

Dynamics of the Earth's Magnetotail in Substorms: Impact of Kinetic Effects

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Abstract

There are two current systems essential for substorms. In the ionosphere, one system has a current closure in the east-west direction while the other has a north-south current closure. The latter requires a dynamo in the magnetotail. A model with a kinetic instability known as the cross-field current instability generates both substorm current systems simultaneously. Supporting evidence for this process is found from in situ magnetotail measurements.

1. Introduction

The Earth's magnetotail provides a natural laboratory for understanding efficient means to accelerate charged particles and to transform energy from one form to another in an explosive fashion. The physical process in the Earth's magnetotail by which substorms are initiated is commonly regarded as a prototype process relevant to understand many explosive energy releases in the plasma universe. It is generally perceived to be a process that involves the break-down of the fluid concept in treating space plasmas, a concept relying on describing plasmas with only bulk parameters such as number density, bulk flow, and temperature. Individual identity of charged particles is lost by this fluid treatment. On the other hand, kinetic treatment holds the key to the understanding of any process that breaks the fluid concept. The physical process initiating substorm disturbances in the Earth's magnetosphere is no exception. In this paper, strong evidence for kinetic processes in the dynamics of magnetotail in substorm is presented. A substorm model invoking a kinetic instability as the key process is discussed and found to account readily many observed substorm features.

2. Observations of Current Disruption in the Magnetotail

A well recognized substorm feature is current disruption/dipolarization (CDD) in which large magnetic field fluctuations occur in the transition region between the dipolar-like field geometry to a sheet-like field geometry in the Earthward end of the magnetotail [1]. The associated change of magnetic field configuration is from a sheet-like geometry before to a dipolar-like geometry after, as shown in Figure 1. The local dipole *VDH* coordinates are used to show the magnetic field components in which B_H is the northward pointing component.

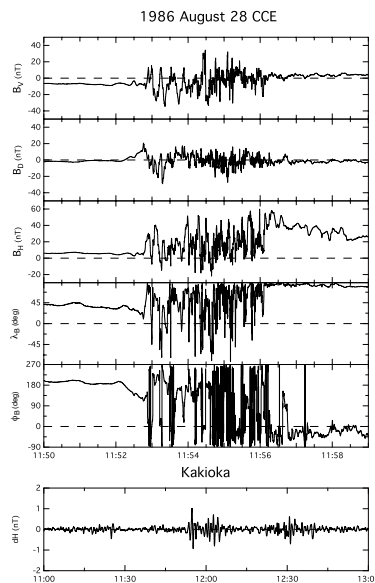


Figure 1. Observations of a CDD event on 1986 August 28, together with ground Pi2 pulsations at Kakioka [1].

In the event shown, large magnetic field fluctuations occurred at ~ 1153 UT and lasted until ~ 1156 UT, settling down to elevation angles λ_B close to 90° . This eventual orientation change of the magnetic field indicates a reduction of the east-west current in the magnetotail. Wavelet analysis for these magnetic fluctuations show intermittent enhancements at several frequencies, some of which are close to the proton cyclotron frequency. This finding indicates the presence of high frequency waves that can only be treated by kinetic analysis and not by fluid approach. Fractal, multifractal, and scaling analyses show these fluctuations to have multiple scales and satisfy the criterion of turbulence [2, 3]. Therefore, the dynamic processes for CDD are kinetic in nature and play an essential role in disruption the current in the magnetotail and diverting it to the ionosphere.

In addition, there is strong observational evidence that substorm current systems consist of two types. One type is the east-west current system referred to as the substorm current wedge (SCW). Another is a meridional current system (MCS) with the ionospheric current portion in the north-south direction [4]. The ionospheric portion of MCS constitutes the main load to the current system and requires a strong dynamo in the magnetotail. The magnetospheric portion of MCS is associated with an Earthward-directed electric field in the equatorial plane.

3. Substorm Current Systems Generated by a Kinetic Instability

One kinetic process providing the dynamo for the substorm current systems is the cross-field current instability (CCI) [3]. This is a current-driven instability and the excited waves, basically highly oblique whistler waves, have frequencies around the proton cyclotron frequency as observed. Once the magnetotail current exceeds the instability threshold, the growth rate is fast enough to satisfy the requirement for the substorm onset process. Many substorm features can be readily understood with this kinetic process. These include precursory activities known as pseudobreakups prior to substorm onset, spatial localization of substorm onset region, three different solar wind condition favorable for substorm occurrence, onset region skewed to the evening local time sector, different acceleration characteristics between ions and electrons, tailward spreading of CDD region, and local time expansion of the east-west substorm current system.

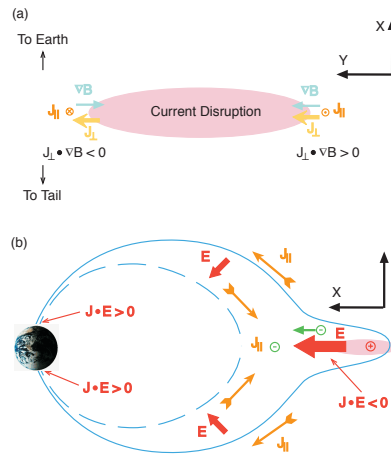


Figure 2. Schematic diagrams to illustrate the dynamo action from field line slippage: (a) CDD shunts the magnetotail current and redirects it to the ionosphere; (b) MCS and Earthward-pointing electric field (red arrows) generated by CDD that causes field line slippage [4].

The two substorm current systems can be generated by one physical kinetic process, as illustrated in Figure 2. The explanation by this kinetic instability model is the following [4]. Just prior to substorm onset, the east-west magnetotail current is enhanced rapidly, causing it to reach the threshold of CCI onset. At this stage, the ions are unmagnetized while the electrons are still magnetized. Ions and electrons are thus decoupled, a key feature of kinetic processes. The onset of CCI excites the growth of whistler waves that impedes the east-west magnetotail current and diverts it to the ionosphere, setting up the SCW. As a consequence, this allows the magnetic field lines to snap back from a sheet-like geometry to a dipolar-like geometry. Since electrons are still magnetized while ions are not, electrons are tied to the magnetic field line motion and move Earthward while the ions lag behind since they are unmagnetized. This differential motion of ions and electrons sets up both a tailward current and an Earthward-pointing electric field. The opposite directions of current and electric field is the required feature for a dynamo to drive the MCS.

4. Observation of Electric Dynamo in the Magnetotail for Meridional Current System

In contrast to other plasma parameters, electric current cannot be directly measured by satellites. It has to be calculated through magnetic field measurements. A major achievement of the Cluster mission is to deduce electric current through a well coordinated magnetic field measurements from four satellites in a tetrahedron configuration [5]. There are other situations that electric current can be deduced from suitable unplanned satellite conjunctions. One such fortuitous case occurred on 2009 February 28 by satellites in a mission called Time History of Events and Macroscale Interactions during Substorms (THEMIS). On this day, two THEMIS satellites P4 and P5 both at $X_{\text{gsm}} = -8.1 R_E$ had nearly identical equatorial projections but separated by their distances from the neutral sheet [6]. Their north-south separation was $\sim 0.7 R_E$. The salient features of this event is shown in Figure 3.

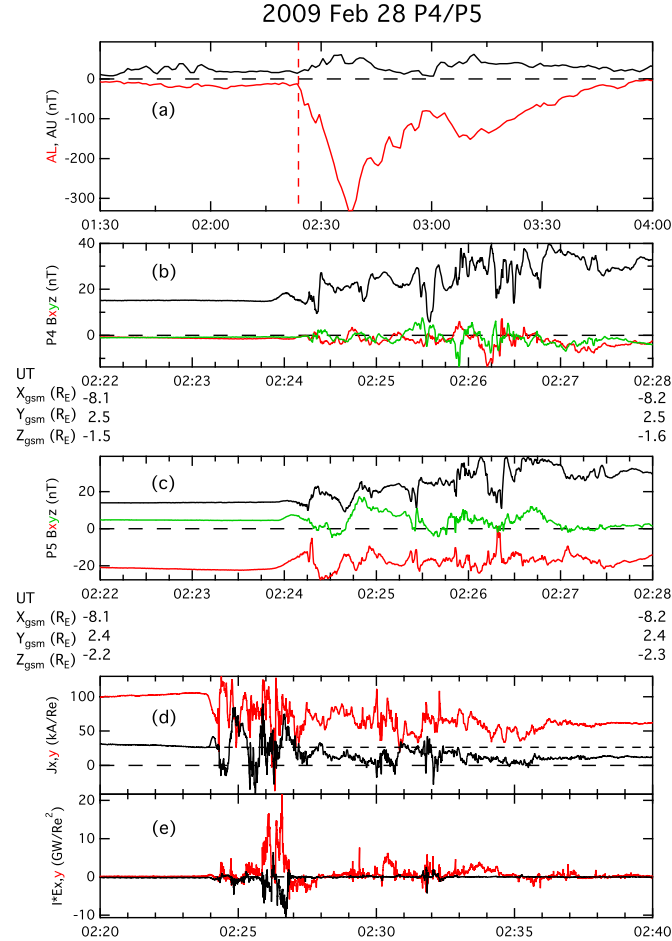


Figure 3. Observations for the CDD event on 2009 February 28. From top to bottom are the AU/AL indices, the magnetic field components in GSM coordinates at P4 and P5 (different colors are used for different components as indicated by the label), current densities in the layer embedded by P4 and P5, and power calculated from the product of current densities and the electric field averaged over the two satellite measurements [6].

A substorm onset occurred at 0224 UT, as indicated by the AU/AL indices and collaborated with ground auroral breakup activity. Before CDD onset at 0223:49 UT, both B_x and B_y components at P4 had small values ($|B_x|, |B_y| < 1.5$ nT) in comparison with the B_z component, indicating the close proximity of P4 to the neutral sheet. CDD onset started with a small increase in the B_z component, followed by large fluctuations with a high value of 39.7 nT and a low value of 6.4 nT during the subsequent 4 min. At 0228 UT, its value became 32.8 nT. The B_z variations and the subsequent increase are characteristics of CDD near the neutral sheet.

P5 was further away from the neutral sheet than P4, as indicated by the high magnitude of the B_x component. However, considerable fluctuations in the B_z component were detected. Since P4 and P5 had nearly identical equatorial projections, the current densities embedded in the layer between these two satellites can be obtained with the

application of the integral form of Ampere's law. Magnetic field data sampled with a time resolution of 0.25s were used in this calculation. The changes in current densities over a larger time interval (0220 – 0240 UT) are shown in Figure 3d. It is found that J_y increased slightly from ~ 100 to 106 kA/R_E just prior to the CDD onset, while J_x decreased slightly from ~ 32 to 26 kA/R_E . At CDD onset, there was a sharp drop in J_y down to 61 kA/R_E accompanied by a substantial increase in J_x up to 42 kA/R_E , suggesting a part of J_y was directed Earthward initially. After onset, both J_x and J_y varied tremendously, with occasional values larger than their values before onset. The time scale of variations was very short, i.e., in the kinetic regime of seconds. For example, at 0224:46 UT, J_y changed from 126 to 85 kA/R_E in 3s. At 0226:18 UT, J_y changed from -17 to 119 kA/R_E in 3s. Similar rapid changes were seen in J_x . At 0224:38 UT, J_x changed from 2 to 34 kA/R_E in 3s. At 0225:58 UT, J_x changed from 42 to 4 kA/R_E in 3s. The value of J_x even became negative at several short intervals. At the end of the interval (0240 UT), J_y and J_x settled down to 62 and 12 kA/R_E , respectively. These values represent reductions of $\sim 42\%$ and $\sim 54\%$.

It is important to distinguish the substorm current system from the R1/R2 current system generated by the solar-wind-magnetosphere dynamo. In the premidnight sector, J_x for R1/R2 near the neutral sheet is positive, as shown by the observed value prior to the CDD onset. Therefore, to isolate J_x current associated with the substorm, the current value prior to CDD onset needs to be used as the base line, which is indicated by the dash line in Figure 3d and has the value of 26 kA/R_E . With this base line, one can see that J_x for the substorm current system due to CDD was often directed tailward. At the end of this interval, it became 12 kA/R_E , well below its value prior to CDD onset. The averaged value of J_x in the interval 0223:49 – 0240:00 UT is 16 kA/R_E , implying an averaged tailward directed current of 10 kA/R_E near the neutral sheet for the north-south substorm current system in the ionosphere.

The amount of power involved in the CDD can be estimated by forming the dot product of the current density with the corresponding electric field averaged over the two satellites. For accurate electric field measurements, the power calculation was done in the despun spacecraft coordinates, which is close to the GSE coordinations. Positive values of power implies dissipation while negative value implies dynamo action. In the y -direction, the power was mainly dissipation although there were brief intervals with a weak dynamo effect. In the x -direction, the power was mainly negative, i.e., a dynamo. There was occasional breakdown of the frozen-in condition during the CDD event [6]. These observed features are predicted by the substorm current system model in [4].

5. Summary

Evidence is presented to show that CDD, a key substorm feature that relaxes the magnetic field configuration and energizes charged particles, is likely caused by a kinetic instability in the Earth's magnetotail. This instability initiates a substorm onset. This kinetic process can readily explain many observed substorm features. In particular, this kinetic instability generates the two substorm current systems and provides the necessary dynamo to drive the MCS.

6. References

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