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Substorm Aurorae and Their Connection to the Inner Magnetosphere

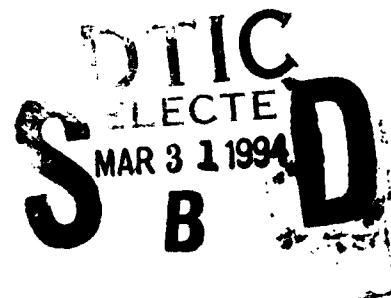
15 April 1994

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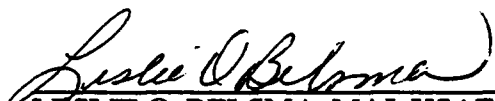
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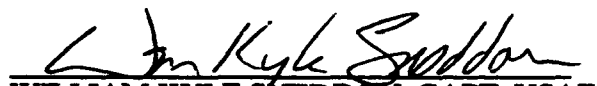
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Substorm Aurorae and Their Connection to the Inner Magnetosphere

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In this paper we present evidence from the low-altitude DMSP F7 satellite that the poleward edge of auroral luminosity in the nightside auroral zone does not necessarily correspond to the boundary between plasma-filled flux tubes and flux tubes devoid of plasma. Assuming that that low-altitude boundary corresponds to the boundary between the lobe and the plasma sheet, this implies that the boundary between open and closed field lines may lie poleward of the most poleward auroral luminosity. Thus the assumption that the poleward boundary of auroral luminosity is a good indicator of the open-closed boundary may not always be correct. Furthermore, we show clear evidence that an auroral surge may also be located equatorward of the open-closed boundary. Therefore, tailward of the region of the plasma sheet to which the surge is connected there may exist undisturbed plasma sheet that has not yet been disconnected from the ionosphere. This means that substorm-associated reconnection does not necessarily begin to reconnect lobe field lines at the onset of a substorm. Moreover, available evidence strongly suggests that the arc that brightens at the onset of a substorm and that develops into a surge maps to the inner magnetotail, to that region at the inner edge of the plasma sheet where the magnetic field changes from a dipolar to a tail-like configuration. This would be consistent with recent studies that connect auroral breakup to the near-Earth ($<10 R_E$) plasma sheet.

1. Introduction

The visible manifestation of magnetospheric processes is the aurora. One of the most important techniques to emerge from the space age is the ability to image the aurora in a global manner (e.g., FRANK and CRAVEN, 1988). Furthermore, low-altitude spacecraft equipped with both particle detectors and imagers have allowed combined studies of auroral images and the precipitating particles that create those emissions (e.g., MENG *et al.*, 1978). Some of these studies have implied that the boundary between open and closed field lines corresponds to the poleward boundary in auroral luminosity (e.g., MENG *et al.*, 1978). Although this may be true in certain cases, it has become accepted by a number of researchers that this is *always* the case. In fact, some work has rested an important part of the interpretation of data on that presumption, such as in LYONS *et al.* (1990), wherein it is stated that "... We assume that the poleward boundary of the aurora lies along, or adjacent to, the separatrix between open and closed geomagnetic field lines." In FRANK *et al.* (1988) the poleward boundary of auroral luminosity has been used as a marker to denote the region of closed field lines for the purposes of determining the amount of open flux in the magnetotail. However, ELPHINSTONE *et al.* (1991) have presented evidence that the auroral luminosity is not well correlated with a model open-

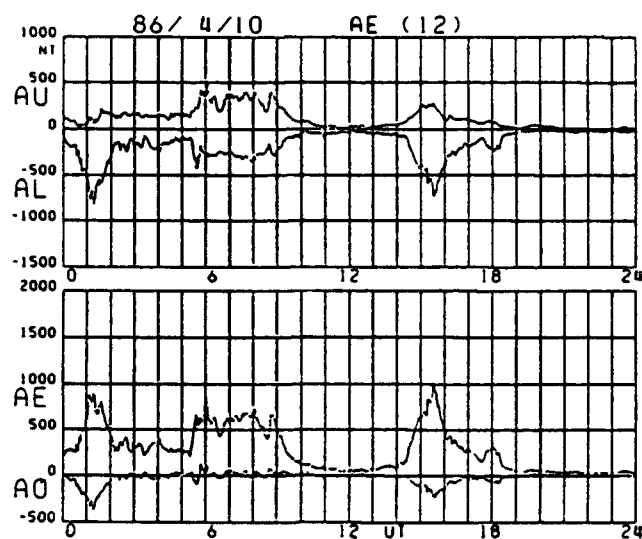


Fig. 1. *AE* for 10 April 1986.

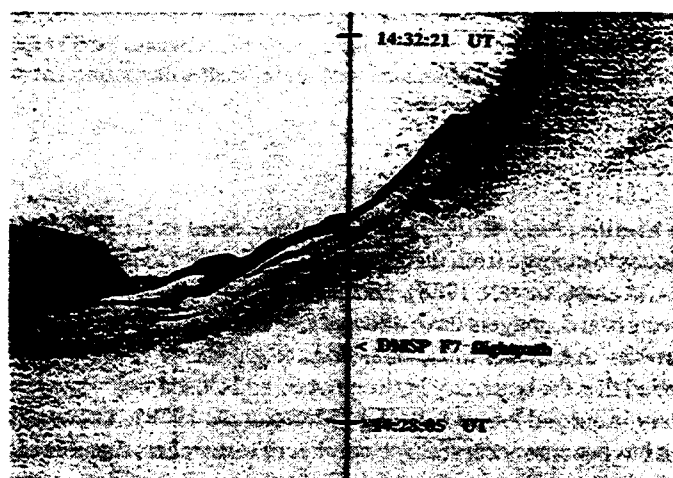


Fig. 2. DMSP F7 auroral image for 10 April 1986. South is at the top of the figure, west is to the right. The line in the center of the image is the satellite track. A surge and auroral bulge lay to the east of the DMSP F7 path, and a bright arc was encountered at 14:30:25 UT (just above the middle tic mark).

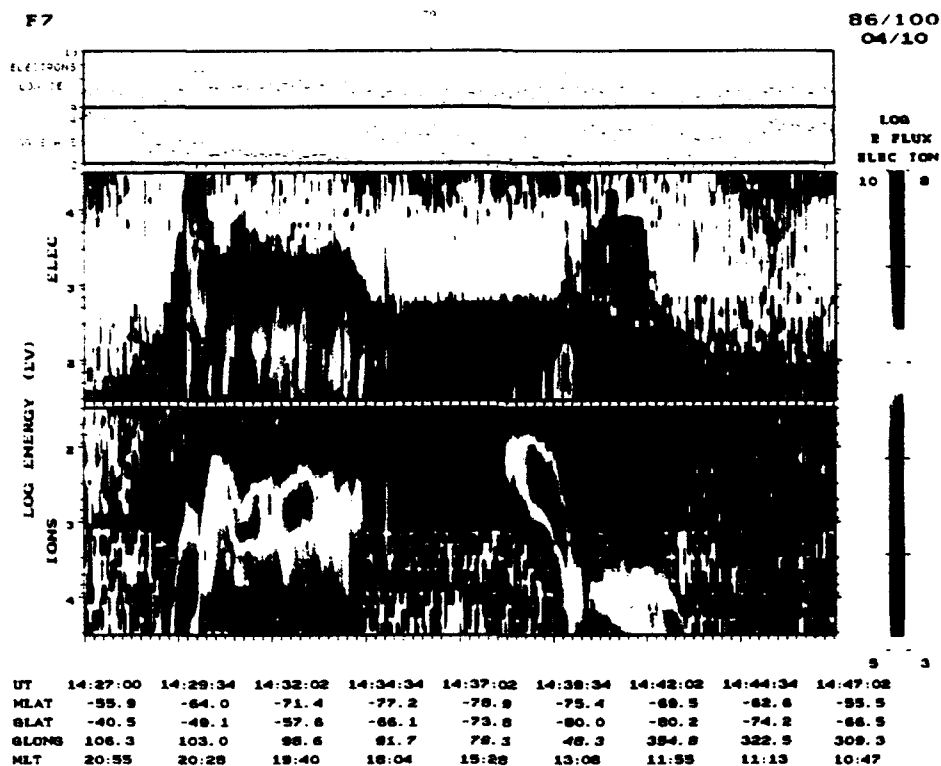


Fig. 3. DMSP F7 particle spectrogram for 10 April 1986. Precipitation extended several degrees poleward of the electron precipitation encountered at 14:30:14 UT that caused the bright arc crossed by DMSP F7 in Fig. 2.

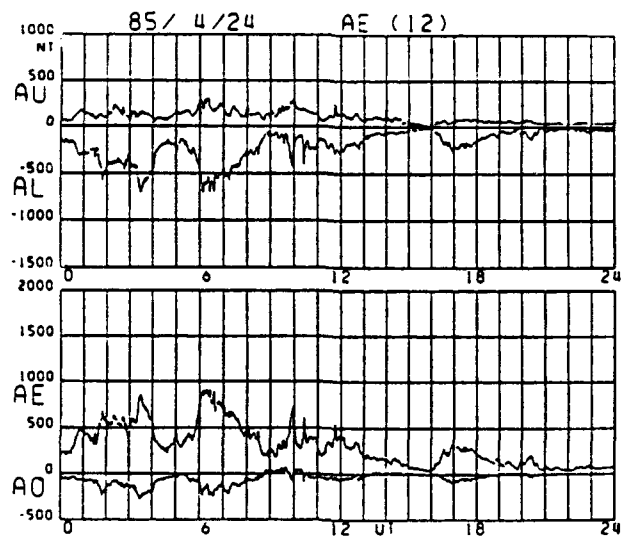


Fig. 4. AE for 24 April 1985.

closed field line boundary derived from the TSYGANENKO (1987) magnetic field model.

In this paper we will examine two cases of precipitating particle and image data from the low-altitude DMSP F7 satellite as it traversed the nightside auroral zone. These data demonstrate that the boundary between plasma-filled flux tubes and flux-tubes devoid of plasma does not necessarily correspond to the poleward edge of visible luminosity. Therefore the assumption that the poleward boundary of the aurora corresponds to the open-closed boundary is not always warranted. Moreover, we shall show that this can also be true for a westward travelling surge, so that surges can be located exclusively on closed field lines that map to the inner edge of the plasma sheet ($<10 R_E$), as is easily inferred from statistical magnetic field models such as TSYGANENKO (1987).

2. Data

The observations to be presented were made by the Defense Meteorological Survey Program (DMSP) satellite F7. DMSP F7 is a low-altitude (835 km) polar-orbiting satellite with the orbital plane approximately along the 1035–2235 local time meridian, and its orbital period is 101.5 minutes. The data to be presented consist of precipitating particle measurements (electrons and ions from 30 eV to 30 keV) and a broadband (4000–9000 nm) image. A more detailed description of the satellite and its instrumentation may be found in HARDY *et al.* (1984), GUSSENHOVEN *et al.* (1985), and RODGERS *et al.* (1974). Two examples of combined particle and image observations of the auroral zone will be presented, along with the appropriate *AE* data. The implications of the observations will then be discussed.

3. Observations

The first set of observations we present were collected at about 1430 UT on 10 April 1986. Figure 1 shows the *AE* record for that day. At about 1420 UT a large substorm erupted. Figure 2 shows the auroral image taken by DMSP F7. The imager scans a 120°-wide segment directly beneath the satellite. This image is a negative, so that the dark areas represent regions of strong visible emissions. In the center of the image the path of the DMSP F7 satellite is marked, as are three equally spaced tic marks; the times at which the satellite passed over that point are given for the first and last tics, the time associated with the middle tic mark is 1430:13 UT. DMSP F7 was in the southern hemisphere, moving poleward through the auroral zone, when the image was recorded. At the left edge of the image a large auroral bulge is visible. Since this image was taken in the southern hemisphere, west is to the right of the image. Therefore we identify the structure with the westward edge of a disturbed region. The satellite itself crossed the auroral zone to the west of this structure, through a region of narrow discrete structures (encountered just after 1430:13 UT) poleward of more diffuse emission. Three bump-like structures were present on that discrete arc to the east of the satellite track, and DMSP F7 passed just to the west of the most westward of them.

Figure 3 presents the DMSP F7 precipitating particle data in spectrogram format. The two main panels show the ion and electron data. Ions (electrons) are plotted in the lower (upper) panel with the lowest energy particles at the top (bottom) of the panel. The small upper panel shows the total precipitating energy flux. The magnetic coordinates given in the figure are those of BAKER and WING (1989). The satellite crossed through the premidnight auroral zone at some what of a slant, exiting the auroral zone into a region near the dusk meridian that has

the spectral characteristics of plasma mantle (NEWELL *et al.*, 1991). The bright discrete arc discussed above, which was located at a magnetic latitude of -64.3° , and the diffuse ion precipitation equatorward of it, are clearly visible in the DMSP F7 particle data. The time that the arc was encountered in the electron data (1430:14 UT) does not agree exactly with the time when the arc was directly beneath the satellite (14:30:25 UT) since even the quiet-time magnetic field threading DMSP F7 does not project exactly to the subsatellite point. Thus in vicinity of field-aligned currents associated with arc, and especially surges, the footpoint of the field line threading DMSP F7 may be significantly shifted relative to the subsatellite point. What is very important to note is that poleward of the bright arc the auroral zone was filled with discrete precipitation, but that precipitation never reached intense flux levels and therefore was not visible. However, the presence of significant fluxes of electrons, and even keV ions, strongly suggests that those flux tubes were closed.

The second set of observations were made on 24 April 1985, just after 0500 UT. Figure 4 shows the *AE* record for that day. The early part of the day featured rather continuous moderate to strong activity that began to diminish around 0400 UT. At 0440 UT, there was an enhancement of activity that reached its peak at 0500 UT. At that time DMSP F7 made a pass through the southern auroral oval in the 2230 MLT sector. The image from this pass is presented in Fig. 5; as in the case of Fig. 2, the image is a negative and the DMSP F7 trajectory is marked on the figure. The satellite flew directly through the head of what appears to be an auroral surge located at the western edge of a disturbed region, crossing the equatorward boundary at 0503:18 UT, and the poleward boundary at 0504 UT. To the east of the surge (left portion of the image) there was a well-developed auroral bulge, which may be a reflection of the activity earlier in the day. Just to the west of the surge one can see the brightening arc located at the equatorward edge of the auroral zone. At some points along that arc there were small bump-like structures that were probably incipient surges. Further to the west, at the right edge of the image, there were looped auroral forms that were located poleward of the equatorward arc, and a weak arc at the poleward edge extending eastward from the most poleward loop. In fact, the poleward edge of that loop, and the arc extending eastward was at approximately the same magnetic latitude as the poleward edge of the auroral bulge, and that magnetic latitude is roughly the latitude at which DMSP F7 encountered the poleward limit of the particle precipitation.

Figure 6 presents four minutes of DMSP F7 particle data for the pass in question. One can see that just after 05:02:56 UT the satellite entered a region of intense, monoenergetic electron precipitation that which extended in magnetic latitude from -65° to -67.7° . This precipitation was basically coincident with the bright surge feature seen in Fig. 5 (the differences in the times being due to the difference between the subsatellite point and the field line footpoint), and the spectrum of the precipitation is the same as that associated with an upward substorm Birkeland current observed during another event (LOPEZ *et al.*, 1991a). Equatorward of the surge was a region of diffuse auroral precipitation. Poleward of the surge there was a region of discrete features, which was not energetic enough to produce visible emissions that could be recorded by the DMSP F7 imager. At the poleward edge of the auroral zone there was a velocity dispersed ion structure. Such structures have been discussed by ZELENYI *et al.* (1990), who argued that they are the signature of the distant neutral line at the boundary between open and closed field lines. Thus we find that in this case, as in the previous one, there existed a region of precipitation, presumably on closed field lines, that was poleward of the poleward edge of auroral luminosity. This also suggests that during this particular event the surge was embedded

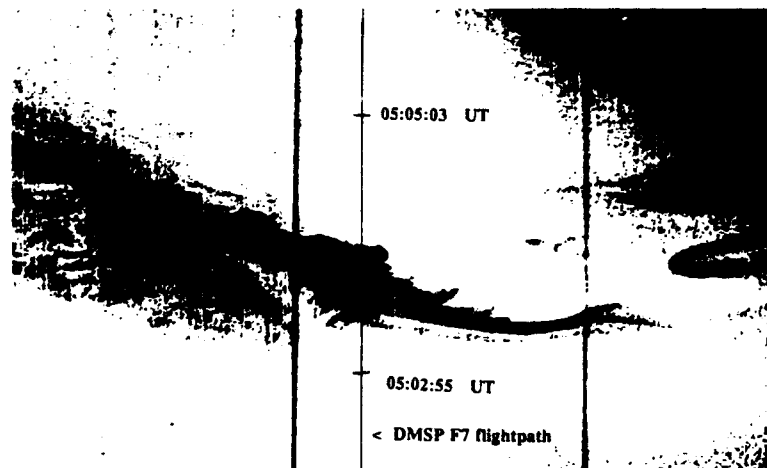


Fig. 5. DMSP F7 auroral image for 24 April 1985. South is at the top of the figure, west is to the right. The line in the center of the image is the satellite track. An auroral bulge lay to the east of the DMSP F7 path, and the satellite flew directly through the head of surge.

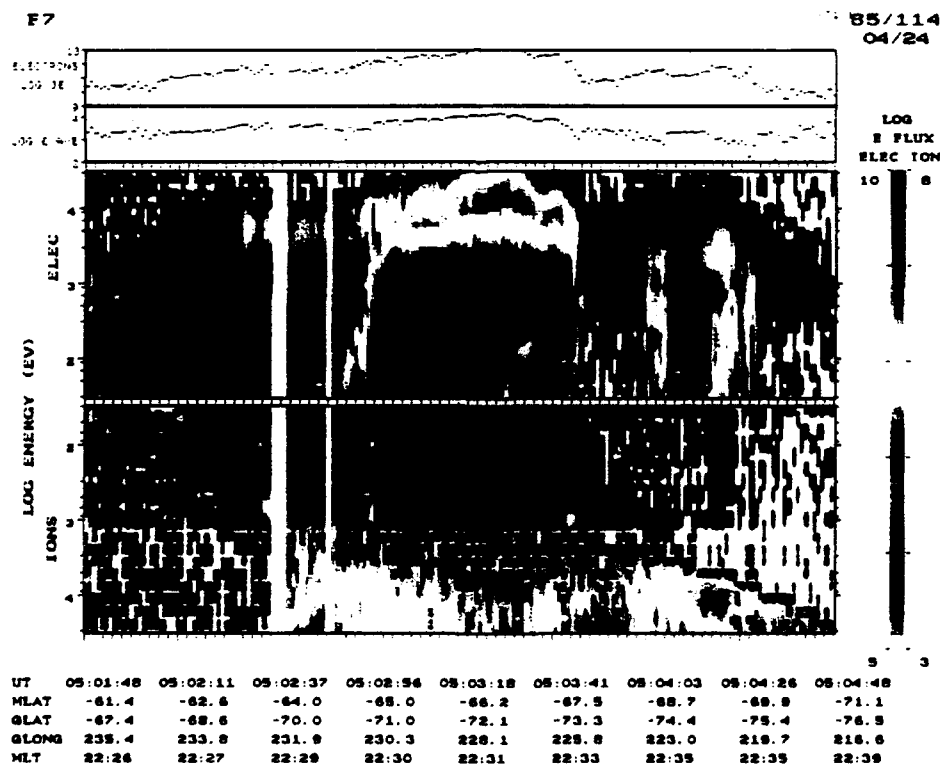


Fig. 6. DMSP F7 particle spectrogram for 24 April 1985. The surge precipitation is clearly identifiable in the center of the spectrogram. Poleward of the surge precipitation there were several discrete features, and at the poleward edge of the precipitation there was a velocity-dispersed ion structure, with higher energies at higher latitudes.

in the center of the auroral zone, apparently several degrees equatorward of the open-closed field line.

In the next section we will discuss the implications of these observations. We will argue that they conclusively show that the poleward boundary of the aurora does not necessarily correspond to the open-closed field line boundary. We will also discuss where the observed features mapped using the model of TSYGANENKO (1987) and show that the mapping is consistent with a near-Earth substorm initiation region.

4. Discussion

In the two cases examined it is clear that in the nightside auroral zone the boundary between plasma-filled flux tubes and those devoid of plasma lay poleward of the auroral luminosity. We take that boundary to be the boundary between open and closed field lines. There is evidence, however, that assumption may be questionable. GUSSENHOVEN and MULLEN (1989) have published DMSP F7 observations showing that the nightside open-closed boundary obtained by examining relativistic electrons during a solar particle event does not agree with the polar cap boundary determined from lower-energy precipitating particle data similar to that presented in this paper. They conclude that the soft precipitation and arcs that fill the polar cap during northward IMF lie on open field lines. If this interpretation is correct then the boundaries that we have determined in our two cases may not be the boundaries between open and closed field lines.

GUSSENHOVEN and MULLEN (1989) also compared a boundary that they called the transition boundary to the relativistic electron boundary. This transition boundary is the point where the average electron energy falls below 500 eV; this definition of the edge of the polar cap was used by HOLZER *et al.* (1986) to estimate changes in the amount of open magnetic flux during substorms. The relativistic electron boundary was always found to be located equatorward of the transition boundary, and GUSSENHOVEN and MULLEN (1989) suggest that this boundary might be a more realistic indicator of the boundary between open and closed field lines. In the first of our cases (10 April 1986) the precipitation extending poleward of the brightening arc does have an average energy below 500 eV. According to the results of GUSSENHOVEN and MULLEN (1989) that would indicate that the open-closed boundary did lie at the poleward edge of the auroral luminosity, and the surge seen to the east does reflect a distortion of that boundary as postulated by LYONS *et al.* (1990). On the other hand, in the second case (24 April 1985) the transition boundary corresponds to the poleward boundary of significant electron precipitation, since the electrons had an average energy well above 1 keV almost all the way up to what we have defined as the boundary (just below that boundary the average energy dropped about 400 eV). This event appears to be solid evidence that the arc that brightens during a substorm and the resulting surge can lie significantly equatorward of the open-closed boundary.

Since the surge lay equatorward of the open-closed boundary, poleward of the surge there was a region of undisturbed plasma sheet that was still connected to the ionosphere. In fact, the observation of a velocity-dispersed ion structure at the poleward edge of the precipitation suggests that that boundary corresponded to the distant neutral line (ZELENYI *et al.*, 1990). This implies that any substorm-associated reconnection had not yet proceeded to the last closed field line in that sector, and that lobe field lines had yet to merge. Since the formation of a surge is a hallmark of substorm onset or intensification, this suggests that the onset of a substorm does

not correspond uniquely to a severance of a portion of the plasma sheet to form a plasmoid. If a substorm can occur and a surge can form without the immediate release of a plasmoid, it is reasonable to suspect that there may be some substorms that produce no plasmoid at all.

The equatorward boundary of the surge crossed by DMSP F7, and thus the arc that was brightening and forming surges to the west of the satellite, was located at about -65° magnetic latitude. This magnetic latitude is not too different from the average latitude of auroral breakup, which was found by CRAVEN and FRANK (1987) to be 66° , and it also lies well within the range of values given by MURPHREE *et al.* (1991). Using the TSYGANENKO (1987) magnetic field model we find that the equatorward edge of the surge mapped to $8.0 R_E$. This result is consistent with the results of MURPHREE *et al.* (1991). That study found that the region of substorm brightening corresponded to the region of the maximum cross-tail current density in the TSYGANENKO (1987) model, which lies in the near-Earth region. Similarly, LOPEZ *et al.* (1991b) found that current disruptions in the near-Earth region corresponded well to regions of electrojet intensifications. Our result is also consistent with LOPEZ *et al.* (1990). They examined a small substorm during which AMPTE/CCE was at the neutral sheet at $8.6 R_E$ during the onset of the event. The projected ionospheric footprint of the field line threading AMPTE/CCE lay in the center of a westward travelling surge observed by the ground station at Syowa, and they concluded that the disruption of the current sheet observed by AMPTE/CCE was directly connected to the surge. Thus it would seem that surges can and do map to the neutral sheet just outside of geosynchronous orbit, and that the region of substorm initiation lies in the inner magnetotail. In that case it is no mystery why the poleward boundary of the nightside auroral oval does not necessarily coincide with the open-closed field line boundary, and why the arc that first brightens during a substorm is so far equatorward of that boundary.

As discussed above, in the first event the criteria of GUSSENHOVEN and MULLEN (1989) would place the open-closed boundary at the poleward edge of the bright arc traversed by DMSP F7. This arc maps to $7.5 R_E$ using the TSYGANENKO (1987) model. Although one presumes that the field was rather tail-like at that time in that sector, it seems unlikely that the field line originating at the arc could have gone to the open-closed boundary (e.g., ELPHINSTONE *et al.*, 1991). Thus we suggest that this event is another example of closed field lines poleward of the poleward edge of auroral luminosity, although one could certainly argue against that interpretation based on the results of GUSSENHOVEN and MULLEN (1989).

The examples presented here are not the only ones available in the DMSP F7 data, but they illustrate our thesis. Our intention is not to dispute that sometimes, perhaps even a majority of times, the poleward boundary of auroral luminosity defines the poleward extent of closed field lines. There are many examples in the DMSP F7 data where this is the case. In particular, the poleward boundary of the auroral bulge that forms to the east of the surge almost always corresponds to the boundary between open and closed field lines. Moreover, the interpretation of growth and shrinkage of the dark polar cap during substorms reported by CRAVEN and FRANK (1987) and FRANK and CRAVEN (1988) in terms of a variation in the amount of open flux is certainly consistent with the proposition that the magnetotail lobes alternatively store and release energy extracted from the solar wind, and a similar result was found by HOLZER *et al.* (1986) using a particle definition of the polar cap. However, the cases presented above are strong evidence that one should not always automatically associate the poleward boundary of the visible aurora with the boundary between open and closed field lines, especially in the case of an auroral surge at the westward limit of the region of substorm activity.

5. Conclusion

In this paper we have examined precipitating particle and image data for the low-altitude satellite DMSP F7 in two cases when that satellite traversed the nightside auroral zone. We have presented strong evidence that the poleward edge of auroral luminosity does not necessarily correspond to the boundary between open and closed field lines. We have also demonstrated in one case that the observed auroral surge was not related to any distortion of the separatrix between open and closed field lines, that the surge was entirely contained within the region of closed flux, and that the equatorward edge of the surge mapped to the near-Earth ($<10 R_E$) magnetotail in the TSYGANENKO (1987) magnetic field model. In the other event we found that the brightening arc located just to the west of a surge also mapped to the near-Earth region. This is consistent with recent studies that connect auroral breakup to the near-Earth plasma sheet. Moreover, the observation of undisturbed plasma sheet on closed field lines poleward of a surge strongly implies that the onset of a substorm does not correspond to the onset of reconnection on lobe field lines, and that any substorm-associated reconnection must still be taking place exclusively on closed plasma sheet field lines.

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