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**Association of Plasma Sheet Variations
With Auroral Changes During Substorms**

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Abstract

Images of the southern auroral oval taken by the University of Iowa auroral imaging instrumentation on the Dynamics Explorer 1 satellite during an isolated substorm are correlated with plasma measurements made concurrently by the ISEE 1 satellite in the magnetotail. Qualitative magnetic field configuration changes necessary to relate the plasma sheet boundary location to the latitude of the auroras are discussed. Evidence is presented that the longitudinal advances of the auroras after expansive phase onset are mappings of a neutral line lengthening across the near-tail. We observe a rapid poleward auroral surge, occurring about 1 hour after expansive phase onset, to coincide with the peak of the AL index and argue that the total set of observations at that time is consistent with the picture of a "poleward leap" of the electrojet marking the beginning of the substorm's recovery.

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Introduction

The capability of imaging the entire auroral oval, or a large part of it, on time scales of a few minutes has been provided by auroral imaging instruments on the DE 1 and Viking satellites (Frank *et al.*/1/; Anger *et al.*/2/). This capability is very important for the study of substorms, which were originally defined in terms of rapid global-scale changes of the aurora that were deduced from ground-based arrays of all-sky cameras. The present discipline of magnetospheric physics has evolved in large part from efforts to understand the auroras in general and substorms in particular. Our current understanding of substorms as a spasmodic release of stored energy by the magnetotail was derived from, and continues to grow through, correlative studies of the auroras and their associated current system on the one hand and plasma phenomena in the outer magnetosphere on the other. Thus the possibility of viewing changes of the entire auroral oval at relatively high time resolution and relating these to satellite measurements in the outer magnetosphere and solar wind holds great promise for improved understanding of substorms.

In this paper we report results of a study correlating particle measurements by ISEE 1 in the magnetotail with images of the southern auroral oval taken by DE 1 during several substorms.

Observations

During the spring season, March, April and May, of 1983 the apogee of the DE 1 orbit was at high southerly latitudes, allowing images to be made of the southern auroral oval throughout much of each orbit. During the same three-month interval the apogee of the ISEE 1 and 2 satellite orbit was in the magnetotail, offering an opportunity to measure phenomena there while images of the auroral oval were being made by DE 1. We discuss simultaneous observations made during one substorm in 1983 for which data were reasonably complete from ISEE 1 and DE 1.

An isolated substorm began at ~0330 UT on March 28, 1983 following four hours of quiet AE conditions ($AE < 50$ nT). Figure 1 shows the AE index from 0230 UT to 0600 UT. DE 1 provided eleven images of the entire southern auroral oval from 0308 UT to 0512 UT. These are shown below the AE index. The center of each image lies at the center of the 12-minute interval during which it was accumulated. The two panels below the images show the fluxes of 2 keV electrons and 6 keV protons measured with electrostatic analyzers on ISEE 1 (Anderson *et al.*/3/). The bottom panel shows the geomagnetic latitude of the aurora's poleward boundary at three magnetic local times.

2100, 0000, and 0300 MLT, measured from the images using the computer graphics system that has been developed for this purpose by the University of Iowa. Also shown in the bottom panel is the geomagnetic latitude of a projection of the ISEE 1 position along magnetic field lines of a magnetosphere model. The model used for this projection was that published by Tsyganenko/4/. The model was computerized for this purpose at Los Alamos (J. Birn, private communication, 1988).

The AE index suggests a substorm onset time of 0330 UT. The first DE 1 image (0308-0320 UT) shows no auroral brightening but the second one (0323-0335 UT) does. The images thus suggest that the substorm started after 0320 and before 0335, in essential agreement with the AE index. The location of ISEE 1 is shown below the middle panels. It was in the early morning sector of the magnetotail about 20 R_E from earth and was far below the estimated position of the neutral sheet ($dz \approx -8 R_E$). Even at this large distance from the neutral sheet, however, measurable fluxes of plasma electrons and protons were present before the substorm, indicating that the half-thickness of the pre-substorm plasma sheet was at least 8 R_E . The bottom panel shows that ISEE 1 projected to 0100-0200 magnetic local time (MLT) and -76° magnetic latitude.

We now note several features of the auroral development and corresponding features in the outer magnetosphere. The early poleward expansion of the auroras (second, third and fourth images) was confined to the 0000 MLT sector. A temporary enhancement of plasma intensity (0333-0350 UT) occurred during this expansion. In the fourth image (0347-0359 UT) the beginning of an extension of the aurora into the morning section is discernable. In the fifth image (0359-0412 UT) this extension is very clear and the bottom panel of Figure 1 shows that there was a poleward expansion of nearly 5 degrees at 0300 MLT in that image. The morningward extension had not reached the 0300 MLT meridian in the 0347-0359 UT image, but computer analysis of that image showed that by 0352 UT the aurora at 0130 MLT, where ISEE 1 projected to earth, had expanded poleward by about 2 degrees. At ~ 0350 UT there was a sharp drop of plasma intensity at ISEE 1, (middle panels of Figure 1) and by 0400 UT the intensity had dropped below the instrument threshold.

The seventh image (0424-0436 UT) shows a remarkable poleward surge of the auroras that produces expansion at all three meridians, 2100, 0000 and 0300 MLT. The interval of this surge

includes a final sharp intensification of AL and the beginning of its recovery, i.e., it encompasses the AL peak. The surge carries the aurora at 0300 MLT to -75° latitude where it then remains through the last image (0512–0524 UT). Geomagnetic z-component records from ground stations in the auroral zone, ranging in magnetic local time from ~ 2200 (Great Whale River and Fort Churchill in Canada) to ~ 0400 (Leivogur in Iceland) registered the signature of overhead poleward passage of a strong westward current between ~ 0425 and ~ 0435 UT. This was the magnetic signature of the rapid poleward expansion of the auroras over this broad local time range.

At geosynchronous orbit (data not shown here) a >30 keV electron detector on satellite 1982-019, at ~ 2345 MLT shows a step-wise injection of electrons there beginning at 0419 UT and reaching its peak at 0431 UT. Also at geosynchronous orbit, a >300 keV ion detector on satellite 1981-025, at ~ 1930 MLT, revealed a series of proton drift echoes, the first in the series starting at 0425 UT and being very narrow (~ 3 minutes) and sharply peaked in time. These proton drift echoes were also observed by geosynchronous satellite 1977-007 at ~ 0900 MLT, about 9 minutes after their appearance at 1981-025, the delay being appropriate for the westward drift of the protons through 10 hours of local time. Belian *et al.*/5/ found that proton drift echoes are seen at geosynchronous orbit in about 10% of substorms. They are thought to be produced by brief, highly localized injections of protons into the pre-midnight region of synchronous orbit in close association with substorm onsets. The extreme narrowness of the initial proton pulse at satellite 1981-025 suggests that the satellite, at ~ 1930 MLT, was quite near the injection site. It is notable, too, that this drift echo series was initiated, not at substorm onset (0330 UT) but about one hour later (0425 UT), at the time of the large poleward surge of the auroras at the AL peak.

No effect of the events at ~ 0430 UT were observed at ISEE 1 which was still outside the plasma sheet. The plasma sheet enveloped ISEE 1 again starting at 0552 UT, and by about 0610 UT the plasma was hotter and more intense than it had been before the dropout at ~ 0350 UT (data not shown here).

Discussion and Conclusions

We briefly discuss our results in terms of (a) the gross configuration changes of the plasma sheet; (b) evidence for progressive cross-tail extension of the substorm neutral line during the substorm; (c) the late phase of the substorm and the "poleward leap" of the aurora.

(a) Figure 2 represents schematically a sequence of plasma sheet configuration changes near the noon-midnight plane of the tail that may occur during a substorm and that are not inconsistent with our results. The hatched region in each panel represents the plasma sheet. Some lobe field lines are shown. The ISEE 1 satellite is shown here at $X_{GSM} = -20 R_E$, $Z_{GSM} = +4 R_E$. The latitude labels on the field lines are not meant to be specific to this substorm but simply representative.

The pre-substorm plasma sheet seems to be thick and its boundary to map to low- or mid-auroral latitudes. Before the March 28 substorm the poleward edge of the auroras lay at -64° to -67° latitude, yet ISEE, mapped to -76° by the Tsyganenko model, was within at least the outer edge of the plasma sheet. Thus we conclude either that the model is very wrong for this occasion and should show field lines from -67° reaching out to ISEE at $X_{GSM} = -20 R_E$, $dZ_{GSM} \approx -8 R_E$, or the high latitude region of the plasma sheet, where ISEE was located and measuring moderate plasma intensity, actually maps to regions higher than -67° but does not produce auroras detectable with the DE 1 imager. This would imply, of course that there are closed field lines at latitudes at least several degrees poleward of the observed auroras.

Regarding the second panel of Figure 2, our data in Figure 1 show the plasma intensity generally decreasing during the one-hour period before the substorm onset at 0330 UT. This is consistent with the plasma sheet thinning from its thick pre-substorm configuration as shown.

Within 20-30 minutes after the expansion phase onset on March 28, ISEE 1 entered the lobe and remained there for nearly two hours even though the auroras were moving to ever higher latitudes. The third panel of Figure 2 represents the configuration that may have prevailed from shortly after 0330 UT to perhaps 0500 UT or later.

The plasma sheet recovered, with high intensity hot plasma about 0600 UT on March 28, about 2.5 hours after onset and about 1.5 hours after AL began to subside from its peak value. (The auroras at the 03 MLT meridian (near the ISEE 1 projection) had reached -75° latitude forty minutes before plasma sheet recovery at ISEE 1.) This long delay after the AL peak can be attributed to the large displacement of ISEE 1 from the neutral sheet. (Pytte *et al.*/6/ reported that the plasma sheet expansion (at $X_{GSM} \approx -18 R_E$) late in a substorm proceeds rapidly at first, attaining a half thickness of $6 R_E$ in about 10-15 minutes. But expansion proceeds very slowly at greater thicknesses. The fourth panel of Figure 2 depicts conditions as the substorm neutral line

retreats down-tail causing the plasma sheet to be re-inflated with hot plasma. To our knowledge no attempt has been made to develop a quantitative model of the magnetosphere that depicts the changing configuration associated with a substorm. Perhaps there is presently no adequate observational data at hand. Repeated correlations of auroral images with magnetotail data may provide the needed information.

(b) The March 28 substorm started at 0330 and we observed (Figure 1) that 20-30 minutes later, as the eastward-extending aurora reached the projected local time of ISEE 1, the plasma sheet disappeared from ISEE 1. Figure 3 shows a possible interpretation of that behavior. The eastward-advancing aurora is a projection of an eastward-extending X-line in the tail earthward of ISEE 1. Magnetic reconnection at the extending X-line causes progressive severing of the plasma sheet, locally releasing elemental closed loops that flow down-tail forming a skewed plasmoid. When the x-line (and the aurora) reached the field lines connecting ISEE 1 to the earth the tailward loss of the newly closed loops caused a dramatic thinning of the plasma sheet tailward of the x-line that left ISEE 1 in the south tail lobe.

(c) The poleward expansion of the aurora in the March 28 substorm was episodic and occurred differently at different local times, typical of the behavior found in other DE 1 substorm image sequences (Craven and Frank/7.8/). The most extensive expansion both in latitude and in longitude was that which occurred between 0424 and 0436 UT and which encompassed a final intensification of the AL disturbance and the beginning of the AL subsidence. This impressive poleward surge of the aurora was accompanied by geomagnetic z-component signatures of a poleward moving current system over a MLT range of six hours or more centered near magnetic local midnight. The evidence is thus that this final and most impressive poleward surge of the auroras was accompanied by a sudden pronounced poleward displacement of the ~2100-0300 MLT sector of the westward electrojet. Such a "poleward leap" of the electrojet was found, by Hones *et al.*/9/, to occur near the time of the plasma sheet's sudden recovery which is a common feature of the late stage of a substorm. In the March 28 substorm there was, indeed a sudden recovery of the plasma sheet but it occurred about 1.5 hours after the apparent poleward leap of the electrojet. But, as we noted, dZ_{SM} of ISEE 1 was $\sim 8 R_E$ and Hones *et al.*/9/ showed that plasma sheet recovery could occur an hour or more after the electrojet's poleward leap at such large values of dZ_{SM} . Our results are

thus not inconsistent with the picture of the poleward leap that has a final large poleward surge of the aurora and of the westward electrojet coinciding closely with a sudden thickening of the plasma sheet beyond 15-20 R_E down tail. This masks the culmination of the substorm's expansive phase and the beginning of its recovery.

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Figure Captions

Fig. 1. Data for a substorm on March 28, 1983

Top panel: The AL index

Auroral Images: DE 1 images of the southern auroral oval as seen in atomic oxygen (OI) 130.4 nm emission. The dawn meridian is toward the upper left of each image and the dusk meridian is toward the lower right. The width of each image is equal to 12 minutes on the horizontal time scale of the figure and each image is centered at the mid-time of its 12-minute accumulation interval.

Middle panels: Fluxes of 2 keV electrons and 6 keV protons measured by the University of California at Berkeley Energetic Particle Detector on ISEE 1. The location of ISEE 1 is given under these panels.

Bottom panel: Latitude of the poleward edge of the aurora at 2100, 0000 and 0300 MLT determined by computer graphics analysis of the DE 1 images. Also shown (by the long-dashed line) is the latitude of the foot point of the field line from ISEE 1 (see text). The MLT of this point is shown every hour.

Fig. 2. Configurations of the plasma sheet that may occur in association with a substorm. Three representative field lines are marked in each panel. The hatched region is the plasma sheet. A satellite is indicated at $X_{GSM} = -20 R_E$, $Z_{GSM} = 4 R_E$.

Fig. 3. Side view and top view of the magnetosphere illustrating the proposed effect of progressive lengthening of the near-earth neutral line after its initial formation at the onset of a substorm expansion phase (see text).

PLASMA SHEET CONFIGURATION CHANGES CAUSED BY SUBSTORMS

Fig. 2

CROSS-TAIL LENGTHENING OF THE NEAR EARTH NEUTRAL LINE DURING SUBSTORMS

Fig. 3