Structure and Kinetic Properties of Plasmoids and Their Boundary Regions


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Based on GEOTAIL/LEP observations in the distant magnetotail, this paper reports on several new features of velocity distribution functions of electrons and ions within a plasmoid and at its boundary. Here we use the term 'plasmoid' in a wider meaning than usual in spite of the presence of significant magnetic $B_y$ fields. In the lobe, as expected from MHD simulations of magnetic reconnection processes, cold plasmas are pushed away from the plasma sheet before the arrival of plasmoids, while after the plasmoid passage the convection is enhanced toward the normal direction to the plasma sheet. The cold ions flow into the plasmoid along magnetic field lines, are heated and accelerated perpendicularly at the boundary, and finally merge with hot plasmas deeper inside the plasmoids. Deep inside plasmoids, however, the ion distribution functions often show the existence of counterstreaming ion beams, while the simultaneously measured electron distribution functions show a flat-top distribution. It is noted that the presence of the counterstreaming ions is a fine structure along magnetic field lines inside the whole distribution convecting tailward with speeds of 500–900 km/s. The relative velocity of the two components along the magnetic field line reaches 1000–1500 km/s, which is much higher than the local Alfven speed. Each component has an anisotropic distribution with respect to its center in the velocity space; the perpendicular temperature is several times higher than the parallel temperature. We conclude that these counterstreaming ions are most likely of lobe origin, and they have not had time enough for thermalization. They might have entered the plasmoid from the northern and southern lobes, being heated and accelerated through slow-mode shocks at the boundaries. Hence, these field lines are open, and both ends are connected to the northern and southern lobes. This phenomenon is observed predominantly in the latter part of the plasmoid after southward turning of the magnetic field, especially after the plasma bulk speed has increased stepwise and the $B_y/B_z$ field magnitudes have attained the peak value. It is also observed even near the neutral sheet, where the magnetic $B_z$ field is very small, but significant $B_y$ and/or $B_z$ fields exist. Since the tailward flow speed becomes faster associated with the above phenomenon, these open field lines would be draped around the leading (core) part of plasmoids. The compression due to the draping may increase the field intensity.

1. Introduction

The near-Earth neutral line model of magnetospheric substorms predicts that a plasmoid is formed at substorm onset due to magnetic reconnection in the near-Earth tail and subsequently propagates downtail at high speed (Hones, 1979). The expected magnetic and plasma signatures are a north-to-south bipolar variation of the magnetic field that contains hot, fast tailward flowing plasma. The ISEE-3 electron plasma, energetic particle and magnetic field data on the geotail orbits have been extensively used to develop a description of general properties and morphology of plasmoids (e.g., Moldwin and Hughes, 1992, and references therein) and to examine their
substorm association (e.g., Moldwin and Hughes, 1993). These previous studies have suggested that plasmoids are generally consistent with the formation due to the near-Earth reconnection.

Though the original model by Hones was two dimensional, it is now well known that there is a significant magnitude of the magnetic $B_y$ fields, which are at times intensified to values comparable to, or even greater than, the $B_z$ value in the lobe. Many researchers regard this as the signature of flux ropes (Hughes and Sibeck, 1987; Slavin et al., 1989; Moldwin and Hughes, 1991). Recent attempts to model the magnetic field variations as force-free flux ropes (Lepping et al., 1995; Slavin et al., 1995; Kivelson and Khurana, preprint, 1995) have shown reasonable agreements with selected data sets. In principle, the force-free models should be applicable only under low $\beta$ (plasma beta) conditions, though the method of Kivelson and Khurana have used a balance of the Lorenz force with the plasma pressure gradient. Actually a majority of the plasmoid region is filled with hot plasmas of high $\beta$. The structure and kinetic properties in the hot plasma regions are yet to be studied. As we will discuss in this paper, the presence of the $B_y$ field does not necessarily imply a helical structure.

Based on the GEOTAIL/LEP observations, this paper presents some new features in the velocity distribution functions of electrons and ions as well as the macroscopic flow properties in plasmoids. The distribution functions in plasmoids have rarely been described until recently (Machida et al., 1994; Frank et al., 1994), so that most of the results to be presented are new findings. The most remarkable feature is the existence of two ion beams counterstreaming along the magnetic field line. We will discuss possible models for the formation of this phenomenon, and suggest its implication to the plasmoid structure.

2. Instrumentation

The GEOTAIL satellite was launched on July 24, 1992 with a comprehensive set of field and plasma instruments to study the structure and dynamics of magnetotail plasmas (Nishida, 1994). In this paper we use the data obtained by the Low Energy Particle-Energy Analyzer (LEP-EA) and the Magnetic Field (MGF) experiments onboard the GEOTAIL spacecraft. LEP-EA consists of two nested sets of quadrispherical electrostatic analyzers to measure three-dimensional energy-per-charge distributions of electrons (with EA-e) and ions (with EA-i) simultaneously and separately. In the present observations, EA-i covers the energy range of 32 eV/q to 39 keV/q divided into 32 bins, in which 24 bins are equally spaced on logarithmic scale in energies higher than 630 eV/q and have width $\pm 9.4\%$ of the center energy, while the lower-energy 8 bins are spaced linearly with width of $\pm 40$ eV/q ($\pm 20$ eV/q for the lowest energy bin). The EA-e covers the energy range of 60 eV to 38 keV, which is also divided into 32 bins with logarithmic spacing for higher 24 bins (>650 eV) and linear spacing for lower 8 bins in a similar way to EA-i. The full energy range is swept in a time which is 1/16 of a spin period (synchronized with the spacecraft spin motion). The field of view is fan-shaped with $\sim 10^\circ \times 145^\circ$, in which the longer dimension is perpendicular to the spin plane and divided into seven directions centered at elevation angles of $0^\circ$, $\pm 22.5^\circ$, $\pm 45^\circ$ and $\pm 67.5^\circ$ with each width of 6–10$^\circ$ (wider for higher elevation angles). While the velocity moments are calculated onboard every spin period, the complete three-dimensional distributions can only be obtained in a period of four spins (about 12 seconds) owing to the telemetry constraints; the count data are accumulated during the four-spin period. A more detailed description of LEP instrumentation is given in Mukai et al. (1994). MGF provides vector magnetic field data with a time resolution of 1/16 second (Kokubun et al., 1994). The magnetic field data used in this paper are averaged over one spin period, or four spin periods when showing distribution functions with reference to the magnetic field direction. The coordinate system used in this paper is the Geocentric Solar Magnetospheric (GSM) coordinates for presentation of the magnetic field and the plasma (ion) bulk velocity. The spacecraft position is also expressed in GSM but modified with the solar wind aberration under the assumption of
400 km/s radial flow speed.

3. Observations

3.1 September 18, 1993

Figure 1 shows an example of a plasmoid observed at 1018–1020 UT on September 18, 1993, in which the GEOTAIL spacecraft was located at (-69.6, 4.4, -0.7) RE. A Pi-2 onset occurred at 1014 UT (at Kakioka, Japan) in association with this event. Before the plasmoid encounter, the spacecraft was in the northern lobe \((B_z > 0)\), where cold ions with density of \(1 \times 10^{-2} \text{ cm}^{-3}\) and temperature of several tens of eV were flowing tailward with a speed of 100 km/s. The plasmoid encounter is identified by detection of fast flowing hot plasmas associated with the north-to-south bipolar signature in the magnetic \(B_z\) field. In more detail, from about one minute before the northward deflection of the magnetic field, the density began to increase with increasing \(V_t\) toward positive values which means that the lobe plasmas were pushed away from the neutral sheet. The northward deflection of the magnetic field was slightly earlier than the encounter with fast flowing hot plasmas. Though not evident in this example, the total magnitude of the magnetic field is at times intensified in other examples (for example, see Fig. 2 of Machida et al. (1994)). These are the signatures of fast magnetosonic waves propagating tailward with speeds much faster than that of the plasmoid. The Alfvén speed (which is nearly the same as the fast wave speed) in the lobe region is 2640 km/s, determined from observed magnetic field magnitude and plasma moments. A simple calculation of the time-of-flight effect for the time difference between the fast waves and the plasmoid indicates that the source region is approximately 10 \(R_E\) earthward of the observation point \((X = -70 \text{ RE})\) in this case. Then, the plasma flow speed increased stepwise to about 750 km/s, and thereafter increased further to 900 km/s. The flow direction of the plasmoid is mainly tailward, but also the \(Y\) and \(Z\) components show significant variations. The magnetic \(B_y\) field also shows significant variations with positive values, and is intensified near the time of changing sign of the \(B_z\) component. The presence of this significant \(B_y\) field is usually considered to represent a flux-rope magnetic structure, but later in this paper we will argue that the whole structure does not necessarily consist of flux ropes. It is noteworthy that there are good correlations between the \(B_y\) and \(V_y\) variations as well as between the \(B_z\) and \(V_z\) variations. A more detailed study (Nishida et al., preprint, 1995) reveals that the correlation is positive in the northern region \((B_z > 0)\), and negative in the southern region \((B_z < 0)\).

Figure 2 shows ion and electron energy-time spectrograms (henceforth, \(E-t\) diagrams) together with two examples of the distribution functions of ions and electrons. A few notable features associated with the plasmoid can be easily seen in the \(E-t\) diagrams. One is the presence of faint, hot electrons (starting from 1016:48 UT) followed by high-energy ions (starting from 1017:24 UT) ahead of the main part of the plasmoid. Their distribution functions (not shown here) reveal that they are field-aligned beams with velocity dispersion. It is noted that the appearance of the electron beams is nearly the same as, or slightly earlier than the time of the fast wave signature noted above. The ion beams are also evident in the post-plasmoid boundary layer around 1021 UT. The presence of electron and ion beams near the outermost boundary of plasmoid is well known in ISEE-3 observations (e.g., Scholer et al., 1984; Richardson and Cowley, 1985) as well as the GEOTAIL observations (Machida et al., 1994), and is not discussed further in this paper. Another notable feature is that cold ions of the lobe region are heated and accelerated in the boundary region on entering the plasmoid. This is one of the new findings in the GEOTAIL observations, as also reported by Machida et al. (1994). Hirahara et al. (1994) have reported details of how the cold ions are accelerated in the plasma sheet boundary layer, and its association with enhancement of the convection electric field. Saito et al. (1995) have also reported the heating of cold ions in the plasma sheet—lobe boundary which can be identified as a slow-mode shock.

The distribution functions of ions and electrons in Fig. 2 (as well as in later figures) are
Fig. 1. Magnetic field data and ion velocity moments during the time interval of 1000-1030 UT on September 18, 1993. From the top, time series of the total magnitude and three components of the magnetic field (nT), root-mean-squares of the magnetic field fluctuations (nT), density (cm$^{-3}$), temperature (eV), and three components of bulk velocity (km/s) are shown. Bottom three rows indicate the spacecraft position. Two vertical lines show the time at which the distribution functions of ions and electrons are shown in Fig. 2.
Fig. 2. Ion and electron energy-time spectrograms in the same time intervals as shown in Fig. 1, and examples of the distribution functions of ions and electrons. In the energy-time spectrograms, color coding scales logarithm of the maximum count rate data in 16 azimuthal sectors and 7 elevation angles at a given energy and time. The vertical scale is energy (keV/e) on logarithmic scale. The times for the distribution functions are indicated in the energy-time spectrograms (and also by vertical lines in Fig. 1). For each time, upper and lower panels show ion and electron distribution functions, respectively. The distribution functions on the left hand panels are shown in the B-C plane which is defined such that 'B' is the magnetic field direction and 'C' is the direction of the convection velocity with reference to the spacecraft frame. The bulk velocity vector is shown by a red arrow in the B-C plane. The phase space density is scaled by color coding on logarithmic scale from $-12.5$ to $-17.5$ s$^3$/m$^6$ for ions, and from $-16.0$ to $-21.0$ s$^3$/m$^6$ for electrons. The contour lines are spaced every one tenth of the specified range on logarithmic scale. For ions, the right hand panels show the distribution functions cut through red lines shown in the corresponding left-hand panels. A smooth curve shows the one-count level. For electrons, the right-hand panels show the distribution functions in the parallel (red) and perpendicular (green) directions to the magnetic field.
displayed in a plane (hereafter, B-C plane) which is defined such that the B axis is the magnetic field direction and the C axis is the direction of the convection velocity with reference to the spacecraft frame. At time A (1018:23-35 UT), the ion distribution function in the B-C plane appears nearly isotropic in the convecting plasma frame, but in more detail, the peak distribution does not coincide with the bulk velocity. This is more evident in the corresponding right-hand panel, in which the ion distribution function shows the existence of a beam-like distribution superimposed on the isotropic, hot component. It is evident that the electron distribution function also consists of two components, bi-streaming electrons at lower energies and isotropic electrons at higher energies. The bi-streaming electrons show a flat-top distribution with shoulder energy of 390 eV (11700 km/s), as shown on the corresponding right-hand panel.

At time B (1018:47-59 UT), the flat-top distribution of electrons can be seen more clearly (see the red curve on the corresponding right-hand panel), and the shoulder energy is 600 eV (14500 km/s). Here, the hotter electron component shows a pancake distribution; the green curve exceeds the red one at higher energies. A more peculiar feature is seen in the ion distribution function, which shows a shell-like distribution. The phase space density on the shell is quite inhomogeneous and shows the existence of two maxima (beams) in the magnetic field directions (parallel and antiparallel) with reference to the bulk velocity. The velocity difference between the two beams is about 1450 km/s and exceeds twice the local Alfvén speed (600 km/s), and hence the two beams are susceptible to resonant electromagnetic ion-ion instability (Tsurutani et al., 1985; Kawano et al., 1994). The ion beams could be pitch-angle scattered by ion cyclotron waves generated by the instability. Thus, the shell distribution is most likely to be a result of pitch angle scattering from counterstreaming beams. It is noted that the magnetic \( B_y \) magnitude at this time is 3.5 nT, much smaller than the value in the lobe region, so that the region would be deep inside the plasmoid. Examination of all the ion distribution functions (every 12 seconds) throughout the plasmoid in this event leads us to conclude that all the ion distribution functions consist essentially of two components counterstreaming along the magnetic field line with reference to the plasma convecting frame.

### 3.2 December 20, 1993

Figures 3 and 4 show a plasmoid event observed on December 20, 1993, at (-140.5, -25.8, -8.6) \( R_E \). In association with this event, Pi-2 onsets occurred twice at 1717 UT and 1726 UT (both at Kakioka), while a negative bay in the H-component magnetogram at Tixie Bay, Russia, started around 1715 UT. The plasmoid signatures are evident in the ion and electron \( E-t \) diagrams (upper two panels of Fig. 4), the magnetic field data (upper four panels of Fig. 3) and the ion temperature and velocity data (lower three panels of Fig. 3) during a time period of 1729 to 1740 UT. Significant \( B_y \) fields were also present throughout the plasmoid, and the peak magnitude was comparable to the magnitude of the lobe \( B_x \) field. The bulk velocity increased stepwise at two separate times inside the plasmoid, corresponding to the times of southward turning of the magnetic field. The region outside of the plasmoid was the southern lobe, in which cold dense ions were observed (Yamamoto et al., 1994; Mozer et al., 1994; Hirahara et al., 1996). Because of the presence of the cold dense plasmas, the density in the lobe was higher than that in the plasmoid. The plasma flow properties in the lobe show the same signatures as mentioned in the previous example. Note, however, that the direction of changes in \( V_x \) is reversed because the spacecraft was in the southern lobe.

The lower six panels in Fig. 4 show the ion distribution functions in the plasmoid and its boundary. The simultaneously measured electron distribution functions are shown in Fig. 5. At time A, which corresponds to the outer boundary, the electron distribution shows a weak flat-top distribution in the antiparallel direction to the magnetic field as well as a heat flux component in the magnetic field direction. The ion distribution function reveals that cold ions of the lobe origin are heated perpendicularly, while a fast ion beam is streaming along the magnetic field.
Fig. 3. Same as Fig. 1, but the time period is from 1700 to 1800 on December 20, 1993.
Fig. 4. Ion and electron energy-time spectrograms and six examples of the ion distribution functions (lower six panels) in the plasmoid event on December 20, 1993. The ion distribution functions are shown in the B-C plane. The phase space density is scaled by color coding on logarithmic scale from $-12.5$ to $-17.5$ s$^3$/m$^6$ as shown on the right hand side. The times are shown by vertical red lines in the upper two panels as A (1729:07-19), B (1730:55-1731:07), C (1732:06-18), D (1734:42-54), E (1735:54-1736:06), and F (1738:54-1739:06).
Fig. 5. Electron distribution functions at the same times as shown in lower six panels of Fig. 4.
line. These electron and ion signatures are consistent with the features expected for slow-mode shocks (Saito et al., 1995). At time B, the cold ions have merged with the nearly isotropic hot component, but two components can be easily discriminated owing to incomplete thermalization. The electron distribution function also appears to consist of two components; low-energy electrons bi-streaming along the magnetic field line superimposed on an isotropic hot component. The bi-streaming electrons (red curve on the right hand in Panel B of Fig. 5) shows a flat-top distribution on one side (the antiparallel direction to the magnetic field), but a rather featureless distribution on the opposite side. At the next time C, the ion distribution function reveals that two beam-like distributions are superimposed on the isotropic hot component, while the electron distribution shows a flat-top distribution along the magnetic field line (in both the parallel and antiparallel directions) at lower energies and an isotropic distribution at higher energies. At times D through F, all the ion distribution functions clearly show the two beams counterstreaming along the magnetic field line, while the electron distribution functions show the same features as noted above. Each of the counterstreaming ion beams has strong anisotropy with the perpendicular velocity spread being a few times greater than the spread in the parallel direction. Note, however, that one of the counterstreaming beams is not necessarily similar to the other in terms of the shape and intensity. The velocity difference between the two beams is 1140 km/s (925 km/s), 1260 km/s (770 km/s), and 960 km/s (560 km/s) for the times of D, E and F, respectively, where the values in the parentheses are the local Alfvén velocities for reference. It should be noted that these counterstreaming ion beams are observed after the tailward bulk speed increased stepwise associated with southward turning of the magnetic field and intensification of the $B_y$ component.

3.3 January 15, 1994

Figure 6 shows magnetic field data and ion velocity moments (density, temperature and bulk velocity) during the time period of 1230 to 1330 UT on January 15, 1994, in which the spacecraft was located at (-96.2, -0.5, -1.9) $R_E$. A Pi-2 onset occurred at 1239 UT (at Kakioka) in association with this event. Different from the previous two examples, this example shows detection of a plasmoid event in the plasma sheet (see also the upper two panels of Fig. 7). At the beginning (1230 UT), the spacecraft was in the southern ($B_z < 0$) plasma sheet, then crossed the neutral sheet ($B_z = 0$) at 1235 UT, and remained in the northern plasma sheet with slow earthward flow until the encounter with the plasmoid. A hatched period of time is identified as the plasmoid. The magnetic $B_z$ field magnitude remained less than a few nT throughout the plasmoid, so that the spacecraft might have traversed near the central portion (current sheet) of the plasmoid. A flow reversal from earthward to tailward occurred at 1251:30 UT, which we identify as the signature of the plasmoid encounter. The tailward flow speed increased rapidly up to 600 km/s, maintained this value for about four minutes, and then increased stepwise to 900 km/s. The tailward flow is accompanied by a clear bipolar signature in the magnetic $B_z$ component. The magnitude of the magnetic $B_y$ field increased toward dawnward ($B_y < 0$) during the period of 1255 to 1259 UT. Because of the strong $B_y$ field, the total pressure during this period was significantly higher than in the ambient region. The ion temperature was 2–3 keV in the plasma sheet with slow earthward flow, and increased by a factor of 1.5–2 associated with the fast tailward flow (plasmoid). The ending of the plasmoid is ambiguous and somewhat arbitrary, followed by a long-duration post-plasmoid plasma sheet flowing tailward with high speeds. In the post-plasmoid plasma sheet, the total magnetic field at times decreased down to ~1 nT with fluctuations of the same order. This may be regarded as a crossing of diffusion regions.

The upper two panels of Fig. 7 shows ion and electron E-t diagrams, which reveal the presence of hot plasmas throughout the period shown here. The ion energy increased around 1253 UT, corresponding to the fast tailward flow associated with the plasmoid encounter. The ion energy spectra extended beyond the uppermost energy of the LEP measurement during a time period of 1302 to 1310 UT, in which the obtained ion density (see Fig. 6) might therefore
Fig. 6. Same as Fig. 1, but the time period is from 1230 to 1330 on January 15, 1994.
Fig. 7. Same as Fig. 4, but the observation corresponds to the previous figure. The times are shown by vertical red lines in the upper two panels as A (1254:42-54), B (1255:18-30), C (1255:42-54), D (1256:42-54), E (1257:18-30), and F (1258:06-18).
Structure and Kinetic Properties of Plasmoids and Their Boundary Regions

Fig. 8. Electron distribution functions at the same times as shown in lower six panels of Fig. 7.
be underestimated, and a gradual decrease in density might not be real.

The lower six panels of Fig. 7 show examples of the ion distribution functions in the $B$-$C$ plane at the times indicated in the upper two panels. At time A, shortly after the northward enhancement of the $B_z$ field (and just before start of the $B_y$ enhancement), the ion distribution functions show the presence of two components counterstreaming along the magnetic field line with reference to the convecting plasma frame. The velocity difference between the two beams is $\sim 1000$ km/s along the magnetic field line, while the local Alfven speed is 640 km/s. At time B, $\sim 30$ seconds before the peak of the $B_y$ field, the ion distribution function consists of a single hot component with anisotropy of $T_1 > T_i$. At time C, around the peak of the $B_y$ field, cold ion beams appear in the field-aligned direction to the hotter component. The velocity difference between the two components is 630 km/s, which is lower than the local Alfven speed of 1095 km/s, in this case owing to the large $B_y$ field intensity. Both components are heated perpendicularly. At times D through F, the ion distribution functions consist essentially of the two components counterstreaming along the magnetic field lines with reference to the convecting plasma frame. It is noted that the time E corresponds to the stepwise increase of the tailward velocity. The velocity difference between the two beams along the magnetic field line is 910 km/s (910 km/s), 1210 km/s (450 km/s), and 1140 km/s (480 km/s) for times of D through F, respectively, where the values in the parentheses are the local Alfven velocities for reference. The counterstreaming ion beams have the same features as noted in the previous example. At times E and F, one component streaming toward the magnetic field direction is obviously colder and more intense than the other. It should be noted that the $B_x$ values at these times are very small (0.25 nT for E, and 2.15 nT for F) with fluctuations of $\sim 1$ nT.

Figure 8 shows the electron distribution functions at the same times as shown in Fig. 7. Similar to the previous examples, the electron distribution functions appear to be the superposition of low-energy bi-streaming electrons and higher-energy isotropic electrons. The clear presence of the flat-top distribution is well correlated with appearance of the counterstreaming ion beams. (The field-aligned direction at time A is outside of the field of view of the LEP/EA-e instrument.) Therefore, field-aligned electrons and ions are likely to be of the same origin.

4. Discussion

We have presented three plasmoid events, of which the first two were observed in the lobe at distances of 70 $R_E$ and 140 $R_E$ downtail from the Earth, and the last one was observed in the plasma sheet at 96 $R_E$ downtail. Among various characteristic features associated with plasmoids, the most remarkable is the existence of two components of ions counterstreaming along the magnetic field lines. (However, it should also be noted that the region of hot plasmas of a single component also surely exist in the plasmoid (see Panel B in Fig. 7), but only in a small portion of the plasmoid.) Here we focus on discussion of possible formation mechanism(s) and its implication to the plasmoid structure. The counterstreaming ion beams have the following properties.

(a) At first, the “counterstreaming” is a fine structure inside the whole distribution function. Since there exists a significant magnitude in the magnetic $B_y$ and/or $B_z$ fields, the direction of the counterstreaming is dawnward/duskward and/or northward/southward with reference to the plasma frame convecting tailward with high speeds.

(b) These events are observed predominantly in the latter part of plasmoids after the southward turning of magnetic fields, but at times also around the leading part of the plasmoid. Their appearance is often associated with a stepwise increase of the tailward bulk velocity and intensification of the $B_y/B_z$ field magnitude. However, they are observed even near the neutral sheet ($B_x \sim 0$).
(c) Each beam has anisotropic distributions with the perpendicular temperature being several times higher than the parallel temperature.

(d) The two beams are not necessarily similar in terms of the shape of the distribution functions and the phase space density, though there are some cases in which they are similar.

(e) The velocity difference between the two components along the magnetic field line is as high as 1000–1500 km/s, which is much higher than the local Alfven speed, and at times, exceeds twice the Alfven speed. In the latter case, the counterstreaming ion beams could be pitch-angle scattered by ion cyclotron waves generated by resonant electromagnetic ion-ion instability, forming a shell-like distribution (see Panel B in Fig. 2).

(f) The appearance of the counterstreaming beams is well correlated with the presence of a flat-top distribution of electrons along the magnetic field line. Figure 9 generally shows possible models for formation of the counterstreaming beams. In model A, ion beams generated at a source region could be mirrored back by a region with stronger magnetic fields, forming the counterstreaming beams. Since the observations have shown that the perpendicular temperature of each beam is generally much higher than the parallel temperature, the source region would be in a region with weaker magnetic fields than the observation point. The magnetic diffusion (reconnection) region, or more generally the current sheet is a candidate for the source region. This model, combined with the velocity filter effect due to earthward and inward convection, has been applied to interpret the velocity-dispersed counterstreaming beams observed in the near-Earth plasma sheet boundary layer (Onsager et al., 1991). However, this model cannot simply explain the observed features, such as properties (b), (d) and (f).

In model B, reconnection occurs at two points on the same field line, forming closed field lines, and hence the counterstreaming ions. This two-point reconnection model has been suggested to interpret a stagnant plasmoid (Nishida et al., 1986; Kawano et al., 1996). Hoshino et al. (1996) has also reported evidence for this model with the GEOTAIL observations. An event as shown in Panel A of Fig. 7 can also be interpreted by this model. In this case, the flow prior to the plasmoid encounter was slow and earthward, which might be produced by reconnection at a distant neutral line. Then, there occurred a near-Earth reconnection, which could form closed loops in combination with the distant neutral line. In terms of this model with $B_z > 0$, the parallel component would be produced in the distant neutral line, while the antiparallel component would come from the near-Earth reconnection region.

As noted in (d), the two beams are not necessarily similar in terms of the shape of the distribution functions and the phase space density. From examination of a time sequence of the counterstreaming beams, we conclude that at least one of the two beams originated from cold ions in the lobe. The cold ions are heated and accelerated perpendicularly through slow-mode shocks (Omidi, 1995; Saito et al., 1995). The electron distribution functions in the downstream plasma sheet have a flat-top distribution along the magnetic field line (Feldman et al., 1985; Schwartz et al., 1987; Saito et al., 1995). The existence of backstreaming field-aligned ions in the upstream region from the slow-mode shock is well known. The velocity difference between the backstreaming and the incoming ions can reach up to twice the Alfven speed in the lobe. By using two-dimensional hybrid-code simulations, Omidi (1995) has shown the presence of backstreaming ions in the downstream region as well, and the downstreaming and backstreaming ions constitute the counterstreaming ions along the magnetic field line. His results are quite similar to the observed distribution functions of the counterstreaming ions as shown in Figs. 2, 4 and 7. Though Omidi has not provided a physical explanation for the presence of backstreaming ions in the downstream region, they might be the ions reflected from a wall used in the simulation. Of course, such a wall does not actually exist in nature, but instead, there may exist ions streaming along the magnetic field line from slow-mode shocks on the opposite side of the plasma sheet -
lobe boundary. These ions might furthermore be heated by the current-sheet acceleration in the neural sheet. This is model C in Fig. 9. This model can explain all the features as noted above; (a)–(f).

One problem with model C is that there are many cases (for example, the event on December 20, 1993) in the distant tail in which the plasma density is lower in plasmoids than in the lobe, and hence the slow-shock condition cannot be satisfied locally. The lower density in plasmoids may reflect lower density in the near-Earth lobe region, where the slow-mode condition might be satisfied. On entering the plasma sheet across the slow-mode shocks, electrons are accelerated by electrostatic potential drops along magnetic field lines, while ions are decelerated by the same potential drops, but heated and accelerated perpendicularly, so that the competing processes of parallel deceleration and perpendicular heating may decide how many cold ions can enter the plasma sheet (plasmoid).

Model C implies that the field line is open, and both ends are connected to the lobe field line. This is reasonable for the post-plasmoid plasma sheet, but the property (b) cannot be overlooked as an important feature pertaining to the plasmoid structure. It has been stated from
ISEE-3 observations that a plasmoid is embedded with isotropic hot plasmas, which was initially regarded as evidence of closed field lines. In the present observations also, isotropic distributions of electrons and ions are surely present at higher energies, but it is noteworthy that the ion beams as well as the low-energy bi-streaming electrons are superimposed on the isotropic component. Then, the isotropic hot component is gradually diffused out, and the counterstreaming beams become more and more prominent. The appearance of the counterstreaming ions is associated with a stepwise increase of the bulk velocity. In other words, plasmas on these open field lines with negative $B_z$ flow faster than the core part of the plasmoid, so that they might be draped around the core part, and at times intensified due to compression. Since the period of southward field is generally longer than that of the northward field in plasmoids, this implies that a majority of field lines are open. The length of magnetic field lines might be so short that there would not be enough time to thermalize the two ion components completely. Therefore, there is no reason for a helical structure in the region in which the counterstreaming ions are observed, even though there are significant $B_y$ fields. The GEOTAIL observations have revealed that the lobe convection in the $Y$ direction is controlled by the IMF-$B_y$ (Nishida et al., 1995). For example, under IMF-$B_y > 0$, the convection in the northern (southern) lobe is duskward (dawnward), and hence the $B_y$ field may be generated in association with reconnection of these field lines, with a convection component in the $Y$ direction. The good correlation between $B_y$ and $V_y$, as shown in Figs. 1 and 3, may suggest such a generation mechanism.

Let us consider the situation of near-Earth reconnection for plasmoid formation. Initially, the field lines in the plasma sheet begin to be reconnected and form flux ropes (or, closed loops) in combination with a distant neutral line. The structure reformaion may generally result in flux ropes, since non-negligible magnitude of the $B_z$ field is usually present in the plasma sheet. In this period, however, both ends of the flux ropes are connected to the Earth, and hence the flux ropes cannot move tailward freely. The flux ropes somewhere have to be reconnected to the lobe field line with the opposite direction so as to be released from the Earth (Hughes and Sibeck, 1987). Then, the lobe field lines begin to be reconnected, and these field lines are obviously open and do not form flux ropes. When the lobe field lines begin to be reconnected, the tailward flow speed is increased from the initial phase in which the plasma-sheet field lines were reconnected, because it is generally determined by the Alfvén velocity in the region of field lines to be reconnected. As time proceeds, the reconnection rate may further increase. Figure 10 shows a schematic drawing of the plasmoid magnetic structure on the basis of the above discussion with model C. The field lines in the core part had been originally of the plasma sheet, and both ends had been connected to the Earth, until the near-Earth reconnection occurred, forming closed-loops and/or flux ropes. The distribution functions of electrons and ions in this part might be hot and isotropic. Observationally, this core part may constitute only a small part of the plasmoid. Since the tailward flow speed becomes faster in association with the presence of the counterstreaming ion beams along open field lines (model C), these open field lines are draped around the core part of the plasmoid. The compression due to the draping may increase the field intensity. It should be noted that the slope from north to south in the bipolar $B_z$ variation is generally steep, which can also be explained by the compression of the draped field lines.

Based on the above model, we would like to emphasize that the field lines are open even in the regions in which the field lines have hitherto been considered as closed loops and/or flux ropes. In other words, the region of closed loops and/or flux ropes constitute only a small portion of plasmoid, if we take a definition of plasmoid as the region starting from a northward increase of the $B_z$ field associated with the appearance of fast tailward convecting plasmas. This does not necessarily imply that the region of closed loops and/or flux ropes is small. However, the flow velocity in much of such a region may be slow and/or even earthward until the effect of the fast tailward bulk flow caused by reconnection of the lobe field lines arrives there (e.g., see the third example on January 15, 1994).
Finally, what is the physical process that determines the velocity difference between the two ion beams along the magnetic field line? Can the cross-shock potential quantitatively explain the flat-top (shoulder) energy in the electron distribution functions? These issues are new and challenging problems, in both an observational and a theoretical sense, to be studied in the future. According to a simple slow-shock model, the velocity difference between the two ion beams can reach twice the Alfvén velocity based on the $B_z$ magnitude and the density in the lobe, but the observed values are much higher than this estimation. Accelerations in the reconnection region may play an important role for determination of the ion velocity difference as well as the electron flat-top energy. Observationally, temporal/spatial variations of the above features in the electron and ion distribution functions in the post-plasmoid plasma sheet may provide a key clue for this problem.

5. Conclusion

GEOTAIL observations have revealed several new features of plasmoids as follows:
1. Prior to plasmoid arrival, the $Z$ component of convection in the lobe is reversed (pushed away from the plasma sheet), while the convection toward the plasma sheet is enhanced after the plasmoid passage.
2. Cold ions in the lobe flow into the plasmoid, and they are heated and accelerated around the outer boundary. Electrons are accelerated along magnetic field lines, showing flat-top distribution functions (or, abrupt change in the slope) in the downstream (plasmoid) region. These features are consistent with the signatures of slow-mode shocks.
3. Cold ions of lobe origin, which have been considerably heated perpendicularly, merge into hot plasmas in the plasmoid, but remnant features are clearly recognized even deep inside the plasmoid. This implies that the thermalization is not fast enough, or the time is not long enough, to merge the two components into a single isotropic distribution.

4. The ion beams counterstreaming along magnetic field lines are often observed predominantly in the latter part of the plasmoid after southward turning of the magnetic field. Electrons observed simultaneously show flat-top distribution functions along magnetic field lines. This phenomenon is seen even near the neutral sheet ($B_z = 0$).

5. At least one of the two ion beams mentioned above is most likely of the same one as mentioned in items (1) and (2). This implies that most field lines in plasmoids are connected across short distances to the lobe field lines.

We have discussed possible models for the counterstreaming ion beams, and suggested the implication of these beams to the structure of plasmoids (see Fig. 10). New, interesting problems for quantitative understanding of the above features have also been addressed. Data shown in this paper were acquired in the middle to distant tail region. In this tail region, intervals other than those presented here have shown similar features, but the number of events is still small. Whether the data presented in this paper represent features common to all plasmoids, or how often these features are observed, requires further work. The dependence on downtail distance is also important for understanding the formation and evolution of plasmoids. Results from these studies are expected to be reported in the future.

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