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ION VELOCITY DISTRIBUTIONS IN THE VICINITY OF THE CURRENT SHEET IN EARTH'S DISTANT MAGNETOTAIL

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Abstract

Observations of the three-dimensional velocity distributions of positive ions and electrons have been recently gained for the first time in Earth's distant magnetotail with the Galileo and Geotail spacecraft. For this brief discussion of these exciting results the focus is on the overall character of the ion velocity distributions during substorm activity. The ion velocity distributions within and near the magnetotail current sheet are not accurately described as convecting, isotropic Maxwellians. The observed velocity distributions are characterized by at least two robust types. The first type is similar to the "lima-bean"-shaped velocity distributions that are expected from the nonadiabatic acceleration of ions which execute Speiser-type trajectories in the current sheet. The second distribution is associated with the presence of cold ion beams that presumably also arise from the acceleration of plasma mantle ions in the electric and weak magnetic fields in the current sheet. The ion velocity distributions in a magnetic field structure that is similar to that for plasmoids are also examined. Again the velocity distributions are not Maxwellian but are indicative of nonadiabatic acceleration. An example of the pressure tensor within the plasmoid-like event is also presented because it is anticipated that the off-diagonal elements are important in

a description of magnetotail dynamics. Thus our concept of magnetotail dynamics must advance from the present assumption of co-moving electron and ion Maxwellian distributions into reformulations in terms of global kinematical models and nonadiabatic particle motion.

1. Introduction

Recent observations of the three-dimensional velocity distributions of electrons and positive ions in the distant magnetotail with the Galileo and Geotail spacecraft have greatly altered our perceptions of the nature of plasma acceleration and transport in that region [Frank et al., 1993; Frank et al., 1994a,b,c; Paterson and Frank, 1994; Frank and Paterson, 1994]. Our previous knowledge of the plasmas in the magnetotail was largely acquired with the ISEE-3 spacecraft [Zwickl et al., 1984; Baker et al., 1987; Slavin et al., 1985; Hones et al., 1984]. Because only observations of the intensities of thermal electrons in directions nearly parallel to the ecliptic plane were available with the plasma analyzer on board ISEE 3, the interpretation of these thermal electron measurements in terms of magnetotail dynamics generally proceeded for the past decade or so with the assumption of co-moving, Maxwellian thermal ions. The comprehensive observations of the thermal plasma distributions with the instrumentation on board Galileo and Geotail show that this assumption is grossly inadequate as a description of fundamental ion dynamics within the plasma sheet and its current sheet and boundary layers. The ion velocity distributions clearly exhibit the effects of nonadiabatic acceleration in the electric and tenuous magnetic fields in these regions.

We present a brief overview of the exciting observations of the three-dimensional velocity distributions of positive ions in Earth's distant magnetotail with the Galileo and Geotail spacecraft. In particular our attention is drawn to current sheet crossings with Galileo and an encounter with plasmas in a plasmoid-like magnetic field structure with Geotail. These observations were acquired during periods of substorm activity. The current sheet is believed to play a fundamental role in the energization of plasma during all phases of substorm activity, including magnetic quiescence.

2. The Current Sheet

On 8 December 1990 the Galileo spacecraft obtained a remarkably fortuitous series of observations of field-and-particles in the distant magnetotail. The trajectory of this spacecraft as it approached Earth for one of its orbital assists to its final destination, Jupiter, is shown in Figure 1. Descriptions of the plasma instrumentation and the magnetometer are given by Frank et al. [1992] and Kivelson et al. [1992], respectively. Numerous crossings of the magnetotail current sheet during the period 0400 to 1400 UT have been previously reported by Frank et al. [1994a]. This interval was characterized by the occurrence of substantial substorm activity [Kivelson et al., 1993; Frank et al., 1994a]. The three-dimensional velocity distributions of positive ions near and within the current sheet displayed features that were interpreted in terms of the nonadiabatic acceleration of ions in cross-tail electric and weak magnetic fields in this region of the plasma sheet. Here we provide an overview of these findings that were reported by Frank et al. [1994a]. These velocity distributions are inadequately described as convecting, quasi-adiabatic Maxwellians.

Examples of the ion velocity distributions in the vicinity of the current sheet are shown in Figure 2. The solar-magnetospheric coordinates of the spacecraft position were **X** = (-68.8, -14.4, -9.1 R_e). A sequence of three consecutive determinations of the velocity distributions are displayed. The isodensity contours in units of s^3/cm^6 are given in the V_x-V_y and V_x-V_z planes. The intermediate values for the densities are 2 and 5. The components of the magnetic field for each velocity distribution are also indicated, and a vector is superposed upon each velocity distribution that is in the direction of the projection of the magnetic field. The lengths of these vectors are not proportional to the field components. There are two major features of the velocity distributions that can be noted in Figure 2. First a hot, "lima-bean"-shaped velocity distribution with a bulk speed of about 1000 km/s is present. The direction of the bulk flow is tailward. This component of the velocity distribution is qualitatively similar to that previously observed with the IMPs -7 and -8 spacecraft at positions nearer to Earth when these spacecraft were positioned in the plasma sheet boundary layer [DeCoster and Frank, 1979]. The bulk flows of these boundary layer plasmas are directed earthward. The second notable feature of the velocity distributions is the cooler ions with tailward bulk flow components in the range of about 500 km/s and which exhibit a ring, or possibly a nongyrotropic angular distribution with axis generally directed parallel to the X-axis.

The "lima-bean"-shaped and cold-ion velocity distributions noted above were found to be robust features of the plasmas in and near the magnetotail current sheet during the Galileo flyby [Frank et al., 1994a]. An attempt to organize these observations in terms of magnetotail dynamics is given in Figure 3. The current sheet earthward and tailward of the neutral line is drawn as two slabs, respectively, and the X component of the magnetic field reverses from tailward to earthward as the current sheet is crossed from south to north. A larger sampling of the velocity distributions has been given by Frank et al. [1994a]. Cold, tailward convecting plasma from the polar plasma mantle [Rosenbauer et al., 1975] and/or the low-latitude magnetopause boundary along the flanks of the magnetotail appear to be the principal sources of plasmas which are subsequently accelerated in the current sheet. As shown in the interpretive diagram of Figure 3 these cold ions enter the cross-tail electric fields and weak magnetic fields near the neutral line and begin the process of nonadiabatic acceleration. The tailward flowing velocity distributions such as those shown in Figure 2 are presumably found tailward of the neutral line, i.e., in region 5. The hot, "lima-bean"-shaped velocity distributions are believed to be associated with the meandering, or Speiser orbits in the current sheet [Speiser, 1965; Lyons and Speiser, 1982; Ashour-Abdalla et al., 1993]. The simplified interpretive diagram shown in Figure 3 is offered with the assumption that the large-scale magnetic field geometry in the current sheet permits conservation of the action invariant I [Sonnerup, 1971]. Of course, the ion acceleration occurs due to the nonadiabatic motion parallel to the cross-tail electric field. Examination of the sketches of the meandering particle trajectories in Figure 3 shows that the B_z component in the current sheet gradually turns the trajectories and causes eventual ejection of the ions out of the current sheet and into the plasma sheet boundary layer. This boundary layer is indicated as regions 3, 4 and 5 in Figure 3.

Considerably more speculative is the interpretation of the colder, ring or nongyrotropic ion velocity distributions that are evident in Figure 2. This is the second type of robust velocity distributions that are encountered within or in the vicinity of the magnetotail current sheet. Frank et al. [1994a] suggest that these ion velocity distributions are due to nonadiabatic acceleration of plasma mantle ions during only a partial gyromotion, or at most less than several gyromotions, in the vicinity of the extremely weak magnetic fields near the neutral line before ejection from this region into the stronger magnetic fields contiguous to the current sheet. For typical cross-tail electric field strengths and the ion gyroradii in these weak magnetic fields sufficient acceleration to account for the approximately 500-km/s speeds of the ions is possible during half of a gyromotion. These trajectories are also shown in Figure 3. A few comments are required here in order to further address the initial nonadiabatic acceleration of the plasma mantle ions. The parameter of adiabaticity κ is defined as the square root of the ratio of the minimum radius of curvature of the magnetic field lines to the Larmor radius [Büchner and Zelenyi, 1989]. For $\kappa > 1$ the particle motion is expected to be adiabatic. For $\kappa < 1$ the ion trajectories are nonadiabatic. This latter situation is generally satisfied by ions with speeds ≥ 500 km/s for the radii of curvature in the center of the current sheet as observed with the Galileo spacecraft [Frank et al., 1994a]. Thus, for these higher-speed protons, meandering orbits in the current sheet are plausible. On the other hand, there must be an initial acceleration of the slow, cold plasma mantle ions to these higher speeds because their gyroradii appear to be insufficiently large to satisfy the nonadiabaticity criterion noted above. This initial acceleration can occur in the region of the neutral line, i.e., due to the very large ion gyroradii in the extremely weak magnetic fields. In this case, κ is not the applicable parameter and should be replaced with a measure of the ratio of the magnitudes of the cross-tail electric field and the magnetic field.

All five plasma regions that are shown in Figure 3 were detected by Galileo as it rapidly traversed the magnetotail [Frank et al., 1994a]. Region 3 is the qualitative mirror image of the ion velocity distribution shown in Figure 2. That is, the "lima-bean"-shaped velocity distributions and the cold ions are present but the bulk flow of these plasmas is earthward because the spacecraft is earthward of the neutral line. A major asymmetry of the spatial distributions in the plasmas appears to be associated with region 4 that is characterized by only "lima-bean"-shaped velocity distributions. This region has been previously identified with plasma measurements with other spacecraft at positions nearer to Earth [DeCoster and Frank, 1979; Eastman et al., 1984]. This situation may arise because plasma convection along the Z direction toward the midplane of the plasma sheet may force the return of the slower, colder ions into the current sheet and subsequent reprocessing in Speiser orbits to yield contributions to the "lima-bean"-shaped velocity distributions. Such convection may not be prevalent tailward of the neutral line.

Further credence to the undoubtedly oversimplified diagram in Figure 3 is provided by the character of the ion velocity distributions in region 2, i.e., in and near the neutral line. Two consecutive observations of the three-dimensional velocity distributions of ions near the neutral line are shown in Figure 4. The spacecraft position was $\mathbf{X} = (-67.5, -14.2, -8.8\ R_e)$. As expected, the hot "lima-bean"-shaped velocity distributions that arise from meandering orbits in the current sheet are not present near the neutral line. However, a complex distribution of cold ion beams is observed. The temperatures of some of these beams are sufficiently low that they are not well determined with the energy resolution of the plasma analyzer. Comparison of the detailed structure of the two velocity distributions in Figure 4 shows that the observations are not greatly time-aliased. The sampling times are similar to the proton gyroperiod which is about 25 to 40 s.

In the interpretive diagram of Figure 3 each cold ion beam is to be associated with a particular position and gyrophase for entry of plasma mantle ions into the plasma sheet.

It is clear that the recent Galileo observations of the ion velocity distributions in and near the magnetotail current sheet have ushered in an exciting era for the investigation of magnetotail plasma dynamics. The complex velocity distributions clearly exhibit the effects of nonadiabatic ion acceleration during periods of substorm activity, a feature which also may be present during magnetically quiescent periods. Extensive global kinetic modeling will be required to confirm or refute the tantalizing speculations that are offered above.

3. Passage of a Plasmoid-Like Object

The Geotail spacecraft is providing a marvelous series of plasma observations in Earth's distant magnetotail [Frank et al., 1994b,c; Paterson and Frank, 1994; Frank and Paterson, 1994; Siscoe et al., 1994a,b; Williams et al., 1994]. For the first time survey measurements of the three-dimensional velocity distributions of the thermal ions and electrons are being recorded in this dynamic region of the magnetosphere. The previous observations of thermal plasmas in the magnetotail, other than those gained by Galileo during its brief visit to Earth, were limited to determinations of the directional intensities of only electrons in directions restricted to those nearly parallel to the ecliptic plane [Bame et al., 1983]. The interpretation of substorm phenomena in the distant magnetotail often relied upon the explicit or implicit assumption the thermal ion plasmas were approximately described as quasi-Maxwellian distributions that co-moved with the thermal electron plasmas [Hones et al., 1984; Baker et al., 1984, 1987; Scholer et al., 1984; Slavin et al., 1993]. In the framework of the popular plasmoid model of Hones [1976] a key step in the dynamical behavior is the formation of a near-Earth neutral line at about 10 R_e geocentric radial distance during the onset of a magnetic substorm. An O-type magnetic geometry as viewed in a meridional plane along the tail axis is created by the transient formation of the near-Earth neutral line and the previously existing neutral line in the more distant magnetotail. Subsequently this O-type magnetic feature propagates downstream at relatively high speeds due to stresses associated with the magnetic topology of the magnetotail. The tailward speed is inferred to be about 500 to 1000 km/s, e.g., speeds in excess of those typically observed in the downstream magnetosheath. Unfortunately, the recent plasma observations with Galileo and Geotail show that the thermal ions and electrons are not generally co-moving in the plasma sheet and the ion velocity distributions cannot be characterized as quasi-isotropic Maxwellians [Frank et al., 1993, 1994a,b,c; Frank and Paterson, 1994].

An example of the plasmas and magnetic fields observed with the Geotail spacecraft in the distant magnetotail during the passage of a plasmoid-like magnetic structure is shown in Figure 5. Descriptions of the magnetometer (MGF) and the plasma instrumentation (CPI) are previously given by Kokubun et al. [1994] and Frank et al. [1994b], respectively. Although appropriate ground-based magnetic indices are not yet available to us we assume that the presence of the plasmoid during 1813 to 1822 UT on 23 January 1993 as shown in Figure 5 is associated with a substorm. This assumption arises from our general impression from previous literature that plasmoids are only present during periods of substorm activity [Slavin et al., 1993]. The magnetic signature of the plasmoid is clearly evident in the Z component of the magnetic field, i.e., the northward deflection of the magnetic vector and subsequent southward turning. The duration of these events is typically in the range of 10 to 20 minutes. For the event shown in Figure 5 the spacecraft was located at **X** = (-96.6, 0.6, -6.3 R_e) at 1817 UT.

Our primary interests here are the ion bulk flows and the ion velocity distributions during the passage of the plasmoid. In the upper three panels of Figure 5 are shown the number densities, temperatures and X component of the bulk flow velocity for the ions. Plasmas with ion temperatures $< 2 \times 10^6$ K are generally indicative of the presence of plasma mantle ions, an identification that is further supported by their relatively steady tailward flow of about 100 km/s. The ion temperatures within the plasmoid are hotter, about 5×10^6 K, but are considerably lesser than the temperatures of 10^7 to 10^8 K for the isotropic, hot plasmas in the central plasma sheet at radial distances 10 to 20 R_e. The observed, relatively cool temperatures are not supportive of the presence of hot plasmas that are expected for plasmoids birthed in the near-Earth plasma sheet.

The tailward ion bulk flow within the plasmoid is about 200 km/s and is considerably lesser than those inferred from ISEE-3 observations of electrons [Hones et al., 1984; Baker et al., 1984]. Frank and Paterson [1994] have reported similarly slow ion bulk flows for other plasmoid events and have examined the electron and ion velocity distributions in detail to find that the discrepancy in the bulk flows for these distributions arises from the presence of two ion distributions, a hot, high-speed component and accompanying cold ions. A proton velocity distribution within the plasmoid recorded in Figure 5 is shown in Figure 6. Slices of the velocity distribution in the V_y-V_z and V_x-V_z planes are displayed. Even a cursory examination of Figure 6 reveals that the ion velocity distributions cannot be described as quasi-Maxwellian. As with the Galileo observations presented in the previous section, the distributions are composed of a hot component and cold ion beams. The plasma instrumentation for Geotail and its generous telemetry allotment from the spacecraft allow sampling of the velocity distributions within time intervals that are similar to the ion gyroperiods in the weak magnetic fields in the distant plasma sheet. Thus, even though the temporal variations of the velocity distributions are also of these time scales it is reasonable to begin the derivation of pressure tensors for these plasmas. An example of such a pressure tensor is shown in Table 1. The errors due to counting statistics are also indicated. The trace of the tensor is 14.6×10^{12} Pa. Inspection of the magnitudes of the off-diagonal elements finds that it is probable that the corresponding forces are significant if the spatial scales for their variations are sufficiently small. Ashour-Abdalla et al. [1994] have previously noted the importance of the off-diagonal terms in the pressure tensor from large-scale kinetic simulations of the current sheet. We are continuing our analyses of these off-diagonal terms of the pressure tensor.

4. Summary

We have presented several observations of the three-dimensional velocity distributions of ions in Earth's distant magnetotail with the Galileo and Geotail spacecraft. For almost a decade phenomenological models of the dynamics of the magnetotail plasma sheet have principally relied upon the observations of thermal electrons only with the ISEE-3 spacecraft with visions of quasi-Maxwellian ion velocity distributions that co-move with the thermal electrons. In the absence of thermal ion observations this assumption is reasonable in order to progress studies of the magnetotail. Unfortunately, this assumption for the character of the ion velocity distributions within the plasma sheet is shown to be grossly inadequate by the first direct detections with the Galileo and Geotail plasma instruments. Some of these observations have been reported above. The ion velocity distributions in the plasma sheet and its boundary layer often exhibit hot components that are mixed with cold ion beams. The velocity distribution of the hot component is "lima-bean"-shaped and is similar to the distributions that are expected for nonadiabatic acceleration of ions along Speiser-type trajectories in the magnetotail current sheet. The origin of the cold ion beams is more open for speculation. One such speculation offered in the present paper is that these cold ion beams are the result of nonadiabatic acceleration of cold plasma mantle ions during a partial gyromotion in the cross-tail electric and weak magnetic fields in the current sheet before ejection into the stronger magnetic fields of the plasma sheet boundary layer. These recent plasma measurements can be expected to greatly advance our understanding of the mechanisms for substorm onset and subsequent plasma transport. Because of the complex character of the observed ion velocity distributions it is anticipated that this advancement will require the close interaction of the efforts of data analysis and interpretation with those for the development of global kinetic and MHD models of the magnetotail.

Acknowledgments

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Figure Captions

Figure 1. The trajectory of the Galileo spacecraft in Earth-centered solar-magnetospheric coordinates during 8 December 1990 [Frank et al., 1994a].

Figure 2. Proton velocity distributions in the vicinity of the magnetotail current sheet. The bulk flow velocity is directed tailward [Frank et al., 1994a].

Figure 3. An interpretive diagram for the Galileo observations of proton velocity distributions in terms of nonadiabatic acceleration of plasma mantle ions in the current sheet [Frank et al., 1994a].

Figure 4. Two consecutive determinations of the three-dimensional velocity distributions of protons near the neutral line in the current sheet. A complex distribution of cold ion beams is observed [Frank et al., 1994a].

Figure 5. Plasma and magnetic field observations in the distant magnetotail with the Geotail spacecraft on 23 January 1993. In order from top to bottom panels are shown the ion number density, temperature and bulk flow component along the X-axis, the components of the magnetic field and its magnitude. The vertical dashed lines indicate the interval for the presence of a plasmoid-like magnetic structure.

Figure 6. Proton velocity distribution in the plasmoid encountered by the Geotail spacecraft on 23 January 1993.

Table 1. Proton Pressure Tensor in Units of 10^{-12} Pa,
1817:25 UT, 23 January 1993, $N = 0.15\ \mathrm{cm}^{-3}$,
Solar–Magnetospheric Coordinates

$$P_{ij}\ (\pm 1\sigma) = \begin{bmatrix} 22.5\ (\pm 5.4) & 7.2\ (\pm 2.1) & -8.5\ (\pm 3.1) \\ 7.2\ (\pm 2.1) & 6.9\ (\pm 1.5) & -3.6\ (\pm 1.7) \\ -8.5\ (\pm 3.1) & -3.6\ (\pm 1.7) & 14.3\ (\pm 3.1) \end{bmatrix}$$

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GALILEO - EARTH-I FLYBY, 8 DECEMBER 1990
- GEOCENTRIC SOLAR-MAGNETOSPHERIC COORDINATES

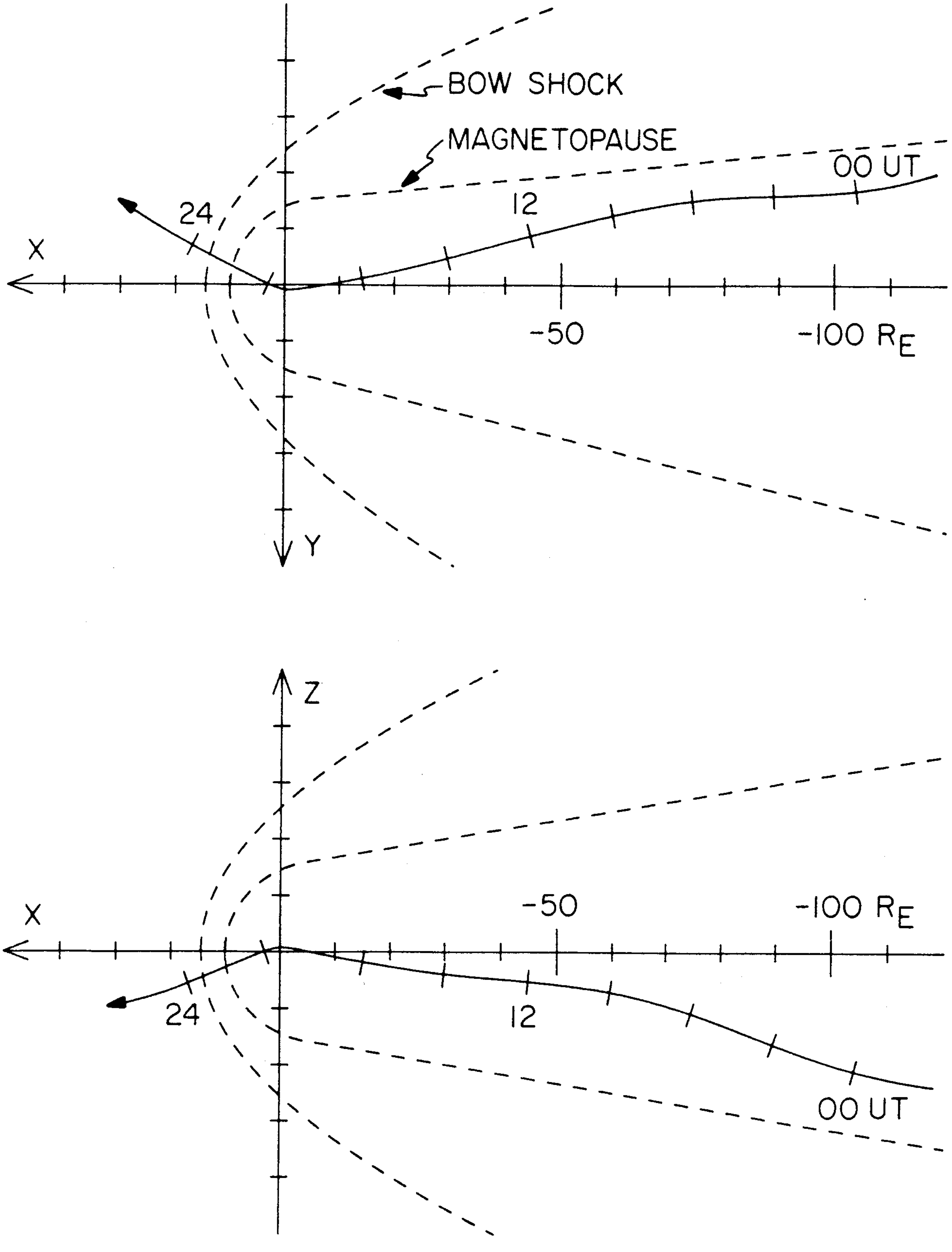
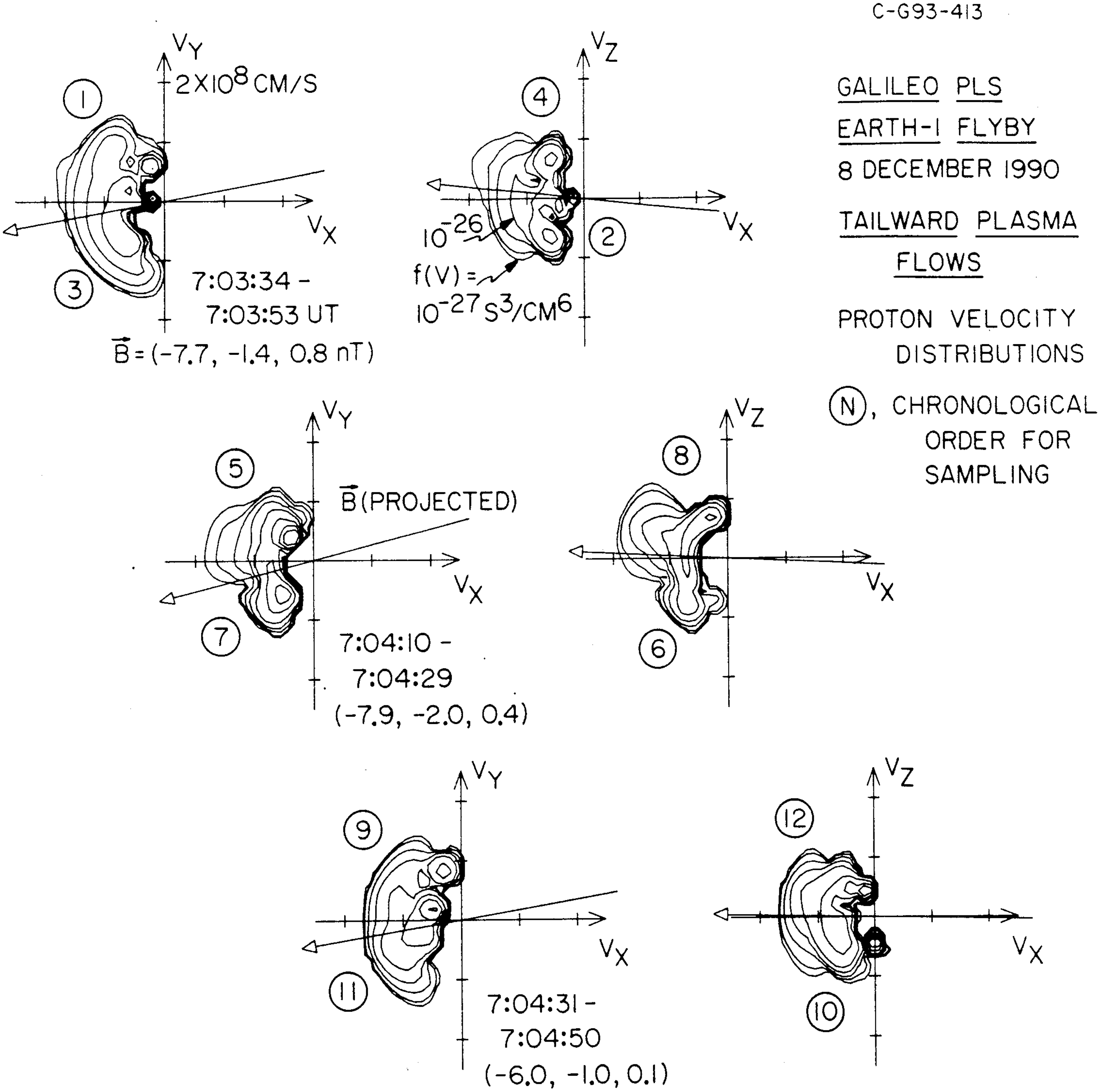


Figure 1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GALILEO PLS
EARTH-1 FLYBY
8 DECEMBER 1990
TAILWARD PLASMA FLOWS
PROTON VELOCITY DISTRIBUTIONS
(N), CHRONOLOGICAL ORDER FOR SAMPLING
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B = (-7.7, -1.4, 0.8 nT)
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V_Y
⑤
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B (PROJECTED)
V_X
7:04:10 -
7:04:29
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V_X
7:04:31 -
7:04:50
(-6.0, -1.0, 0.1)
V_Z
⑫
⑩
V_X

Figure 2

B-G93-434-2

ION TRAJECTORIES WITHIN AND ABOVE THE MAGNETOTAIL CURRENT SHEET

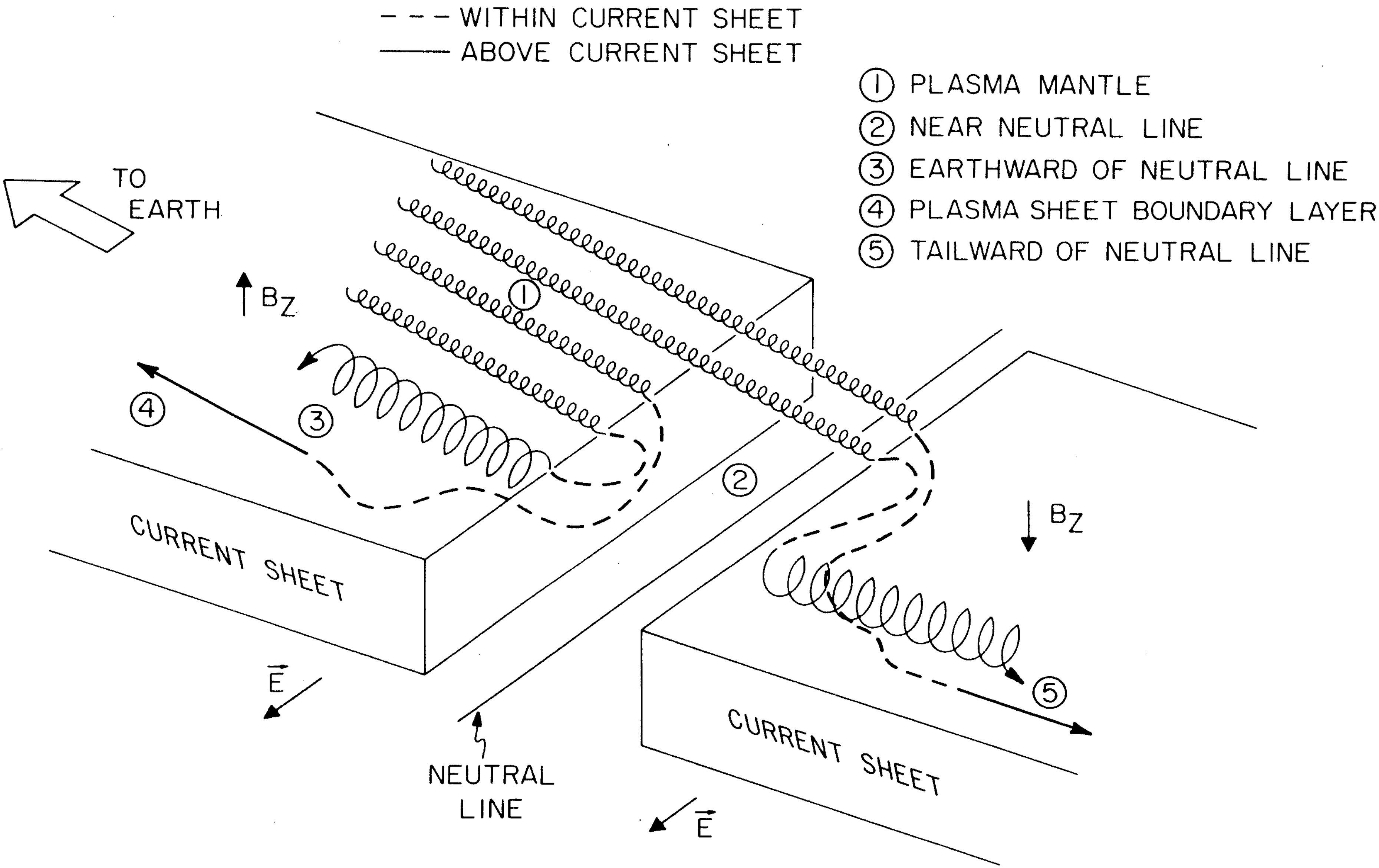
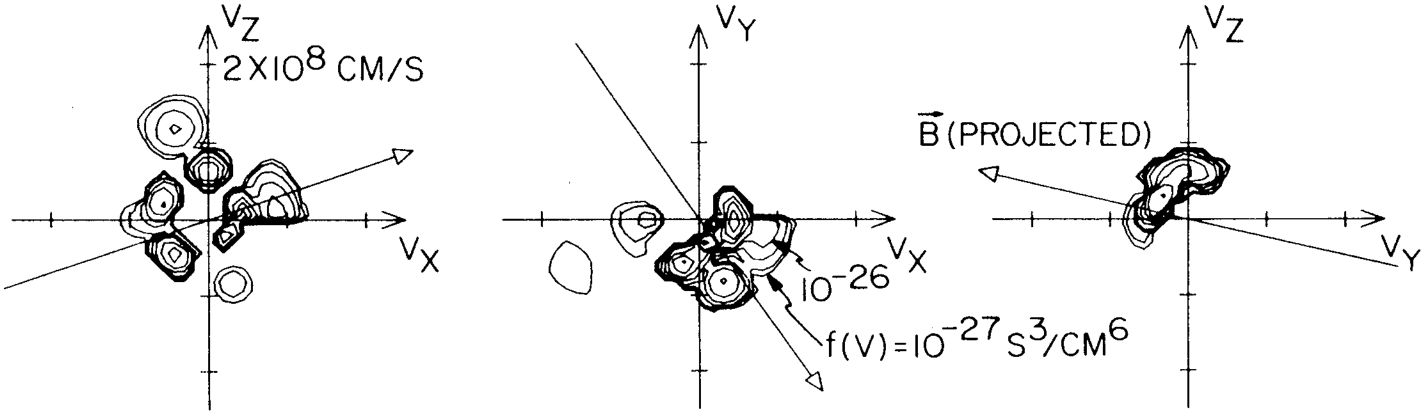


Figure 3

C-G93-416

GALILEO PLS, EARTH-I FLYBY, 8 DECEMBER 1990
PROTON VELOCITY DISTRIBUTIONS
SOLAR MAGNETOSPHERIC COORDINATES

(a) 7:19:45 – 7:20:04 UT, $\vec{B} = (0.9, -1.3, 0.3 \text{ nT})$



(b) 7:20:21 – 7:20:40 UT, $\vec{B} = (-2.2, -0.7, 0.0 \text{ nT})$

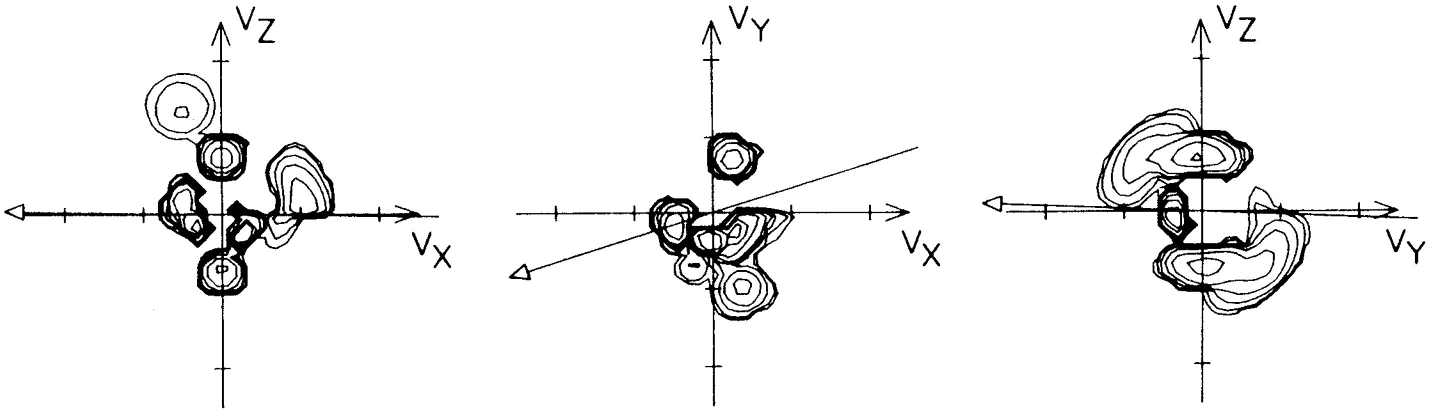


Figure 4

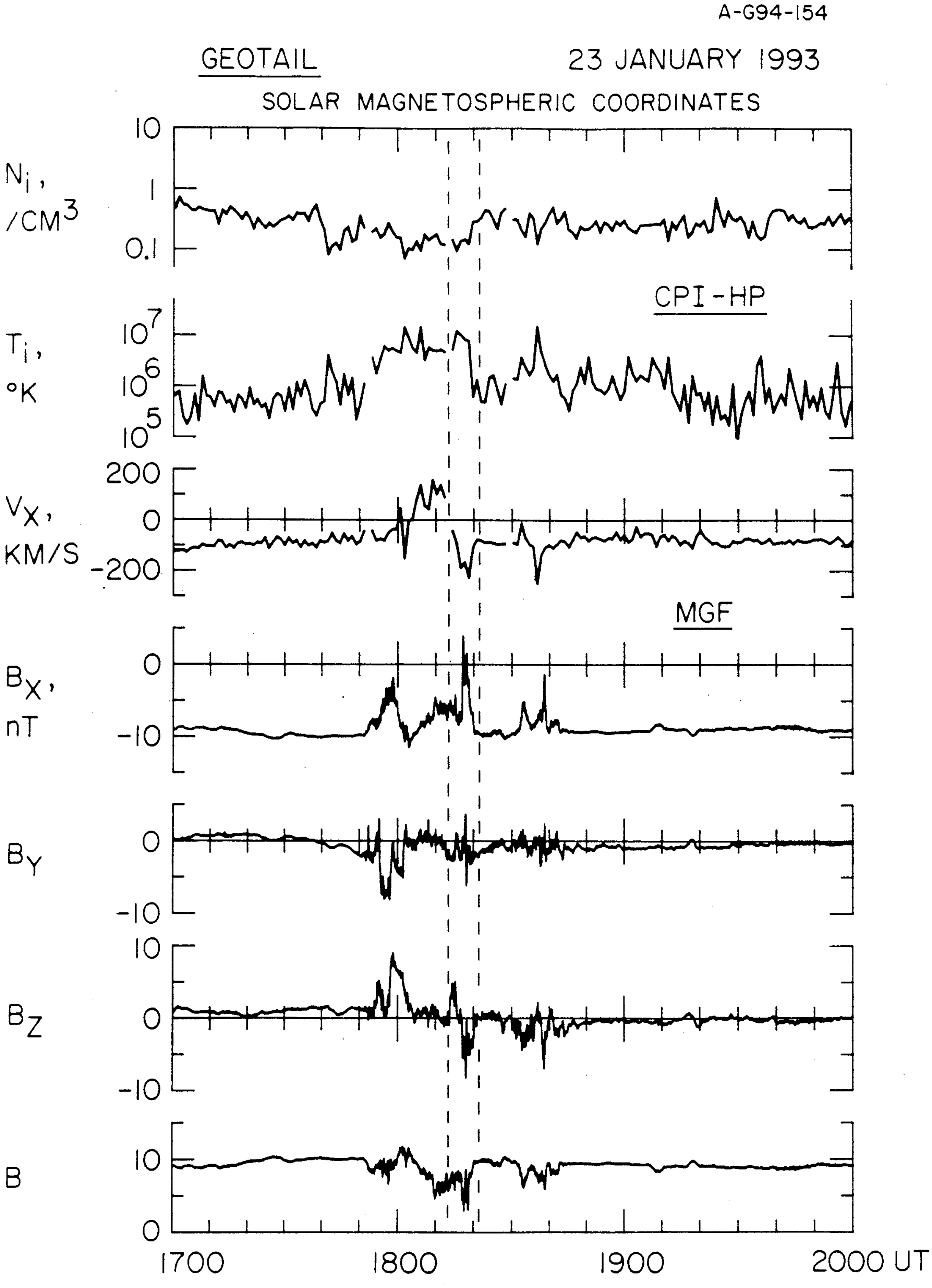

A-G94-154
GEOTAIL
23 JANUARY 1993
SOLAR MAGNETOSPHERIC COORDINATES
N_i, /CM^3
10
1
0.1
CPI-HP
T_i, °K
10^7
10^6
10^5
V_X, KM/S
200
0
-200
MGF
B_X, nT
0
-10
B_Y
0
-10
B_Z
10
0
-10
B
10
0
1700
1800
1900
2000 UT

Figure 5

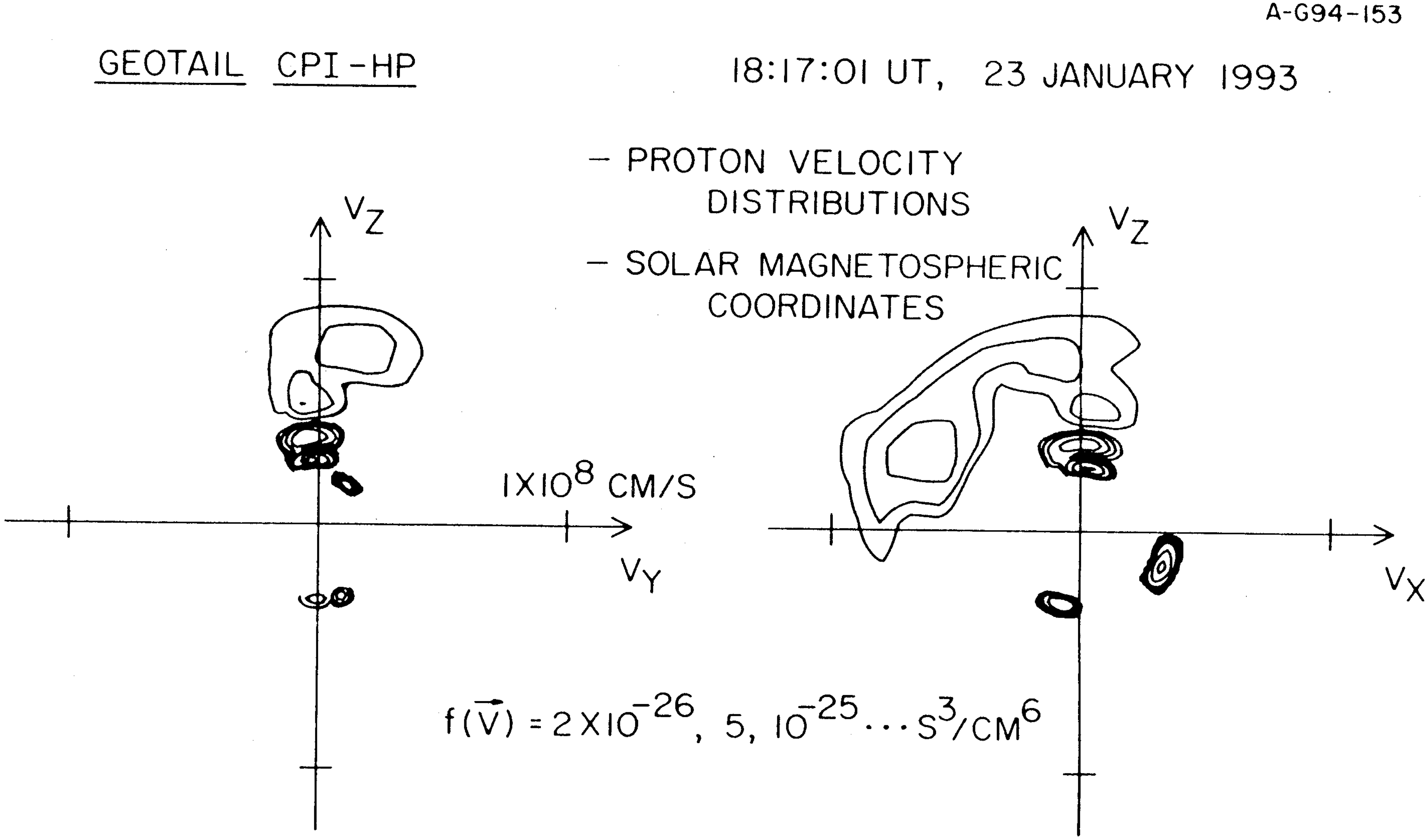

A-G94-153
GEOTAIL CPI-HP
18:17:01 UT, 23 JANUARY 1993
- PROTON VELOCITY DISTRIBUTIONS
- SOLAR MAGNETOSPHERIC COORDINATES
V_Z
1×10^8 CM/S
V_Y
V_Z
V_X
$f(\vec{V}) = 2 \times 10^{-26}, 5, 10^{-25} \cdots S^3/CM^6$

Figure 6