

OBSERVATIONS OF SOLAR WIND PENETRATION INTO THE EARTH'S MAGNETOSPHERE: THE PLASMA MANTLE

The large database provided by the continuous coverage of the Defense Meteorological Satellite Program polar orbiting satellites constitutes an important source of information on particle precipitation in the ionosphere. This information can be used to monitor and map the Earth's magnetosphere (the cavity around the Earth that forms as the stream of particles and magnetic field ejected from the Sun, known as the solar wind, encounters the Earth's magnetic field) and for a large variety of statistical studies of its morphology and dynamics. The boundary between the magnetosphere and the solar wind is presumably open in some places and at some times, thus allowing the direct entry of solar-wind plasma into the magnetosphere through a boundary layer known as the plasma mantle. The preliminary results of a statistical study of the plasma-mantle precipitation in the ionosphere are presented. The first quantitative mapping of the ionospheric region where the plasma-mantle particles precipitate is obtained.

INTRODUCTION

Polar orbiting satellites are very useful platforms for studying the properties of the environment surrounding the Earth at distances well above the ionosphere. This article focuses on a description of the enormous potential of those platforms, especially when they are combined with other means of measurement, such as ground-based stations and other satellites. We describe in some detail the first results of the kind of study for which the polar orbiting satellites are ideal instruments. Let us start out with a brief description of the important concepts.

The magnetosphere is a cavity around the Earth that is formed as the solar wind (the stream of particles and magnetic field ejected by the Sun) encounters an obstacle, the Earth's magnetic field.

The energy deposited in the magnetosphere by the solar wind through different means drives a global circulation of plasmas (gases of charged particles) inside the magnetosphere. The particles that compose the plasmas are subjected to the Lorentz force, $q \cdot (\mathbf{E} + \mathbf{V} \times \mathbf{B})$, where q is the electric charge of the particle, \mathbf{V} is its velocity, \mathbf{E} is the ambient electric field, and \mathbf{B} is the ambient magnetic field. The particle trajectories corresponding to the Lorentz force are helices whose axes are the field lines (Fig. 1). The helices can always be considered to be the vectorial contribution of a motion perpendicular to the magnetic field (gyration around the magnetic field line) and a motion parallel to the field. At any given time, the angle between a magnetic field line and the particle's direction of motion is calculated as $\alpha = \tan^{-1}(V_{\perp}/V_{\parallel})$, where V_{\perp} is the perpendicular component of the particle's velocity, which is directly proportional to the field magnitude, and V_{\parallel} is its parallel component. The angle α , shown schematically

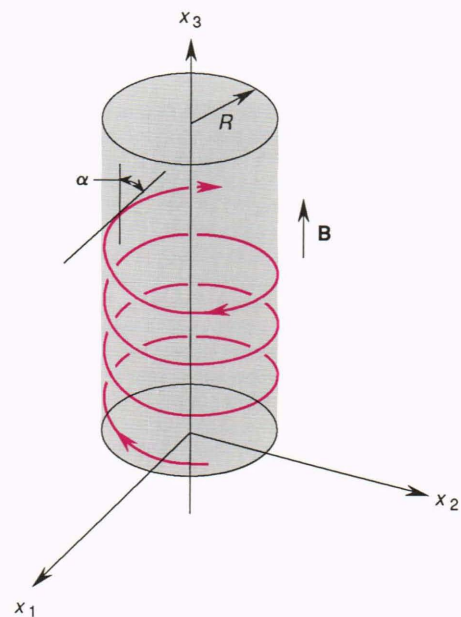


Figure 1. Trajectory of a charged particle in a magnetic field oriented along the x_3 -axis. R is the radius of the gyromotion around the field line, α is the angle between the particle's trajectory and the magnetic field, and \mathbf{B} is the ambient magnetic field.

in Figure 1, is the pitch angle. In a dipolar magnetic field configuration (which is a reasonable approximation in the Earth's vicinity), field lines converge toward the dipole that generates the field (assumed to be near the Earth's center); that is, the field strength increases. Therefore, as a particle approaches the Earth, its pitch angle approaches 90° because V_{\perp} increases at the same

time that V_{\parallel} decreases due to conservation of its magnetic moment until, at some point along the field line (the mirror point), the particle's momentum is entirely in V_{\perp} and it bounces back along the same field line. If the pitch angle is still small enough, however, the particle can precipitate into the atmosphere. The particle's trajectory is said to be within the loss cone. The Defense Meteorological Satellite Program satellites used in the present study, DMSP F6 and F7, are three-axis stabilized, and the detector apertures are always oriented toward local zenith. Therefore, they detect particles whose trajectories are well within the loss cone (i.e., nearly aligned with the magnetic field lines) at high geomagnetic latitudes and also particles with large pitch angles at low geomagnetic latitudes.

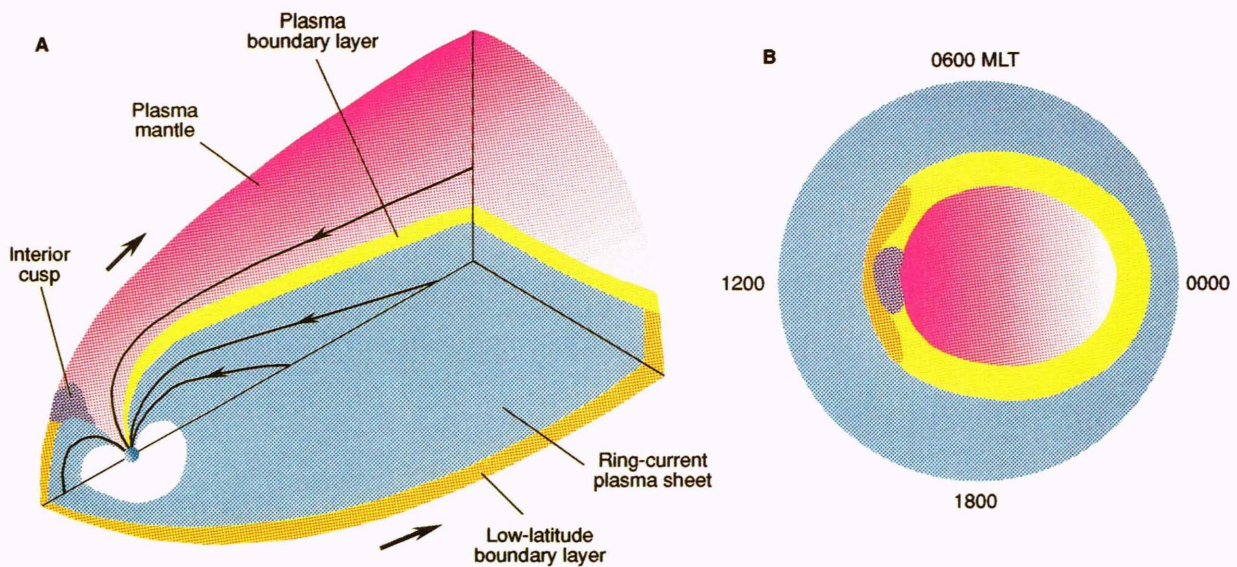
Because the particles intercepted by the spacecraft are presumably a sample of the populations that exist along the field line, one can get a good idea of the properties of different regions of the Earth's magnetosphere if one knows the characteristics of the particle flux at different latitudes. The usefulness of a polar orbiting satellite resides in the fact that, in progressing along its orbit, it sweeps different latitudes that can be mapped along the field lines to different regions of the magnetosphere, according to specified rules. The simplest rule, which envisions the Earth's magnetic field lines as dipolar, is a good approximation at distances not far from Earth, but an accurate description of the magnetic field topology at greater distances requires important modifications to the dipolar field configuration introduced by the current systems set up by the very interaction of the solar wind and the magnetosphere. The problem is not simple. Nevertheless, better field approximations are being developed as a result of an intense effort by the space physics community.

It is not surprising that particles from different magnetospheric regions precipitate into specific regions in the ionosphere. A qualitative distribution of these regions is shown in Figure 2 (from Ref. 1). Figure 2A is a sketch of the magnetosphere and its regions. The two high-latitude structures (the plasma mantle and interior cusp) occur in the regions where solar-wind particles are likely to penetrate directly into the magnetosphere. Figure 2B shows qualitatively how the different regions map in the ionosphere. Note that all the precipitation is confined to a circle (which typically extends 25° from the polar axis) known as the auroral precipitation region.

The latitudinal coverage of the auroral precipitation region by the DMSP satellites is one of the most comprehensive to date, resulting in a large database that can be used to monitor the Earth's magnetosphere and for statistical analyses. The preliminary results of one such analysis are described in this article.

INSTRUMENTATION

The DMSP F6 and F7 satellites are in sun-synchronous polar circular orbits at about 835 km altitude, with a 101-min period. The F7 orbit lies approximately in the 1030–2230 magnetic local time (MLT) meridian, the F6 in the 0600–1800 MLT meridian. Because of the short orbital period, each spacecraft cuts across a wide range of latitudes in a relatively short time. It takes, for instance, about fifteen minutes for a spacecraft to cover the diameter of the region that comprises the polar cap and the auroral oval and about thirty-five minutes between consecutive equatorward oval boundary crossings. The SSJ/4 instrumental package included on both satellites is a curved-plate electrostatic analyzer that measures the energy per unit charge of electrons and ions from



Note: The plasma mantle, interior cusp, and low-latitude boundary layer are magnetopause boundary layers.

Figure 2. A. The magnetosphere. B. The regions of particle precipitation into the ionosphere. The arrows outside the magnetosphere represent the solar-wind flow. The arrows inside it represent the direction of the Earth's magnetic field. The magnetopause is the surface adjacent to the exterior arrows. (Reprinted, with permission, from Ref. 1. Published by courtesy of by the European Space Agency.)

32 eV to 30 keV in twenty logarithmically spaced steps.²

A STUDY OF THE EARTH'S PLASMA MANTLE

An example of the many problems that can be treated with the aid of polar orbiting satellites concerns the openness of the Earth's magnetosphere and the resulting penetration of solar-wind plasma. This is a problem of great importance because, after all, it is the energy deposited by the solar wind in the magnetosphere that is responsible for triggering a myriad of phenomena.

A fairly comprehensive knowledge of the magnetosphere's different regions has been gained since the first theories were proposed and the first observations made, but some fundamental questions still have not been answered. For instance, there is reasonable evidence that the magnetopause, the boundary separating the solar-wind regime from the magnetospheric regime, is open (i.e., it allows the direct transfer of energy and mass between the two regimes) in some of its regions and at some intervals of time. At other times and regions, it behaves like a closed boundary (thus preventing any direct mass or energy transfer and limiting the entry of solar wind to, perhaps, just diffusion mechanisms). What has not been determined to a reasonable degree of confidence is how, when, and even where the transition between open and closed configurations takes place.

A widely accepted idea is that the magnetopause becomes open when the magnetic field just outside has a component antiparallel to the magnetic field just inside. On the dayside portion of the magnetopause, that geometry is likely to occur when the magnetic field of the solar wind points essentially southward, since the Earth's field at the dayside magnetopause points northward. For a coordinate system where the positive x -axis points toward the Sun along the Sun-Earth line, the positive z -axis points northward along the Earth's magnetic polar axis, and the positive y -axis completes the right-handed system, pointing essentially toward dusk, we say that the antiparallel geometry occurs when the interplanetary magnetic field (IMF) B_z is negative since the Earth's magnetic field B_z just inside the magnetopause is positive. It is believed that the antiparallel geometry favors the reconnection of terrestrial and solar magnetic field lines in the dayside region of the magnetopause, thus allowing the solar wind to penetrate into the magnetosphere.³ The penetration continues downstream and forms at high latitudes a thick boundary layer known as the plasma mantle.⁴⁻⁶ This situation is sketched in Figure 3 (from Ref. 4), which shows a cut of the magnetosphere along the noon-midnight meridian. Solar wind particles (open and closed circles) flow into the magnetosphere essentially along the reconnected field lines (note the antiparallel geometry at the leftmost part of the figure), bounce at their polar mirror points, and continue their trajectories in the antisunward direction. The collection of penetrating particles constitutes the plasma mantle (shaded region). The DMSP satellites detect those particles that precipitate before encountering their mirror points.

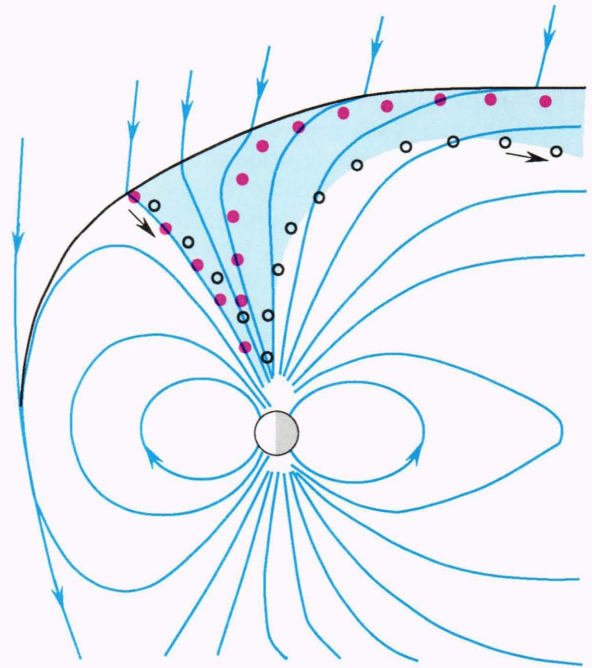


Figure 3. Illustration of the solar-wind penetration into the magnetosphere at the high-latitude regions in the noon-midnight meridian plane. (Reprinted, with permission, from Ref. 4. © 1975 by the American Geophysical Union.)

The plasma and magnetic field signatures characteristic of the plasma mantle have been detected with different spacecraft at different locations in the high-latitude magnetopause.^{4,7,8} (The characteristics of the plasma mantle are decreasing mass density, bulk speed, and temperature accompanied by an increase in magnetic-field magnitude along the trajectory of a spacecraft that crosses the magnetopause in going from the solar wind into the magnetosphere.) Qualitatively similar variations in the same parameters observed with DMSP have been interpreted as the low-altitude signatures of the plasma mantle.⁹ That interpretation is based on the fact that mass density, bulk speed, and temperature decrease in going from low latitudes (at the location that presumably maps to field lines at the transition between closed and open magnetopause regions) to high latitudes (presumably well within the wide-open portion of the magnetopause). An example is shown in Figure 4, which corresponds to a northern dayside portion of F7's orbit during a prolonged period of consistently southward IMF orientation on 10 December 1983. It is in the format of a spectrogram, which is a color-coded plot of differential energy flux (energy flux per unit energy) of the particles precipitating into the analyzer versus time (or, equivalently, geomagnetic location). Red tones correspond to high energy flux ($\approx 10^7$ ions/cm² · s · sr and $\approx 10^9$ electrons/cm² · s · sr) and blue tones to low energy flux ($\approx 10^4$ ions/cm² · s · sr and $\approx 10^6$ electrons/cm² · s · sr), as seen on the right side of the spectrogram. The upper and lower panels correspond to electron and ion (proton) precipitation, respectively. Note that the ion energy scale has been inverted so that

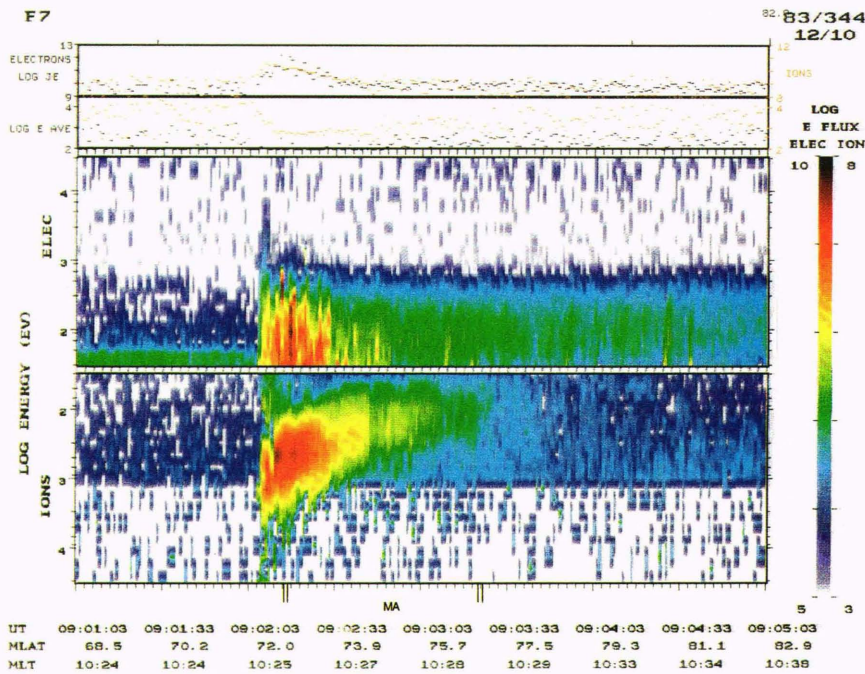


Figure 4. A spectrogram of the electron and ion precipitation signatures of the plasma mantle on 10 December 1983.

the lowest energies for both species are near the center line. Each kind of particle population has been identified by means of the neural network algorithm devised by Newell et al. (see the article by Newell et al., this issue). The plasma mantle, labeled MA at the bottom of the ion scale between 0902:19 and 0903:29 UT, shows the typical energy flux decrease with increasing latitude (toward the right). In some instances, the signature involves a more complicated structure where the decrease in energy and mass density is not monotonic but instead shows alternate increases and decreases of the plasma parameters. The explanation of that behavior in terms of oscillations of the plasma mantle or entry of solar wind plasma at different magnetopause locations is the subject of continuing research.

In the present study, we searched for all the mantle crossings in the period between 1 December 1983 and 31 January 1984 and measured the latitudinal and longitudinal extension of each. Then we classified them according to the orientation of the solar wind magnetic field¹⁰ (also known as the IMF). The reason for such classification is that previous studies indicated that the location of the region where the magnetopause opens changes, according to the IMF orientation.^{11,12} The results of the classification using only Southern Hemisphere events measured with DMSP F7 are shown in Figure 5, where the closed circle in each mantle segment marks the location of the most intense flux and average energy. Figure 5A corresponds to the events observed during a downward IMF orientation ($B_y < 0$) and Figure 5B to a duskward orientation ($B_y > 0$). A comparison of the two panels reveals no strong B_y dependence, although a closer inspection indicates that the mantle tends to reach toward lower latitudes in the pre-noon sector for a dawnward IMF orientation and

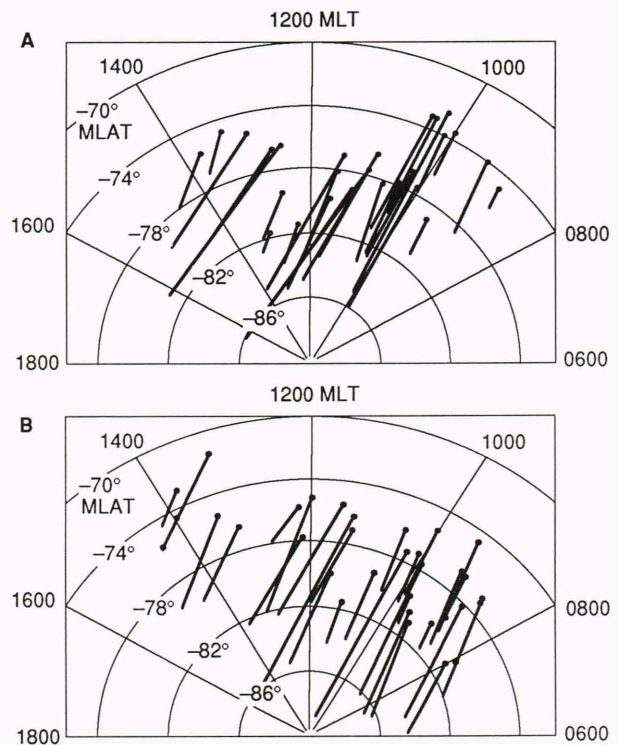


Figure 5. Distribution of plasma-mantle precipitation for two orientations of the interplanetary (solar wind) magnetic field with DMSP F7. **A.** Negative IMF B_y . **B.** Positive IMF B_y . The solid circles mark the locations of maximum flux and average energy.

in the post-noon sector for a duskward orientation. An expanded database will help estimate the asymmetry more accurately.

The high- and low-latitude average boundaries of the plasma mantle precipitation region can be estimated when the panels are merged (Fig. 6). The low-latitude boundary consists of a semicircle that extends to about -75° geomagnetic latitude (GLAT) at noon. At a GLAT of about -72° , the semicircle extends to 1030 MLT in the pre-noon sector and to 1330 MLT in the post-noon sector. The high-latitude boundary near the noon-midnight meridian is approximately a semicircle that reaches to about -85° in the region sampled, roughly between 0700 and 1500 MLT.

The extent of the mantle region in the dawn-dusk direction is better measured with DMSP F6, also in the Southern Hemisphere. A strong B_y dependence of the mantle precipitation properties is immediately apparent. Figure 7 summarizes the different mantle morphologies. Figure 7A is characteristic of the mantle precipitation during strongly southward IMF, when B_z is negative and noticeably bigger than B_y (in this case, $B_z = -6.5$ nT and $B_y = -2.1$ nT). A very interesting feature is that the mantle extends nearly uniformly over a wide local time sector, probably indicating a nearly uniform particle entry over a wide region. When B_y is stronger so that the IMF is more inclined toward the dawn-dusk line, the mantle precipitation is still found over a wide region, but it is not nearly as uniform. Instead, strong asymmetries develop, as can be seen in Figures 7B and 7C. In the former, where $B_y = 2.6$ nT and $B_z = 1.1$ nT, the strongest energy flux and the average energy of the precipitating ions and electrons occur at the pre-noon end of the mantle and decrease toward dusk. In the latter, where $B_y = -5.7$ nT and $B_z = -0.9$ nT, the strongest precipitation occurs at the post-noon flank and decreases toward dawn. The mantle dependence on the IMF orientation can be summarized as follows: southward

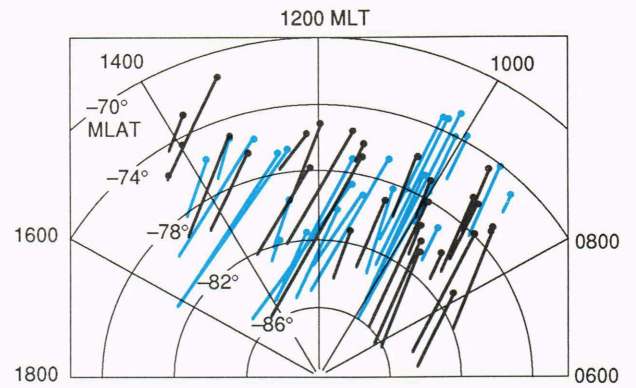
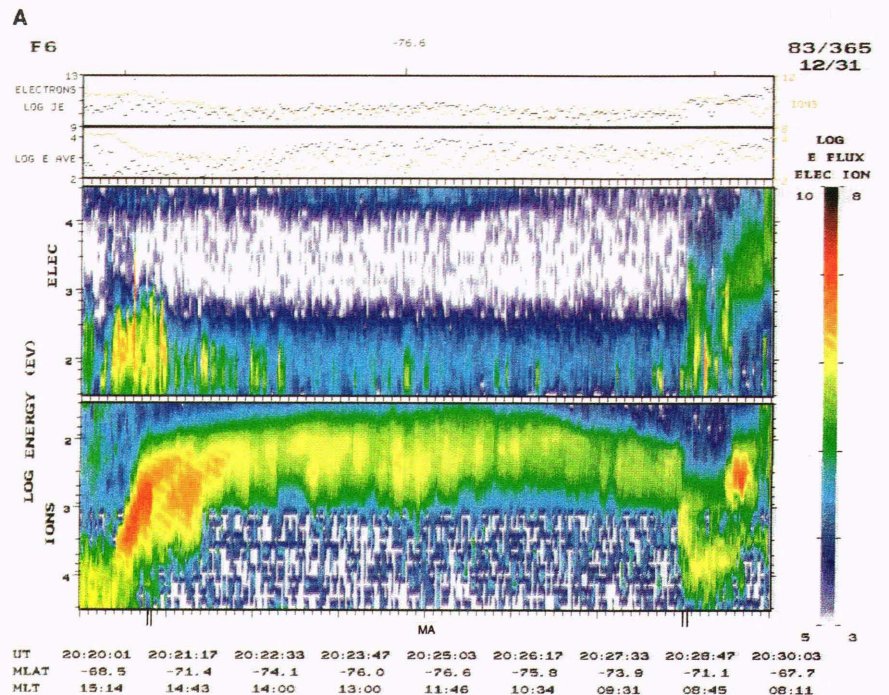


Figure 6. Merging of the plasma-mantle distributions for the two orientations of the IMF. The blue lines correspond to the mantle distribution for a negative IMF B_y .

IMF's are consistent with wide, symmetric mantle precipitation; positive B_y 's are consistent with stronger dawnward precipitation and negative B_y 's with stronger duskward precipitation. The generality of this conclusion is verified in Figure 8. In Figure 8A, corresponding to $B_y < 0$, the maximum flux and average energy of all the mantle segments are in the post-noon sector, distributed in the region between about -70° and -85° and between about 1300 and 1500 MLT. The mantle distribution for $B_y > 0$ (Fig. 8B) results in the maxima being distributed in the region between about -70° and -85° and between about 1100 and 0830 MLT. When the panels are merged (Fig. 9), the overall mantle region is bounded on the dusk side by a line stretching between about -70° and -85° along the 1500 MLT meridian and on the dawn side by a line stretching between the same latitudes but along the 0900 MLT meridian.

Figure 7. Mantle morphologies measured with DMSP F6. A. A spectrogram showing the plasma-mantle electron and ion signatures between dawn and dusk for a strongly southward IMF orientation on 31 December 1983. B. (next page) A spectrogram for a plasma mantle during a period of positive B_y on 23 December 1983. C. (next page) A spectrogram for a plasma mantle during a period of negative B_y on 15 January 1984.



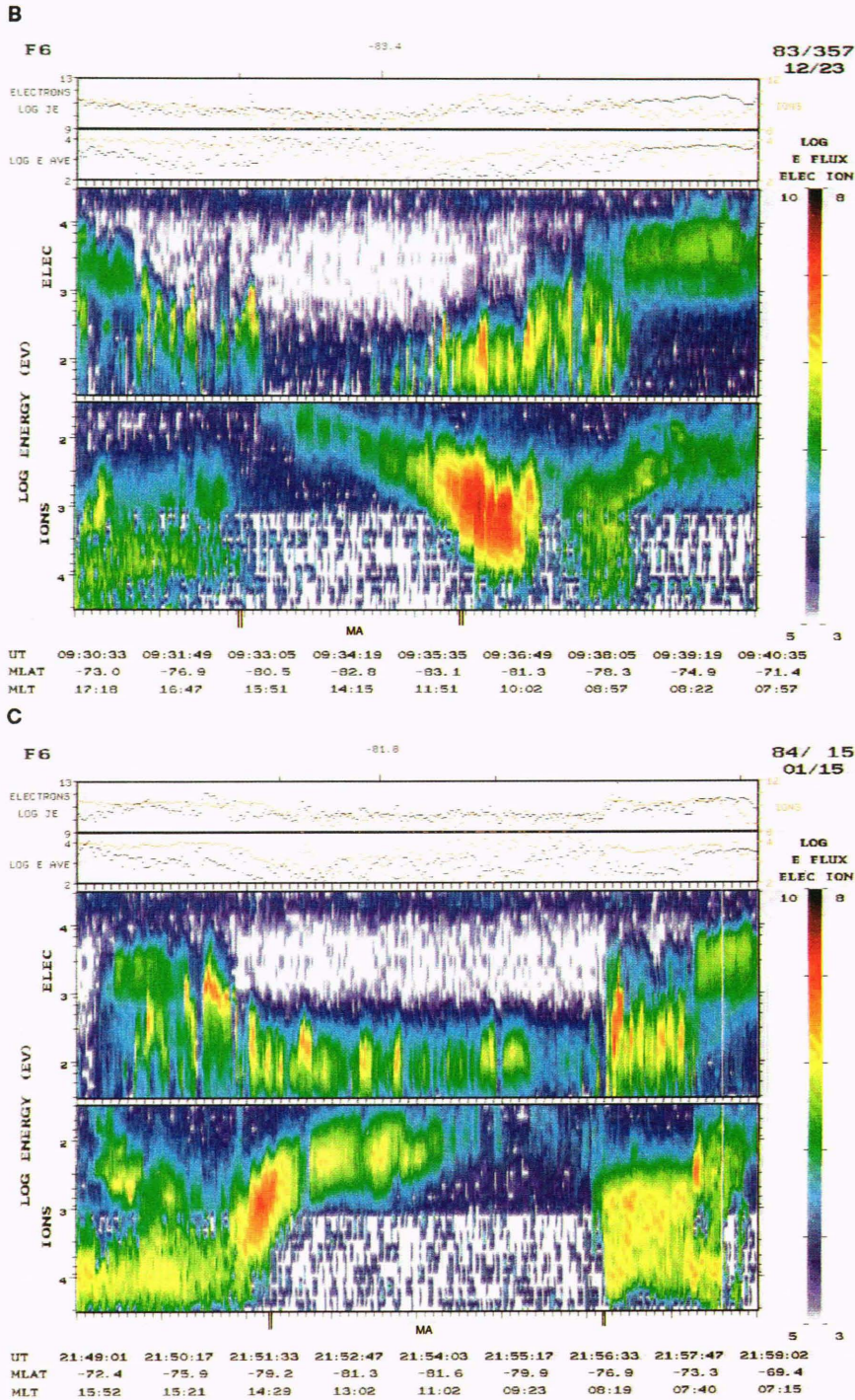


Figure 7. (continued).

CONCLUSIONS

We have presented the first quantitative mapping of the plasma-mantle precipitation in the ionosphere. Future work will address a more refined mapping as well as other important issues, such as the mantle behavior during highly perturbed states of the magnetosphere. Furthermore, this is just one piece of the puzzle that contains several other pieces like the cusp, the central plasma sheet, the low-latitude boundary layer, and the boundary plasma sheet. A great deal of work is still ahead to

complete the important problem of a comprehensive mapping of all the precipitation regions for different orientations of the IMF and different states of energization of the magnetosphere.

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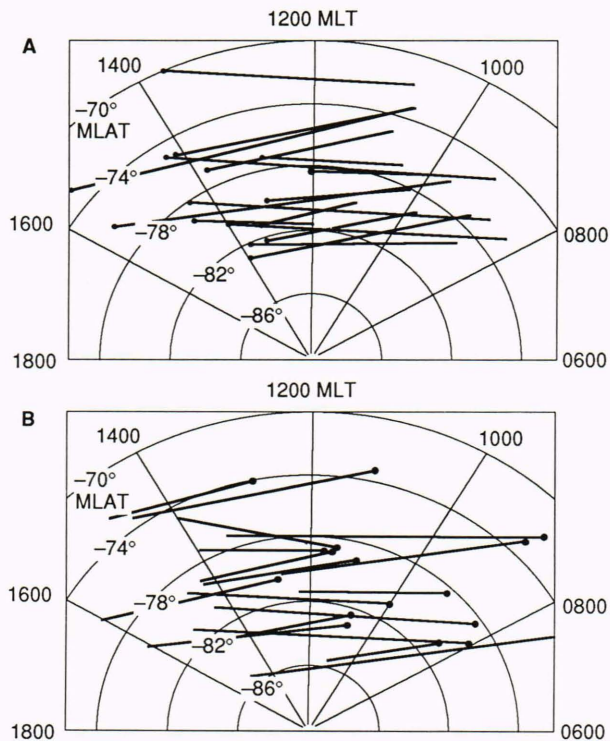


Figure 8. Distribution of plasma-mantle precipitation obtained for two orientations of the IMF with DMSP F6. **A.** Negative IMF B_y . **B.** Positive IMF B_y .

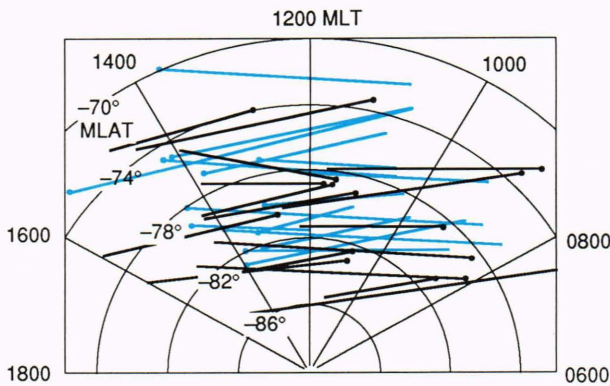


Figure 9. Merging of the plasma-mantle distributions for the two orientations of the IMF. The blue lines correspond to mantle distribution for a negative IMF B_y .

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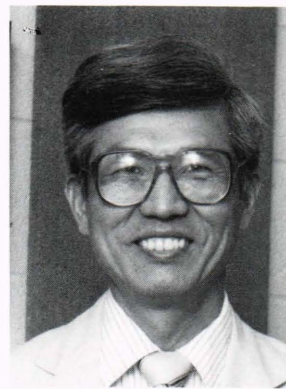
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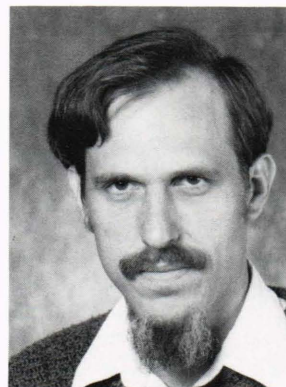
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