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Simultaneous Observations of the Westward Electrojet and the Cross-Tail Current Sheet During Substorms

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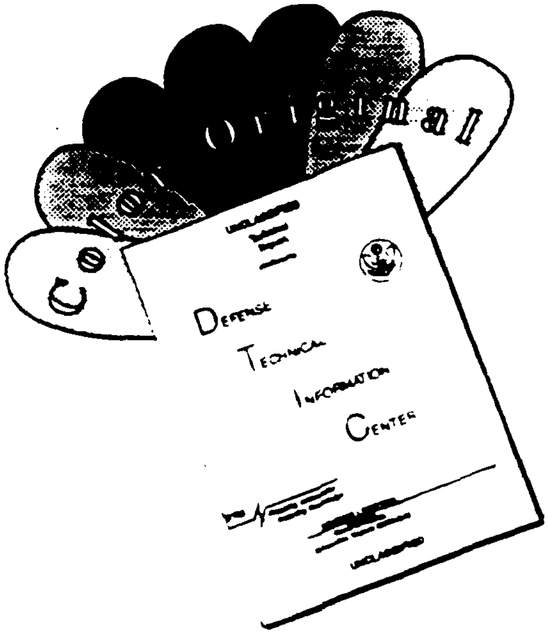

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13. ABSTRACT (*Maximum 200 words*)

In this report we present the results of a study using data from AMPTE/CCE, ground stations, and DMSP F7 during substorms. We have examined 12 events during which CCE was located near the neutral sheet and observed the disruption of the cross-tail current. During these events there were simultaneous ground magnetic field data near to the CCE local time sector. DMSP F7 crossed the nightside auroral oval within 40 minutes of substorm onset at CCE during five of the events. We find that the data are consisent with a near-Earth substorm initiation. We also find that the Tsyganenko (1987) magnetic field model requires an additional tail-like stress during substorms, which corresponds to an equatorward displacement of auroral zone field lines. Assuming that the center of the electrojet is drawn from the near-Earth region, the magnitude of this displacement is about 1° to 2°.

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Simultaneous Observations of the Westward Electrojet and the Cross-Tail Current Sheet During Substorms

R.E. Lopez,[1] H. Spence,[2] and C.-I. Meng[3]

In this paper we present the results of a study using data from AMPTE/CCE, ground stations, and DMSP F7 during substorms. We have examined 12 events during which CCE was located near the neutral sheet and observed the disruption of the cross-tail current. During these events there were simultaneous ground magnetic field data near to the CCE local time sector. DMSP F7 crossed the nightside auroral oval within 40 minutes of substorm onset at CCE during five of the events. We find that the data are consistent with a near-Earth substorm initiation. We also find that the Tsyganenko [1987] magnetic field model requires an additional tail-like stress during substorms, which corresponds to an equatorward displacement of auroral zone field lines. Assuming that the center of the electrojet is drawn from the near-Earth region, the magnitude of this displacement is about 1° to 2°.

1.0 INTRODUCTION

One of the most important signatures of a magnetospheric substorm is the reconfiguration of the magnetotail magnetic field towards a more dipolar orientation [*McPherron et al.*, 1973], which is known as a dipolarization. The dipolarization of the magnetic field is due to the reduction of a portion of the cross-tail current [*Lui*, 1978; *Kaufmann*, 1987]. That reduction has been interpreted in terms of the formation of a substorm current wedge [e.g., *McPherron et al.*, 1973] which diverts a portion of the current into the ionosphere via field-aligned currents (FACs), thereby reducing the equatorial current within a longitudinally limited sector. The sector encompassed by the current wedge expands longitudinally with time [e.g., *Nagai*, 1982]. The current wedge closes in the ionosphere through an enhanced westward electrojet, which terminates in a structure known as the westward travelling surge (WTS) [*Baumjohann et al.*, 1981; *Lühr and Buchert*, 1988].

The origin of the FACs which feed the substorm current wedge, and thus the westward electrojet and the WTS, is an important question which bears on the basic nature of substorms. The boundary layer model [e.g., *Rostoker and Eastman*, 1987] explicitly addresses this issue. That model postulates that the WTS is composed of FACs flowing through the plasma sheet boundary layer at the boundary between the lobe and the plasma sheet, which implies that the FACs map to the distant tail. On the other hand, models such as the near-Earth neutral line model [e.g., *McPherron et al.*, 1973] and the current disruption model [e.g., *Akasofu*, 1972] suggest that the FACs which constitute the current wedge have a relatively near-Earth origin.

The near-Earth ($\leq 10\ R_E$) region of the magnetotail beyond geosynchronous orbit has been extensively explored by the AMPTE/CCE satellite. Among other results, it has been found that the phenomenological features of the dipolarization, and the associated injection of energetic particles, depend critically upon the position of the observing satellite relative to the neutral sheet [*Lopez et al.*, 1988*a*; 1989]. A satellite near the neutral sheet will observe an increase in the total field magnitude, whereas a satellite far from the neutral sheet will observed a decrease in the field magnitude [*Lopez et al.*, 1988*a*]. Several cases have been published in which CCE was very close to the neutral sheet during substorms [*Takahashi et al.*, 1987; *Lui et al.*, 1988; *Lopez et al.*, 1989; 1990*a*]. In those events CCE observed dramatic magnetic field and energetic particle variations during what has been termed current sheet disruption, and during one of these events the current sheet disruption was apparently linked to a WTS observed on the ground [*Lopez et al.*, 1990*a*].

The observation of current sheet disruption in the near-Earth magnetotail, along with multisatellite studies [*Lopez et al.*, 1988*b*; 1990*b*; *Lopez and Lui*, 1990; *Ohtani et al.*, 1988], extensive analysis of the geosynchronous energetic particle data [e.g., *Baker et al.*, 1984; *Baker and McPherron*, 1990], a thorough review of auroral morphology [*Feldstein and Galperin*, 1985], modeling studies [e.g., *Kaufmann*, 1987], and the fact that the most equatorward discrete arc is the one that brightens at the onset of the substorm [*Akasofu*, 1964] provide considerable support for a near-Earth

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substorm initiation region. If this is the case, in the early phase of a substorm the westward electrojet must be linked exclusively to the near-Earth magnetotail. We have examined a number of events during which simultaneous observations of the westward electrojet (made by ground stations) and of the near-Earth cross-tail current near the neutral sheet (made by CCE) were available. The ionospheric footpoints of the field lines threading CCE were calculated using the Tsyganenko [1987] field model. During some of the events data from the low-altitude DMSP F7 satellite were available and these have allowed us to place those events in a broader global context. We find that the observations are consistent with the near-Earth initiation of substorms, and that during substorm periods the Tsyganenko [1987] model requires an additional tail-like stress corresponding to an equatorward displacement of auroral zone field lines in the ionosphere of about 1° to 2° in magnetic latitude, assuming that the center of the the substorm electrojet is fed by currents drawn from the near-Earth magnetotail.

2.0 Data

The data to be presented consist of magnetic field measurements from AMPTE/CCE, ground magnetograms from a variety of stations, and precipitating particle data from DMSP F7. CCE is in an equatorial, elliptical orbit with apogee at ~ 8.8 R_E. The magnetic field experiment is described in detail by Potemra et al. [1984]. Ground magnetometer data from Tixie Bay, College, Leirvogur, Syowa, Abisko, and the stations of the EISCAT magnetometer cross were used during this study; those data generally have a time resolution of 1 minute. DMSP F7 is a sun-synchronous polar-orbiting satellite with an altitude of about 840 km, a period of 101.5 minutes, and an orbital plane approximately along the 1035–2235 local time meridian. A more detailed description of the DMSP spacecraft and the instrumentation may be found in Hardy et al. [1984] and Gussenhoven et al. [1985].

The CCE magnetometer data were examined to find substorms that occurred when CCE was not too far from the neutral sheet. Some of these are current sheet disruptions that have been described in detail in previous studies [*Takahashi et al.*, 1987; *Lui et al.*, 1988; *Lopez et al.*, 1989; 1990*a*]. Others are events that occurred when CCE was relatively close to the neutral sheet, but not within the main distribution of the cross-tail current. They resemble the transitional event discussed by Lopez et al. [1989]. Twelve events were selected due to the relatively close longitudinal proximity of an auroral zone ground station, or set of stations. For each event we have calculated the ionospheric footpoints at 100 km altitude of the field line threading CCE using the model of Tsyganenko [1987]. The truncated version of the model was used with the growth phase Kp value, and all ground coordinates are given in PACE corrected geomagnetic coordinate system [*Baker and Wing*, 1989]. Software to implement this coordinate system is available from K. Baker, who may be contacted at APLSP::BAKER. In the following section two events will be discussed in some detail, and an overview of the remaining 10 events will be presented.

3.0 Observations

The first event to be discussed occurred on 7 June 1985, at 2209 UT. This event is notable for its excellent magnetometer coverage and the unusually close longitudinal conjunction between CCE and the ground stations. However, DMSP F7 data are not available for this event. CCE was located at a radial distance of 8.1 R_E, a magnetic local time of 0038 MLT, and a magnetic latitude of –6.4°. Given that K_p was 2, the estimated position of the neutral sheet was 0.2 R_E north of CCE [*Lopez*, 1990]. This "neutral sheet" position, which is to say the point at which the V component is expected to reverse sign, is 0.3 R_E north of the minimum magnetic field value along the field line threading CCE in the Tsyganenko [1987] model. The model ionospheric footpoint at 100 km of the CCE field line was 66.6° N, 105.9° E in PACE coordinates.

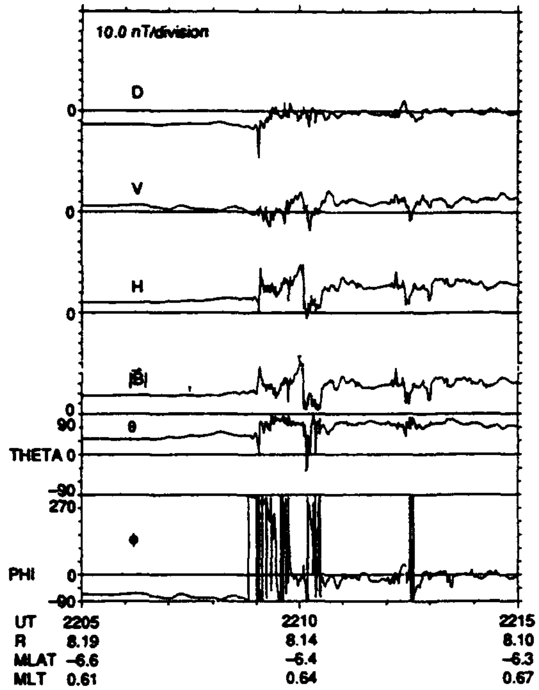

Fig. 1. CCE magnetometer data for 7 June 1985. The data are 0.125s samples and are in VDH coordinates. The onset began at ~ 2209 UT.

The magnetic field data for the event are presented in Figure 1. These data are 0.125s samples and are in VDH coordinates, where V is positive radially outward, H is positive northward along the dipole axis, and D is positive eastward. The V component of the magnetic field was positive, confirming that CCE was south of the neutral sheet. The onset of the event occurred at 2209 *UT*, when dramatic variations in the magnetic field began. At this time the flux of energetic particles (not shown) dramatically increased. These signatures are typical of substorms observed by CCE when the satellite was near the neutral sheet [*Lopez et al.*, 1989]. Also, at 2212:30 UT, there was a brief intensification of activity in both the magnetic field and energetic particles. The particle data indicate that the source of the energetic ions at that time was tailward of CCE, suggesting that the activity moved tailward. A similar phenomena was reported by Lopez et al. [1989] during another current disruption event.

Magnetometer data from the EISCAT magnetometer cross (provided courtesy of H. Koskinen and T. Pulkkinen) are presented in Figures 2 and 3, which show the X (positive northward) and Z (positive downward) components, respectively. The vertical order of the stations reflects their respective latitudes (although some stations such as KIL and KAU are almost at the same latitude—their separation is mainly longitudinal). Those data show that the substorm-associated magnetic deflections began at 2209 UT, in excellent agreement with the onset at CCE. On closer inspection, there was also an intensification of activity at 2213 UT, again in accord with the CCE observations. At the 2209 UT onset of activity, KAU and stations poleward of it observed positive Z perturbations, MUO observed essentially no Z variation, and PEL recorded a negative Z deflection. The sign of the Z perturbation allows one to determine the latitudinal position of the center of the westward electrojet relative to the observing station [e.g., *Samson and Rostoker*, 1983]. Therefore we infer that at the onset of the activity the westward electrojet was centered directly over MUO, at 64.7° N, 106.6° E. These coordinates assume that the electrojet was at an altitude of 100 km, the altitude of the field line footpoints, and this same altitude will be used in calculating all ground coordinates. The stations PEL and KAU are 1° equatorward and poleward, respectively, of MUO, and the Z perturbations indicate that the electrojet was poleward and equatorward, respectively, of those stations. Thus in this case it is possible to localize the latitudinal position of the center of the electrojet with a precision of ~ 1°.

We may also use the ground data to determine the poleward boundary of the westward electrojet. At 2212 UT, positive Z perturbations of roughly equal magnitude were observed at KIL and KAU. Since these were also the largest such perturbations, we infer that the poleward boundary of the westward electrojet at that time was located roughly at 65.7° latitude, midway between KIL and KAU. On the other hand, the negative Z perturbation at PEL was roughly half the value of the positive ones at KIL and KAU, so, assuming a uniform electrojet, the equatorward boundary of the westward electrojet was equatorward of PEL (63.3°, which maps to 6 R_E in the tail). As stated above there was an intensification of activity at 2213 UT, which resulted in an decrease in the Z component at PEL, a very slight decrease in Z at MUO, and an increase in Z at stations poleward of MUO. This suggests that the poleward boundary of the electrojet moved significantly poleward, but that the center of the electrojet moved only slightly poleward. Such a poleward motion would be consistent with the tailward motion of the current disruption region inferred from the CCE data. Later, at 2230 UT, the center of the electrojet moved poleward of MUO to a position equatorward of KIL.

The second event occurred on 28 August 1986 at 1153 UT, and it has been previously examined by Takahashi et al. [1987]. It is one of the most dramatic examples of the turbulent disruption of the current sheet. This event does not have as good a conjunction between the magnetometers and CCE as the previous one, however, DMSP F7 was superbly placed to provide critical information about auroral precipitation morphology. CCE was at a radial distance of 8.1 R_E, a magnetic local time of 2326 MLT, a magnetic latitude of −2.3°, and K_p was 2. The empirical neutral sheet model of Lopez [1990] places CCE precisely at the neutral sheet, while

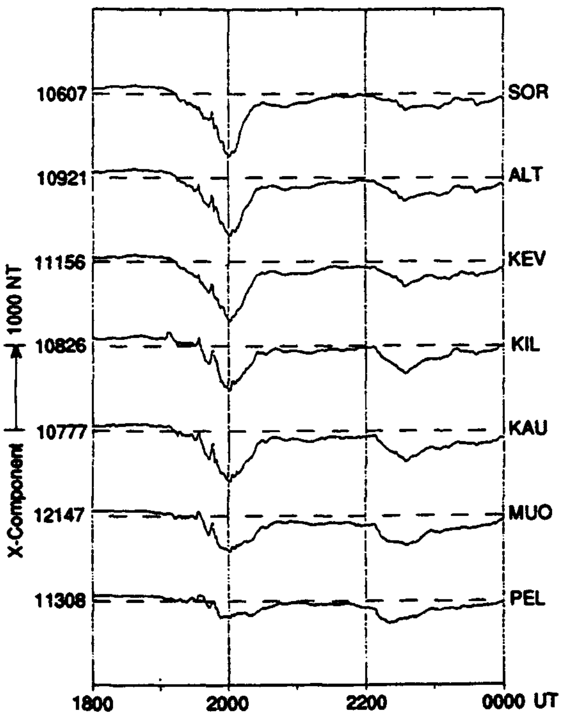

Fig. 2. H component (positive northward) magnetometer data from the EISCAT magnetometer chain on 7 June 1985. The negative bay indicating an increase in the westward electrojet began at 2209 UT.

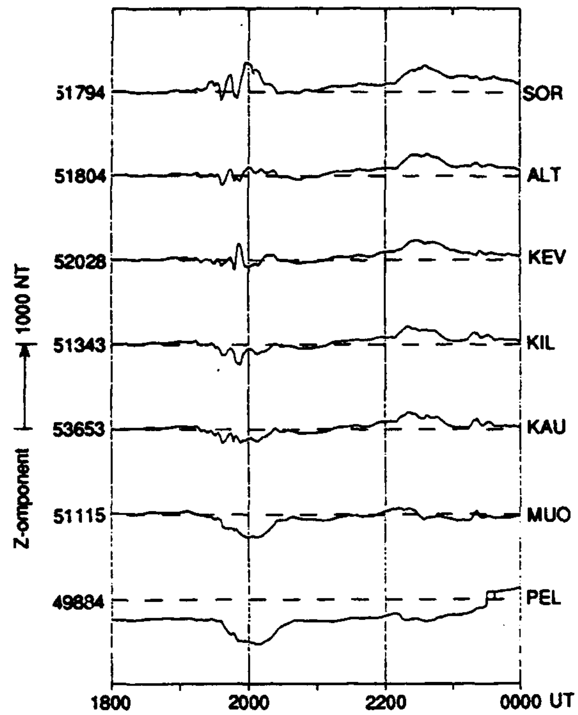

Fig. 3. Z component (positive downward) magnetometer data from the EISCAT magnetometer chain on 7 June 1985. Perturbations associated with the increase in the westward electrojet began at 2209 UT.

the minimum magnetic field magnitude along the Tsyganenko [1987] field line threading CCE was located 0.3 R_E north of the satellite. The ionospheric foot of that field line was located at 66.7° N, 116.9° W. The CCE magnetic field data are presented in Figure 4; the difference in the time axis between this figure and that in Takahashi et al. [1987] is due to a 20s offset in (all) the CCE data that has been corrected in this figure. The V component was negative indicating that CCE was slightly above the neutral sheet, in contrast to the neutral sheet model prediction. The field magnitude was ~ 8 nT; this is a typical value when CCE is very close to the neutral sheet during the late growth phase. The onset of activity occurred just before 1153 UT, and there was an intensification of activity just before 1200 UT.

Magnetic field data from the ground station at College (65.3° N, 98.4° W) are presented in Figure 5. College was 1.2 hours east of the CCE footpoint, which adds some uncertainty to the determination of the latitudinal position of the westward electrojet at the CCE local time meridian. At 1153 UT, College observed a slowly growing westward electrojet equatorward of the station that was probably associated with the substorm, but there was no signature in the D component. A much more rapid development of the electrojet, this time accompanied by a D perturbation, occurred just after 1200 UT, several minutes after the 1153 UT onset at CCE. We consider this later development to be the expansion of the substorm current wedge into the College sector. The seven minute delay may be a local time effect since on average it takes ~ 7 minutes for the edge of a substorm current wedge to expand one hour of local time [*Lopez et al.*, 1988*b*]. Also, it may be that the 1200 UT intensification at CCE was responsible for the 1200 UT electrojet enhancement recorded at College, and that the expansion of the longitudinal sector affected by the substorm expanded in discrete steps as discussed by Wiens and Rostoker [1975].

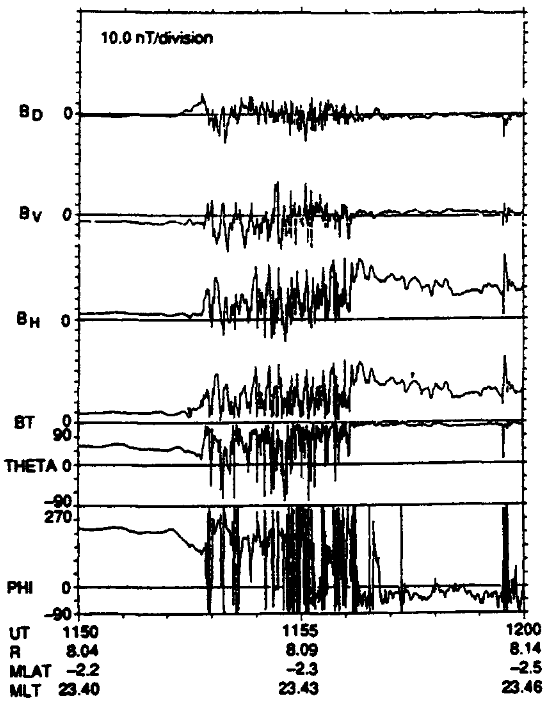

Fig. 4. CCE magnetometer data for 28 August 1986. The data are 0.125s samples and are in VDH coordinates. The onset began at ~ 1153 UT.

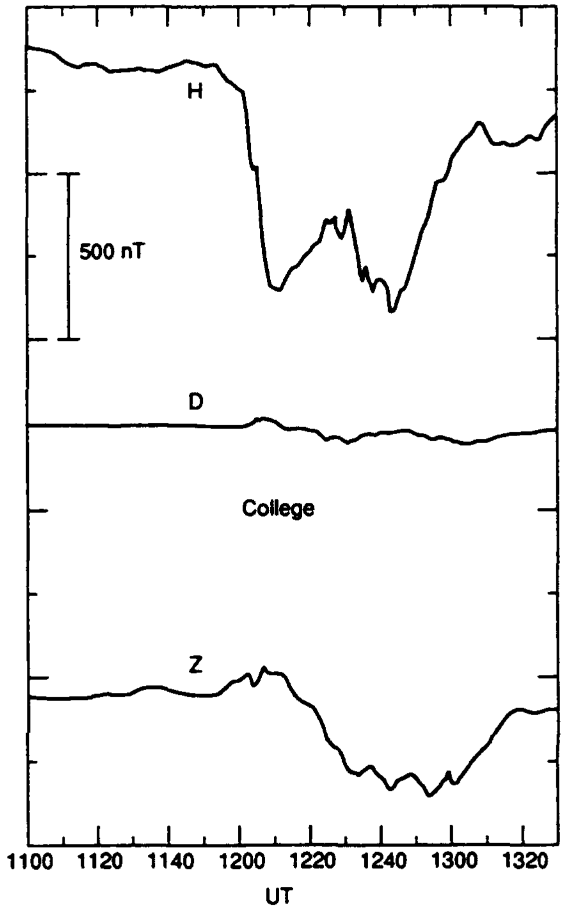

Fig. 5. Ground magnetogram from College on 28 August 1986. The onset began shortly after 1200 UT.

Since CCE did not move very much from 1153 UT to 1200 UT, the model ionospheric footpoint is essentially the same in both cases. The real footpoints were almost certainly different since there had been a measurable change in the field between 1153 UT and 1200 UT. At the onset of the sharp H decrease, the Z component exhibited small negative and positive perturbations. This suggests that the electrojet center oscillated slightly over the station, or that several small, variable electrojets formed in close latitudinal proximity. Therefore we conclude that at the onset of the event the electrojet center was located at ~ 65.3° N in the College sector, and at ~ 1215 UT the electrojet center moved poleward of College. Just after the 1153 UT onset at CCE, DMSP F7 passed over auroral zone 1.2 hours west of the CCE footpoint. The particle data from this pass are presented in Figure 6. Electrons and ions from 30 eV to 30 keV are plotted with the lowest energies at the center of the plot. The geomagnetic coordinates on the plot are in the PACE coordinate system. The equatorward edge of the auroral zone is an

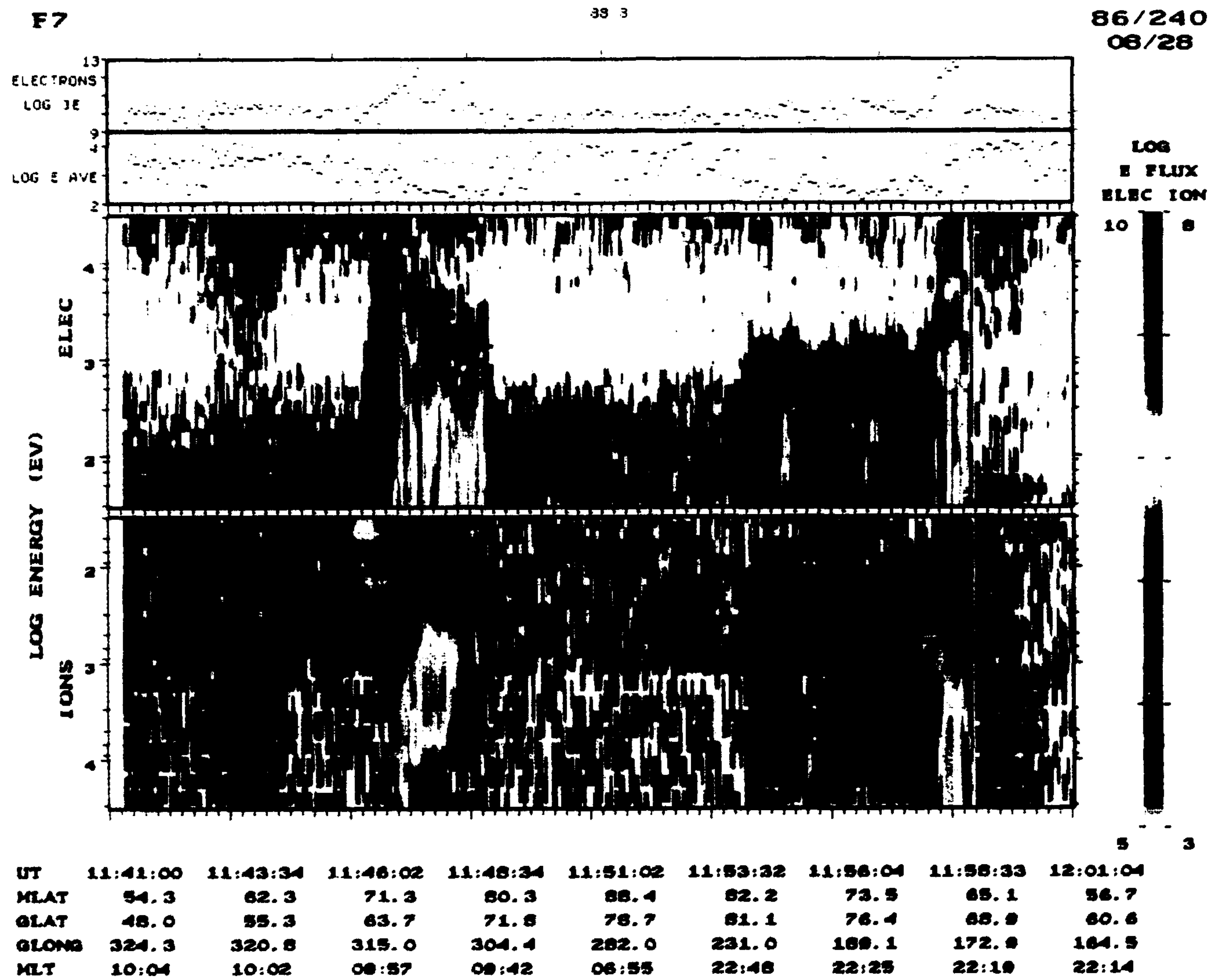

Fig. 6. Precipitating particle data DMSP F7 on 28 August 1986. DMSP F7 passed over the polar cap just ~ 1 hour to the west of CCE in close temporal proximity to the onset of the event. At 1154 UT it encountered the boundary between the lobe and the plasma sheet at a latitude of 80°. Continuing equatorward, the satellite reached the poleward edge of a bright arc at 1158 UT. The arc was located at ~ 66°, and we associate it with the substorm westward electrojet.

example of the low altitude signature of the dispersionless substorm injection boundary discussed by Newell and Meng [1987]. Poleward of the injection boundary a bright discrete feature was observed. It was composed of a monoenergetic (~ 4 keV) electron region, with a lower energy feature at the poleward boundary. The latitude of the poleward edge of the monoenergetic electron part was 65.5°, and the entire discrete arc extended to a latitude of 66.2°. It is important to note that poleward of the arc there was a region filled with weak discrete features, and that the boundary between the lobe and the plasma sheet was located at a geomagnetic latitude of 80° just 11.2° west of the CCE footpoint.

The DMSP F7 image data (not shown) indicates that the bright arc seen in the particle data was associated with the substorm. The event took place in late August and DMSP F7 was in the northern hemisphere; this is not the best situation for auroral photography. However, DMSP F7 crossed the arc before it crossed the terminator, and a limited region just to the east and west of the flight path is visible. The point at which the arc was crossed was the westernmost extension of a bright region which had expanded poleward just to the east of DMSP F7, while to the west the arc was narrow, and it faded out. The satellite apparently crossed the most equatorward discrete arc just as it started to brighten as the substorm was expanding into that sector. Assuming that the poleward edge of the bright arc is near the center of the the auroral electrojet [e.g., *Samsom and Rostoker*, 1983], we find that one hour to the west of CCE the electrojet was centered at ~ 66°, and one hour to the east it was centered at ~ 65.3°. From this information we estimate that the latitude of the electrojet center in the CCE sector was ~ 65.7°.

The remaining ten events have been analyzed in a similar fashion as those discussed above. The results of this investigation are presented in Table 1. Each event, including those discussed above, is listed by the time (within 5 minutes) and date of occurrence. The second column gives the radius (in R_E) and the magnetic local time (in SM coordinates) of CCE at the time indicated for each event. The third column lists the ionospheric footpoints of the field line threading CCE. Northern and southern footpoints are given for those events for which data from both auroral zones were available. The center positions of the westward electrojets were determined exclusively from the ground magnetometer data, with the exception of the 28 August 1986 event (discussed above), and southern electrojet on 7 May 1985. That position was determined from the poleward boundary of a discrete arc (the only one) observed by DMSP F7. Since it was almost certain that this arc was the one that brightened, its position may be used as an indicator of the electrojet position. The arc was observed 20 minutes before the onset of the substorm. During the growth phase discrete arcs drift equatorward [e.g., *Tanskanen et al.*, 1987]. Therefore the position of the arc 20 minutes before the breakup provides us with the maximum possible latitude for the center of the substorm electrojet. The boundary between the plasma sheet and lobe was determined from DMSP F7 particle data. The position of the boundary (magnetic latitude and longitude), and the time at which the boundary was crossed are listed. This position is listed only for those events when F7 reached the boundary within 40 minutes of the onset, which limits us to five out of the twelve events. The final column is labeled "Shift." It will be discussed in the next section when we examine the implications of these results.

4.0 Discussion

The results presented in Table 1 are completely consistent with the near-Earth substorm initiation scenario. The electrojet positions found in this study are also consistent with the results of Craven and Frank [1987], who found that during substorms auroral brightening begins at ~ 66°, then expands poleward. Moreover, the neutral sheet at R ~ 8 to 9 R_E consistently maps to the equatorward edge of the auroral zone, which is additional evidence that the near-Earth region surveyed in detail by CCE is indeed the region of substorm initiation. In those cases where the center of the electrojet is well-placed, that latitudinal position was always equatorward of the CCE footpoint, and there is no case were the center of the electrojet was observed to be initially poleward of the CCE footpoint. Moreover, in the case of the 28 August 1986 event, it is obvious that the most equatorward portion of the auroral oval brightened first.

The available evidence argues strongly against the boundary layer model [e.g., *Rostoker and Eastman*, 1987]. Again, the 28 August 1986 case is unambiguous. The brightening arc and the center of the substorm westward electrojet were located 14°

Table 1: CCE Footprints Relative to Electrojet Centers

Event	R[1], MLT[2]	CCE Footprint[3]	Electrojet Center	Plasma Sheet-Lobe Boundary	Shift
7 May 1985, 1105 UT	8.7, 0039	67.6 N, 81.7 W 67.8 S, 83.1 W	> 65.3 N, 98.4 W < 67.0 S, 93.5 W	68.9 S, 93.7 W, 1044 UT	< 2.3 > 0.8
17 May 1985, 2350 UT	8.7, 0111	66.8 N, 90.4 E 67.6 S, 90.2 E	< 65.2 N, 103.2 E > 66.8 S, 72.8 E		> 1.6 < 1.2
1 June 1985, 2120 UT	8.6, 2340	66.9 N, 100.1 E	65.7 N, 107.1 E		~ 1.2
1 June 1985, 2315 UT	8.8, 0016	67.9 S, 83.4 E	> 66.8 S, 72.8 E		< 1.1
3 June 1985, 2240 UT	8.8, 0010	67.4 N, 91.8 E 68.2 S, 92.8 E	65.2 N, 103.2 E > 66.8 S, 72.8 E		~ 2.2 < 1.4
7 June 1985, 2210 UT	8.1, 0039	66.6 N, 105.9 E	64.7 N, 106.6 E		~ 1.9
20 June 1985, 2310 UT	8.2, 2355	66.3 N, 78.3 E 67.5 S, 79.7 E	< 65.3 N, 69.1 E > 66.8 S, 72.8 E		> 1.0 < 0.7
9 August 1986, 1450 UT	8.5, 0040	66.9 N, 137.0 W	> 65.2 N, 164.2 W	73.2 N, 77.5 W, 1500 UT	< 1.7
24 August 1986, 1345 UT	8.0, 2332	66.5 N, 142.0 W	> 65.2 N, 164.2 W	68.1 N, 90.8 W, 1319 UT	< 1.3
28 August 1986, 1155 UT	8.1, 2325	66.7 N, 116.9 W	~ 65.7 N, 116.0 W	80 N, 125.6 W, 1154 UT	~ 1.0
29 August 1986, 2050 UT	8.7, 0012	67.0 N, 120.3 E	> 65.2 N, 103.2 E		< 1.8
30 August 1986, 1220 UT	8.7, 2351	67.1 N, 115.5 W	> 65.3 N, 98.4 W	73.7 N, 88.5 W, 1256 UT	< 1.8

[1] CCE position in R_E
[2] SM local time
[3] All latitudes and longitudes in PACE geomagnetic coordinates

equatorward of the boundary between the lobe and the plasma sheet. The same is true for the 7 May 1985 case, when the presumed electrojet center was 1.9° equatorward of the boundary. Since the westward electrojet terminates in the surge head and the westward electrojet center is located near the poleward edge of the surge [e.g., *Baumjohann et al.* 1981; *Samson and Rostoker*, 1983], our results are consistent with the proposition that the surge is connected to the near-Earth tail, at least in the initial phase of a substorm [e.g., *Lopez et al.*, 1990a].

The other major result of this study concerns the stretching of the field during the growth phase of a substorm. As the cross-tail current intensifies, the field becomes more tail-like. This corresponds to an equatorward shift in the ionospheric footpoint of a field line that maps to a fixed equatorial crossing point in the tail. An important question is the magnitude of that shift. If we assume that the electrojet current is being drawn primarily from the near-Earth tail, then the observed difference between the electrojet center and the mapped footpoint can provide an indication of that shift. This difference is listed in the final column of Table 1. On the other hand, if the poleward boundary of the westward electrojet corresponds to the disruption region, then the inferred shift could be considerable smaller. For example, for the 7 June 1985 event, we were able to determine that the poleward boundary of the electrojet was at ~ 65.7°. The CCE footpoint was at 66.6°, which implies a shift of only 0.9°. The other event for which we have good latitudinal magnetogram coverage occurred on 1 June 1985 at 2120 UT. In that case the poleward boundary was at least at 67.2° (the position of the most poleward station), so that the disruption region could map to the poleward portion of the westward electrojet without any modification of the magnetic field model.

Since we do not have adequate ground coverage to determine the full latitudinal extent of the electrojet in every case, we shall simply assume that the near-Earth region connects to the center of the electrojet during the disruptions. This gives an equatorward displacement of auroral field lines in general between 1° and 2°, although we recognize that this is probably an upper limit. Another point of interest is that the latitudinal position of the electrojet varies whether one considers the northern or southern hemispheres. Part of this difference may be due to the seasonal dependence of conjugacy, as discussed by Wu et al. [1991]. However, in some cases it could be a local time effect since the electrojet moves poleward during substorms and different longitudes will have experienced varying degrees of poleward expansion.

5.0 CONCLUSION

We have examined a dozen substorm events during which CCE was located near to, or within, the cross-tail current, and for which there are auroral zone magnetometer data from a nearby local time sector. DMSP F7 observations of the polar cap are available for five of the events. We find that the observations are consistent with a near-Earth substorm initiation region, and inconsistent with the model of Rostoker and Eastman [1987]. Furthermore we find that additional tail-like stress is required in the Tsyganenko [1987] model during substorms. The magnitude of the stress is such to produce an equatorward displacement of auroral zone field lines from 1° to 2° in latitude, assuming that the near-Earth region provides the bulk of the current for the westward electrojet.

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