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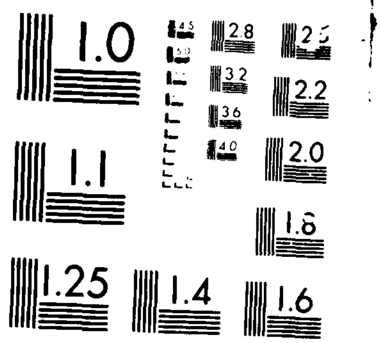

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High-Latitude Convection on Open and Closed Field Lines for Large IMF B_y

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

4/22/86

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S3-3 electric field observations for August, 1976 show a single convection cell engulfing the northern polar cap. The flow direction is that for a positive IMF B_y component. The particle data indicate that nearly half the duskside sunward flow occurs on closed field lines, whereas the dawnside flow is entirely on open field lines. We interpret this in terms of an IMF B_y-induced deformation in the polar cap boundary, where the deformation moves with the convective flow. Thus, convection streamlines cross the

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deformed polar cap boundary, but no flow crosses the boundary because it is carried by the flow. Since southern hemisphere convection is expected to occur with the opposite sense of rotation, we predict that closed field lines will be forced to tilt azimuthally. On the nightside, the tilt produces a y component of the magnetic field in the same direction as the IMF for either sign of IMF B_y. Our interpretation is consistent with observations of a greater y component in the plasma sheet than the tail lobes, which are difficult to understand in terms of the common explanation of IMF penetration. Alternatives to this interpretation are also discussed.

CONTENTS

INTRODUCTION

Prior theoretical (e.g., Russell and Atkinson, 1973; Jorgensen et al., 1972; Stern, 1973; Crooker, 1979; Lyons, 1984) and observational (e.g., Heppner, 1972; Friis-Christensen and Wilhjelm, 1975; Potemra et al., 1980; Heelis, 1984; Burch et al., 1985) work has shown the governing influence of IMF orientation on high-latitude near-earth convection patterns. In the case of large IMF B_y, a circular cell dominates the flow in each polar region. This pattern was first deduced from ground-based magnetogram signatures (Svalgaard, 1973; Mansurov and Mansurova, 1971a,b) and later ascribed to IMF B_y (Friis-Christensen et al., 1972). The flow rotation sense in the cells is opposite in opposite hemispheres. Flow antisymmetry can lead to interesting implications if the cellular flow does not occur entirely on open field lines. Examples of cellular rotational flow are abundant, but prior work emphasizes patterns in the open region alone rather than patterns linking closed and open regions.

In this report we discuss an apparent large, positive IMF B_y case characterized by sunward flow in the northern dusk sector and an equal anti-sunward flow in the northern dawn sector. The case is of special interest because the data imply that all of the anti-sunward flow occurs on open field lines while only half of the flow returns in the dusk on open field lines. The convection pattern consistent with the data is a simple one-cell clockwise circulation. If we assume a steady state, then open field lines must close somehow in their nightside sweep from dawn to dusk, and the dayside and nightside merging rates must balance. Instead, we suggest a less radical interpretation, which neither invokes a new merging pattern nor postulates an unlikely cooperation between widely separated merging sites. We interpret the event in terms of a moving deformation in the polar cap boundary. By symmetry, the flow in the opposite hemisphere is in the opposite rotational sense. This causes an azimuthal tilt of closed field lines which would appear in the nightside as an apparent plasma sheet "penetration" of the IMF B_y component.

S3-3 Observations

Figure 1 displays a standard S3-3 energy-versus-time particle spectrogram along with the integrated electrical potential for an event on 23 August 1976 (cf. Chiu and Gorney, 1983). The corotation electrical potential has been removed. The spectrogram shows electron energy flux for energies 170 eV - 33 keV in the upper panel and ion energy flux for energies 90 eV - 3.9 keV plotted on a reversed energy scale in the lower panel. Also plotted is the flux of 235 keV electrons and > 80 keV protons. The spacecraft's 20-second spin period modulates the particle data in pitch angle. The time interval covered in Figure 1 is 71000 to 74300 sec UT. During this interval S3-3 was near apogee and crossed the high latitude region from dusk toward dawn (from 20:00 to 8:00 MLT). Interplanetary magnetic field data are unavailable for this specific time interval, but IMF B_x, B_y and B_z values of -3.1, 13.4 and -4.1 γ were observed a few hours prior to this event. The event occurred in the middle of a long away sector (i.e., positive B_y) and during an extended period of negative Dst (i.e., negative B_z). Thus, the unusually large IMF B_y component and small negative B_z component probably also pertain to the period of interest.

The particle spectrogram readily identifies the pre-midnight central and boundary plasma sheet regimes extending up to $\Lambda = 76.5°$ (71950 sec UT). Note that the electron flux within the plasma sheet is modulated at twice the spacecraft spin period, the signature of conjugate loss cones and diagnostic of closed field lines. Characteristic of the evening discrete aurora,

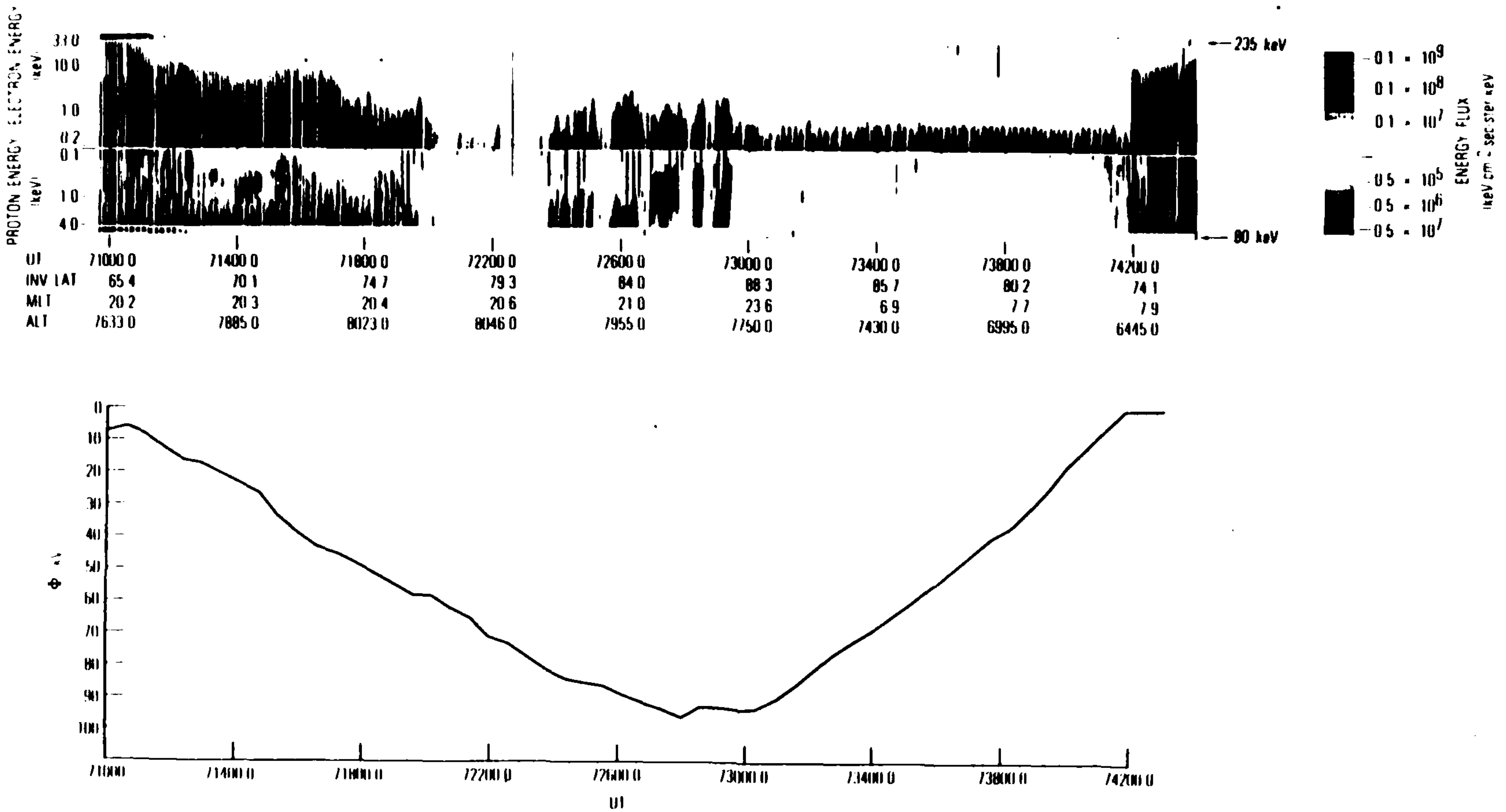

Figure 1. S3-3 Energy vs Time Spectrogram for 71000-74400 sec UT on day 236, 1976. The electrical potential distribution along the satellite trajectory is shown in the lower panel, with the corotation electric potential removed. The spacecraft travels from dusk toward dawn and encounters sunward flow in the dusk sector from 71100-72800 sec UT and anti-sunward flow in the dawn sector from 72800-74150 sec UT. Particle flux modulation at twice the spacecrafts' 20-sec spin period is indicative of closed field lines and the presence of isotropic polar rain is suggestive of open magnetic field lines. Note that approximately half of the sunward flow occurs on closed field lines in the dusk sector (71000-71800 sec UT) while all of the anti-sunward flow occurs on open field lines.

electron and ion acceleration appear near the high latitude boundary of the plasma sheet at 71950 sec UT. Regions of polar rain extend from 71950 to 72350 sec UT and from 72950 to 74200 sec UT. At extremely high magnetic latitudes, these two regions are separated by a broad region of multiple inverted-V electron precipitation events along with upflowing accelerated ion beams. The reversal of the large scale flow pattern associates clearly with this broad region of plasma acceleration. Note that the more typical evening discrete auroral activity near 71950 sec UT lies rather arbitrarily within this flow pattern, although it corresponds to a narrow region of weakly divergent convection electric fields within a very broad region of sunward flow. The polar cap boundary in the dawn sector is at 74200 sec UT. It is marked by the onset of the plasma sheet particle signature and is virtually colocated with the cessation of anti-sunward convection.

The potential pattern indicates sunward flow on the dusk side and anti-sunward flow on the dawn side. The inferred sense of rotation of this single, broad convection cell is consistent with that expected for periods of dominantly positive IMF B_y. The total potential associated with the flow is substantial, exceeding 80 kV. A comparison with the particle signatures indicates that the equatorward half of the return sunward flow in the dusk sector occurs on closed field lines.

Interpretation

Figure 2 shows an interpretation of the high latitude circulation pattern based on the data presented in the previous section. Noon is at the top of the figure, with dawn to the right. The heavy line represents the boundary between open and closed field lines. The thin lines indicate flow streamlines. The satellite trajectory passes from ~ 20:00 to ~ 8:00 MLT. Crosses

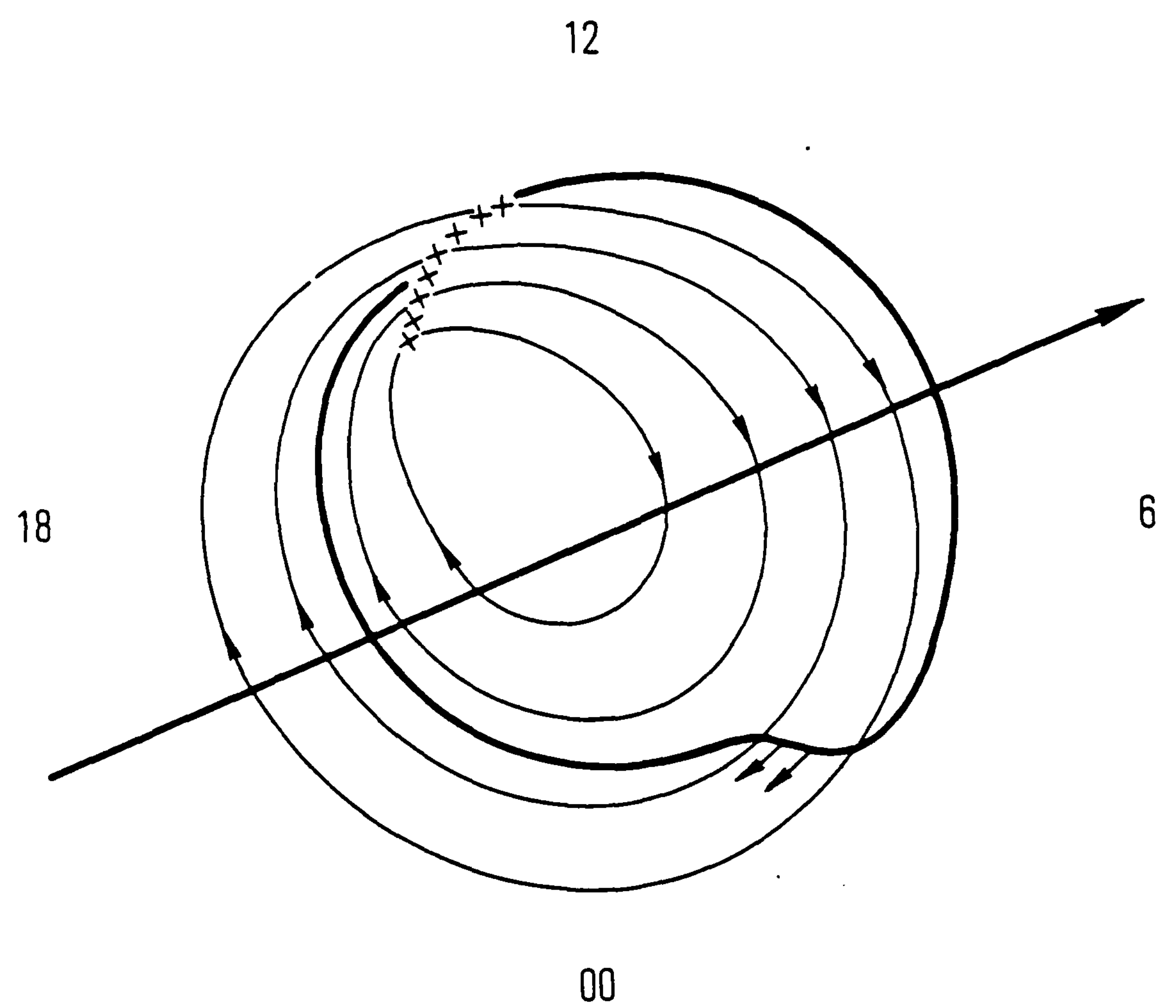

Figure 2. A proposed High Latitude Convection Pattern. The heavy curve is the deformed polar cap boundary separating open from closed field lines. Crosses mark the merging line mapped from the dayside magnetopause to the ionosphere. Part of the merging line fills the gap in the boundary where freshly merged field lines enter the polar cap along the thin flow lines. On the night side, streamlines cross the bulge in the boundary, but no flow crosses the boundary since the bulge moves with the flow. The flow pattern relative to the boundary location along the heavy satellite trajectory line matches the observations in Figure 1.

mark the mapping of the merging line from the dayside magnetopause to the ionosphere. Its position with respect to noon reflects an assumed negligible IMF B_x (cf., Heelis, 1984; Reiff and Burch, 1985). Open flux created by dayside merging of closed field lines enters the polar cap through the gap spanned by a portion of the merging line. The remaining portion extends into the polar cap. Dayside merging along this portion affects only an interchange of open field lines and the formation of lobe convection cells (cf. Reiff and Burch, 1985). Convection generated at the polar cap boundary gap extends to closed flux regions on the evening side.

Here we consider the polar cap boundary in the same manner as Siscoe and Huang (1985). That is, open flux flows across the gap created by merging but not across the boundary itself. In the absence of tail merging, Siscoe and Huang suggest that the polar cap expands as open flux enters it. We propose that this same process is acting here in the following manner. Due to the evident strong IMF B_y component, open flux enters the polar cap and convects toward the morning side boundary. The added flux forms a bulge which propagates around the polar cap. The bulge pushes on closed field lines, enlarging the polar cap and setting up the circulation.

If dayside merging of closed field lines continues at a steady rate, the bulge continues to propagate around the polar cap in ever-widening circles, thus increasing its size by adding layers around the circumference. Eventually some critical threshold is reached and flux loss begins through nightside merging (e.g., Siscoe, 1982). If dayside merging of closed field lines ceases, flux is no longer added to the polar cap, and only open field lines circulate within it, as is commonly pictured.

It is important to understand that although this interpretation is time dependent, it does not depend upon the spacecraft having crossed the polar cap at some single, specific point in the time history of a pattern change. What we require for this intepretation is a quasi-steady period of large, positive IMF B_y and somewhat negative B_z. The polar cap then expands steadily in spiral fashion. We require only that the spacecraft crosses during that half of the spiral cycle when the bulge is on the nightside. Thus, given the steady, required IMF conditions, there is a 50% chance of observing the pattern in Figure 1, with part of the sunward convection on closed field lines.

The alternative interpretation of a steady state requires that the polar cap boundary remains fixed and that merging allows the convecting field lines to cross the nightside polar cap boundary at the same rate at which they merge on the dayside. Observations do not support this picture. It is well known that the polar cap expands and contracts, and changing size demands an imbalance in dayside and nightside merging rates. Further, recent DE-1 observations of the auroral regions suggest that the polar cap behaves very much like a fluid, with bulges and turbulence around its circumference (Frank, 1984). In Figure 2, a series of bulges and turbulence around the polar cap boundary would reflect variations in the dayside merging rate.

For the southern hemisphere, one should reverse the pattern in Figure 2. (Data were unavailable for the southern hemisphere.) The presence of a similar, but antisymmetric bulge in the southern hemisphere creates an interesting change in the closed field line configuration. Figure 3 shows an earth view from the night side with the proposed circulation patterns superimposed at high latitudes. The bulge in the northern polar cap pushes closed field lines from morning to evening while the reverse occurs in the southern hemisphere. This would produce a tilt in the field lines around the

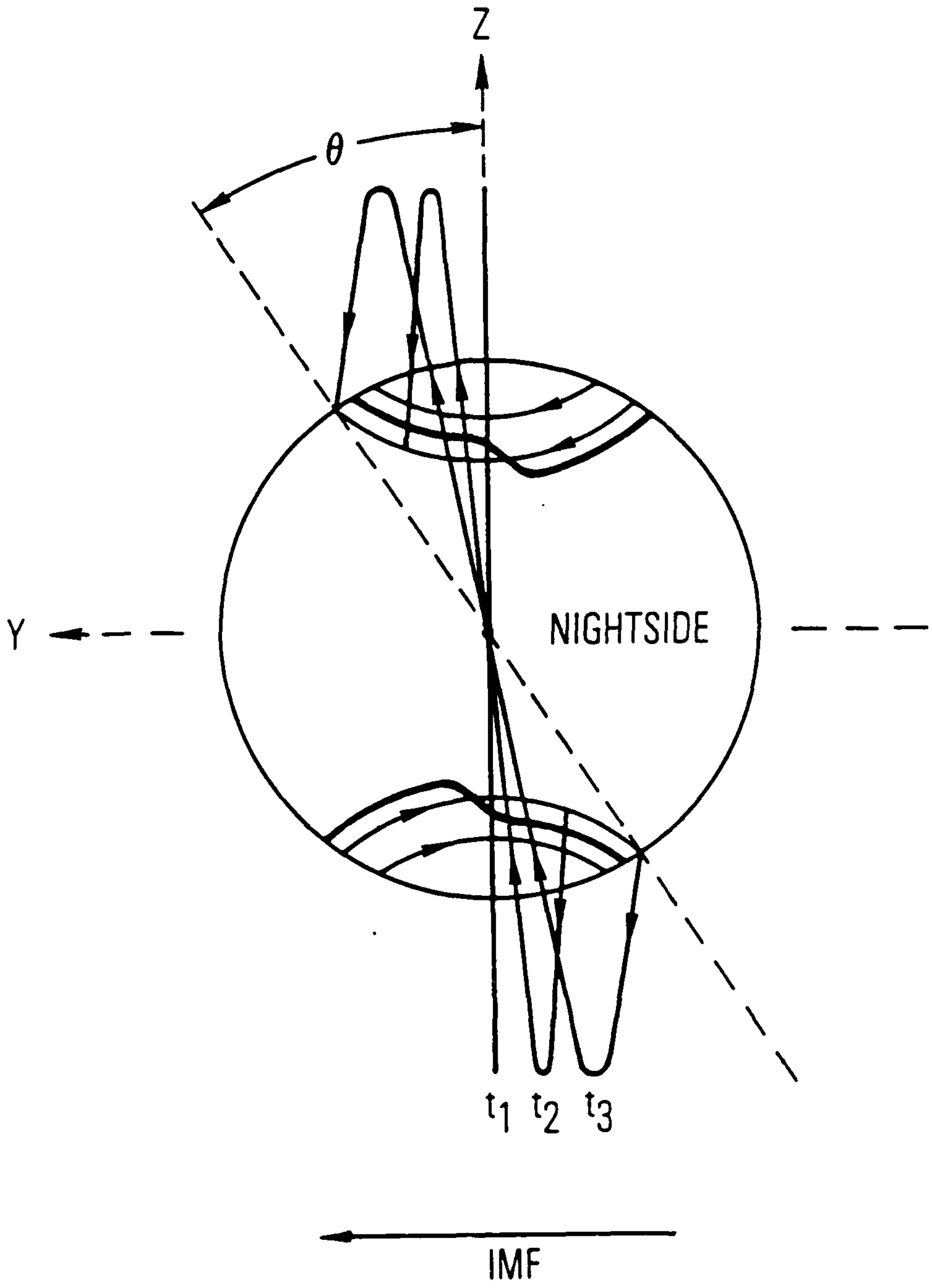

Figure 3. Proposed Field Line Tilting Sequence Which Results from Oppositely Directed Convection of Closed Field Lines in Each Hemisphere. The view is toward the sun from behind the earth. A dipole-like field line aligned with the midnight meridian at t_1, tilts to a maximum angle at t_3. This angle can be no larger than θ.

circumference of the polar cap. The field line illustrated on the night side at times t_1, t_2, and t_3 tilts in the IMF B_y direction. On the dayside the same azimuthal tilt would be opposite the IMF B_y direction.

Two notes of caution are in order here. First, the maximum possible angle of tilt, θ, is probably never attained both because the field lines may bend out of their plane, as shown in Figure 3, and because their conjugate feet may not be fully coupled owing to field-aligned potential drops. Second, cusp-related effects may mask or eliminate the predicted dayside tilting (See, for example, Burch, 1979).

The predicted nightside tilting may explain some puzzling observational results. Lui (1983) compared measurements of the neutral sheet B_y and IMF B_y components. He found that the IMF and plasma sheet y-components correlate positively. Fairfield (1979) found a similar but weaker correlation between the orientation of open lobe field lines and the IMF. Both observations were interpreted in terms of penetration of the IMF, but penetration should be stronger, not weaker, on open field lines. Our interpretation of azimuthal tilting of closed field lines solves this dilemma.

An alternative interpretation of the observed convection pattern would have the closed field lines in the southern and northern hemispheres convecting in the same direction, namely, sunward at dusk. This would create a two-cell convection pattern in the southern hemisphere but retain a single cell in the north. We consider this unlikely since there is no reason to expect one hemisphere to "drive" convection in the opposite hemisphere, especially near equinox. Reversing the argument implies that a two-celled pattern is equally likely in the north for these conditions. This is not observed. Therefore, we argue that neither hemisphere "drives" the other, and predict azimuthal tilting of the closed field lines.

Cowley and Hughes (1983) tested synchronous satellite data for IMF penetration and found a significant effect with large local time and seasonal variations. Unfortunately, it is difficult to tell if their results are consistent with our predictions due to the format of their data presentation. The predicted azimuthal tilting should be tested directly at synchronous orbit.

A problem which has not been addressed in our interpretation is the source of accelerated particles in the central polar cap in Figure 1. Lyons (1984) and Chiu et al. (1985) point out that the negative electric field divergence in the center of a clockwise cell should accelerate the particles there. But the accelerated particles appear to be from the plasma sheet or boundary plasma sheet (Chiu and Gorney, 1983). No flow lines lead from the plasma sheet to the center of the polar cap in Figure 2. Small-scale flows evident near the center of the potential pattern may be part of a second order flow pattern bringing boundary plasma into the polar cap. One can expect that the advancing bulge "scours" the particles up and into the polar cap. As mentioned earlier, auroral images often show evidence of such boundary turbulence.

Summary

We present an observation of plasma and convection morphology over the northern high-latitude regions which shows a single convection cell rotating in the clockwise sense, appropriate for IMF $B_y > 0$. All of the anti-sunward flow occurs on open field lines while only half of the dusk region return sunward flow occurs on open field lines. We interpret these observations in terms of a polar cap expanding by means of an advancing bulge in the boundary. Although we developed the model to explain a specific observation, its application is general. It follows as a natural extension of the work of Siscoe and Huang (1985) and describes the manner in which the polar cap expands when B_y is large. A consequence of this interpretation is that a polar cap boundary bulge must also occur in the opposite hemisphere, circulating in the opposite sense, and cause an azimuthal tilting of closed field lines.

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