

DISRUPTION OF THE MAGNETOTAIL CURRENT SHEET OBSERVED BY AMPTE/CCE

K. Takahashi,¹ L. J. Zanetti,¹ R. E. Lopez,^{1,2}
R. W. McEntire,¹ T. A. Potemra,¹ and K. Yumoto³¹The Johns Hopkins University Applied Physics Laboratory²Applied Research Corporation³Onagawa Magnetic Observatory, Tohoku University

Abstract. The Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer (AMPTE/CCE), with a small inclination of 4.8° and an apogee of $\sim 8.8 R_E$, is capable of exploring the dynamical behavior of the near-earth magnetotail current sheet during substorms. At ~ 1153 UT on day 240 (August 28), 1986, the spacecraft was on the midplane of the magnetotail near midnight (~ 23.4 h LT) at a radial distance of $\sim 8 R_E$, when the onset of a substorm took place. The magnetic field data for the ~ 3.5 -min interval following the onset indicated a variation of the magnetic field that has not been observed by geostationary satellites or by other spacecraft flown in the near-earth tail ($r \lesssim 20 R_E$). The variation was characterized by a large-amplitude (from less than 10 nT to greater than 40 nT) oscillation of the total field with a period of ~ 13 s and also by southward turning of the field during most cycles of the oscillation. At times the magnetic field became strongly southward, and in a few measurements the magnitude of the southward component exceeded 20 nT. The level of high-frequency perturbations (periods shorter than ~ 10 s) was also enhanced during the event. The observations may be due to the formation of an X-type neutral line and its motion near the spacecraft.

Introduction

The near-earth part of the magnetotail is a region of great importance in the study of magnetospheric substorms. At $r \sim 10 R_E$, the structure of the magnetic field is observed to change abruptly from tail-like to dipole-like at the onset (of the expansion phase) of a substorm [McPherron, 1972], where r is the geocentric distance along the sun-earth line. A similar "dipolarization" phenomenon has been repeatedly observed at geostationary orbit [e.g., Cummings et al., 1968]. In terms of currents in space, these observations have been described as the following. Prior to the onset of a substorm, the inner edge of the cross-tail current sheet moves closer to the earth and the current density increases. At the onset, the near-earth, near-midnight portion of the cross-

tail current is disrupted and short circuited through the ionosphere via field-aligned currents [McPherron et al., 1973; Nagai, 1982].

A possible mechanism to initiate the current disruption is an instability of the current sheet and the subsequent formation of an X-type neutral line. Although the microscopic process leading to this reconnection process is still under theoretical study [e.g., Coroniti, 1985], phenomenological models that incorporate the neutral line have been proposed to organize the observed configurational changes in the tail during substorms [Russell and McPherron, 1973; Nishida and Nagayama, 1973; Hoffman and Burch, 1973; Hones et al., 1973]. To date no in-situ observation of the neutral line has been made, perhaps owing to small amounts of time spent by satellites in the region between $r \sim 7 R_E$ and $r \sim 20 R_E$, where the reconnection is expected to occur [Nishida, 1984].

With the launch of CCE, we now have the capability of studying the near-earth tail ($r \lesssim 8.8 R_E$) in great detail with regard to substorms. On August 28 (day 240), 1986, CCE observed the onset of a substorm virtually on the tail midplane near the midnight meridian at a radial distance of $\sim 8 R_E$. Together with a typical dipolarization of the magnetic field and an increase in the flux of medium-energy ions, the spacecraft observed an unusual magnetic oscillation characterized by ~ 13 -s periodicity and southward turnings of the field. It appears that the spacecraft made an in-situ observation of the disruption of the current sheet.

Observation

Figure 1 gives an overview of a 2-h interval surrounding the event of interest. The top six panels show the magnetic field observed at CCE. The data are averaged over 6.2-s intervals and are presented in the local dipole V_{DH} coordinate system in which \hat{e}_H (north) is antiparallel to the geomagnetic dipole, \hat{e}_D (east) is perpendicular to the dipole meridian of the spacecraft, and $\hat{e}_V = \hat{e}_D \times \hat{e}_H$. B_T is the magnitude of the field. The polar angles are defined as $\theta \equiv \sin^{-1}(B_H/B_T)$ and $\phi \equiv \tan^{-1}(B_D/B_V)$. With the removal of the spacecraft field [Fairfield et al., 1987], the magnetic field measurements are expected to have an accuracy of ~ 0.1 nT. The seventh panel shows the flux of medium-energy ions observed at CCE. The data are averaged over four detector spins (~ 24 s). The bottom panel shows the band-pass-filtered horizontal component of the magnetic field observed on the ground at Kakioka ($L = 1.25$).

The most obvious change in the field and ion fluxes at CCE occurred at ~ 1153 UT. Prior to 1153 UT, the magnetic field had a small magnitude ($B_T \sim 10$ nT) and a

¹The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland 20707.²Applied Research Corporation, 8201 Corporate Drive, Suite 920, Landover, Maryland 20785.³Onagawa Magnetic Observatory and Geophysical Institute, Tohoku University, Sendai, Japan.

Copyright 1987 by the American Geophysical Union.

Paper number 7L6633.

0094-8276/87/007L-6633\$03.00

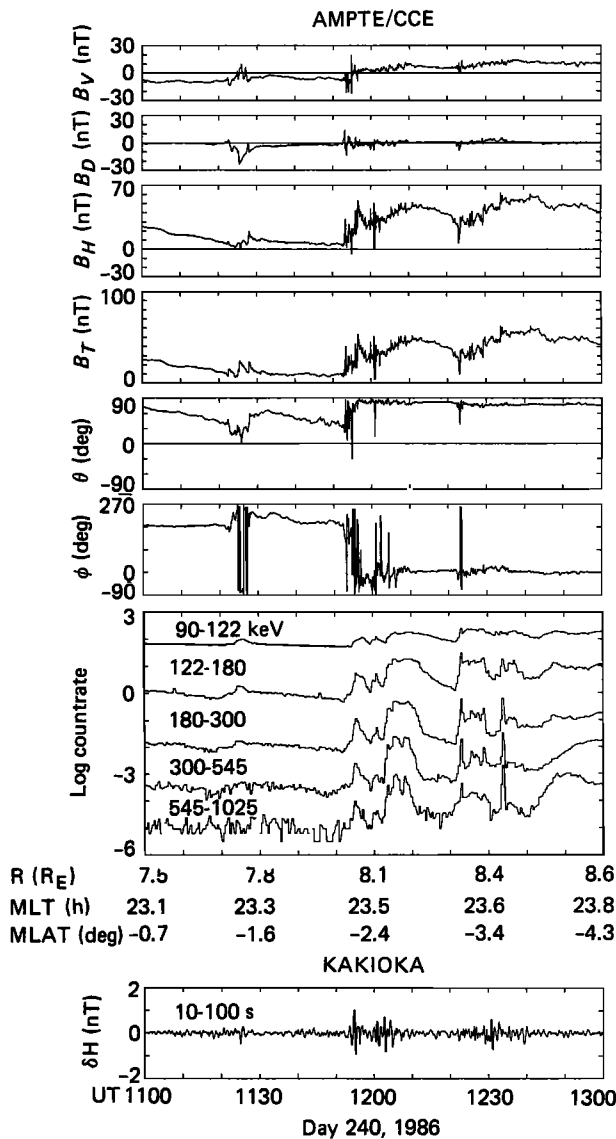


Fig. 1. Magnetic field and ion flux observed at AMPTE/CCE and bandpass-filtered ground magnetogram from Kakioka. The base line for the ion flux is offset by one order of magnitude from one energy channel to another. R is the geocentric distance of the satellite, LT is the magnetic local time, and MLAT is the dipole latitude.

stretched configuration as indicated by $\theta < 45^\circ$. After 1153 UT, B_T began to increase, and θ became close to 90° as is expected for a dipole field at the CCE location. In other words, disruption of the cross-tail current occurred at ~ 1153 UT. The intensity of ion flux also began to rise at ~ 1153 UT.

Thus, with the time resolution of Figure 1, it appears that the 1153 UT event is just a good example of dipolarization and ion injection associated with the onset of a substorm as often observed at or near geostationary orbit. The onset is evidenced by the Kakioka magnetogram that shows that Pi2 activity started at 1154 (± 1 min) UT (~ 2110 LT at Kakioka). Also, a geostationary satellite located at ~ 0130 LT detected an enhancement of energetic electron (30 to 95 keV)

fluxes at ~ 1153 UT, a signature of substorm onset (D. N. Baker, personal communication).

At this point we should emphasize that CCE was very near the tail current sheet at 1153 UT. To quantitatively estimate the satellite separation from the current sheet, we used an empirical formula derived by Fairfield et al. [1987] that has an explicit dependence on the dipole tilt angle. According to the formula, the current sheet at 1153 UT was located only $0.15 R_E$ above CCE. In addition, the sign change of B_V from negative before 1153 UT to positive after 1156 UT is consistent with our view that the 1153 UT event was observed essentially at the current sheet.

A 5-min interval of the magnetic field variation around 1153 UT is illustrated in Figure 2 using data with the highest time resolution (0.124 s). We now see a quasiperiodic oscillation characterizing the ~ 3.5 -min interval starting at 1153:00 UT. The oscillation seems to be most regular for B_H and B_T , with the dominant period of ~ 13 s. Between 1154:30 and 1156:30 UT, additional high-frequency oscillations (periods less than 10 s) are present in all components. The amplitude of the 13-s oscillation is quite large: B_T changes from less than 10 nT to greater than 40 nT. The minimum and maximum values for B_T in the interval of Figure 2 are, respectively, 0.9 nT (1156:07 UT) and 59.9 nT (1156:19 UT). The latter is almost exactly the value (59 nT) for the local dipole field.

The most striking feature of the oscillation is that the magnetic field becomes southward. This occurred roughly 20 times in the 3.5-min interval. The detail of the southward turning is illustrated in Figure 3 using an expanded time scale. Now we can see that the duration of the southward field is 1 to 3 s and that the magnitude of the southward component of-

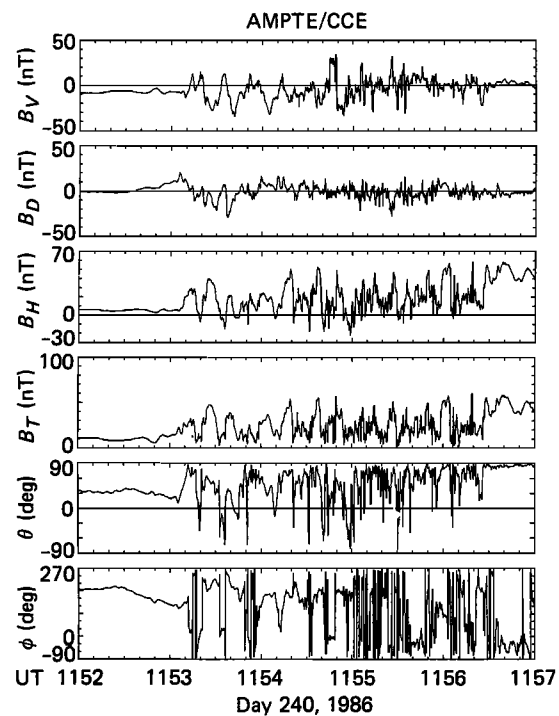


Fig. 2. High-time-resolution (0.124 s) magnetic field data from CCE indicating a highly variable field at the beginning of the geomagnetic activity.

ten exceeds 10 nT. At 1154:58 UT, we recorded the largest southward component $B_H = -22.1$ nT ($\theta = -74^\circ$). The data point following this (0.124 s apart) had the largest southward inclination $\theta = -81^\circ$ ($B_H = -20.2$ nT).

High time resolution (~ 6 s) ion data (>90 keV) show a factor of ~ 10 increase in ion flux starting at ~ 1153 UT and reaching a peak at ~ 1155 UT. The count rate of one of the microchannel plates of the particle analyzer, which is a measure of lower energy (~ 10 keV) ion flux, is also observed to increase a similar amount after ~ 1153 UT. These particle observations suggest that the magnetic field variation is accompanied by a strong electric field that energizes the particles.

Discussion

The magnetic field data presented above have features that have not been observed at $r < 7 R_E$. At geostationary orbit, the field remains northward, and its magnitude is typically larger than 40 nT throughout dipolarization (see Figure 3 of Cummings et al., 1968). Our observation suggests that at substorm onset the magnetic field configuration at $r \sim 8 R_E$ can be drastically different than at $r \sim 7 R_E$.

Based on the small perturbation in B_D for the 1153 UT event, we may discuss the possible magnetic field structures within a two-dimensional geometry. Of course we must remember that the event was observed with a single spacecraft, and, therefore, we can only speculate about the spatial structure of the magnetic field during the event. As Lui [1984]

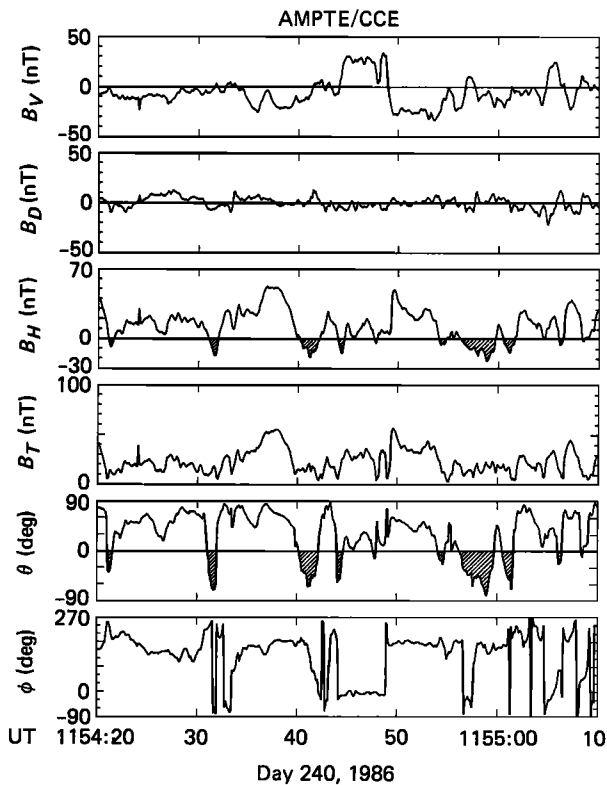


Fig. 3. Part of the data shown in Figure 2 that gives details of the southward turnings of the magnetic field. The shading indicates the intervals of southward B .

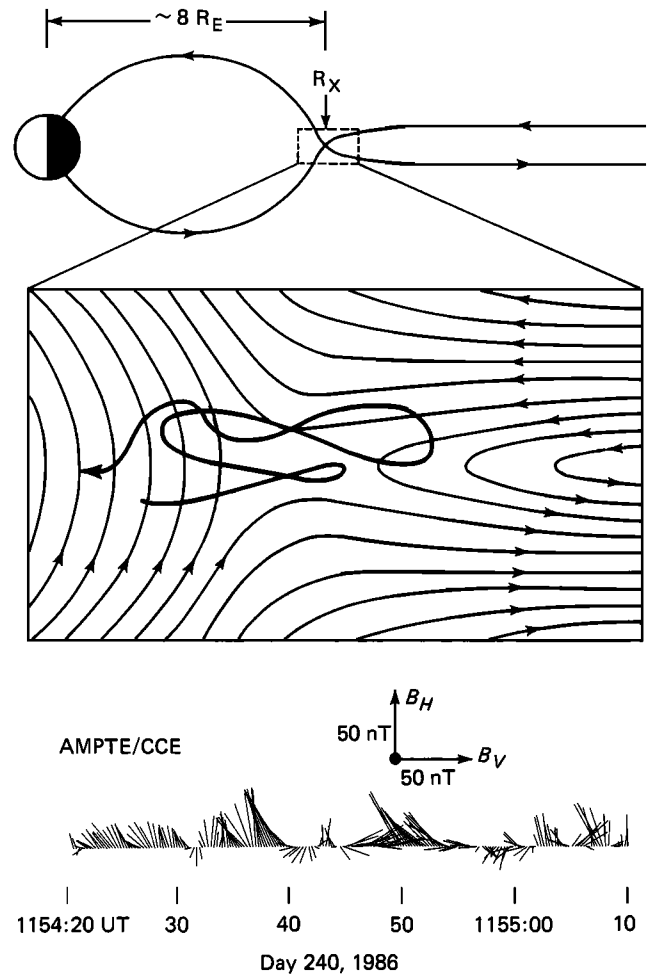


Fig. 4. Schematics of a possible magnetic field configuration during the 1153 UT event (top and middle) and two-dimensional projection of the observed magnetic field for an interval of a large-amplitude oscillation (bottom). In the bottom figure, the origin of the magnetic field vector is located on the horizontal base line and uniformly progresses to the right with time.

has discussed, there are many possible configurations of B that give rise to southward B .

One obvious possibility is a wavy motion of the tail current sheet. In this case, the magnetic field may be taken tangent to the local current sheet. However, this model cannot explain our observation unless the wave has a highly developed waveform along the sun-earth line so that almost purely southward B can be produced. At present, there is no known theory for the generation of such a wave on the current sheet.

An alternative explanation is the formation of a neutral line. As illustrated in Figure 4, we assume that an X-type neutral line is formed near $r = 8 R_E$ and that its location moves quasiperiodically. For intuitive interpretation of the observation such as that given at the bottom of Figure 4, let us assume that the neutral line is stationary and that the spacecraft moves about it. In the middle panel of Figure 4, the relative motion of the spacecraft is schematically illustrated with a heavy curve. The asymmetry of the field configuration about $r = R_X$, the location of the neutral line,

explains the different peak magnitudes of the northward B (~ 50 nT) and the southward B (~ 20 nT) observed during the oscillation.

The observed ~ 13 -s oscillation in B_H is thus primarily accounted for by an oscillatory motion of the neutral line along the sun–earth line (the orbital motion of the spacecraft can be ignored for the 3.5-min interval of interest). The oscillation in B_V , which has a somewhat longer period and a more irregular waveform, can be explained by adding a north–south motion of the neutral line.

The physical mechanism for the 13-s periodicity is not known at present. We shall only note some characteristic periods at $L \sim 8$ based on a dipole magnetic field: the bounce period (~ 13 s) of 0.5-keV electrons or 1-MeV protons, the gyroperiod (~ 20 s) of O^+ , and a (probably higher than 10th) harmonic of a standing Alfvén wave. There could be other characteristic time constants related to the thickness of the current sheet, but they remain much more ambiguous than the above-mentioned quantities.

The high-frequency oscillations (periods shorter than 10 s) superposed on the above-mentioned oscillations do not exhibit outstanding frequency components when the power spectral density is calculated. These noisy oscillations could well be related to microscopic processes in the creation of a neutral line.

Instead of having a single neutral line that moves about the spacecraft, we might have tearing islands [Coppi et al., 1966; Schindler and Ness, 1972] that are convected or created in a periodic fashion. With the limited data set from a single spacecraft, it is difficult to determine the scale size of the magnetic field structure. Thus, the model illustrated in Figure 4 should be taken as indicating the simplest possible configuration. The important point here is that there is strong evidence in the magnetic field observations of magnetic reconnection in the plasma sheet at the onset of this particular substorm.

An event like that on day 240 is not a common occurrence at the CCE orbit. Of more than 25 dipolarization events observed during the CCE tail passes in 1986 within ± 1 hour of midnight and within $\pm 5^\circ$ of the dipole equator, only the day 240 event exhibited a persistent oscillation and a very large southward component of B . Thus we may conclude that the formation of a neutral line or lines at $r \lesssim 8 R_E$ is possible but is very rare.

Acknowledgments. We are grateful to D. N. Baker, D. H. Fairfield, and M. Hoshino for their comments on this work. Magnetic field data from Kakioka were supplied by the Kakioka Geomagnetic Observatory. Work at The Johns Hopkins University Applied Physics Laboratory was supported by NASA under Task I of contract N00039-87-C-5301.

References

Coppi, B., G. Laval, and R. Pellat, Dynamics of the geomagnetic tail, *Phys. Rev. Lett.*, **16**, 1207, 1966.

- Coroniti, F. V., Explosive tail reconnection: The growth and expansion phases of magnetospheric substorms, *J. Geophys. Res.*, **90**, 7427, 1985.
- Cummings, W. D., J. N. Barfield, and P. J. Coleman, Jr., Magnetospheric substorms observed at the synchronous orbit, *J. Geophys. Res.*, **73**, 6687, 1968.
- Fairfield, D. H., M. H. Acuña, L. J. Zanetti, T. A. Potemra, The magnetic field of the equatorial magnetotail: AMPTE/CCE observations at $R < 8.8 R_E$, *J. Geophys. Res.*, **92**, 7432, 1987.
- Hoffman, R. A., and J. L. Burch, Electron precipitation patterns and substorm morphology, *J. Geophys. Res.*, **78**, 2867, 1973.
- Hones, E. W., Jr., J. R. Asbridge, S. J. Bame, and S. Singer, Substorm variations of the magnetotail plasma sheet from $X_{SM} \approx -6 R_E$ to $X_{SM} \approx -60 R_E$, *J. Geophys. Res.*, **78**, 109, 1973.
- Lui, A. T. Y., Characteristics of the cross-tail current in the earth's magnetotail, in *Magnetospheric Currents*, edited by T. A. Potemra, p. 158, AGU, Washington, D.C., 1984.
- McPherron, R. L., Substorm related changes in the geomagnetic tail: The growth phase, *Planet. Space Sci.*, **20**, 1521, 1972.
- McPherron, R. L., C. T. Russell, and M. P. Aubry, Satellite studies of magnetospheric substorms on August 15, 1968, 9. Phenomenological model for substorms, *J. Geophys. Res.*, **78**, 3131, 1973.
- Nagai, T., Observed magnetic substorm signatures at synchronous altitude, *J. Geophys. Res.*, **87**, 4405, 1982.
- Nishida, A., Reconnection in the earth's magnetotail: An overview, in *Magnetospheric Reconnection in Space and Laboratory Plasmas*, edited by E. W. Hones, Jr., p. 159, AGU, Washington, D. C., 1984.
- Nishida, A., and N. Nagayama, Synoptic survey for the neutral line in the magnetotail during the substorm expansion phase, *J. Geophys. Res.*, **78**, 3782, 1973.
- Russell, C. T., and R. L. McPherron, The magnetotail and substorms, *Space Sci. Rev.*, **15**, 205, 1973.
- Schindler, K., and N. F. Ness, Internal structure of the geomagnetic neutral sheet, *J. Geophys. Res.*, **77**, 91, 1972.

- K. Takahashi, L. J. Zanetti, R. E. Lopez, R. W. McEntire and T. A. Potemra, The Johns Hopkins University Applied Physics Laboratory, Johns Hopkins Road, Laurel, Maryland 20707.
- R. E. Lopez, Applied Research Corporation, 8201 Corporate Drive, Suite 920, Landover, Maryland 20785.
- K. Yumoto, Onagawa Magnetic Observatory and Geophysical Institute, Tohoku University, Sendai, Japan.

(Received July 21, 1987;
accepted August 7, 1987)