, at local evening. Recent measurements of the plasmaspheric ions have readily dispelled this oversimplified concept. Observations of ion densities in the plasmasphere and beyond have been reported by Chappell [1972b; 1974]; several of these measurements for various local-time sectors of the magnetosphere are summarized in Figure 17. The remarkable finding is one of highly structured ion profiles with radial distance, both inside the plasmasphere and outside the plasmapause within the plasmatrough [cf. Taylor et al., 1971]. These structures, or more accurately 'detached plasmas', are expected to play an important role in stimulating pitch angle and energy diffusion of the more energetic plasmas of the ring current and plasma sheet and thus also in their precipitation into the auroral zone [Cornwall et al., 1970, 1971]. Williams and his coworkers have applied this suggestion to their comprehensive measurements of ring-current proton distributions in the vicinity of the plasmapause during the recovery phase of magnetic storms [cf. Williams and Lyons, 1974]. Their results support moderate pitch angle scattering by ion cyclotron waves in the region where the ring current interacts with the thermal plasmas of the plasmasphere. This interaction also occurs at L-values corresponding to those at or very near midlatitude red arcs, and hence is suggested as the energy source for these dim, but fascinating arcs. No unassailable identification of the plasma, possibly low-energy electrons, directly energizing these midlatitude emissions is available in the literature. There is one persistent feature that is again stressed by these observations and others throughout the magnetosphere -- the strong interaction, or coupling, between earth's magnetosphere and her ionosphere.

IV. EPILOGUE

This past quadrennium has seen a substantial progress in understanding the nature of the major plasma domains which play critical roles in the dynamics of the magnetosphere: the plasma sheet and its earthward extension as 'the ring current', the plasmasphere, the polar cusp, the polar wind, and the diverse auroral plasmas including the striking 'inverted-V' events. It is of interest here to briefly predict goals and achievements of the next quadrennium. First, considerably more effort will be expended in analyses of plasma wave-particle interactions, the ubiquitous presence of which is suggested by current researches in such areas as anomalous resistivity in sustaining parallel electric fields, merging and reconnection of magnetic field lines, precipitation of magnetospheric plasmas into the auroral zones, interaction of ring-current plasmas with the plasmasphere, and many others. Instrumentation on many current satellites will allow substantial progress in this area. We should also encounter significant progress in discerning the mechanisms responsible for field-aligned currents and the participation of these currents in the coupling of the magnetosphere and the ionosphere. Global surveys of the polar wind and of the species compositions of hot auroral and magnetospheric plasmas will define more clearly the contributions of the ionosphere to the large bodies of plasmas found in the distant magnetosphere. Significant advances are forthcoming in the area of convection electric fields over the polar and auroral ionospheres -- many of these from in situ observations of ion drifts. Missions into the distant polar magnetosphere will firmly establish the role that the polar cusp plays in supplying magnetosheath plasmas into the magnetotail. And, hopefully, the plasma in the distant magnetosphere, which is to be associated with 'inverted-V' precipitation events, will be identified. Great promise in overcoming such obstacles as the immense sizes and temporal variabilities of the magnetospheric and auroral plasma domains is offered by dual satellite missions and by global auroral imaging. The next quadrennium indeed promises to be exciting and rewarding in terms of researches into auroral and magnetospheric plasmas.

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Figure Captions

Figure 1. Meridional cross-section of the earth's magnetosphere in the vicinity of earth, which shows the major plasma regimes encountered at local noon and midnight.

Figure 2. E-t spectrogram of electron intensities precipitating into the local evening sector of the auroral zone as observed with Injun 5. This series of measurements provides several good examples of 'inverted-V' precipitation events (after Frank and Ackerson [1972]).

Figure 3. Model electron energy spectrum computed by assuming a 400-volt potential difference along a magnetic field line and an unenergized Maxwellian electron distribution with temperature of 800 eV and density 5 $(cm)^{-3}$. The data are taken from an 'inverted-V' electron spectrum reported by Frank and Ackerson [1971] (after Evans [1974]).

Figure 4. E-t spectrograms of electron and proton intensities for a crossing of the polar cusp with the low-altitude satellite ISIS 2. The satellite passes out of the more energetic

plasmas on closed field lines into the low-energy plasmas of the polar cusp at approximately 0015:40 U.T. The angle θ_p is the pitch angle for each spectral scan (after Dyson and Winningham [1974]; see also Heikkila and Winningham [1971]).

Figure 5. An interpretive diagram for the auroral zones and polar cap, including the low-altitude signatures of plasma in the distant magnetosphere, the major convection zones, and the field topology (after Frank and Ackerson [1972]).

Figure 6. The electric fields and precipitated electron energy fluxes observed over the auroral zones near local midnight with the low-altitude satellite Injun 5 (after Gurnett and Frank [1973]).

Figure 7. Polar plots in the coordinates invariant latitude (Λ) and magnetic local time (MLT), which summarize the electron precipitation patterns for the five substorm phases (after Hoffman and Burch [1974]).

Figure 8. A possible current system including four Birkeland currents and an eastward electrojet that is capable of reproducing the magnetic

field changes observed during the rocket flight. The electrojet, Birkeland currents, and visible arc extend horizontally perpendicular to the plane of the figure. The position of the southern visible arc inferred from Fort Yukon all-sky photographs and photometer data was within the southernmost region of downward current, moving from the southern to northern edges in the time interval 180-220 sec. The northern arc was less intense than the southern arc near the end of the flight but may have been associated with the northern region of upward current (after Cloutier _et al_. [1973].

Figure 9. Field-aligned anisotropies within the 'inverted-V' events of Figure 2. The field aligned electron intensities, $J(\alpha = 0^\circ) / J(\alpha = 90^\circ) > 1$, are an upward directed current. Typically the most energetic portions, or centers, of these events are not favored with field-aligned intensities.

Figure 10. Observations of energetic O^+ ions with an ion mass spectrometer on satellite 1969-25B during a traversal of the northern hemisphere on March 24, 1969 (after Sharp _et al_., 1974).

Figure 11. An example of observations of the polar wind with ISIS 2. Bottom panel gives the roll modulation curves for H^+ and O^+ concentrations. The angle θ is the angle between the ram direction due to satellite motion and the instrument field of view. If the two ion species have merely thermal velocities the roll modulation maximums will coincide both in time and with the ram direction. If one species (H^+, in this case) has a bulk velocity its maximum will be shifted away from the ram direction. This bulk velocity of H^+ is the signature of the polar wind. Typical velocities at these altitudes are several kilometers $(sec)^{-1}$ (after Hoffman [1974]; see also Hoffman et al., 1974).

Figure 12. A diagram of the relationship of various plasma regions in the distant magnetosphere.

Figure 13. A diagram showing the geometry and location of the polar cusp within the polar magnetosphere in the noon meridional plane during periods of relative magnetic quiescence. The coordinates are geocentric radial distance R and dipole magnetic latitude λ_m. The polar

cusp intersects the auroral zone at $\Lambda \simeq 79^\circ$. Several sample trajectories of IMP 5 through the dayside magnetosphere are also shown (after Frank [1971c]).

Figure 14. Schematic representation of plasma sheet behavior during a substorm: (a) The plasma sheet may thin gradually for some tens of minutes before breakup (signified by T = 0). The question marks indicate that Vela measurements have as yet not identified any characteristic pattern of flow during such periods of gradual plasma loss. The solid arrow B_1 and the dashed arrows suggest the possible role that the interplanetary field may play in this (and the subsequent two) epoch(s). (b) The field line reconnection (star) starts somewhere earthward of the Vela satellite (V) at T = 0. Very rapid flow of plasma earthward and tailward from the neutral line begins. A Vela satellite more than $\sim 1\ R_E$ from the neutral sheet encounters a rapid reduction of plasma intensity to background at this time. A rapid tailward flow of the disappearing plasma is quite typically encountered. (c) Recon-

nection continues near the site of its initial onset throughout the expansive phase of the substorm. (d) The reconnection region suddenly moves much farther tailward as substorm recovery begins. Earthward of the reconnection region the plasma sheet becomes much thicker, and the reappearing plasma flows very rapidly earthward (after Hones _et al_. [1974]).

Figure 15. Plasma flows at two positions in the plasma sheet prior to and during a magnetic substorm. IMP 6 is in the evening sector of the plasma sheet at geocentric radial distances 25 to 30 R_E for this period of observations. IMP 7 is in the morning sector at 34 R_E. Note the strong antisunward streaming of plasma at IMP 7 during 2200 to 2300 U.T. (after Frank _et al_. [1973]).

Figure 16.. E-t spectrograms of proton and electron intensities at the geostationary orbit of ATS 5 for a period of 48 hours. (Note that the proton energy scale is inverted relative to that for electrons.) The pitch angles sampled for this period of observations ranged from 10° to 30° (after McIlwain [1974]).

Figure 17. A composite figure showing the change in the location of the detached plasma regions with respect to the plasmapause and magnetopause. At dusk the regions are located at the plasmapause. At earlier local times the regions are found farther away from the plasmapause, as is shown by the different cases. The shaded area covers the general location of the detached regions (after Chappell [1974]).

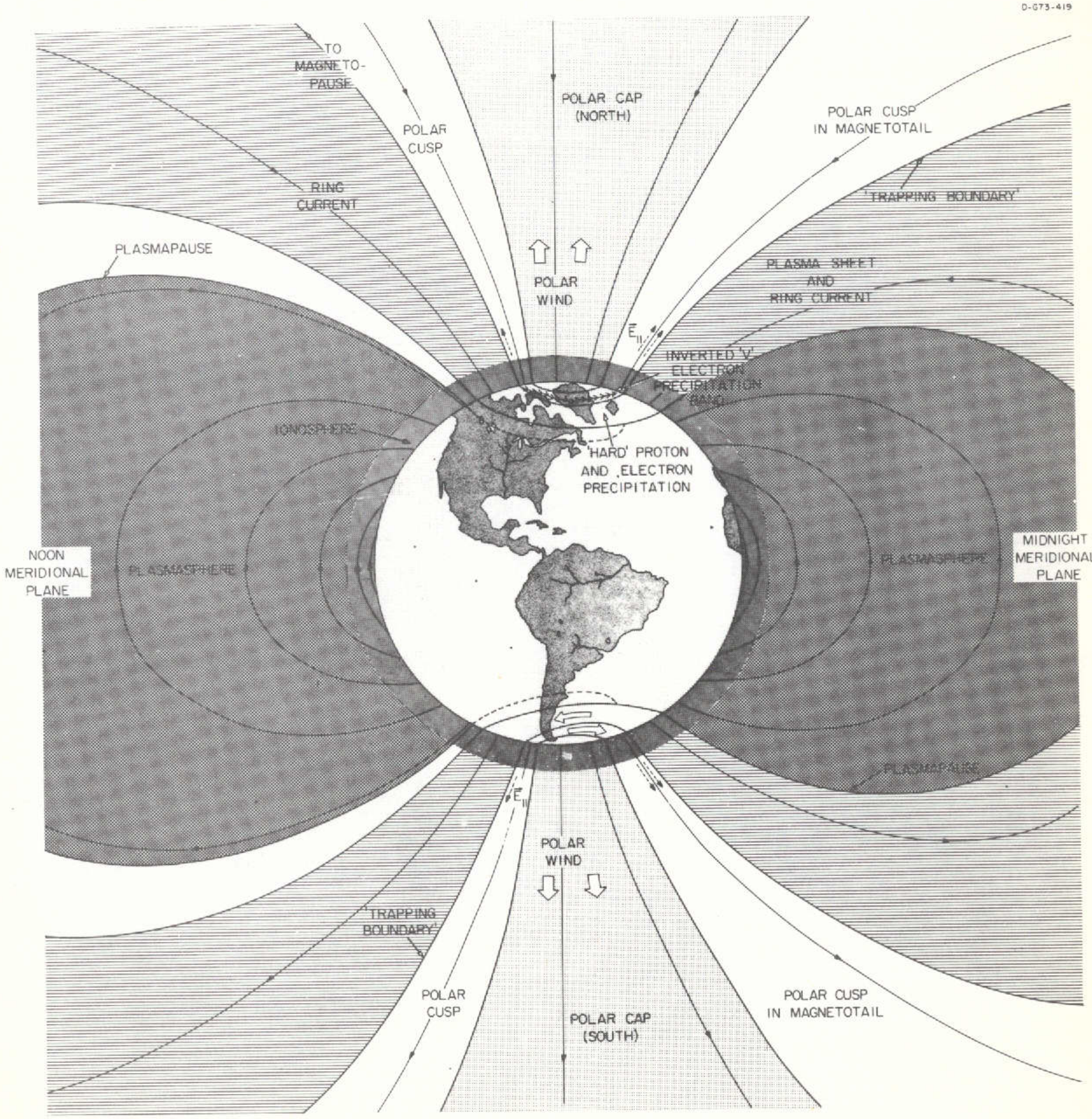

D-G73-419
TO
MAGNETO-
PAUSE
POLAR
CUSP
POLAR CAP
(NORTH)
POLAR CUSP
IN MAGNETOTAIL
'TRAPPING BOUNDARY'
RING
CURRENT
PLASMAPAUSE
POLAR
WIND
PLASMA SHEET
AND
RING CURRENT
INVERTED 'V'
ELECTRON
PRECIPITATION
BAND
IONOSPHERE
'HARD' PROTON
AND ELECTRON
PRECIPITATION
NOON
MERIDIONAL
PLANE
PLASMASPHERE
PLASMASPHERE
MIDNIGHT
MERIDIONAL
PLANE
PLASMAPAUSE
POLAR
WIND
'TRAPPING
BOUNDARY'
POLAR
CUSP
POLAR CAP
(SOUTH)
POLAR CUSP
IN MAGNETOTAIL

Figure 1.

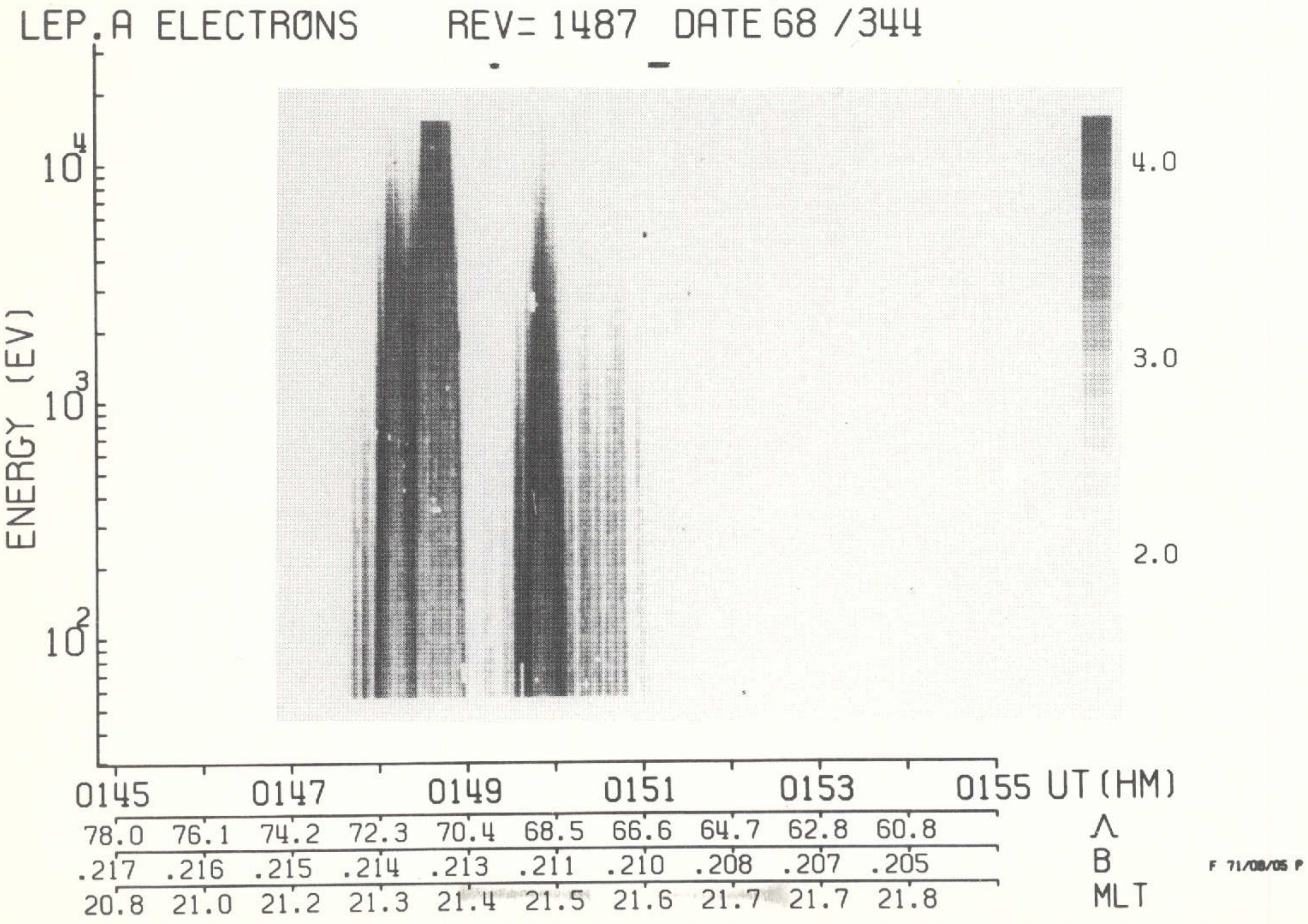

LEP.A ELECTRONS REV= 1487 DATE 68 /344
ENERGY (EV)
10^4
10^3
10^2
4.0
3.0
2.0
0145
0147
0149
0151
0153
0155 UT (HM)
78.0 76.1 74.2 72.3 70.4 68.5 66.6 64.7 62.8 60.8
Λ
.217 .216 .215 .214 .213 .211 .210 .208 .207 .205
B
20.8 21.0 21.2 21.3 21.4 21.5 21.6 21.7 21.7 21.8
MLT
F 71/08/05 P

Figure 2.

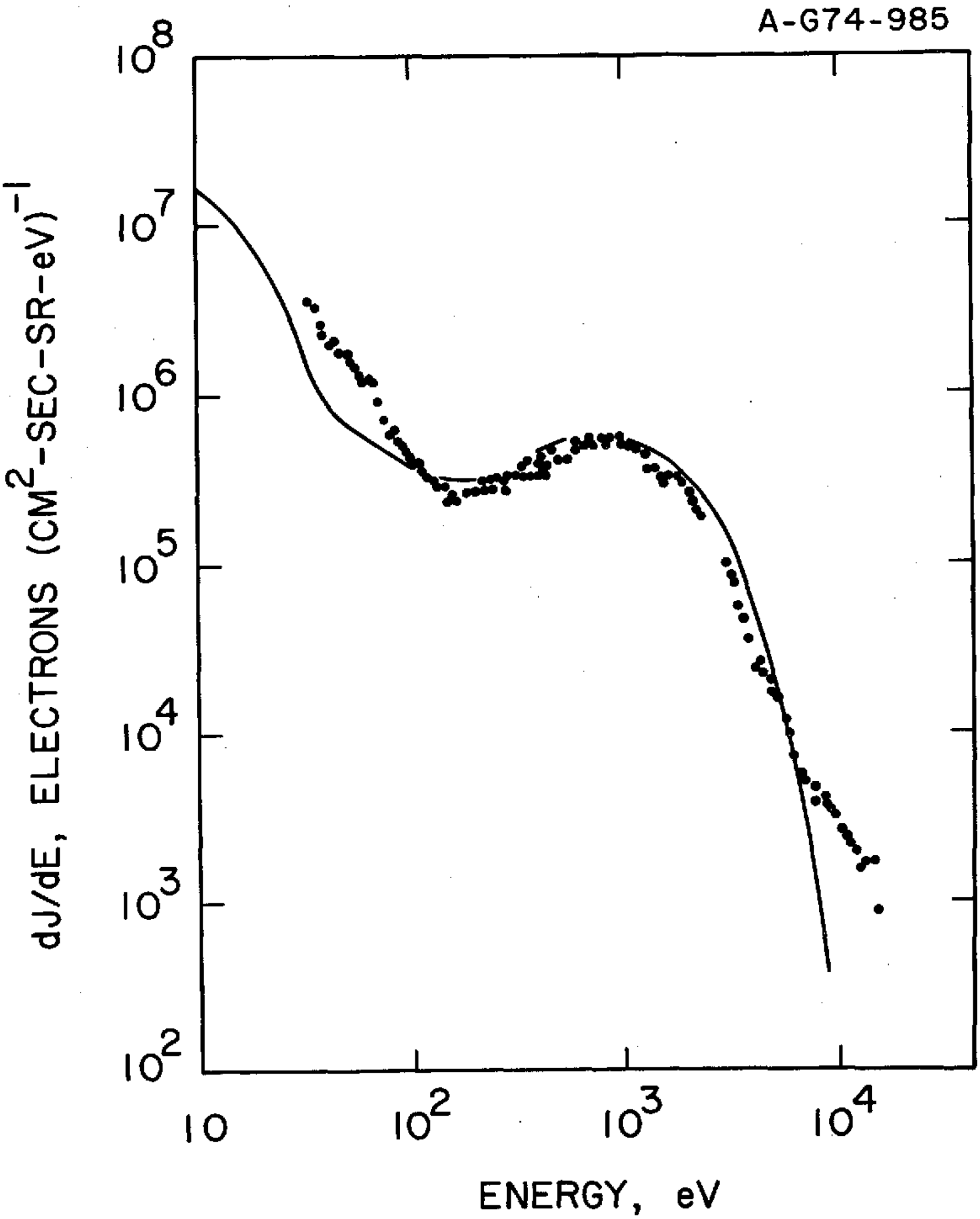

A-G74-985
10^8
10^7
10^6
10^5
10^4
10^3
10^2
dJ/dE, ELECTRONS (CM2-SEC-SR-eV)-1
10
10^2
10^3
10^4
ENERGY, eV

Figure 3.

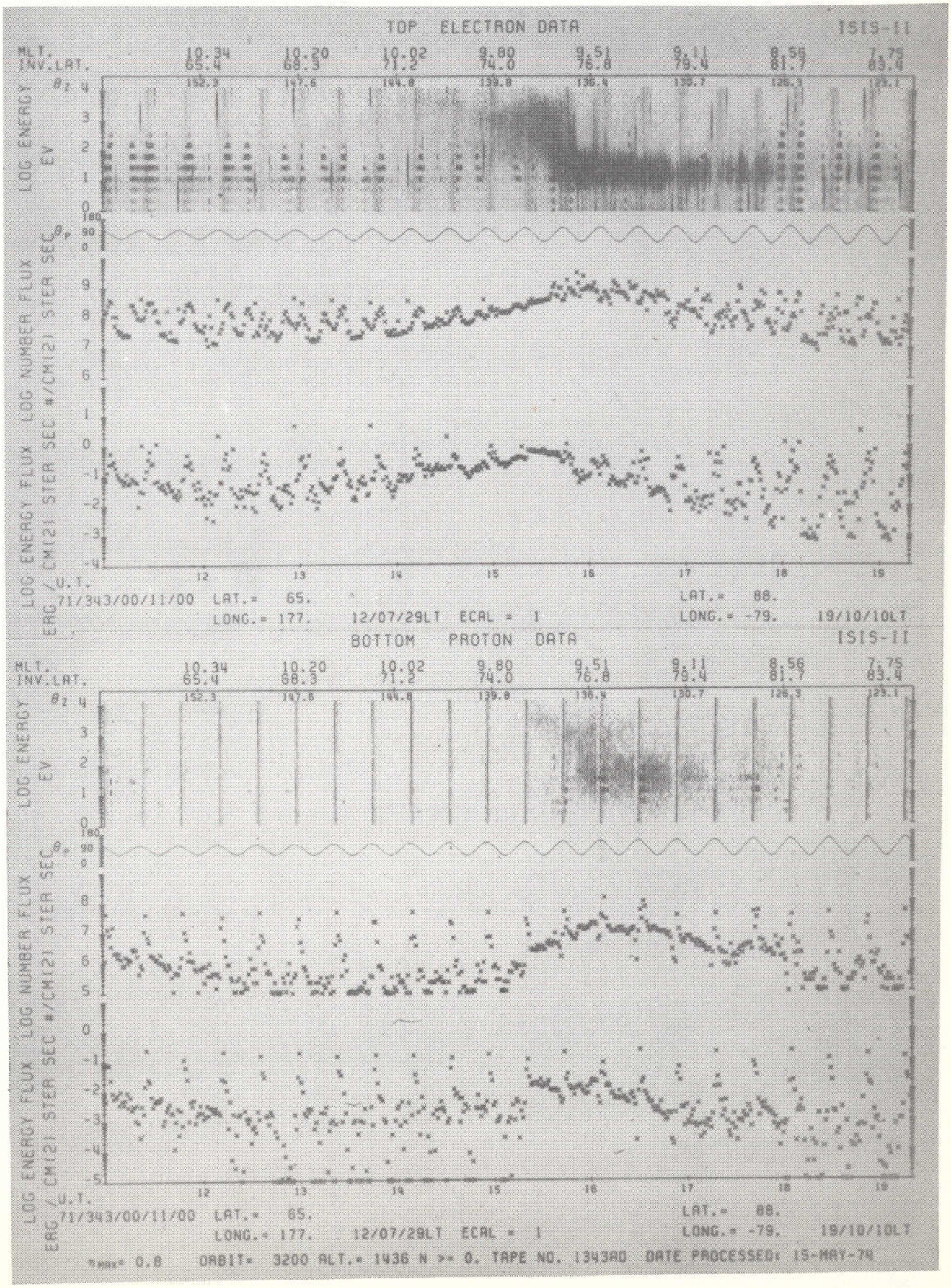

TOP ELECTRON DATA
ISIS-II
MLT.
INV.LAT.
10.34 65.4
10.20 68.3
10.02 71.2
9.80 74.0
9.51 76.8
9.11 79.4
8.56 81.7
7.75 83.4
LOG ENERGY EV
LOG NUMBER FLUX
LOG ENERGY FLUX
ERG / CM(2) STER SEC #/CM(2) STER SEC
U.T.
71/343/00/11/00 LAT.= 65.
LONG.= 177. 12/07/29LT ECAL = 1
LAT.= 88.
LONG.= -79. 19/10/10LT
BOTTOM PROTON DATA
ISIS-II
ORBIT= 3200 ALT.= 1436 N >= 0. TAPE NO. 1343AD DATE PROCESSED: 15-MAY-74

Figure 4.

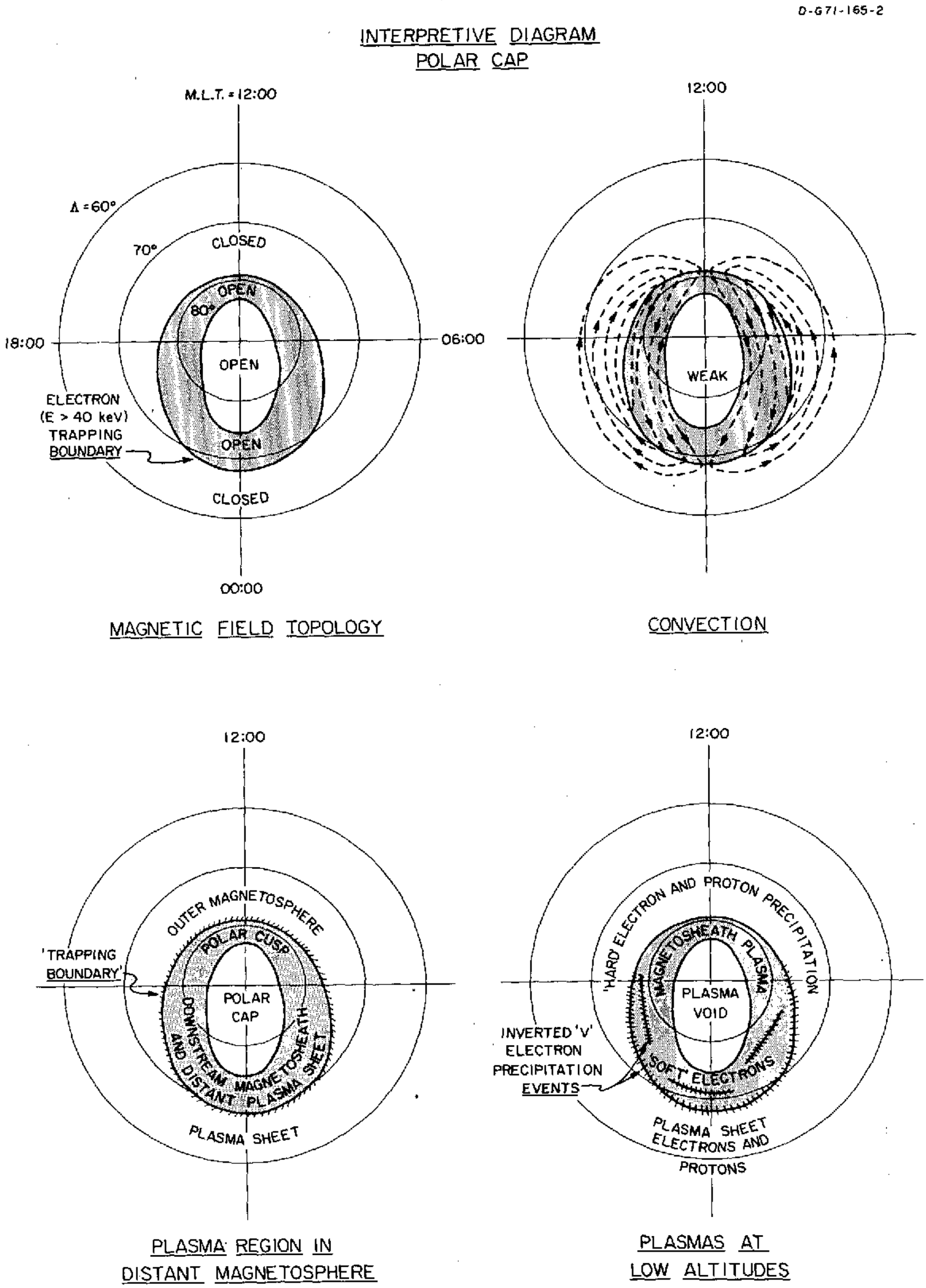

D-G71-165-2
INTERPRETIVE DIAGRAM
POLAR CAP
M.L.T. = 12:00
Λ = 60°
70°
80°
CLOSED
OPEN
OPEN
OPEN
18:00
06:00
ELECTRON
(E > 40 keV)
TRAPPING
BOUNDARY
CLOSED
00:00
MAGNETIC FIELD TOPOLOGY
12:00
WEAK
CONVECTION
12:00
OUTER MAGNETOSPHERE
POLAR CUSP
'TRAPPING
BOUNDARY'
POLAR
CAP
DOWNSTREAM MAGNETOSHEATH
AND DISTANT PLASMA SHEET
PLASMA SHEET
PLASMA REGION IN
DISTANT MAGNETOSPHERE
12:00
'HARD' ELECTRON AND PROTON PRECIPITATION
MAGNETOSHEATH PLASMA
PLASMA
VOID
INVERTED 'V'
ELECTRON
PRECIPITATION
EVENTS
'SOFT' ELECTRONS
PLASMA SHEET
ELECTRONS AND
PROTONS
PLASMAS AT
LOW ALTITUDES

Figure 5.

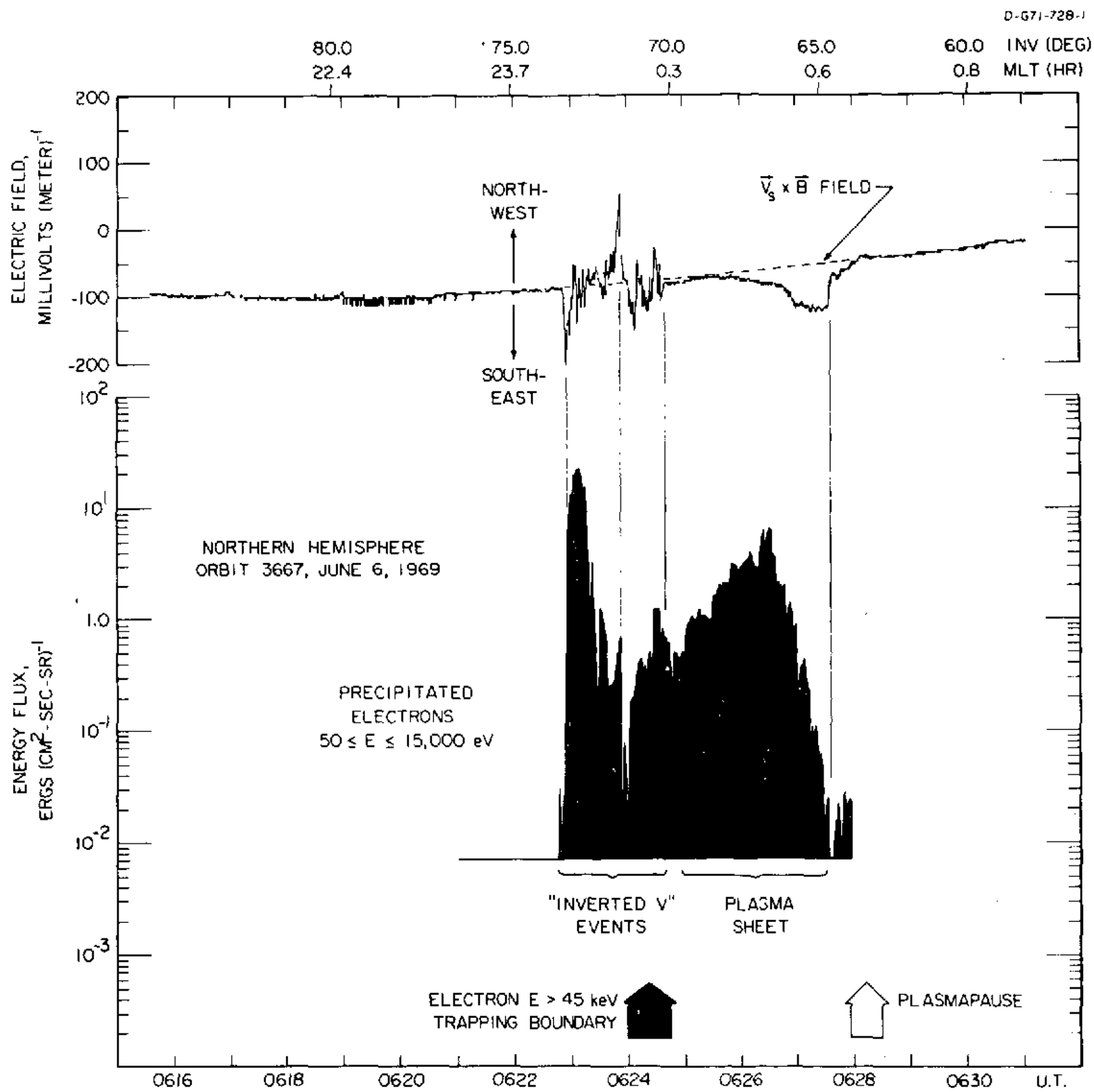

D-G71-728-1
80.0
22.4
75.0
23.7
70.0
0.3
65.0
0.6
60.0
0.8
INV (DEG)
MLT (HR)
ELECTRIC FIELD, MILLIVOLTS (METER)$^{-1}$
200
100
0
-100
-200
NORTH-WEST
SOUTH-EAST
$\vec{V}_s \times \vec{B}$ FIELD
ENERGY FLUX, ERGS (CM^2-SEC-SR)$^{-1}$
10^2
10^1
1.0
10^{-1}
10^{-2}
10^{-3}
NORTHERN HEMISPHERE
ORBIT 3667, JUNE 6, 1969
PRECIPITATED
ELECTRONS
$50 \leq E \leq 15,000$ eV
"INVERTED V"
EVENTS
PLASMA
SHEET
ELECTRON E > 45 keV
TRAPPING BOUNDARY
PLASMAPAUSE
0616
0618
0620
0622
0624
0626
0628
0630
U.T.

Figure 6.

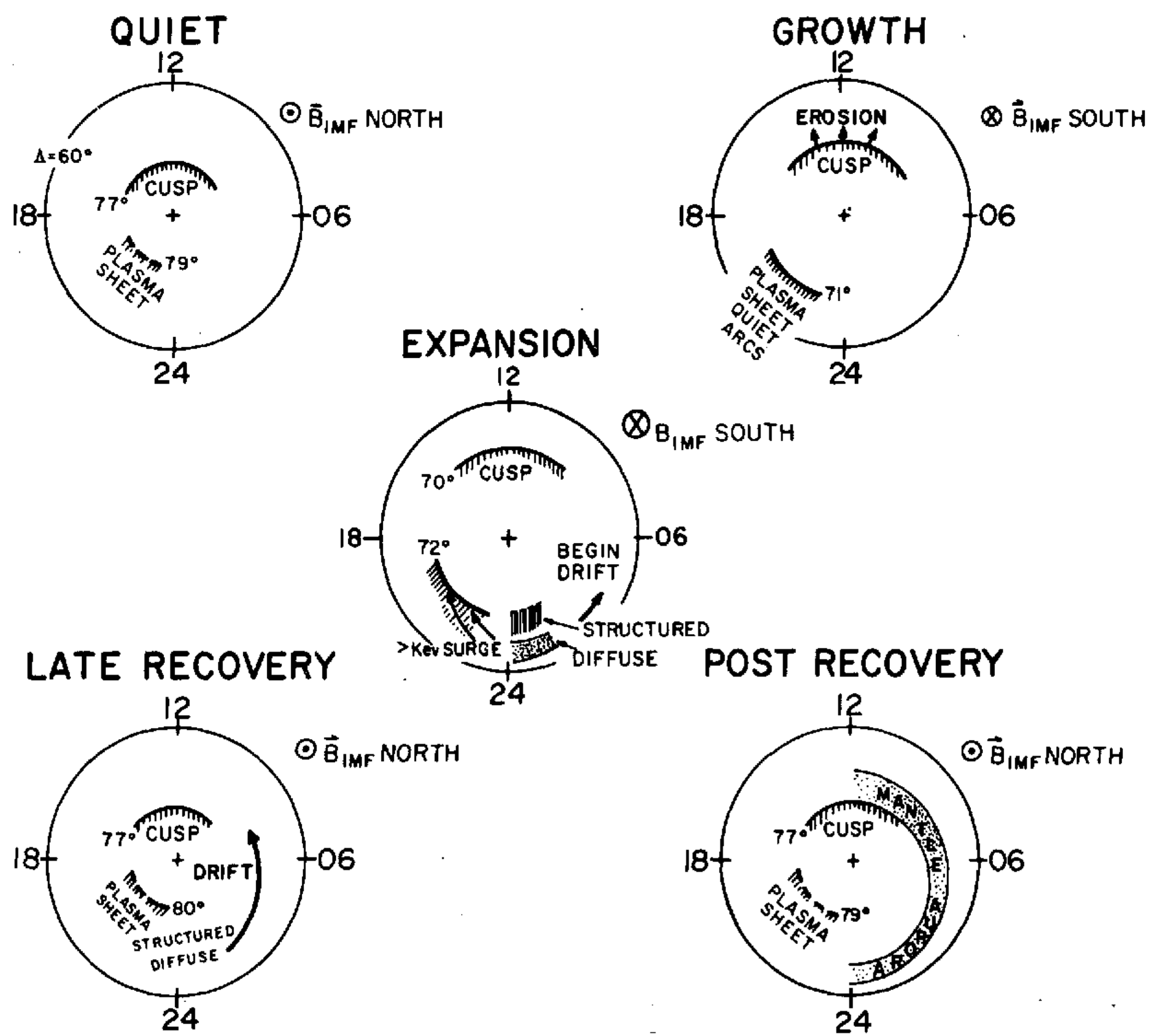

QUIET
12
18
06
24
$\odot \vec{B}_{IMF}$ NORTH
Δ=60°
CUSP
77°
79°
PLASMA SHEET
GROWTH
12
18
06
24
$\otimes \vec{B}_{IMF}$ SOUTH
EROSION
CUSP
71°
PLASMA SHEET QUIET ARCS
EXPANSION
12
18
06
24
$\otimes B_{IMF}$ SOUTH
70°
CUSP
72°
BEGIN DRIFT
STRUCTURED
DIFFUSE
>Kev SURGE
LATE RECOVERY
12
18
06
24
$\odot \vec{B}_{IMF}$ NORTH
77°
CUSP
DRIFT
80°
PLASMA SHEET
STRUCTURED
DIFFUSE
POST RECOVERY
12
18
06
24
$\odot \vec{B}_{IMF}$ NORTH
77°
CUSP
79°
PLASMA SHEET

Figure 7.

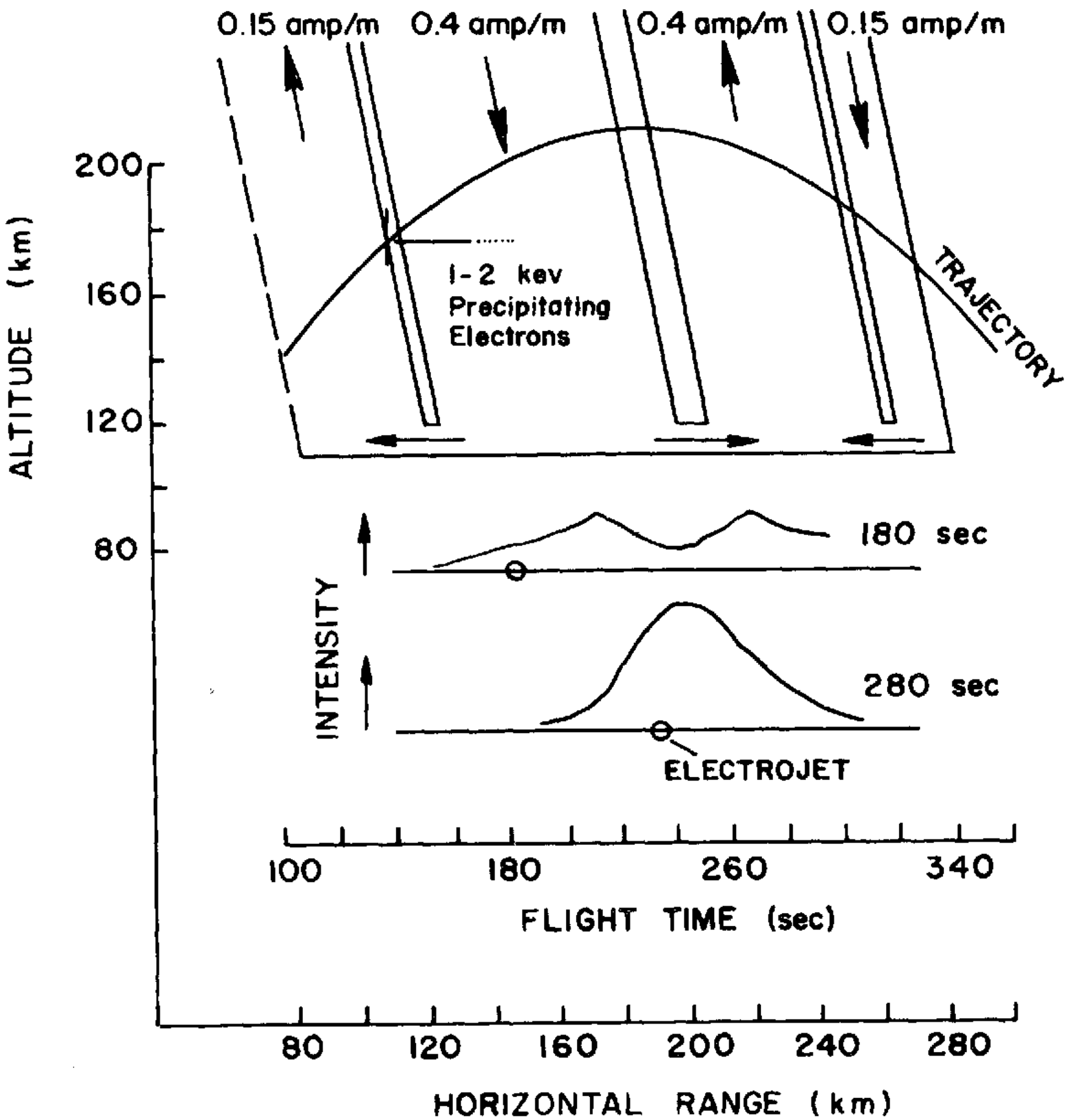

0.15 amp/m
0.4 amp/m
0.4 amp/m
0.15 amp/m
200
160
120
80
ALTITUDE (km)
1-2 kev
Precipitating
Electrons
TRAJECTORY
INTENSITY
180 sec
280 sec
ELECTROJET
100
180
260
340
FLIGHT TIME (sec)
80
120
160
200
240
280
HORIZONTAL RANGE (km)

Figure 8.

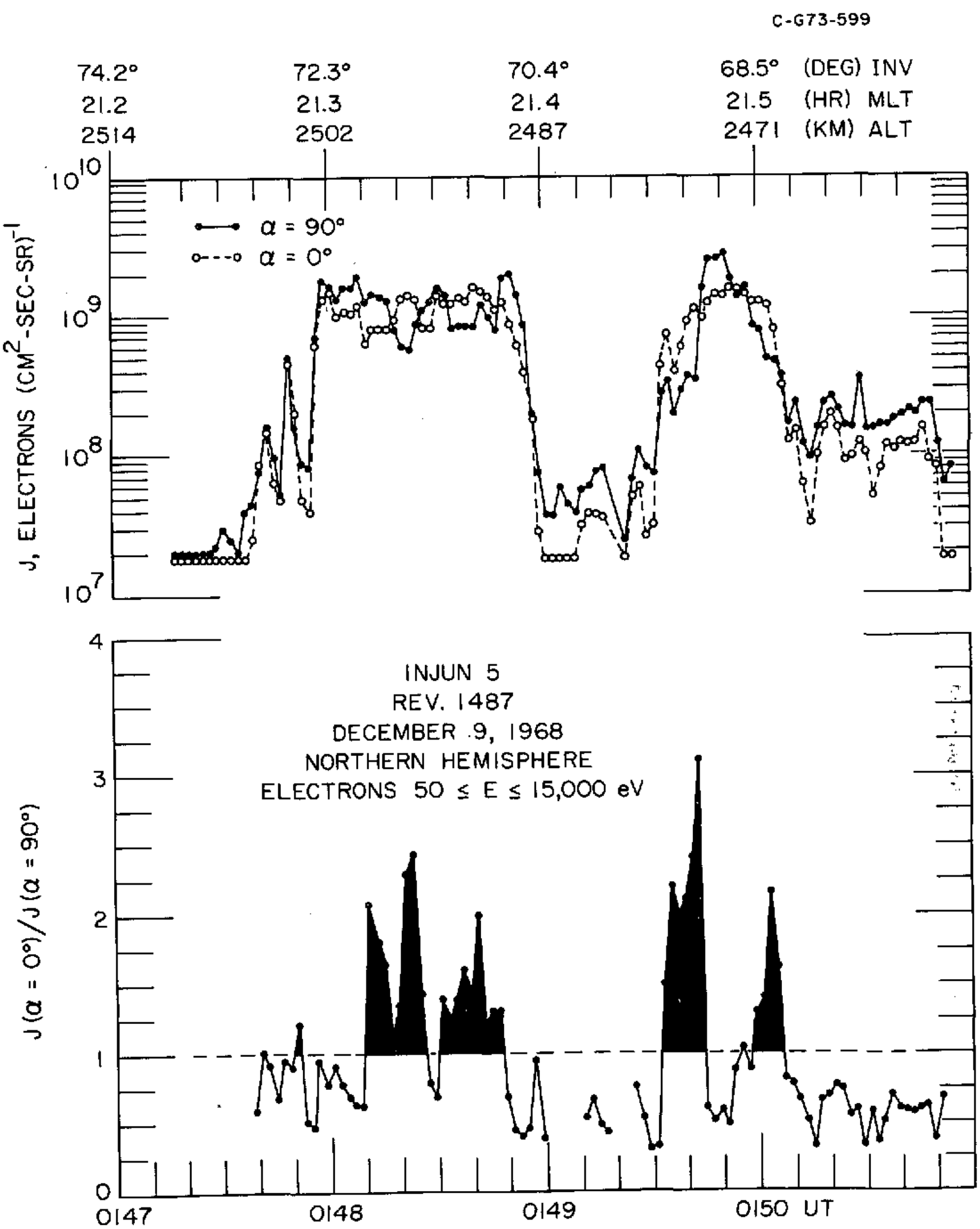

C-G73-599
74.2°
21.2
2514
72.3°
21.3
2502
70.4°
21.4
2487
68.5° (DEG) INV
21.5 (HR) MLT
2471 (KM) ALT
α = 90°
α = 0°
J, ELECTRONS (CM²-SEC-SR)⁻¹
10¹⁰
10⁹
10⁸
10⁷
INJUN 5
REV. 1487
DECEMBER 9, 1968
NORTHERN HEMISPHERE
ELECTRONS 50 ≤ E ≤ 15,000 eV
J(α = 0°)/J(α = 90°)
4
3
2
1
0
0147
0148
0149
0150 UT

Figure 9.

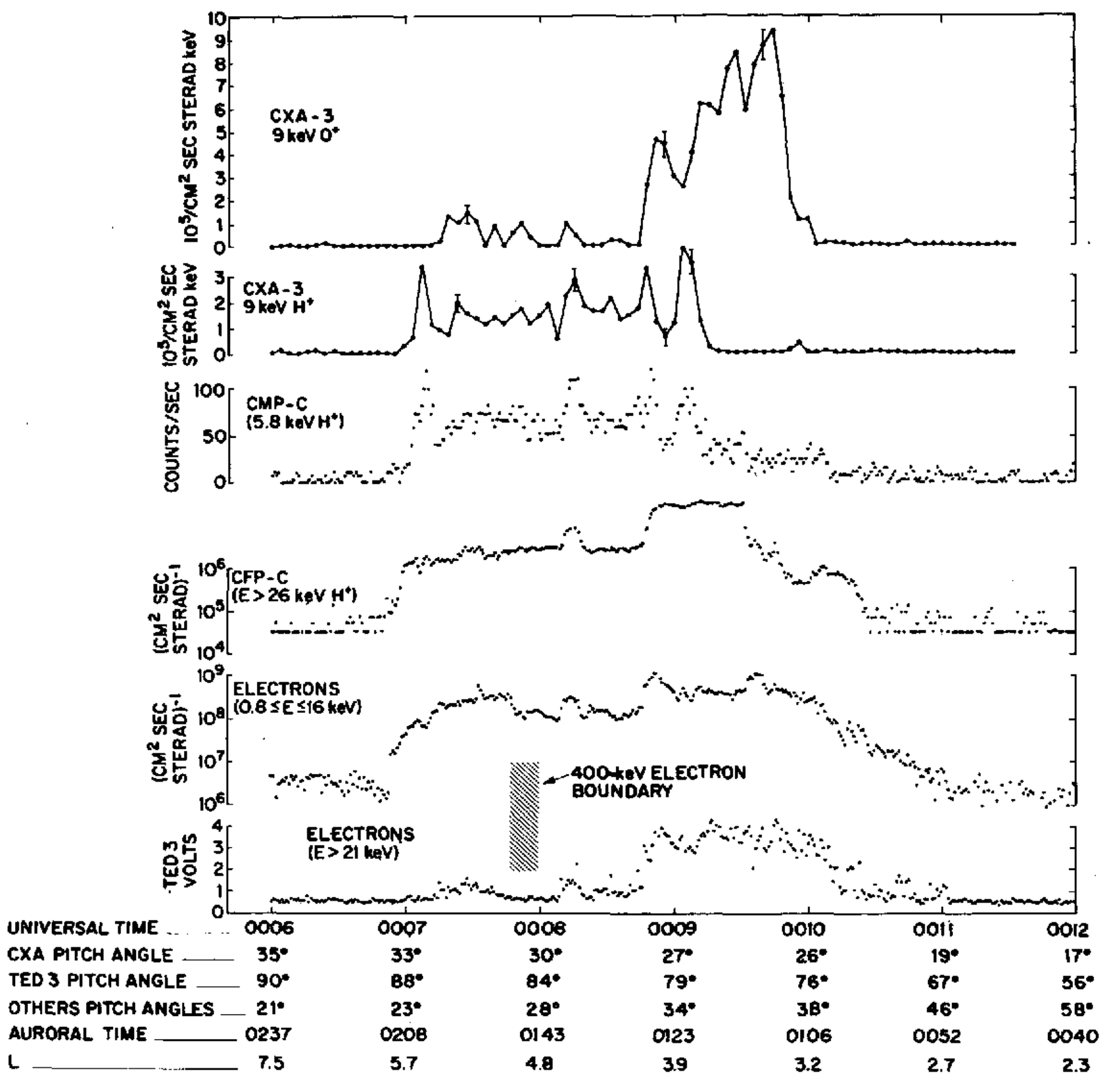
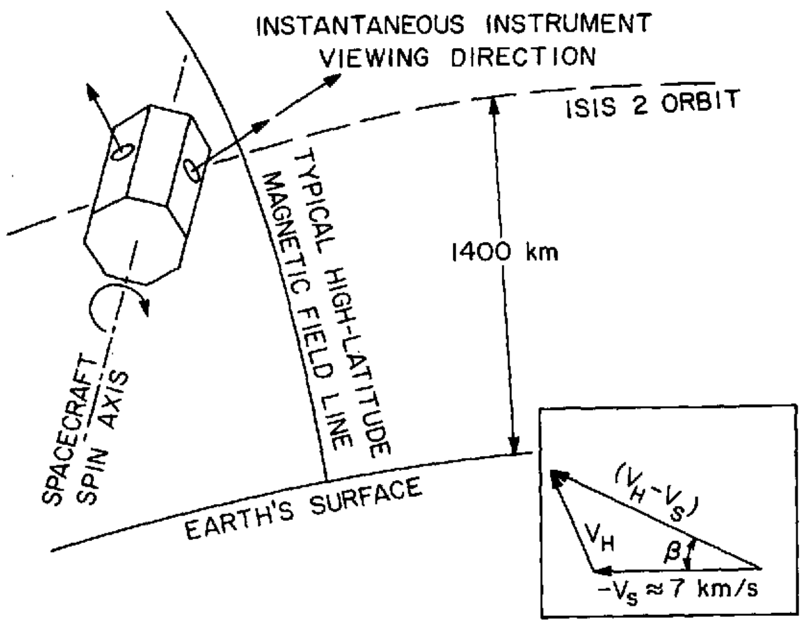

CXA-3
9 keV O+
10^5/CM² SEC STERAD keV
CXA-3
9 keV H+
10^5/CM² SEC STERAD keV
CMP-C
(5.8 keV H+)
COUNTS/SEC
CFP-C
(E > 26 keV H+)
(CM² SEC STERAD)$^{-1}$
ELECTRONS
(0.8 ≤ E ≤ 16 keV)
(CM² SEC STERAD)$^{-1}$
400-keV ELECTRON BOUNDARY
ELECTRONS
(E > 21 keV)
TED 3 VOLTS
UNIVERSAL TIME 0006 0007 0008 0009 0010 0011 0012
CXA PITCH ANGLE 35° 33° 30° 27° 26° 19° 17°
TED 3 PITCH ANGLE 90° 88° 84° 79° 76° 67° 56°
OTHERS PITCH ANGLES 21° 23° 28° 34° 38° 46° 58°
AURORAL TIME 0237 0208 0143 0123 0106 0052 0040
L 7.5 5.7 4.8 3.9 3.2 2.7 2.3

Figure 10.

B-G74-986



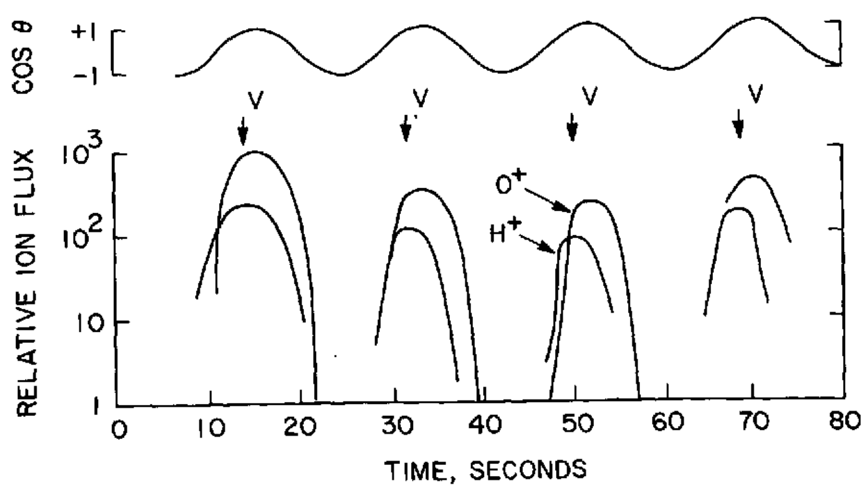


Figure 11.

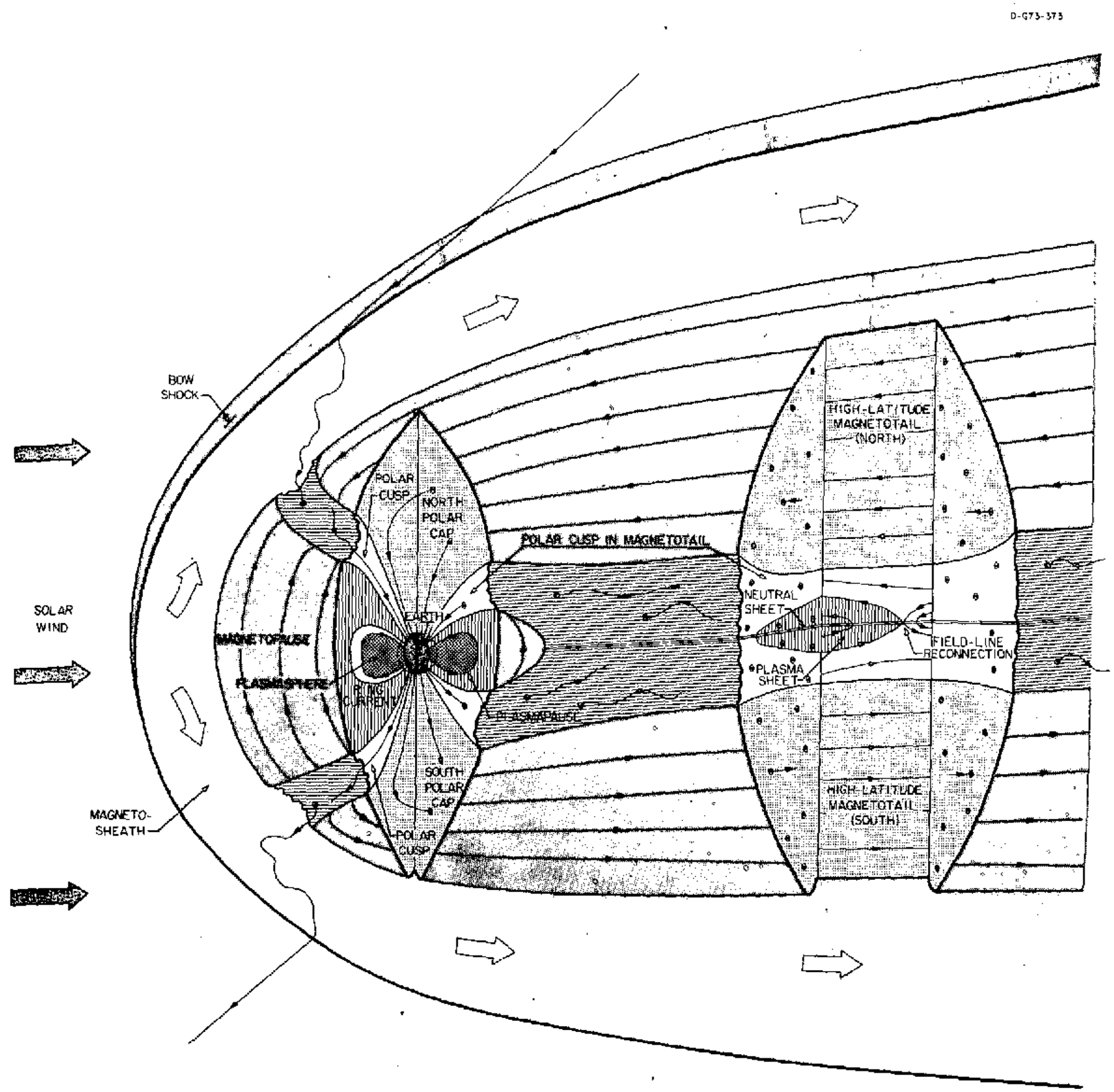
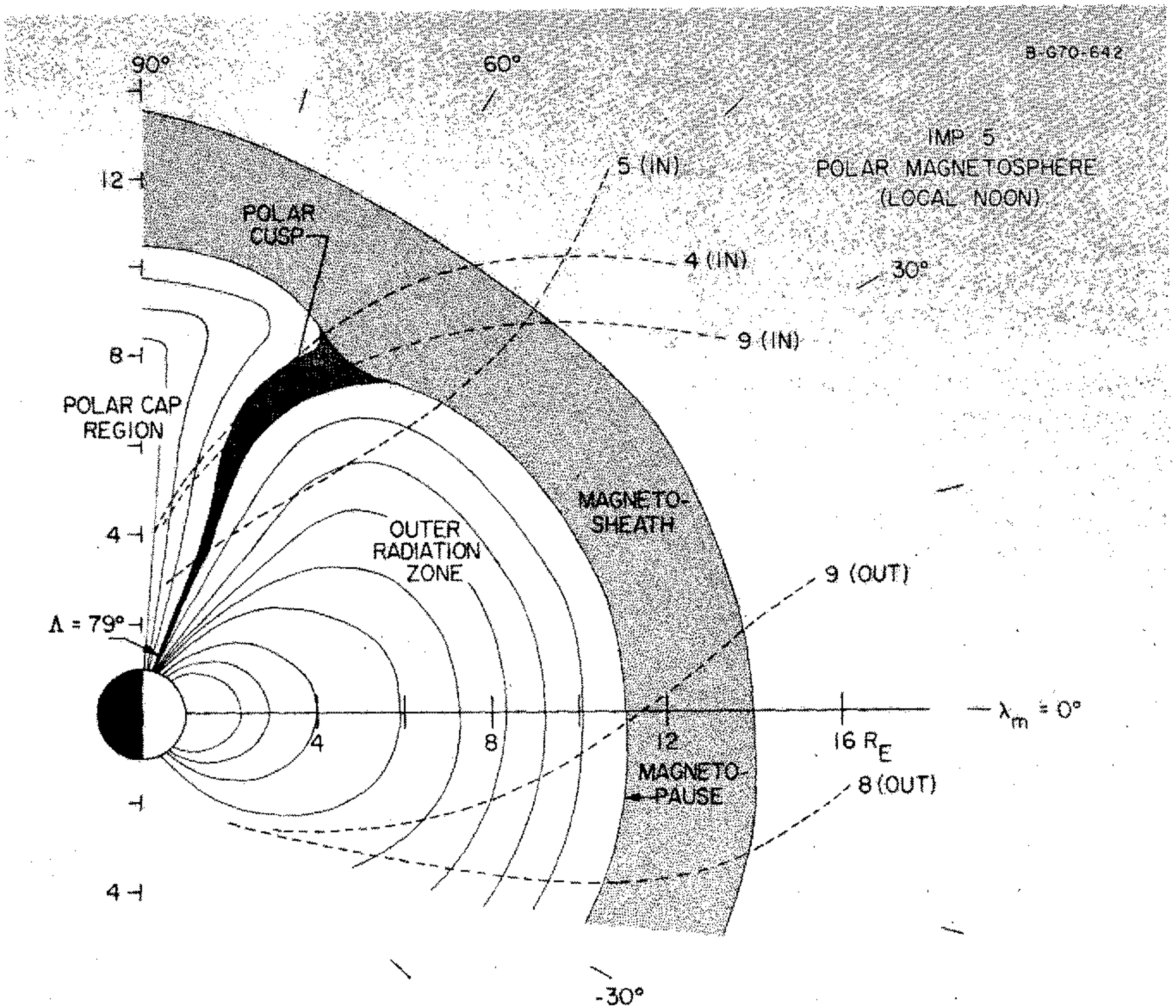

D-G73-373
BOW SHOCK
SOLAR WIND
MAGNETO-SHEATH
MAGNETOPAUSE
PLASMASPHERE
RING CURRENT
POLAR CUSP
NORTH POLAR CAP
EARTH
SOUTH POLAR CAP
POLAR CUSP
POLAR CUSP IN MAGNETOTAIL
PLASMAPAUSE
HIGH-LATITUDE MAGNETOTAIL (NORTH)
NEUTRAL SHEET
PLASMA SHEET
FIELD-LINE RECONNECTION
HIGH-LATITUDE MAGNETOTAIL (SOUTH)

Figure 12.



B-G70-642
90°
60°
30°
-30°
IMP 5
POLAR MAGNETOSPHERE
(LOCAL NOON)
5 (IN)
4 (IN)
9 (IN)
9 (OUT)
8 (OUT)
12
8
4
4
POLAR CUSP
POLAR CAP REGION
Λ = 79°
OUTER RADIATION ZONE
MAGNETO-SHEATH
MAGNETO-PAUSE
4
8
12
16 R_E
$\lambda_m = 0°$

Figure 13.

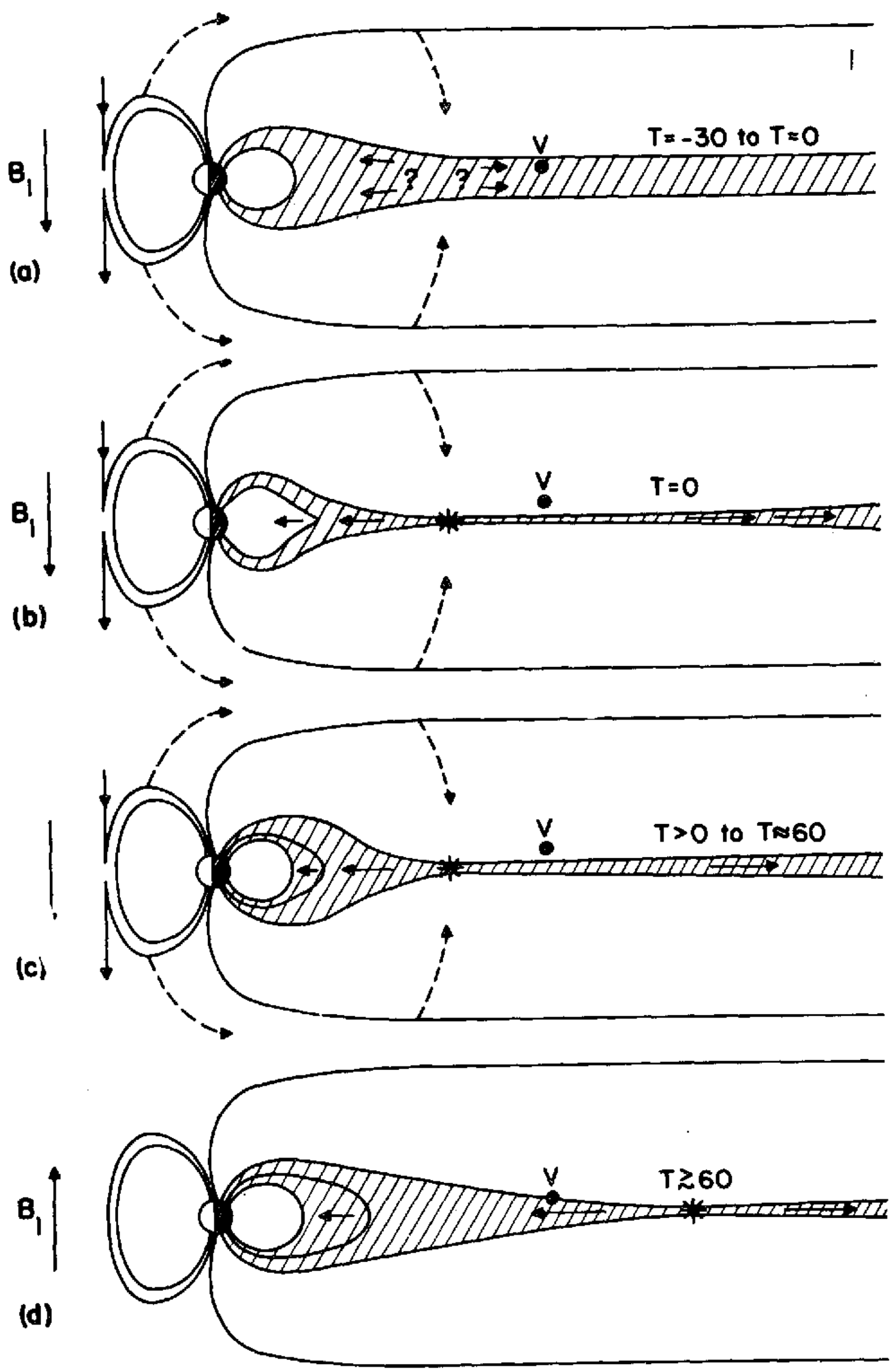


Figure 14.

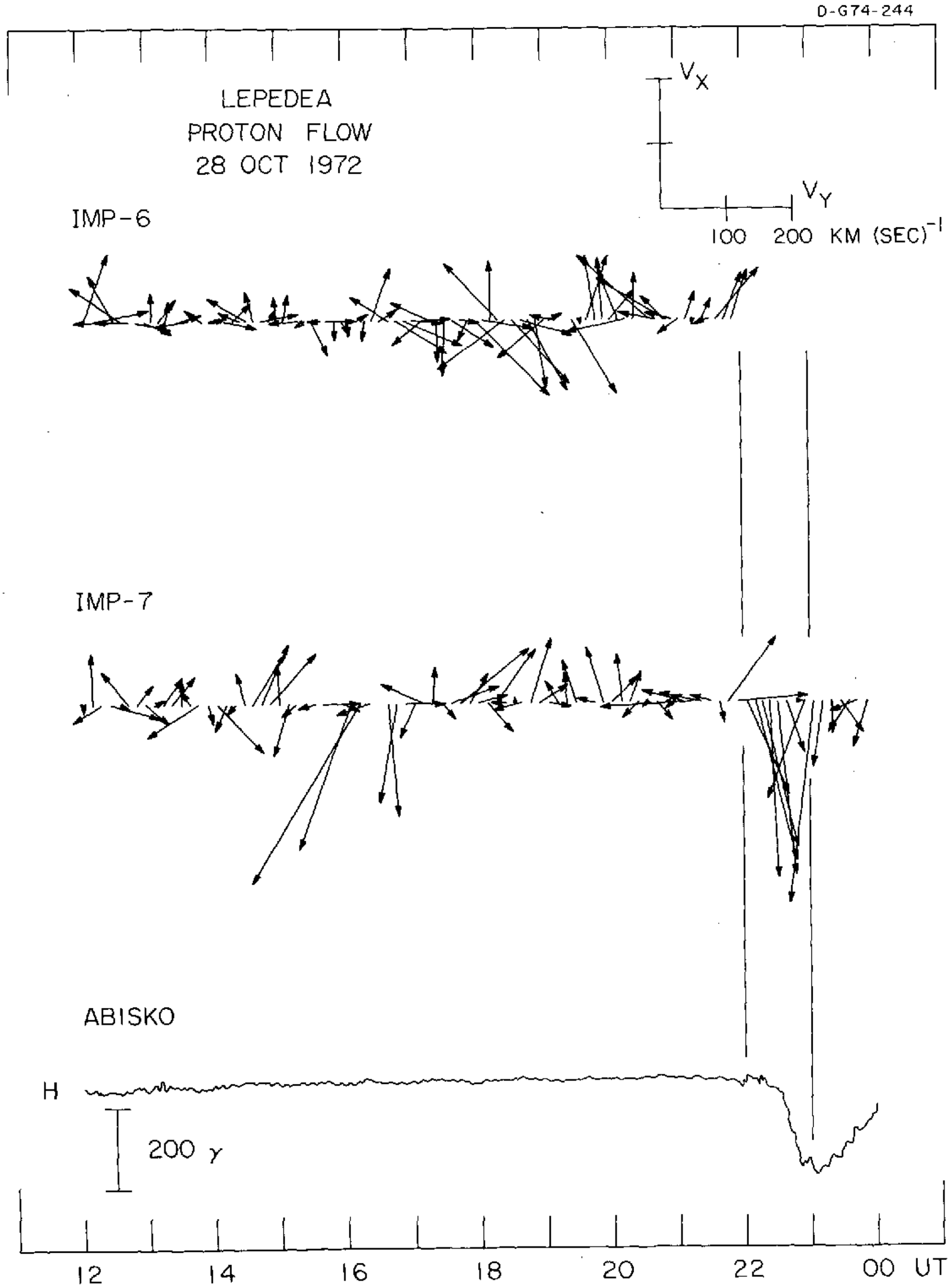

D-G74-244
LEPEDEA
PROTON FLOW
28 OCT 1972
V_X
V_Y
100 200 KM (SEC)$^{-1}$
IMP-6
IMP-7
ABISKO
H
200 γ
12
14
16
18
20
22
00 UT

Figure 15.

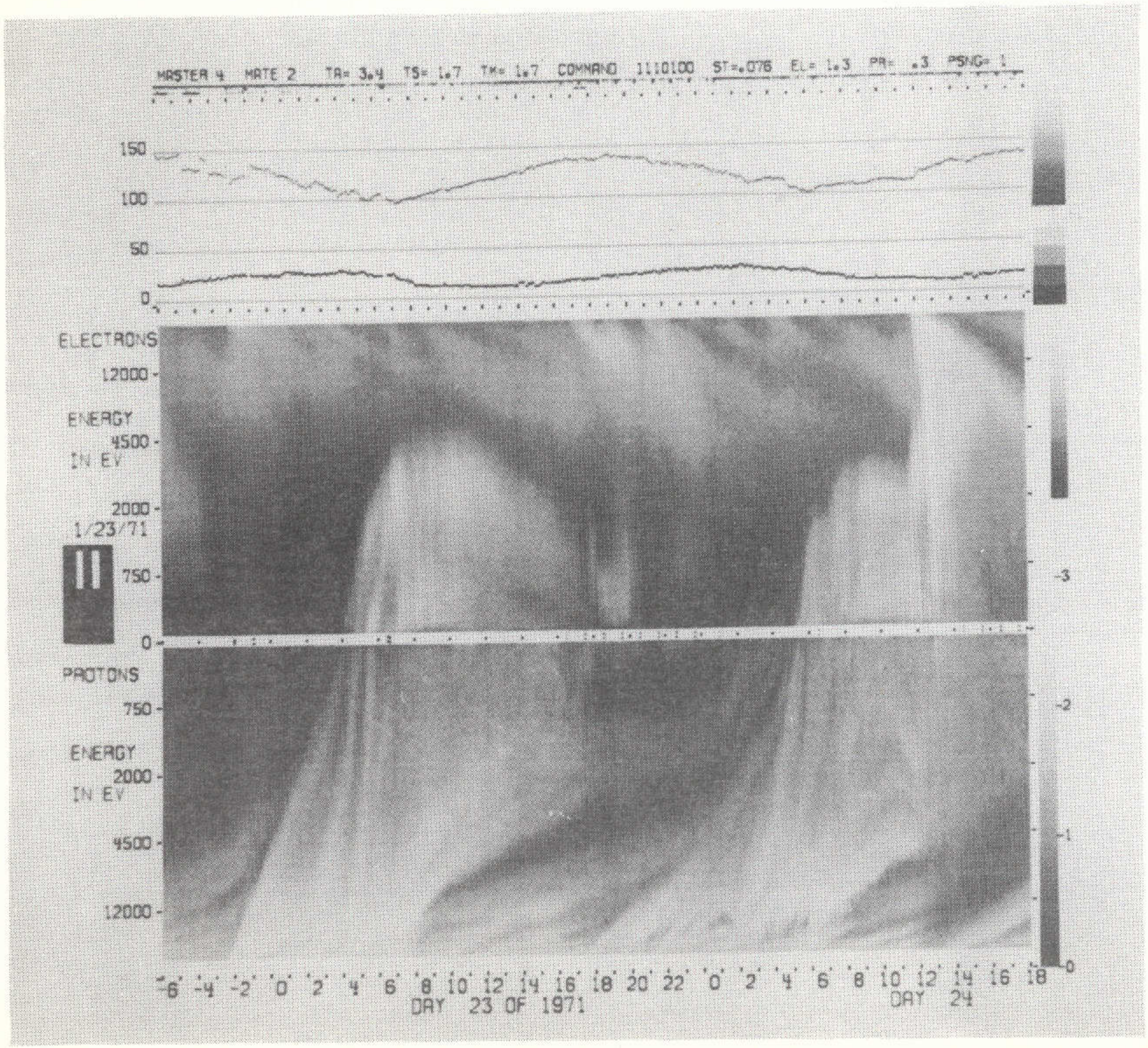

MASTER 4 MATE 2 TA= 3.4 TS= 1.7 TM= 1.7 COMMAND 1110100 ST=.076 EL= 1.3 PA= .3 PSNG= 1
150
100
50
0
ELECTRONS
12000
ENERGY
IN EV
4500
2000
1/23/71
750
0
PROTONS
750
ENERGY
IN EV
2000
4500
12000
-3
-2
-1
0
DAY 23 OF 1971
DAY 24

Figure 16.

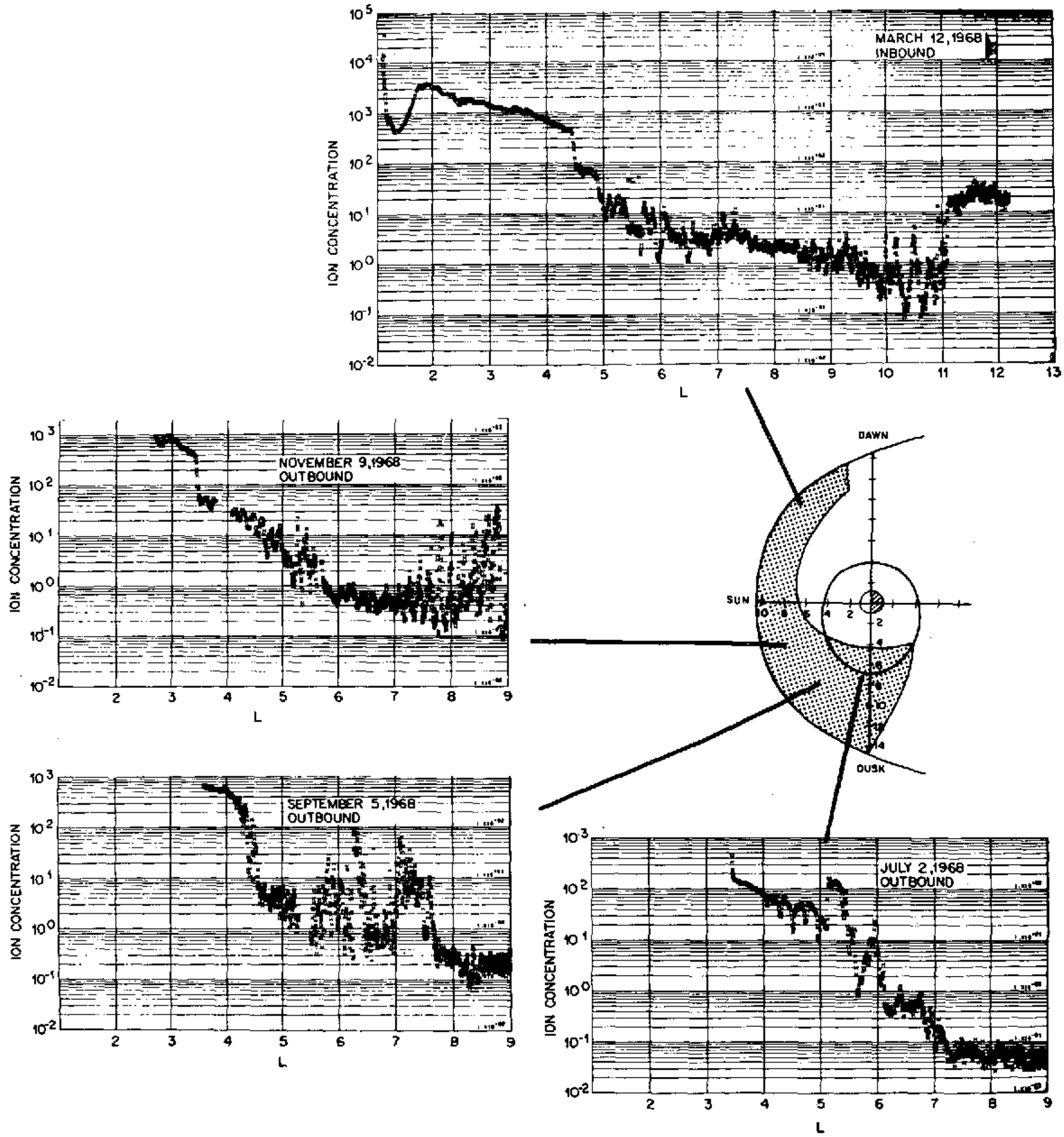

MARCH 12, 1968
INBOUND
NOVEMBER 9, 1968
OUTBOUND
SEPTEMBER 5, 1968
OUTBOUND
JULY 2, 1968
OUTBOUND
ION CONCENTRATION
L
DAWN
DUSK
SUN

Figure 17.

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