Observations of nonadiabatic acceleration of ions in Earth's magnetotail

L. A. Frank and W. R. Paterson
Department of Physics and Astronomy, University of Iowa, Iowa City

M. G. Kivelson
Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics
University of California, Los Angeles

Abstract. We present observations of the three-dimensional velocity distributions of protons in the energy range 20 eV to 52 keV at locations within and near the current sheet of Earth's magnetotail at geocentric radial distances 35 to 87 RE. These measurements were acquired on December 8, 1990, with a set of electrostatic analyzers on board the Galileo spacecraft during its approach to Earth in order to obtain one of its gravitational assists to Jupiter. It is found that the velocity distributions are inadequately described as quasi-Maxwellian distributions such as those found in the central plasma sheet at positions nearer to Earth. Instead the proton velocity distributions can be categorized into two major types. The first type is the "lima bean" shaped distribution with high-speed bulk flows and high temperatures that are similar to those found nearer to Earth in the plasma sheet boundary layer. The second type consists of colder protons with considerably lesser bulk flow speeds. Examples of velocity distributions are given for the plasma mantle, a region near the magnetic neutral line, positions earthward and tailward of the neutral line, and the plasma sheet boundary layer. At positions near the neutral line, only complex velocity distributions consisting of the colder protons are found, whereas both of the above types of distributions are found in and near the current sheet at earthward and tailward locations. Bulk flows are directed generally earthward and tailward at positions earthward and tailward of the neutral line, respectively. Only the high-speed, hot distribution is present in the plasma sheet boundary layer. The observations are interpreted in terms of the nonadiabatic acceleration of protons that flow into the current sheet from the plasma mantle. For this interpretation the hot, "lima bean" shaped distributions are associated with meandering, or Speiser, orbits in the current sheet. It is suggested that the colder, lower-speed proton velocity distributions are the result of fractional or few gyromotions before ejection out of the current sheet, but this speculation must be further investigated with appropriate kinetic simulation of trajectories.

Introduction

The importance of nonadiabatic acceleration of plasma in the weak magnetic fields near the midplane of the magnetotail in the presence of a convection electric field has been recognized for more than 2 decades [Speiser, 1965a, b]. Because of their larger Larmor radii of motion relative to those of the electrons, ions can be expected to exhibit significantly more acceleration in the current sheet in the magnetotail midplane and should be observed as high-speed ion streams after their exit into the stronger magnetic fields surrounding the current sheet. The first observations of high-speed ion streams in the magnetotail were reported by Akasofu et al. [1973] from analysis of plasma observations from Vela spacecraft at geocentric radial distances of about 18 RE. Because these measurements were taken from a single spacecraft for a given example, it was not clear whether these high-speed flows were the signature of motion of the entire plasma sheet in the magnetotail or of the existence of boundary layers between the plasma sheet and the magnetotail lobes. Simultaneous observations of these high-speed ion flows with two IMP spacecraft were later used to firmly establish that these flows were generally restricted to a boundary layer, now often referred to as the plasma sheet boundary layer [DeCosta and Frank, 1979].
Thus the overview of the magnetotail was, and still is, a thin current sheet [Ness, 1965] imbedded in a thicker, hot plasma sheet at the magnetotail midplane with the frequent appearance of high-speed ion streams in a boundary layer between the plasma sheet and the relatively plasma barren lobes. The observations that contributed to this overview were acquired at geocentric distances inside the lunar orbit.

Numerical calculations of the trajectories of charged particles in a model of magnetic and electric fields in the current sheet showed clearly that ions could be accelerated from energies of several hundreds of eV to energies in the range of tens of keV [Lyons and Speiser, 1982]. In fact the computed velocity distributions from current sheet acceleration exhibited the same qualitative "lima-bean" shapes as reported by Decoster and Frank [1979] for the plasma sheet boundary layer. An additional important milestone in investigations of the transport and acceleration of plasmas in the magnetotail was the discovery of the plasma mantle in the high-altitude polar magnetosphere by Heos 2 as reported by Rosenbauer et al. [1975]. That is, a likely source of the plasma flowing into the magnetotail current sheet had been identified. These plasmas are magnetosheath plasmas that have directly entered the polar magnetosphere and are flowing along the geomagnetic field. As these ions in the plasma mantle flow along the magnetic field to tailward positions, dispersion is expected, and was observed, in the ion spatial and velocity distributions. The cross-tail electric field causes convection of these mantle plasmas toward the current sheet. The presence of the plasma mantle in the magnetotail was also detected with lunar-based Apollo instrumentation [Hardy et al., 1979].

There is now extensive literature concerning the spatial and temporal morphology of ion beams in the plasma sheet and its boundary layer [Eastman et al., 1984; Huang et al., 1987; Takahashi and Hones, 1988; Baumjohann et al., 1990]. These observations were taken at geocentric radial distances of about 20 R_E or less. The primary feature of the reported ion beams is the most frequent occurrence of magnetically field-aligned earthward flows. There is also extensive theoretical modeling to obtain the characteristics of the ion velocity distributions within the plasma sheet and its boundary layer that arise from nonadiabatic motion within the current sheet [Martin and Speiser, 1988; Chen and Palmadesso, 1986; Büchner and Zelenyi, 1989; Ashour-Abdalla et al., 1992, 1993]. The theoretical approaches and results have been recently reviewed by Chen [1992]. To our knowledge there are no reported detections of ion velocity distributions that exhibit the features of nonadiabatic acceleration directly within the current sheet in the present literature. Such ion velocity distributions should firmly establish the link between the incoming mantle plasmas and the ion beams exiting the current sheet. Our present purpose is to provide these previously elusive velocity distributions with plasma observations with the Galileo spacecraft.

We report a 10-hour series of observations of the three-dimensional velocity distributions of ions with the plasma instrumentation on board the Galileo spacecraft at distances ranging from about 87 to 35 R_E in the magnetotail. The measurements were fortuitous in that the spacecraft trajectory repeatedly entered the plasma sheet in response to fluctuations in the solar wind direction during a period of abundant geomagnetic activity. These circumstances allowed sampling of both high-speed earthward and tailward flows, mantle plasmas, and ion acceleration in the current sheet. We interpret these observations in terms of nonadiabatic acceleration of ions in the current sheet.

**Orbit, Instrumentation, and Geomagnetic Activity**

During the first of two flybys of Earth in order to gain orbital assistance to its final destination, Jupiter, the Galileo spacecraft provided a series of observations of fields and charged particles in the magnetotail. The trajectory of the spacecraft is shown in Figure 1 in the geocentric solar magnetospheric (GSM) coordinate system. Nominal positions for bow shock and aberrated magnetopause positions are shown. The magnetopause position is derived from previously reported models [Petrinec et al., 1991; Fairfield, 1971] and is consistent with observations with Explorers 33 and 35 [Howe and Binsack, 1970].

![Figure 1. The trajectory of the Galileo spacecraft in Earth-centered solar-magnetospheric coordinates. The three-dimensional proton velocity distributions obtained during the period 0400-1400 UT are used in the present analysis of ion dynamics in the magnetotail.](https://example.com/galileo_traj.png)
A set of spherical-plate electrostatic analyzers is included in the plasma instrumentation (PLS) on board the Galileo spacecraft. This instrument is described in detail by Frank et al. [1992]. The three-dimensional velocity distributions of positive ions and electrons are measured over the energy-per-unit-charge \((E/Q)\) range 0.9 V to 52 kV. These electrostatic analyzers provide coverage of the particle velocity vectors in the latitude ranges 14° to 171° and 9° to 166° with respect to the spacecraft spin axis for electrons and positive ions, respectively. Each of these fan-shaped fields of view is divided into seven angular segments with the positioning of the same number of sensors at the exit apertures of the electrostatic analyzers. For the mode of instrument operation during the Earth flyby the electron and ion velocity distributions were each sampled in 56 directions, i.e., the above seven latitudinal segments in each of eight spin sectors. For each direction, 24 \(E/Q\) passbands were used to cover the range 20 V to 52 kV. Thus 1344-sample velocity distributions were acquired with a repetition rate of about 60 s. These 1344-sample velocity distributions are used in the present paper to derive plasma moments, e.g., density, bulk flow, and temperature. However, it is found that the temporal variations of the ion directional intensities within the current sheet require that the best possible temporal resolution be employed to minimize temporal aliasing of the three-dimensional velocity distributions. For determinations of these ion velocity distributions, 672 samples obtained during a single spacecraft spin period of 19 s are used. These samples are gathered in 56 directions, with 12 passbands within the above \(E/Q\) range in each direction. In addition, the electron and ion velocity distributions over the \(E/Q\) range 0.9 to 15 V were sampled once each 240 s and employed to determine the spacecraft potential [Frank et al., 1993]. Because of thermal constraints the mass spectrometers within the plasma instrument could not be operated in an effective manner. However, the upper limit for the fraction of the density that can be attributed to the presence of ions with \(M/Q\) greater than 1 ranges from 0.1 to 0.25 for this series of observations [Frank et al., 1993]. Thus the composition of the ion plasmas is identified as predominantly protons. The proton velocity distributions and plasma moments reported here are corrected for the effects of the spacecraft potential using the Liouville theorem.

Kivelson et al. [1993] have previously published an extensive summary of observations of the solar wind with IMP 8 and of geomagnetic activity with ground-based stations during the Galileo traversal of the magnetotail. The solar wind density and speed were about 7 cm\(^3\) and 350 km/s, respectively, during the period 0000 UT to 1400 UT. At 1418 UT an interplanetary shock crossed the IMP 8 orbital position in the solar wind upstream from Earth. During the above period the Interplanetary magnetic field was about 5 to 6 nT in magnitude. The component \(B_x\) was generally positive or nearly 0 nT until about 0440 UT, after which it could be characterized as about -2 to -3 nT prior to the arrival of the interplanetary shock, with intermittent periods of positive \(B_x\). This interval of southward interplanetary fields was associated with the occurrence of several substorms and auroral electrojet intensifications during the period ~ 0440 to 0930 UT. Provisional values for the AE index [Kivelson et al., 1993, Figure 6] range from about 100 to 400 nT during the interval of present interest, 0400 to 1400 UT, and indicate that substantial magnetic activity occurred. The fortuitous occurrence of this geomagnetic activity is reflected in the complex and dynamic plasmas which were recorded with the Galileo spacecraft.

**Observations**

Energy-time (E-t) spectrograms for several of the sensors in the electrostatic analyzers are shown in Plate 1 for the period 0400 to 1400 UT. The responses of three ion sensors (upper panels) and one electron sensor (lower panel) are displayed as functions of UT and the logarithm base 10 of the energy-per-unit-charge \((E/Q)\). The sensor responses are color coded as shown by the color bars. At the top of the plate are given the spacecraft positions in the Earth-centered solar magnetospheric (GSM) coordinate system. Because the spin axis of the spacecraft is nearly aligned with the spacecraft-Sun direction, sensor P1 is responding to ions with velocity vectors generally directed toward the Sun and Earth, P4 records ion intensities in the plane perpendicular to the spacecraft-Sun direction, and P7 is responding to ions with velocity vectors directed away from the Sun and Earth. The field of view of electron sensor E4 is directed parallel to that of P4. The responses of all four sensors are summed over the spacecraft spin period of 19 s. Inspection of the ion E-t spectrograms finds the following features, for example, (1) a high-speed beam of ions at about 10 keV directed tailward at 0655 UT, (2) a low-energy ion distribution flowing tailward during 0900 to 1040 UT, and (3) an earthward directed beam of 10–keV ions at 1340 UT. Our following analysis of the three-dimensional ion velocity distributions shows that these three examples are taken in (1) the vicinity of the current sheet, (2) the plasma mantle, and (3) the plasma sheet boundary layer, respectively.

An overview of plasma parameters and of the magnetic fields with the Galileo magnetometer [Kivelson et al., 1992] is given in Figure 2. In this paper all vectors are given in GSM coordinates. In the upper three panels of Figure 2 are shown the proton densities, temperatures, and bulk flow speeds. In the lower four panels are displayed the components of the magnetic field vector and the field magnitude. The vertical lines indicate crossings or approaches to the current sheet as determined by reversals or near nulls, respectively, in the \(B_x\) component of the magnetic field and a coincident decrease of field magnitudes to values of several nanoteslas or less. At this point in the analysis there is no unique signature of the current sheet crossings in the plasma parameters displayed in Figure 2. The densities and temperatures...
Plate 1. Energy–time spectrograms for the spin–averaged responses of three ion sensors (upper three panels) and one electron sensor (lower panel) of the electrostatic analyzers on board the Galileo spacecraft during the passage through Earth's magnetotail on December 8, 1990. Sensors P1 and P7 are viewing positive ions with velocity vectors directed approximately earthward and tailward, respectively. Sensors P4 and E4 are viewing intensities in a plane almost perpendicular to the Earth-Sun direction. The counts accumulated during a total of eight sample periods, or a total sample time of 1.28 s, are color coded according to the logarithmic scales shown in the plate.

clearly do not offer a unique signature of the current crossings. The speeds do increase at the current sheet crossings but also display maxima at other locations, e.g., at 1340 UT.

The three components of bulk flow are shown in the upper three panels of Figure 3. The errors due to counting statistics, i.e., $\sigma$ (standard deviation), are shown at the top of each panel. These statistical uncertainties seldom exceed $\pm 50$ km/s and are typically lesser by factors of 2 or 3. As expected from previously published literature the flows are dominated by the component along the $X$ axis. Tailward and earthward flows are seen in the top panel of Figure 3. Flows in excess of 100 km/s are present at the current sheet crossings and at a
FRANK ET AL.: NONADIABATIC ACCELERATION OF IONS

FIGURE 2. Overview of plasma parameters and magnetic fields. The proton densities, temperatures, and bulk flow speeds are given in the upper three panels. The components and magnitudes of the magnetic field are shown in the lower four panels. The vertical dashed lines are used to designate crossings of the magnetotail current sheet that are identified on the basis of observations of the magnetic field. The spacecraft was located near the current sheet during the interval 1200-1240 UT.

considerable number of other magnetotail locations. For some of the current sheet crossings the components of flow along the Y axis are in the range of 100 km/s. The sign of this component is negative, indicating dusk-to-dawn flow. Occasionally the Z component is in the range of 50 to 100 km/s but is generally lesser than the X and Y components. The plasma moments and magnetic field parameters provide an overview of the diverse plasma regions encountered along the Galileo trajectory at these distances in the magnetotail.

The pressure balance during this series of observations in the magnetotail is summarized in Figure 4. The upper panel gives the sum of the electron and proton thermal pressures, and the magnetic field pressure is summarized in the second panel. The total pressure (third panel) indicates that the various regions in the magnetotail were in a condition of static equilibrium, even though substantial substorm activity was occurring. The ratio of the plasma pressure to magnetic pressure, $\beta$, is shown in the bottom panel. For the current sheet crossings, $\beta$ is typically in the range of 3 to 20 with the exception of the crossing centered at 0720 UT. For this current sheet crossing, $\beta \approx 1000$ and is found in a region at or very near the neutral line as identified with the proton velocity distributions presented here.

It is important to note that we have examined all of the velocity distributions for the 10-hour interval in the magnetotail at these intermediate distances. It is somewhat unexpected that there was no detection of hot, quasi-Maxwellian ion velocity distributions that are the signature of the central plasma sheet. Such plasmas were detected at lesser radial distances, $<35 R_E$, and are the topic of another paper.

In order to provide some organization to our discussion of the diverse velocity distributions we first present observations within the plasma mantle, because these plasmas are believed to be the one of the principal sources of ions that are accelerated in the current sheet. A selection of velocity distributions in and near the current sheet follows. Finally, the proton velocity distributions in the plasma sheet boundary layer are examined as the product of acceleration in the current sheet.

Plasma mantle ions are encountered during the period 0900 UT to about 1040 UT (see Plate 1). The densities decrease with increasing time, and the temperatures remain more or less constant, as shown in Figure 2. Tailward flow speeds are about 100 km/s. The magnetic field is primarily tailward, and hence the spacecraft is south of the position of the current sheet. An ion velo-
ity distribution for the beginning of the above interval is shown in Figures 5a and 5b. Slices of the velocity distribution in the $V_x-V_y$ and $V_x-V_z$ planes are shown. In this figure and following ones the projection of the direction of the magnetic field is shown for each plane. The lengths of the arrows are not proportional to the field components, which are given in the figure legends. The same velocity distribution is shown in Figures 5a and 5b but with different scales for the coordinates. The scale in Figure 5a is chosen to be identical to that used for the proton velocity distributions in the current sheet and plasma sheet boundary layer that are shown in the following figures. Comparison of the plasma mantle distribution with the distributions associated with the current sheet acceleration provides a good visual impression of the large acceleration that is required for the slow, cold mantle ions to be the source of the high-speed, hot ions. Figure 5b displays the plasma mantle distribution with a coordinate scale that shows its features. These primary features are the larger $T_3$ relative to $T_1$, bulk flow in the range of 100 km/s, density of about $10^9$ cm$^{-3}$, and average $kT$ of ~100 eV that are to be favorably compared to those of the plasma mantle ions observed in the distant polar magnetosphere with Heos 2 [Rosenbauer et al., 1975].

Perhaps the simplest crossing of a current sheet occurs during the interval centered at 1122 UT (see Figure 2). Examination of the magnetic fields alone gives the impression of passage of the spacecraft from the southern magnetotail lobe, across the current sheet, and thence into the northern lobe. However, the proton densities remain relatively high during this sequence of events. The proton velocity distributions in the $V_x-V_z$ plane are shown in Figure 6. First of all, note that there are no quasi-Maxwellian plasmas that are usually associated with the central plasma sheet. The temporal variations of the velocity distributions are rapid on time scales of tens of seconds or less. For the distribution in Figure 6b, for example, substantial variations occurring between the sampling for half planes $+V_z$ and $-V_z$ are evident. Remember that the spin axis of the spacecraft is approximately along the $V_x$ axis, and with a spin period of 19 s, each of these two half planes is sampled within a time period of 9.5 s. The velocity distributions in Figure 6b are typical of those found within the plasma sheet boundary layer. Besides the obvious complexity of the proton velocity distributions in Figure 6 there are several notable features. There are cold ion beams with bulk speeds of about ~200 km/s in the $Z$ direction that are detected before and after the current sheet crossing (see Figures 6a and 6i, j, and k, respectively). Another recognizable feature of these velocity distributions is the "lima bean" shaped distributions that have been previously found in the plasma sheet boundary layer at dis-
Figure 6. A series of velocity distributions in the $V_x-V_z$ plane for a rapid crossing of the current sheet as the magnetotail moves southward across the spacecraft position in response to a southerly change of the solar wind direction. The velocity distributions exhibit the presence of a high-speed velocity distribution that is mixed with slower and colder beams. The flow is directed earthward.

Let us return to the cold ion beams along the $-V_z$ axis that are seen in Figures 6a, 6i, 6j, and 6k. Although there is no apparent motion of these cold ions along the $X$ axis as expected for plasma mantle ions, the consideration of the sampling of the ion velocity distributions with respect to the sensor fields of view shows that the lack of a $V_x$ component could be an artifact of the measurement. Figure 7 shows the sampling of the ion distributions in the three Cartesian planes passing through the origin. The centers of the bins in velocity space are shown. The coordinates are referenced to the spacecraft spin axis, but these are nearly the solar magnetospheric coordinates. For the cold ions with flow nearly along the $Z$ axis it is possible that there is an $X$ component with magnitude in the range ~50 km/s that would not be re-
Figure 7. Sampling of the velocity distributions in three Cartesian planes in the solar magnetospheric coordinate system. The spacecraft spin axis is aligned nearly parallel to the X axis. The samples are taken within an elevation angle range of ±22.5° with respect to the $V_x-V_y$ and $V_x-V_z$ planes as the analyzers are stepped through their $E/Q$ passband sequence during a 45° rotation of the spacecraft.

solved with the angular resolution of the plasma instrument [see also Frank et al., 1992, Table 1]. It is also important to note that these cold ion beams, and those shown in following figures, are often sampled in only several velocity–space bins. Thus the thermal speeds for these cold beams as shown by the interpolated contours represent maximum thermal speeds. The reason for the large $V_z$ component of flow during the current sheet crossing in Figure 6 is the southerly deflection of the solar wind of about 5° during the period of ~1020 to 1050 UT as observed with IMP 8 upstream from Earth [Kivelson et al., 1993]. For the observed solar wind speed of about 350 km/s the transport delay from IMP 8 to Galileo is about 25 min. Thus the large $V_z$ component of the plasma mantle flows as seen in Figure 6 is most probably due to the deflection of the magnetotail in response to the fluctuation in the direction of the solar wind ion flow. For a $V_z$ component of about -200 km/s the corresponding combined thickness of the plasma sheet boundary layers and current sheet is about 8 R_E.

The proton velocity vectors in and near the current sheet as shown in Figure 6 are directed earthward, and thus are the signature of acceleration at positions tailward of the Galileo spacecraft. Velocity distributions at a farther geocentric radial distance, about 70 R_E, during the time interval centered at 0720 UT are shown in Figure 8. There are two immediately distinguishable differences in these observations relative to those displayed in Figure 6: the bulk flows are slower, and the scalar magnetic field is lesser (see Figures 2 and 3). The velocity distributions are also dramatically different. The two consecutive samples of the three-dimensional velocity distributions shown in Figure 8 find that the higher speed "lima bean" velocity distributions are absent and that a complex system of colder beams is present. The replication of the major features of the two consecutive samples shows that there is not a great amount of time aliasing. The velocity distributions appear to be unaffected by the presence of the weak magnetic field. On the basis of the weak magnetic field, the absence of the high-speed beams, and the complex assemblage of the relatively cold beams shown in Figure 8 we interpret these observations as those corresponding to the initial acceleration of plasma mantle ions in the proximity of the magnetotail neutral line.

If this is the case, then high-speed tailward flowing ions could be expected at positions downstream from the neutral line. Such an example of tailward flows is shown in Figure 9 for the period centered at 0704 UT (see Figures 2 and 3). Three consecutive samples of the velocity distributions each in the $V_x-V_y$ and $V_x-V_z$ planes are displayed. The chronological order of sampling the half planes as the spacecraft rotates about its spin axis is also identified. The familiar lima bean velocity distributions at speeds in the range of ~1000 km/s are evident, but the direction of these high-speed ions is now tailward and to be compared to the earthward flow of the such ions at positions nearer Earth. In addition, the angular distributions appear to be most frequently asymmetric with respect to the magnetic field. This effect is most readily seen in the $V_x-V_y$ plane and is interpreted as the gyro-bunching of ions. In addition to the high-speed ion distribution there is a colder distribution with lesser tailward speeds, about 200 to 500 km/s.

It is possible to gain insight into whether these cold proton velocity distributions are in a ring distribution in phase space or are gyrobunched by slicing the velocity distribution in the $V_y-V_z$ plane at $V_x = -200$ km/s. These velocity distributions are shown in Figure 10. The magnetic field is approximately perpendicular to this plane. Examination of these slices of the velocity distribution clearly shows that these are not simple ring distributions. The appearance of several beams could mean that there are several gyrobunched beams. However, it should be remembered that the fields of view of the sensors are rotating in this plane and sample the distribution in 19 s. Thus if the gyrobunching of a single beam is characterized by relatively small changes in phase with
Figure 8. Proton velocity distributions for a region of low magnetic field strength near the neutral line in the current sheet. The velocity distributions indicate the presence of several cold ion beams and the absence of high-speed, hotter distributions that are observed earthward and tailward of this position.

respect to the spacecraft, as would occur with modest motion of the upstream injection point, for example, then the multiple beams seen in Figure 10 can be accounted for by a single beam. We favor the interpretation of these observations as being due to a single gyrobunched beam at a constant speed (radius) in the $V_x-V_z$ plane because the velocity distributions are sampled in ~19 s, which is comparable to the proton gyroperiod. There is some evidence of a second gyrobunched beam at lesser speeds in the contours shown in Figure 10. On the other hand, the contours can also be interpreted in terms of a ring distribution with severe intensity variations during the instrument sampling period. At present the identification of the velocity distributions of the cold ions as ring or gyrobunched is not decisively concluded.

We note that the general character of the ion velocity distributions for tailward and earthward flows is very similar. For example, the velocity distributions for the current sheet crossing in the interval centered at 1310 UT (see Figure 3) exhibit lima bean and cold components similar to those shown in Figure 9. In fact, at the current sheet crossings the velocity distributions for tailward flowing protons are the qualitative mirror images of those for the earthward flowing protons, with the exception of the velocity distributions observed in the close vicinity of the neutral line at 0720 UT (see Figure 8). With this persistent feature in mind, examination of the $V_x$ component of bulk flow shown in Figure 3 finds that the neutral line was earthward, then tailward, and again earthward of the spacecraft position during the period 0700 to 0820 UT; was tailward during 1120–1200 UT; and was earthward during 1235–1310 UT. Not unexpectedly, the neutral line moved at least tens of Earth radii during this substorm period.

Our final example of the three-dimensional velocity distributions is taken in the plasma sheet boundary layer. It is useful to examine Figures 2 and 3, which show a high-speed, earthward flow centered at about 1340 UT. In contrast to our previous examples, this high-speed flow does not occur at a current sheet crossing. The field is relatively strong, about 10 to 12 nT, and there is no reversal in the $B_x$ component. The spacecraft is south of the current sheet. An example of the proton velocity distribution within the boundary layer is shown in Figure 11. The velocity distributions in the $V_x-V_y$ and $V_x-V_z$ planes display typical lima bean shapes that have been observed in the plasma sheet boundary layer at distances nearer Earth with such spacecraft as IMP and ISEE 1. These slices through the distributions are taken at $V_z = 0$ and $V_y = 0$, respec-
Discussion and Summary

We have presented the results from our analysis of the three-dimensional proton velocity distributions which were observed during the passage of Galileo through Earth's magnetotail on December 8, 1990, during a period of substantial substorm activity. The analysis was limited to a 10-hour period during which the spacecraft traveled from a radial distance of 86.5 $R_E$ to 35.3 $R_E$. The proton number densities, temperatures, and bulk flow velocities showed that several plasma regions were encountered in the magnetotail, including the plasma mantle, the magnetotail lobe, and the plasma sheet boundary layer. However, these plasma moments do not reveal the most important result of the observations. That result is the finding that none of the velocity distributions, with the possible exception of the plasma mantle, exhibited the features of a quasi-Maxwellian plasma. In fact, the velocity distributions can be generally described as mixtures of beams with different speeds and temperatures and with frequent gyrbunching. Even though the ion velocity distributions are complex and not accurately described as convecting, isotropic Maxwellian plasmas, the moments provide an accurate assessment of number densities and plasma pressures. Because the velocity distributions are non-Maxwellian, the temperature is to be interpreted as a measure of the average ion kinetic energy in the rest frame. The moment for ion bulk flow is useful in identifying net tailward and earthward fluxes of ions in the vicinity of the
current sheet, regardless of the nongyrotropy of the velocity distributions.

The velocity distributions shown in the previous section are extremely complex and cannot be reasonably interpreted in terms of adiabatic theory for which the guiding center approximation is valid. We interpret the velocity distributions in terms of the nonadiabatic motion of the ions in the magnetotail current sheet. This interpretation is principally guided by the previous theoretical work by Speiser [1965a], Cowley [1978], Lyons and Speiser [1982], Chen and Palmadesso [1986], and Ashour-Abdalla et al. [1992, 1993]. A simple, idealized interpretation of the present observations is offered in Figure 12. The circled numbers identify the general location of the measurements of three-dimensional velocity distributions shown in the previous section. The plasma mantle is the source of the ions that are accelerated in the current sheet. For simplicity the current sheet is shown as a slab bounded on the top and bottom by the two magnetotail lobes. The magnetic field is assumed to reverse in the X direction in a region of weak magnetic fields in the center of the current sheet. The region tailward of the neutral line is also shown in Figure 12. This region is associated with the detection of tailward streaming that is similar in other features to the earthward moving beams on the earthward side of the neutral line.

The parameter of adiabaticity, κ, identified by Büchner and Zelenyi [1989] can be used to determine whether the ion motion is expected to be nonadiabatic. This parameter is defined as the square root of the ratio of the minimum radius of curvature of the magnetic field lines to the ion Larmor radius. For κ < 1, the motion is ex-

---

**Figure 10.** Proton velocity distributions in the \( V_x - V_z \) plane for \( V_x = -200 \text{ km/s} \). These two velocity distributions correspond to two velocity distributions shown in Figure 9.

**Figure 11.** An example of the velocity distributions observed in the plasma sheet boundary layer. The cold ion beams are not detected within the high-speed, hot velocity distributions with the "lima bean" shape.
Figure 12. A simplified diagram for a possible interpretation of the complex ion velocity distributions observed with the Galileo spacecraft in terms of nonadiabatic acceleration in the magnetotail current sheet.

The observed range of thermal speeds of the plasma mantle ions, 100 to 200 km/s, the Larmor radii in a 1-nT magnetic field is about 1000 to 2000 km. Such field magnitudes are observed in the vicinity of the neutral line. For $k < 1$ the radius of curvature of the field lines at the center of the current sheet must be considerably less than the above Larmor radii. The Larmor radii of the plasma mantle ions are sufficiently small that the initial acceleration of the plasma mantle ions probably occurs near the neutral line for the most part. At farther earthward distances from the neutral line the magnetic fields are considerably larger, 3 to 5 nT, at the position of reversal of the $B_z$ component. For the crossing that provided a determination of the curvature of the field at the reversal (see Figure 6), as a change in the direction of the solar wind ions provided a rapid deflection of the magnetotail across the spacecraft position, this radius of curvature was about 1000 to 2000 km. Such radii of curvature and field magnitudes are considerably less likely for providing the initial acceleration of the cold plasma mantle ions. Of course, as the ions gain speeds in the range of 500 to 1000 km/s, their Larmor radii become sufficiently large that nonadiabatic acceleration, $k < 1$, is probable throughout a large region of the current sheet. For example, the Larmor radius of a proton with velocity 1000 km/s perpendicular to the magnetic field vector is about 3000 km in a 3-nT magnetic field and only 300 km for a plasma mantle proton with speed 100 km/s.

With the above considerations and the present observations of the three-dimensional velocity distributions of protons at various positions within the magnetotail we have arrived at the interpretation offered in Figure 12. In general, two different velocity distributions are found. One of these is associated with the "lima bean" distributions that are characterized by speeds in the range of 1000 to 1500 km/s. These distributions are produced by the meandering, or Speiser, orbits shown in Figure 12. The trajectories are drawn with the assumption that temporal variations and current sheet topology allow the conservation of the action invariant $I$ [Sonnerup, 1971]. Nonadiabatic acceleration in the cross-tail electric field and the turning of the trajectory by the $B_z$ component of the magnetic field in the current sheet accelerates the proton and causes eventual ejection of the proton more or less parallel to the stronger magnetic fields outside the current sheet, respectively. The lima bean shape of the distribution is the signature of the ensemble of trajectories through the current sheet that arrive at the spacecraft position [Lyons and Speiser, 1982]. The second velocity distribution is the colder ions that occur at lower speeds. The speeds of these ions are typically 100 to 500 km/s, both perpendicular and parallel to the magnetic field. It is speculated that these velocity distributions are associated with the half-period motions of ions in the current sheet as shown in Figure 12. It is possible that the motion consists of two or three gyroperiods, but the number of such motions must be limited so that the velocity distributions are not greatly dispersed at a given observational location, in contrast to the case for the Speiser orbits. Detailed kinetic modeling of ion trajectories in realistic magnetic and electric fields is required in order to confirm or reject this speculation.

We suggest that the initial acceleration of cold plasma mantle ions occurs in the weak magnetic fields at and near the neutral line and is not critically dependent upon the radius of curvature of the magnetic field. It is reasonable to account for the proton speeds in the cold beams with the acceleration of the plasma mantle ions during a half-period gyromotion. The gyroradius of a 100-km/s proton in a 1-nT magnetic field is about 1000 km. The electric field strength in the magnetotail during
another time period is reported to be about 0.4 mV/m [Frank et al., 1993]. Without accounting for the increase in gyroradii as the proton gains energy, the speed after the half-period motion between entry and ejection from the current sheet is about 400 km/s. This speed is typical of those for the protons in the cold beams.

The observed complex velocity distributions can be in part interpreted in terms of the simplified diagram shown in Figure 12. At position 1 the incoming plasma mantle ions are detected (see Figure 5). At locations near the neutral line (position 2) within the current sheet a complex velocity distribution consisting of a number of cold ion beams should be seen (see Figure 8). The beams at a given spacecraft location are the signature of the gyrophase and position of entry of the plasma mantle ions into the current sheet. The limited amount of dispersion in the individual beams may be due to the limited gyromotion within the current sheet and limited number of trajectories to this spacecraft position. This region corresponds to the acceleration region for the cold ions that are observed outside the current sheet. Note that there are no significant lima-bean-shaped distributions or high-speed protons with speeds of >1000 km/s. Such distributions are not expected at this position in the diagram of Figure 12. Earthward of the neutral line and in the vicinity of the current sheet (position 3) both the lima-bean-shaped distributions and the cold ion beams should be detected. These distributions are seen in Figure 6. As expected, the flow of both ion distributions is directed earthward. Under the influence of the cross-tail electric field these accelerated ion distributions will convect toward the center of the plasma sheet. Then these ions should again undergo nonadiabatic acceleration. However, the cold protons in the ring or gyrobunched velocity distributions are propagating along the magnetic field at a significantly lower speed than the high-speed protons in the lima bean distributions. Thus the colder, slower protons are more likely to be reprocessed by the current sheet. Their gyroradii are now significantly larger than those for the plasma mantle ions, and the reprocessing is likely to occur in meandering orbits. That is, a second current sheet crossing is likely to further accelerate the colder ions. At farther distances from the neutral line (position 4), and thus closer to Earth, then only the lima bean distributions are expected to be observed in the plasma sheet boundary layer (see Figure 11). Tailward of the neutral line at position 5 both the lima bean and the cold ion distributions are expected, and the flows for both populations should be tailward. These proton velocity distributions are shown in Figure 9, and the flow is tailward. The reader should note that the lima bean velocity distributions appear to be nongyrotropic both earthward and tailward of the neutral line. This probable nongyrotropy is not as dramatic in the phase space diagrams as that for the cold ions because of their larger “thermal” speeds. The nongyrotropy of the higher-speed ions may be the signature of selective effects of the Speiser orbits in the current sheet.

In summary it is evident from the present series of observations of the proton three-dimensional velocity distributions within the magnetotail at intermediate distances that the description of dynamics in terms of convecting, quasi-Maxwellian distributions is inadequate. On the other hand, it is fortunate that the observed complex velocity distributions could be categorized into two major types: the high-speed “lima bean” distributions and the slower cold ion velocity distributions that are either ring-type or gyrobunched. These distributions can be interpreted, respectively, in terms of acceleration by meandering, or Speiser, orbits in the current sheet [Lyons and Speiser, 1982; Ashour-Abdalla et al., 1993] and by the initial acceleration of plasma mantle protons during a partial gyromotion, or at most several gyromotions, in the current sheet in the vicinity of the neutral line. As noted above, the relevant parameter for the nonadiabatic behavior of the higher-speed velocity distribution is the adiabatic index \( \kappa \), with \( \kappa < 1 \). For production of the cold ion velocity distributions the appropriate condition may be the requirement that the plasma mantle ions must enter a region of sufficiently low magnetic fields, i.e., in the vicinity of the neutral line, such that a significant acceleration is acquired over half a gyromotion in the cross-tail electric field. These ions then become the “seed” ions for further acceleration in the current sheet.

Our next analysis of ion dynamics in Earth’s magnetotail will be directed toward the quasi-Maxwellian velocity distributions in the central plasma sheet. An extensive series of such observations is available from this Galileo traversal of the magnetotail, but at lesser radial distances than for those presented here. In particular, attention will be directed toward identifying relatively subtle features of the velocity distributions that are predicted by global kinetic modeling for regions with \( \kappa < 1 \) (nonadiabatic motion), \( \kappa \sim 1 \) (chaotic trajectories), and \( \kappa > 1 \) (adiabatic motion) [Ashour-Abdalla et al., 1992] and toward searching for the existence of differential memory effects in the ion velocity distributions that are predicted from a formulation of nonlinear ion dynamics [Chen et al., 1990; Burkhart and Chen, 1991].

Acknowledgments. The authors appreciate several useful discussions with M. Ashour-Abdalla concerning the theoretical aspects of nonadiabatic acceleration of ions in the magnetotail current sheet. This research was supported in part by NASA under JPL contract 958778 at The University of Iowa and under JPL contract 958694 at the University of California, Los Angeles.

The Editor thanks C. A. Gurgiolo and another referee for their assistance in evaluating this paper.

References


L. A. Frank and W. R. Paterson, Department of Physics and Astronomy, The University of Iowa, Van Allen Hall, Iowa City, IA 52242. (e-mail: frank@iowasp.physics.uiowa.edu; paterson@iowasp.physics.uiowa.edu)

M. G. Kivelson, Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024. (e-mail: mkivelson@igpp.ucla.edu)

(Received November 12, 1993; revised March 15, 1994; accepted March 17, 1994.)