On the Possibility of Observing the Microphysics of Magnetic Reconnection

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Abstract. Recent observations of fields and plasmas in the magnetotail by the Geotail spacecraft have enabled us to explore the processes of magnetic reconnection in association with substorm onsets. Magnetic reconnection consists of highly localized phenomena, so that the spacecraft seldom encounters the reconnection site. Good orbit design is therefore important for future missions. The magnetic field and plasma flows are highly variable in the magnetic reconnection site. Multipoint measurements of complete three-dimensional distribution functions with a high time resolution are needed to obtain a greater understanding of the magnetic reconnection.

1. Introduction

The physical processes of magnetic reconnection are a major research topic in space plasma physics. Magnetic reconnection is an important process in the conversion of magnetic field energy to particle kinetic and thermal energy. Recently, the Geotail spacecraft has added significantly to our understanding of magnetic reconnection in association with substorm onsets. It has now become well-established that magnetic reconnection associated with substorm onsets usually takes place in the pre-midnight sector of the magnetotail at radial distances of 20-30 R_E, and that magnetic reconnection starts a few minutes prior to ground substorm onsets [e.g., *Nagai et al.,* 1998; *Nagai and Machida,* 1998]. These facts imply that various substorm phenomena originate from magnetic reconnection. Three-dimensional ion and electron distribution function data have provided important findings on ion and electron dynamics during magnetic reconnection; and these findings have been compared with the results of simulations of magnetic reconnection performed using a hybrid code and a full particle code [e.g., *Hoshino et al.,* 1998; *Nakamura and Fujimoto,* 1998; *Nakamura et al.,* 1998].

It has been recognized, however, that the physical processes occurring in the vicinity of magnetic reconnection have fine structure and high temporal variability. In this paper, we clarify the field and particle characteristics of magnetic reconnection processes using data from Geotail. We use these findings to make recommendations on the design of future missions.

2. Geotail Mission

Geotail was launched in July 1992 [*Nishida,* 1994]. Until October 1994, Geotail surveyed mostly in the distant tail. In the 1994-1995 winter season, it surveyed in the magnetotail up to 50 R_E. The apogee of Geotail was changed to approximately 30 R_E in February 1995, and it was in a 10 by 30 R_E orbit until June 1997. In June 1997, the perigee of Geotail was changed to approximately 9 R_E. Geotail has made an extensive survey of the plasma sheet at radial distances of 20-30 R_E in the winter season after 1995. Magnetic field measurements have been carried out with the magnetic field (MGF) experiment [*Kokubun et al.,* 1994]. The basic time resolution of the magnetic field data is 1/16 s. We use Bx, By, Bz, and Bt (the magnetic field intensity) in the GSM coordinate system. Ion and electron measurements have been carried out with the low-energy particle (LEP) experiment [*Mukai et al.,* 1994]. The upper energy limit of this instrument is 40 keV for ions and electrons, and the time resolution of the LEP data is 12 s. Number density, ion temperature, and plasma velocity (Vx, Vy, Vz) have been obtained for all observation intervals. These values are calculated assuming that all ions are protons. Two-dimensional distribution functions (in the equatorial plane) have been obtained for all observation intervals, whereas three-dimensional distribution functions are available only for the time intervals when the data are received at the Japanese station Usuda.

3. Probability of Encounters with Magnetic Reconnection

It is difficult to determine whether the Geotail observations were made in the magnetic reconnection site. The total magnetic field never becomes zero in observations, although this might be due to the spacecraft magnetic field. The electric field along the neutral line cannot be measured. The most practical parameters to measure are particles and fields. At the tailward side of magnetic reconnection, outflows are fast tailward convection plasma flows with southward Bz. Indeed, Geotail observes fast tailward flows with southward Bz in association with substorm onsets. The speed of these tailward flows exceeds 2000 km/s, which corresponds to theAlfvén velocity in the tail lobe. Occasionally, highly accelerated electrons appear. The highest-energy (10-keV) component of these electrons shows tailward anisotropy. The simultaneous appearance of high-speed tailward escaping electrons and tailward flowing ions means that the observations are carried out in the immediate vicinity of the magnetic reconnection site; otherwise, we would first observe tailward flowing electrons and then tailward flowing ions, because of the large difference in velocities. We frequently observe tailward flows with southward Bz and then earthward flows with northward Bz (flow reversal) in these events. These signatures are thought to be caused by an encounter of the spacecraft with the magnetic reconnection site.

In the 1995-1996 winter season, three-dimensional distribution function data were taken for 485.3 hours in the magnetotail of $X_{GSM} <$ -15 R_E (the region of -20 $R_E < Y_{GSM} <$ +20 R_E). Geotail stayed in the plasma sheet (ion plasma $\beta > 0.1$) for 412.7 hours. There were two substorm events in which Geotail observed highly accelerated electrons [*Nagai et al.,* 1998]. In the 1996-1997 winter season, three-dimensional distribution function data were taken for 495.8 hours in the magnetotail of $X_{GSM} <$ -15 R_E. Geotail stayed in the plasma sheet for 450.1 hours. During this time, there were 10 substorm events that had accelerated electrons. Figure 1 presents the orbit segments and positions of these 12 events. It is found that magnetic reconnection takes place only in the limited region of $0 < Y_{GSM} <$ +10 R_E. Although the orbit of Geotail was designed to stay near the equatorial plane at radial distances of 20-30 R_E, and Geotail could stay inside the plasma sheet for more than 85% of its hours of operation, the probability of an encounter with the magnetic reconnection site is fairly small.

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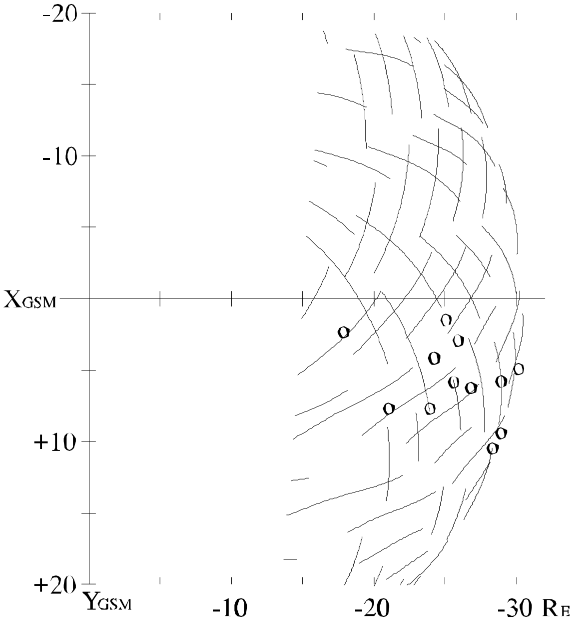

Figure 1. Geotail positions for 12 electron acceleration events and Geotail orbit coverage in the magnetotail beyond 15 R_E, from October 1995 to March 1996 and from October 1996 to March 19

4. Reconnection Event

We now examine the field and plasma characteristics of the magnetic reconnection site. Substorm activity started near 1650 UT on December 10, 1996. There were three substorm intensifications in this activity. The third intensification started near 1740 UT, when Geotail was located at (-25.4, 1.1, -2.5 R_E) in the GSM coordinate system. For the period 1742-1803 UT, highly accelerated electrons were observed, and ion energies exceeded the upper energy limit (40 keV) of the LEP instrument. The high-energy ions showed fast earthward flows (a speed higher than 2000 km/s), fast tailward flows, and then fast earthward flows. For the tailward flow interval, the magnetic field became southward. Hence, Geotail was in the immediate vicinity of the magnetic reconnection site for this event.

Figure 2 presents magnetic field data with 1/16 s time resolution and energy-time diagrams for ions and electrons with 12 s time resolution, for the period 1740-1810 UT. Geotail was located near the plasma sheet/tail lobe boundary and observed earthward flowing ions until 1746:50 UT, at which time the magnetic field intensity suddenly decreased, and tailward flowing ions were then observed after 1746:50 UT. For this first flow reversal, Geotail was in the plasma sheet. Geotail then approached the plasma sheet/tail lobe boundary again and observed the second flow reversal near 1752 UT.

Figure 3 presents the magnetic field data with 1/16 s time resolution. Two time intervals are shown for plasma data sampling in the first flow-reversal period. High-energy ions flowing earthward and duskward were observed in the plasma sampling at 1746:38 - 1746:50 UT (see Figure 2). Low-energy ions convecting dawnward were also observed; they were presumably inflows for magnetic reconnection. High-energy (>10 keV) electrons had the earthward escaping component. The magnetic field was fairly stable, and its intensity was near 18 nT for this plasma sampling interval. It is likely that Geotail was near the separatrix region earthward of the magnetic reconnection site. In the plasma sampling interval 1746:50-1747:02 UT, almost all ions showed tailward flows, and high-energy electrons had the tailward flowing component. The magnetic field intensity changed from 19 nT to 2 nT, and the direction of the magnetic field was variable. Near the equatorial plane, variations in Bz had time scales of 1 s. The magnetic field intensity was small, and the field was almost southward. It is important to resolve particle signatures in this sampling.

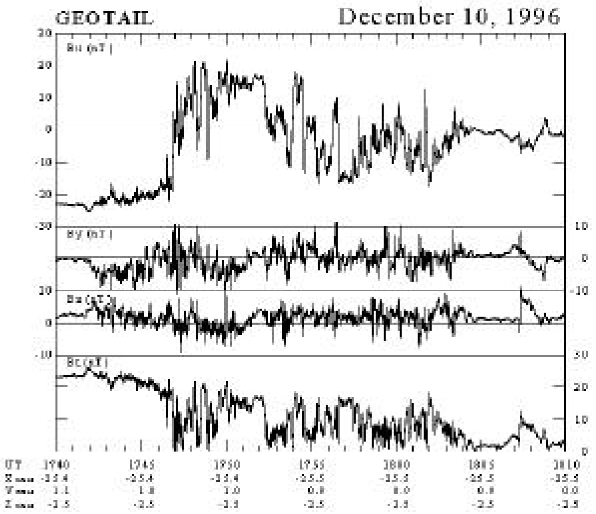

Figure 2. Magnetic field variations and ion and electron energy-time diagramsfor the period 1740-1805 UT on December10, 1996.

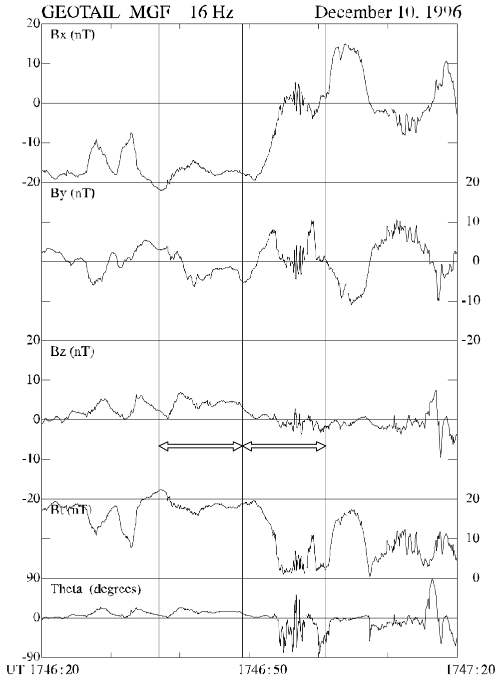

Figure 3. Magnetic field data for the period 1746:20-1747:20 UT on December 10, 1996. Two time intervals are shown for plasma data sampling.

Figure 4 presents magnetic field data with 1/16 s time resolution. Three time intervals are shown for plasma data sampling in the second flow-reversal period. The magnetic field was fairly stable and near 15 nT. Figure 5 presents electron distribution functions in the BC plane, which contains the magnetic field and the plasma flow vector. The B

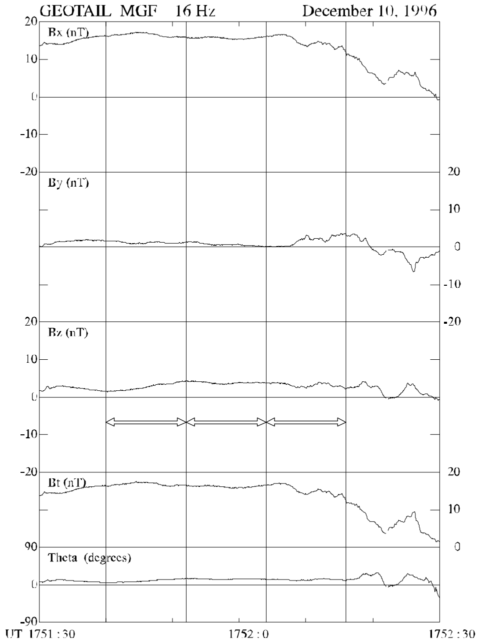

Figure 4. Magnetic field data for the period 1751:30 - 1752:30 UT on December 10, 1996. Three time intervals are shown for plasma data sampling.

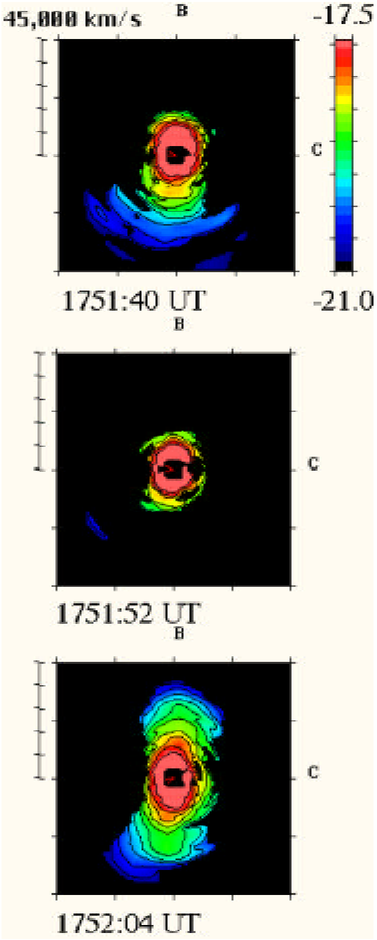

Figure 5. Electron distribution functions in the BC plane. The B axis is the direction of the magnetic field, approximately earthward. The C axis is the direction of the plasma flow component perpendicular to the magnetic field, approximately duskward.

axis is along the local magnetic field, and the C axis is the direction of the plasma flow component perpendicular to the local magnetic field. At 1751:40 UT (the start time of the sampling interval), electrons had a bi-directional field-aligned cold component and an accelerated tailward flowing component. At 1751:52 UT, electrons had only a bi-directional field-aligned cold component. At 1752:04 UT, although electrons had a bi-directional field-aligned component, both field-aligned components were accelerated. Since the magnetic field was stable, these variations in the electrons were likely temporal phenomena. As seen in Figure 2, high-energy (>10 keV) ions were observed as duskward flowing ions, whereas low-energy (< 1 keV) ions were observed as dawnward flowing ions. The dawnward flowing ions showed convection, so that these were inflows for magnetic reconnection. The duskward flowing ions were not really flowing but were part of cyclotron motion. The Larmor radius of 1-keV ions in 15nT is 1000 km. Geotail was located just above the magnetic reconnection site. After 1752:16 UT, the magnetic field intensity became less than 5nT. Ions showed earthward flows, and electrons showed almost isotropic distributions.

8. Discussion and Conclusions

Geotail has observed signatures of ongoing magnetic reconnection for substorm onsets in the magnetotail at radial distances of 20-30 R_E. The probability of an encounter with the magnetic reconnection site is fairly small, even though the orbit of Geotail was designed to make the spacecraft stay in the equatorial plane at radial distances of 20-30 R_E. It is likely that the plasma sheet becomes very thin in magnetic reconnection and that the longitudinal extent of the magnetic reconnection site is limited. The duration of magnetic reconnection at any given site seems to be short. Therefore, good orbit design is extremely important for observing magnetic reconnection processes. At the magnetic reconnection site, fields and particles are highly variable, and their scale lengths are very small. Near the equatorial plane, the time scales of magnetic field variations are typically 1 s. Even with a stable magnetic field, electrons have variations with time scales of less than 12 s. In these cases, multipoint measurements of three-dimensional distribution functions with a time resolution of 1 s would enable us to understand the structure of magnetic reconnection. It is desirable to put at least four spacecraft at four vertices of a tetrahedron, in order to get information on the three-dimensional structure. In summary, in order to understand the microphysics of magnetic reconnection, we need:

1) good orbit design,
2) multipoint measurements,
3) complete three-dimensional distribution functions with a time resolution of 1 s,
4) good energy coverage for ions and electrons, and
5) reduction of the spacecraft magnetic field.

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References

Hoshino, M., T. Mukai, T. Yamamoto, and S. Kokubun, Ion dynamics in magnetic reconnection: Comparison between numerical simulation and Geotail observations, *J. Geophys. Res., 103,* 4509-4530, 1998.

Kokubun, S., T. Yamamoto, M. H. Acuña, K. Hayashi, K. Shiokawa, and H.Kawano, The GEOTAIL magnetic field experiment, *J. Geomagn. Geoelectr.,46,* 7-21, 1994.

Mukai, T., S. Machida, Y. Saito, M. Hirahara, T. Terasawa, N. Kaya, T.Obara, M. Ejiri, and A. Nishida, The low energy particle (LEP) experiment onboard the GEOTAIL satellite, *J. Geomagn. Geoelectr., 46,* 669-692, 1994.

Nagai, T., and S. Machida, Magnetic reconnection in the near-Earthmagnetotail, in *New Perspective on the Earth's Magnetotail,Geophysical Monograph Series*, vol. 105, edited by A. Nishida, D. N. Baker,and S. W. H. Cowley, pp. 211-225, AGU, Washington, D.C., 1998.

Nagai, T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T.Yamamoto, T. Mukai, A. Nishida, and S. Kokubun, Structure and dynamics ofmagnetic reconnection for substorm onsets with Geotail observations, *J. Geophys. Res., 103,* 4419-4440, 1998.

Nakamura, M. S., and M. Fujimoto, A three-dimensional hybrid simulation of magnetic reconnection, *Geophys. Res. Lett., 25,* 2917-2920, 1998.

Nakamura, M. S., M. Fujimoto, and K. Maezawa, Ion dynamics and resultant velocity space distributions in the course of magnetic reconnection, *J. Geophys. Res., 103,* 4531-4546, 1998.

Nishida, A., The Geotail mission, *Geophys. Res. Lett., 21,* 2871-2873, 1994.

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