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Inferences Concerning the Magnetospheric Source Region for Auroral Breakup

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Engineering and Technology Group

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El Segundo, California

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NOTE

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INFERENCES CONCERNING THE MAGNETOSPHERIC SOURCE REGION FOR AURORAL BREAKUP

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ABSTRACT

It is argued that the magnetospheric source region for auroral arc breakup and substorm initiation is along boundary plasma sheet (BPS) magnetic field lines. This source region lies beyond a distinct central plasma sheet (CPS) region and sufficiently far from the Earth that energetic ion motion violates the guiding center approximation (i.e., is chaotic). The source region is not constrained to any particular range of distances from the Earth, and substorm initiation may be possible over a wide range of distances from near synchronous orbit to the distant tail. It is also argued that the layer of low-energy electrons and velocity-dispersed ion beams observed at low altitudes on Aureol 3 is not a different region from the region of auroral arcs. Both comprise the BPS. The two regions occasionally appear distinct at low altitudes because of the effects of arc field-aligned potential drops on precipitating particles.

1. INTRODUCTION

A major problem in magnetospheric research is understanding the processes responsible for substorms. An important aspect of this problem is determining the region of the magnetosphere in which substorms are initiated; this topic is currently one of considerable controversy. It is generally agreed that the region is located near magnetic midnight, but specific proposed regions range from distant tail boundary layers to the central plasma sheet and the inner edge of the central plasma sheet.

Initiation of substorms has been identified with the breakup of quiet auroral arcs (e.g., Ref. 1), so that it is reasonable to presume that substorms are initiated along arc magnetic field lines. Thus the magnetospheric region responsible for quiet arcs should also be the region of substorm initiation. (It is also possible that substorms are initiated elsewhere in the magnetosphere, and that the information is rapidly transmitted to arc field lines. If this were the case, we would need to identify the magnetospheric region of breakup as well as the transmittal process.) In this

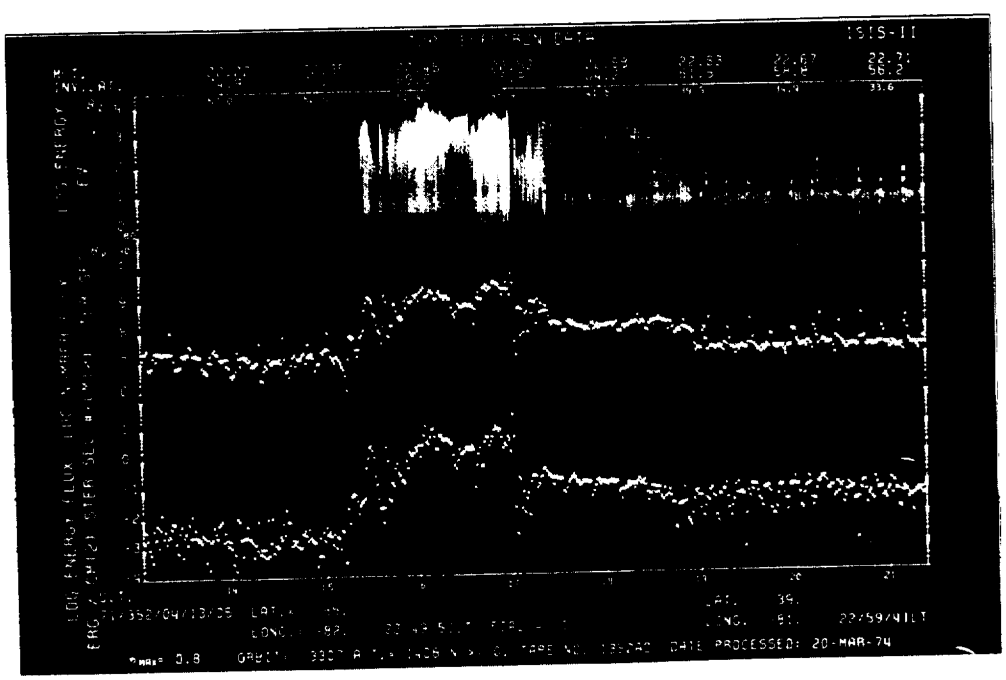

Figure 1. Electron data from Isis 2 on December 18, 1971. The top panel gives an energy-time spectrogram. The ordinate is log10 of the electron energy and the abscissa is minutes of UT. The data begins at 0022 UT. The small panel labeled qp is the pitch angle for each measurement (<90 is downward), and the middle and lower panels give total number and energy fluxes over the energy range 5 eV to 15 keV (from Ref. 6).

paper, I present inferences concerning the magnetospheric source region for auroral arcs that have been obtained from particle measurements on polar-orbiting satellites. I also contrast my ideas (Refs. 2, 3) with those of Feldstein and Galperin (Refs 4, 5).

2. ASSOCIATION WITH BOUNDARY PLASMA SHEET AND CHAOTIC ENERGETIC ION MOTION

A comprehensive analysis of precipitating electron measurements from the polar-orbiting ISIS 1 and 2 satellites was performed by Winningham et al. (Ref. 6). They found that the auroral precipitation could consistently be separated into a poleward boundary plasma sheet (BPS) region and an equatorward central plasma sheet (CPS) region. These regions were identifiable during all phases of substorm activity, and an example of their observations is given in Figure 1.

Figure 1 shows a spectrogram of precipitating electron energy fluxes and total precipitating electron number and energy fluxes versus UT from an ISIS 2 pass traversing the auroral oval from high to low latitudes. Structured electron precipitation, identified by Winningham et al. (Ref. 6) as the BPS, can be seen from ~71.5 to ~ 66 invariant latitude. The electron fluxes within the BPS show occasional peaks at energies above a few hundred eV, which indicates acceleration by magnetic field-aligned electric fields. Discrete auroral arcs are identified with such precipitation. Relatively unstructured precipitation extends from the equatorward boundary of the BPS to ~61 invariant latitude, and is identified as the CPS. The CPS precipitation causes diffuse auroras, which have far less spatial structure than discrete arcs, and particle observations within the CPS do not show the signatures of significant field-aligned potential drops.

A weak uniform flux of low-energy electrons can be seen extending poleward from the poleward boundary of the BPS. These electrons precipitate directly from the magnetosheath along open polar cap magnetic field lines and are referred to as polar rain by Winningham and Heikkila (Ref. 7). It is generally accepted that the BPS lies on closed magnetic field lines, implying that the BPS extends equatorward from the boundary between open and closed magnetic field lines. The extension of the BPS and the CPS along magnetic field lines from the ionosphere to the equatorial plane is illustrated in Figure 2. The outer boundary of the BPS remains at the open-closed field-line boundary, and the CPS extends earthward (or equatorward) from the inner boundary of the BPS. The BPS crosses the weak magnetic field region of the tail current sheet, and at least the outer portion of the CPS probably also crosses this current sheet.

Since auroral arcs are confined to the BPS, the mapping in Figure 2 implies that the region of breakup and substorm initiation must lie within the magnetospheric extension of the BPS. Based on Winningham et al.'s (Ref. 6) result that the CPS exists during all phases of substorm activity, a separate and distinct CPS must exist in the magnetosphere equatorward of the region of breakup in the BPS.

The BPS has been formally identified from relatively low-altitude, polar-orbiting satellites. An analogous region, known as the plasma sheet boundary layer (PSBL) has been identified in the magnetotail extending equatorward from the plasma sheet-lobe

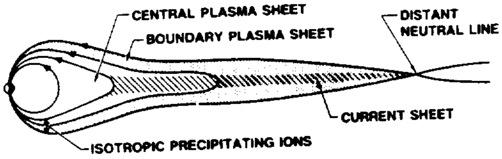

Figure 2. Schematic illustration of the mapping of the CPS and BPS to the geomagnetic tail. The BPS crosses the equatorial plane beyond a well-defined CPS region. It also crosses the equatorial plane sufficiently far from the Earth that the magnetic field distortion causes energetic ion motion to be in violation of the guiding center approximation, which leads to the isotropic precipitation of the ions.

boundary. The PSBL contains ion flows (Refs. 8-11) and field-aligned currents (Refs. 12-15), and it is nearly always present (Ref. 16). It is clear that the PSBL is related to the BPS observed at low altitudes, but it is yet to be determined if the two regions are identical. Certainly the BPS and the PSBL have a common outer boundary at the open-closed field-line boundary, but their inner boundaries may not be identical. If it is found that discrete auroral arcs are confined to the PSBL, then the PSBL could be identified as the magnetospheric extension of the BPS. However, if its found that the arcs extend earthward of the PSBL, then the BPS would be a broader region than the PSBL. To avoid ambiguity, I discuss the BPS in the remainder of this paper, leaving open the possibility that substorm initiation may occur earthward of the region of PSBL ion flows. Nevertheless, the low-altitude observations show that a well-defined CPS region must lie equatorward of the region of initiation within the BPS.

Additional information concerning the magnetospheric region of substorm initiation has been obtained from simultaneous measurements of auroral particles and energetic ions on polar-orbiting satellites. Examples from the S3-3 satellite are shown in Figures 3 and 4. These figures show energy-time spectrograms of electron (0.17 to 33 keV) and ion (E/q from 0.09 to 3.9 keV/q) energy fluxes, and gray-scale strips of 235 keV electrons and >80 keV ions. S3-3 was a spinning satellite, allowing pitch angle distributions to be evaluated. The pitch angle of the measurements is plotted below the particle data. The measurements in these examples are from altitudes of 6000 to 7000 km, which is within the altitude region of the field-aligned electric fields that accelerate discrete arc electrons.

The BPS region is easily identified in Figures 3 and 4 from the structured electrons and from the upgoing (180 pitch angle) ion beams at energies of the order of 1 keV. The ion beams result from acceleration by the portion of the field-aligned electric potential drop that lies below the satellite. The BPS is unusually broad in Figure 3, extending down to ~65 invariant latitude, and is quite narrow near 69.5 latitude in Figure 4.

The additional information comes from the pitch angle distributions of the energetic ions. Within and equatorward of the BPS, these distributions show only one minimum per satellite spin (centered at 180 pitch angle) and are approximately isotropic across the downgoing loss cone (centered at 0 pitch angle). A number of additional examples are shown in Refs. 17 and 18, where it can be seen that the isotropic energetic ion precipitation extends up to the poleward boundary of the BPS whenever the ion fluxes are sufficiently high to be detectable. Based on numerous examples, it was concluded (Refs. 17, 18) that the BPS essentially always lies within the region of isotropic energetic ion precipitation. The isotropic precipitation was found to generally extend equatorward of the BPS. While the ion fluxes occasionally fall below the level of detectability within portions of the BPS, the isotropic ions are nearly always observable somewhere within, or just equatorward of, the BPS. Anisotropic ion distributions were found to be extremely rare within the BPS, and in such cases, the distributions approached isotropy.

The isotropic ion distributions have been attributed to particle motion that violates the guiding center approximation in the region of low magnetic fields of the tail current sheet (Refs. 17-20). Such motion has been termed "chaotic" in recent studies. On this basis, it possible to relate the BPS to the tail current sheet as illustrated in Figure 2. Here the tail current sheet is defined to be the region where energetic ion motion is chaotic. I thus conclude that substorm initiation occurs on BPS field lines that cross the tail current sheet, and that the current sheet extends earthward of the region of initiation (see also Ref. 2).

3. COMMENTS ON AN ALTERNATIVE INTERPRETATION

Feldstein and Galperin (Refs 4, 5) presented a different interpretation of the low-altitude particle measurements. They noted that a zone of low-energy (<1 keV) electron precipitation can be found poleward of the last discrete auroral arc, and suggested that this is the true plasma sheet boundary region. They proposed that discrete arcs lie within the CPS. On this basis, substorm initiation would have to be within the CPS.

Zelenyi et al. (Ref. 20) analyzed data from the low-altitude, polar-orbiting Aureol 3 satellite. They found that velocity-dispersed ion beams (VDIB) could be detected poleward of the last discrete arc as well as the low-energy electrons, and they proposed that these ions are the low-altitude signature of the ions observed flowing earthward at high altitudes within the PSBL. They placed these observations in context with the Feldstein and Galperin proposal and suggested that the ions beams were an additional signature of the BPS. Zelenyi et al. did not directly address the source region for discrete arcs, but their arguments are consistent with those of Feldstein and Galperin.

Observations of particles in the vicinity of synchronous orbit have been used to infer that substorm onset can occur relatively close to the Earth (in the vicinity of synchronous altitudes) on the night side (Refs. 21-24). These inferences suggest that substorm initiation may occur within the CPS and perhaps near its equatorward boundary, and are also consistent with the suggestions of Feldstein and Galperin.

An example of Aureol 3 precipitation measurements (from Ref. 25, where the figure is presented in color) showing a low-energy electron layer and coincident velocity-dispersed ion beams is

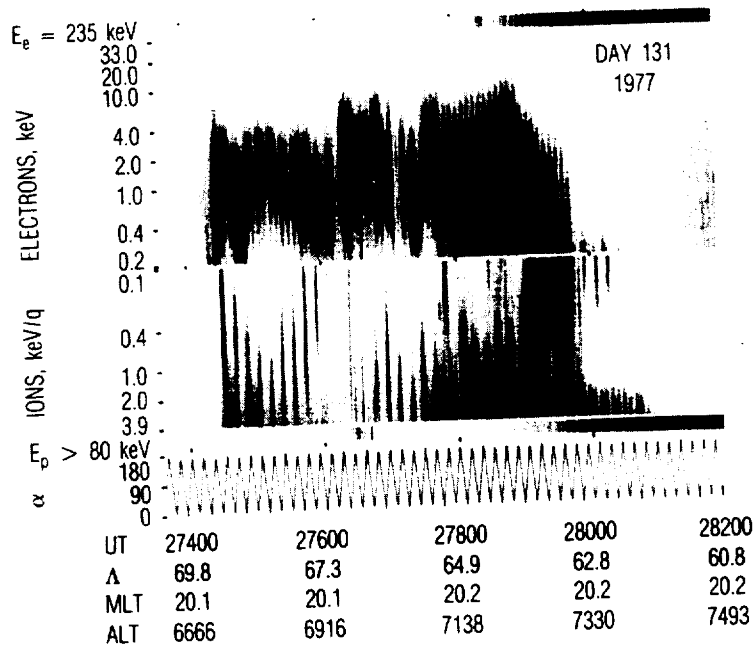

Figure 3. Spectrogram of S3-3 plasma data for 27400 - 28200 s UT on day 131 (May 11), 1977. The energy fluxes are encoded in a gray scale with darker regions representing higher flux. Gray scale bands at the top and bottom of the spectrogram give the intensities of 235 keV electrons and >80 keV protons, respectively. The pitch angle of the measurements is given by a line graph below the data. Time in seconds, invariant latitude in degrees, magnetic local time, and satellite altitude in km are given along the bottom of the figure (from Ref. 18).

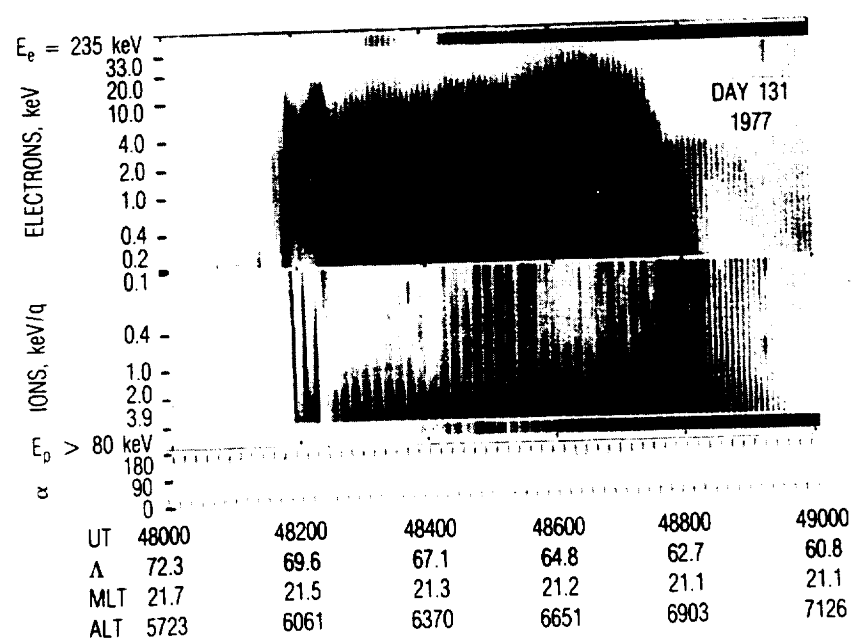

Figure 4. Same as Figure 3, except for 48000 - 29000 s UT on day 131 (May 11), 1977 (from Ref. 18).

shown in Figure 5. This layer, which I shall call the VDIB layer, is identified by the vertical lines below the spectrograms near 72 magnetic latitude. Structured electron precipitation of the form associated with discrete arcs extends equatorward of the VDIB layer to ~68.5 latitude. This structured region would be identified as the BPS using the criteria of Winningham et al. (Ref. 6).

I propose that the VDIB layer and the region of structured electron precipitation together comprise the BPS and that the CPS lies further equatorward. Consistent with this suggestion, the data in Figure 5 show a clear CPS region (based on the Winningham et al. definition) extending equatorward of the region of structured electron precipitation. If we assume that the region of structured precipitation maps to the CPS, then it becomes difficult to determine the mapping of the equatorward precipitation region.

I furthermore propose that the distinction between the VDIB layer and the region of structured electron precipitation seen in the Aureol 3 data is simply a result of the parallel electric fields responsible for forming the auroral arcs, so that this distinction should not be seen at high altitudes within the plasma sheet. Such electric fields do not occur uniformly within the BPS, and at times may not occur with significant magnitudes very near its poleward boundary. However, wherever the they do occur, they will accelerate low-energy electrons towards the atmosphere, so that the electrons will not appear with low energies at low altitudes. The electric fields will also decelerate precipitating ions, and ions having energies insufficient to surmount the total field-aligned potential drop, $\phi_{\parallel}$, will be reflected back towards the outer magnetosphere without precipitating.

This suggests that both the low-energy electrons and the ion beams should have an equatorward boundary at low altitudes that is coincident with the poleward boundary of the discrete arc electrons. If the ion beam energies are less than $e\phi_{\parallel}$, precipitation of the ion beams should cease within the arc region. If the beam energies are greater that $e\phi_{\parallel}$, the energies of the precipitating ions should be reduced. The example in Figure 5 is consistent with this suggestion. The arc electrons equatorward of the VDIB layer could have resulted from the acceleration of electrons from the low-energy electron layer, and the ion beam precipitation cuts off at the poleward boundary of the arcs. The cutoff of the ion beams is expected because their energy is approximately 1 keV just poleward of the arc electrons, whereas the arc electrons show acceleration by 1 to 2 keV. At altitudes above the region of significant $\phi_{\parallel}$, the low-energy electrons and the ion beams should extend onto arc field lines.

If my suggestion is correct, then the VDIB layer should only be observable on polar-orbiting satellites when significant arc $\phi_{\parallel}$'s ($\geq$ 500 V) do not extend to the poleward boundary of the BPS. When they do extend to the poleward boundary, neither the low-energy electrons nor the ion beams (with their initial energies) should be observed. Examination of a significant number of S3-3 satellite passes shows that it is not unusual for the arc acceleration to extend to the poleward boundary, and the examples in Figures 1, 3, and 4 of this paper show this situation. The low-energy electron layer does not occur in these examples, though weak ion precipitation is seen at 3 to 4 keV near the poleward boundary of the BPS region in Figures 3 and 4. Based on the electron observations, these ions should have been decelerated by ~2 keV prior to their observation at S3-3. The ions would be decelerated still further by the potential drop below S3-3 before reaching the lower altitudes of Aureol 3.

It could be argued that the low-energy electrons and the ion beams existed poleward of the observed BPS during the above satellite orbits, but their intensity was below the threshold of detectability by the satellite instrumentation. However, this is clearly not the case, at least for the examples in Figures 1 and 4. In these examples, polar rain can be seen over the polar caps extending equatorward to the poleward boundary of the observed BPS. Polar rain identifies open field lines, and the plasma sheet and its boundary layer presumably exist only on closed field lines. Thus, since observable plasma sheet precipitation extends to the equatorward boundary of the polar rain, there can be no additional plasma sheet precipitation poleward of that which is observable.

The above discussion implies that the VDIB layer should often not be observable because of the existence of significant $\phi_{\parallel}$'s very close to the poleward boundary of the BPS. This may be an important reason why Zelenyi et al. (Ref. 20) found the ion beams in only ~10 % of the cases they examined.

4. CONCLUSIONS

My primary conclusion is that the magnetospheric source region for discrete auroral arcs, and thus for arc breakup and substorm initiation, lies along BPS field lines. While the position and latitudinal width of the BPS varies with time, substorm initiation must occur on field lines that were within the BPS at a time just prior to initiation. These field lines cross the tail current sheet sufficiently far from the Earth that energetic (>80 keV) ion motion violates the guiding center approximation (i.e., is chaotic). The

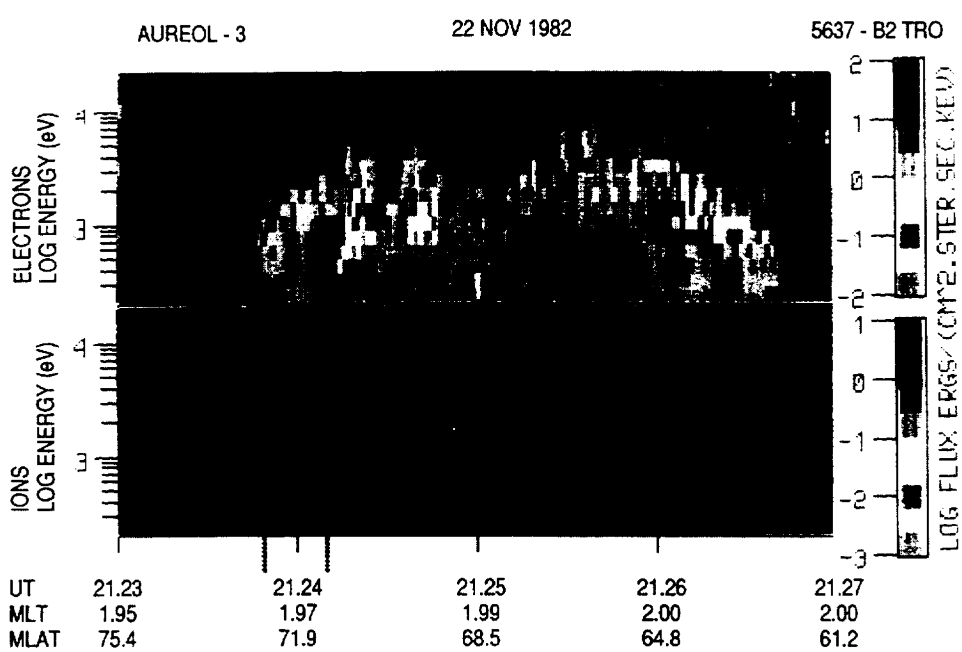

Figure 5. Energy-time spectrogram of precipitating electron and ion measurements from the Aureol-3 satellite (from Ref. 25 where figure is presented in color).

BPS region also lies beyond a distinct CPS region since such a CPS is routinely identifiable at low altitudes equatorward of the BPS. The CPS particle distributions have considerably less spatial structure than does the BPS and do not contain the signatures of significant $\phi_{\parallel}$'s.

I furthermore conclude that the VDIB layer observed at low altitudes, which contains low energy electrons (Refs. 4,5) and the velocity dispersed ion beams from the plasma sheet boundary layer (Ref. 20), is not a plasma sheet layer that is separate from the BPS as defined by Winningham et al. (Ref 6). It can only be observed when significant (above about 500 V) $\phi_{\parallel}$'s do not extend to the polar boundary of the BPS. Even when it is observable, it will have an equatorward cutoff at a location where $\phi_{\parallel}$ becomes significant. A VDIB layer of precipitation that is distinct from the region of auroral arcs should only be observable at low altitudes. It should not be seen at altitudes above the region of significant $\phi_{\parallel}$.

The conclusions above pertain only to the position of the arc region relative to the other regions mentioned. The conclusions do not confine the arc source region, and thus the region of substorm initiation, to any particular range of radial distances from the Earth. Results presented at this conference (Ref. 26) show that small auroral break-ups can be initiated at high invariant latitudes (~74) along the poleward boundary of observable arcs. Such field lines must extend far down the tail, well beyond synchronous orbit. On the other hand, the observations in Figure 3 show significant auroral arcs down to 65 latitude (L = 5.6). While the mapping of field lines to the equatorial plane during very disturbed times is quite uncertain, such an observation implies that substorm initiation is possible within the vicinity of synchronous orbit. While these two examples probably represent extreme conditions, they suggest that substorm initiation within the BPS is possible over a wide range of radial distances from the Earth.

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