GEOTAIL observations of anomalously low density plasma in the magnetosheath

T. Terasawa[1], Y. Kasaba[2], K. Tsubouchi[2], T. Mukai[2], Y. Saito[2], L. A. Frank[3], W. R. Paterson[3], K. Ackerson[3], H. Matsumoto[4], H. Kojima[4], H. Matsui[5,6], D. Larson[7], R. Lin[7], T. Phan[7], J. Steinberg[8], D. McComas[8], R. Skoug[8], M. Fujimoto[5], M. Hoshino[1], and A. Nishida[2]

Abstract. During the anomalously low density solar wind interval of May 1999, GEOTAIL was in the magnetosheath for ∼37 hours after making an inbound crossing of the expanding bow shock at ∼ 8 R_E upstream of its nominal position. Comparison among data sets obtained from GEOTAIL (magnetosheath), WIND (near upstream – bow shock), and ACE (far upstream) reveals several unique features: Firstly, during the interval of 1430-1530 UT on 11 May, we observed both in the solar wind and magnetosheath double-peaked protons with a peak separation of 250-300 km/s, which was close to the local Alfvén velocity during the event. Secondly, we observed extremely strong strahl electrons both in the solar wind and magnetosheath during the interval of 0600-2100 UT on 11 May 1999. We present an overview of the GEOTAIL observations, and discuss their physical significance.

Overview

Typical solar wind at 1 AU has a density of several cm^{-3}. Density reduction well below 1 cm^{-3} is rare, but has been recorded before [*Gosling et al.*, 1982; *Phillips et al.*, 1989]. Such low density intervals provide good opportunities to examine solar-terrestrial interactions with a very inflated bow shock and magnetosphere. On May 10-12, 1999, the solar wind density decreased well below 1 cm^{-3} for more than a day while the velocity was around 350-400 km/s. In this letter, we give an overview of the GEOTAIL observations and a preliminary report from the GEOTAIL-WIND-ACE collaboration. Figure 1 shows the position of GEOTAIL during the 60-hour interval between 12:00 UT on 10 May and 0:00 UT on 13 May (t=12 and 72 h) in the geocentric solar ecliptic (GSE) coordinate system. The nominal bow shock and magnetopause positions for average solar wind conditions are shown as curves with BS and MP. Both the magnetopause and bow shock expanded substantially during this interval as shown below.

[1]DEPS, University of Tokyo
[2]ISAS
[3]Department of Physics and Astronomy,University of Iowa
[4]RASC, Kyoto University
[5]TITECH
[6]JST
[7]UCB/SSL
[8]LANL
[9]MPE

Paper number 2000GL000087.
0094-8276/00/2000GL000087$05.00

Figure 2 (a) shows as an 'E-t' (energy versus time) diagram the variation of the solar wind ion count rate of the CPI/HPA instrument (with a medium geometrical factor $G \sim 6 \times 10^{-5}$ cm^2-sr-eV/eV) on GEOTAIL from t=12 h to 72 h. The decrease of the solar wind density is seen as an overall reduction of this counting rate. The plasma density and bulk velocity were calculated from the ion measurements by CPI/SW (with a low $G \sim 4 \times 10^{-6}$ cm^2-sr-eV/eV for t=12-25, 54.5-56.5, and 57.5-72 h) and by LEP/EAI (with a high $G \sim 1.5 \times 10^{-3}$ cm^2-sr-eV/eV for t=25-54.5 and 56.5-57.5 h). Combination of these ion sensors with different G is essential to obtain a wide dynamic range of ion density measurement (roughly for the five decades from 10^{-3} to 10^2 cm^{-3}). Figure 2 (b) shows a similar E-t diagram for electrons from the LEP/EAE instrument on GEOTAIL. For a description of these instruments and the magnetic field measurement (MGF) we refer the readers to [*Frank et al.*, 1994] (CPI), [*Mukai et al.*, 1994] (LEP), and [*Kokubun et al.*, 1994] (MGF).

The decrease of the solar wind density caused an increase of the Alfvén velocity in the solar wind, V_A, and decreases of the Alfvén and fast Mach numbers, M_A and M_F. The WIND observation (Figure 2 (c), for instrumentations, see

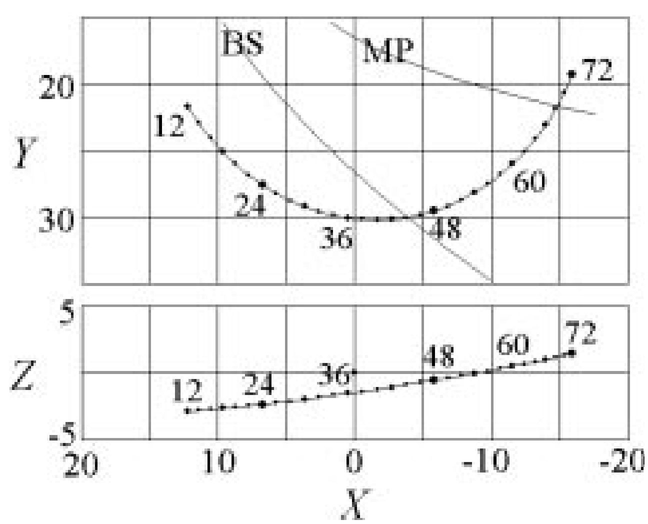

Figure 1. The XY (top) and XZ (bottom) positions of GEOTAIL in the geocentric solar ecliptic (GSE) coordinate system during the 60-hour interval between 12:00 on 10 May and 0:00 on 13 May (t=12 and 72 h). Numbers 12, 24, ... 72 indicate the satellite position every 12 hours. Dots on the orbit are drawn every 2 hours. The unit of the coordinate is earth radii (R_E). Curves with BS and MP show the nominal XY position of the bow shock and magnetopause in the equatorial plane (Z=0)

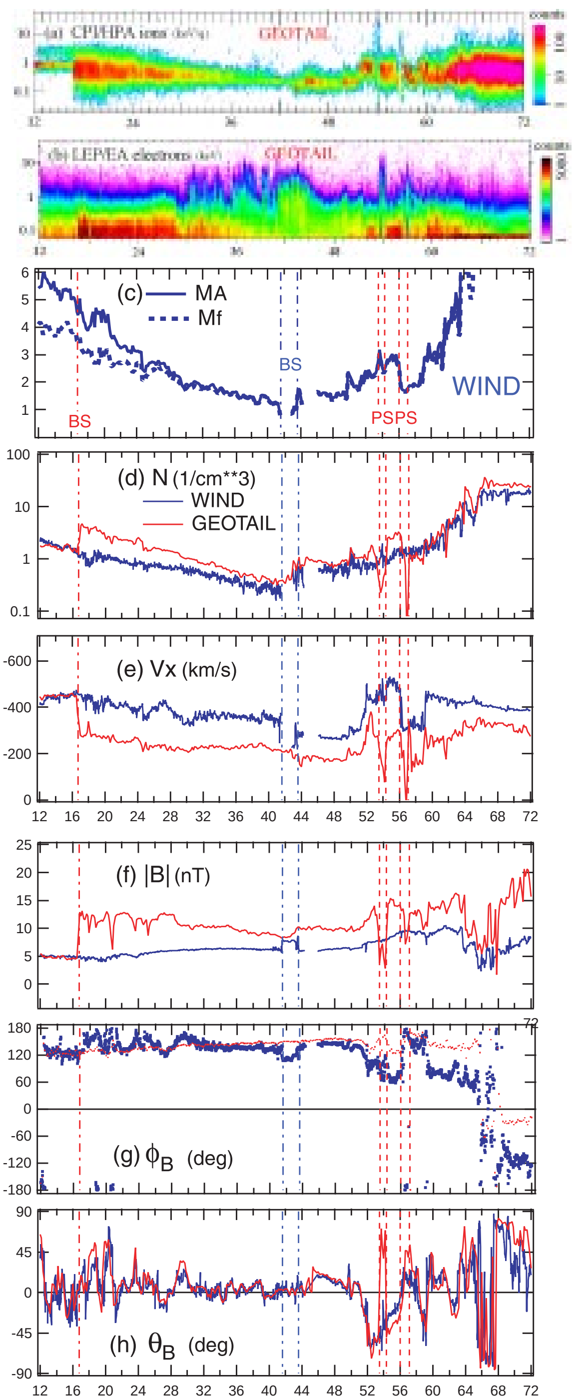

Figure 2. The top two panels show E-t diagrams for GEOTAIL observations of (a) ions (CPI/HPA), and (b) electrons (LEP/EAE). The panel (c) shows Alfvén and fast Mach numbers of the solar wind flow at WIND, M_A and M_F, with solid and dotted curves, respectively. In the panels (d)-(h), upstream (downstream) observations by WIND (GEOTAIL) are shown with blue (red) curves. The plasma parameters are (d) density N (cm^{-3}), and (e) GSE-X component of the velocity, V_X (km/s). The IMF parameters are (f) the absolute value, $|B|$ (nT), and (g) and (h) the azimuthal and longitudinal angles, ϕ_B and θ_B (deg), respectively. (ϕ_B=0^o (180^o) corresponds to the sunward (anti-sunward) direction, and ϕ_B=135^o (or -45^o) to the nominal Parker's spiral direction. θ_B=+90^o (-90^o) points northward (southward).) All data in (a)-(h) are 10-min averaged values. The data from the WIND spacecraft are by courtesy of K. W. Ogilvie (plasma) and R. P. Lepping (magnetic field).

[*Ogilvie et al.*, 1995] and [*Lepping et al.*, 1995]) shows that M_A and M_F were >3 before $t\sim$24 h and after $t\sim$62 h, but became <$\sim$1.5 during the 'core' part of the low density solar wind interval, t=36-44 h. With such a decrease of the Mach numbers, we expect a significant expansion of the earth's bow shock. At $t\sim$16.75 h the inbound bow shock crossing of GEOTAIL occurred $\sim$8 R$_{\rm E}$ upstream of the nominal bow shock surface, which was evident in the Figure 2 as heating of ions and electrons ((a) and (b)), and sudden jumps shown by the red curves for (d) N, (e) V_X, and (f) $|B|$ (red dash-dotted lines). In the midst of the extremely low density interval, t=41.6-43.6 h (blue dash-dotted lines) the bow shock even reached WIND at $X_{\rm GSE}\sim$40 R$_{\rm E}$, which was seen as a box-like increase of $|B|$ in panel (f). The average expansion speed of the bow shock between GEOTAIL and WIND positions was quite slow ($\sim$2 km/s).

The solar wind density started to recover to the nominal value after $t\sim$46 h, and finally reached $\sim$20 cm^{-3} at $t\sim$66 h. A sector boundary crossing was evident in the azimuthal angle $\phi_{\rm B}$ of the interplanetary magnetic field (IMF) between t=66 and 68 h (Figure 2 (g)). Several hours before this crossing there were large Alfvénic fluctuations, which appeared as large variations of V_X, ϕ_B and θ_B in Figure 2 (e,g,h) (t=52-66 h). These fluctuation induced transient entries of GEOTAIL into the magnetotail during t=53.5-54.3 h and t=56.0-57.1 h at $X_{\rm GSE}$=-8$\sim$-10 R$_{\rm E}$, $Y_{\rm GSE}$=+28$\sim$+27 R$_{\rm E}$, and $Z_{\rm GSE}\sim$0 R$_{\rm E}$ (red dashed lines). Note that at these tail entries the E-t diagrams had 'surges' of protons up to $\sim$40 keV and electrons up to $\sim$10 keV (Figure 2 (a) and (b)), showing the existence of the active plasma sheet under the low density solar wind condition. In the following interval of t=57.1-66 h, GEOTAIL seemed to stay near the flank magnetopause or in the low latitude boundary layer (LLBL), where the local plasma density became comparable or even lower than the upstream value (Figure 2 (d)). The final entry of GEOTAIL into the magnetotail (mantle) was observed at $t\sim$73 h (not shown).

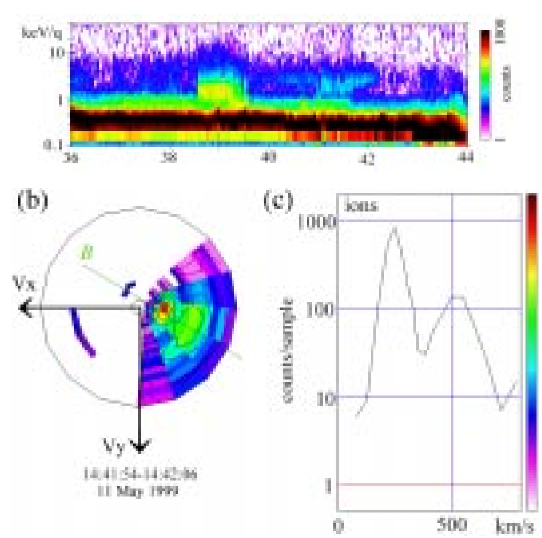

Figure 3. (a) An E-t diagram for ions (LEP/EAI) for the interval of t=36-44 h. (b) An equatorial 2D cut of the ion counting rate profile obtained at $t\sim$38.7 h (14:42 on 11 May 1999) is shown, where a green line shows the magnetic field direction. (c) A 1D cut along the magnetic field direction. The second ion (proton) peak was seen in the field aligned direction from the main proton peak.

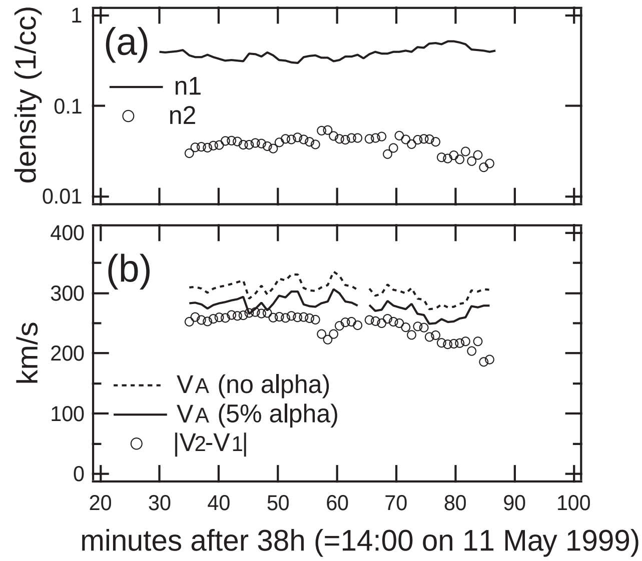

Figure 4. a) Densities of main protons (a solid curve) and subpeak protons (open circles) (preliminary). (b) The local Alfvén velocity is calculated with the assumption either 5 % alpha particles (a solid curve) or no alpha particle (a dashed curve). Open circles show the velocity difference between the main and sub peaks. Geometrical uncertainty in determining the densities due to the two-dimensional data accumulation mode during the event, which is to be eliminated, does not cause any significant error in the velocity determination.

Double proton streams and strahl electrons

We now turn our attention to the microscopic structure of the solar wind. In an expanded ion E-t diagram for t=36-44 h (Figure 3 (a)), an enhancement of the high energy (1-10 keV) component was seen during t∼38.5-39.5 h. A similar but weaker enhancement was also seen during t∼40.1-42 h. From the WIND and ACE observations we have concluded that these enhancements were due to double proton streams intrinsic to the upstream solar wind. The GEOTAIL observation of the double proton peaks in velocity phase space (Figure 3 (b) and (c)) showed that this velocity space structure survived during the passage through the low Mach number bow shock. (Identification that both two peaks consisted of protons was due to their field-aligned nature seen in Figure 3 (b).) By taking the moments of the ion distribution separately for the main and sub peaks, we obtain their densities and flow velocities (Figure 4). The main/sub density ratio was ∼10, and their velocity difference was close to the local Alfvén velocity (∼250-300 km/s). Quantitative comparisons of these parameters for double streams among three spacecraft are now under way. In Figure 2 (b) electrons also showed intermittent enhancements in the high energy range (1-10 keV) during t=30-45 h. They were due to the existence of extremely strong strahl electrons, namely suprathermal electrons having a strong anisotropy along the magnetic field away from the sun. A detailed comparison of electron properties among GEOTAIL, WIND and ACE observations is reported by *Kasaba et al.* [2000].

Discussion and Comments

As the solar wind density decreases to values less than ∼10 % of the nominal density, the magnetosphere expands substantially to keep pressure balance with the reduced ram pressure of the solar wind. GEOTAIL encountered with the magnetopause at the tail flank ∼8 R_E toward dusk from the nominal position, when the solar wind density was still low (∼1 cm^{-3}). Following the transient entry into the tail, GEOTAIL was within the magnetosheath, where the local plasma density was comparable or even lower than the upstream value. The physical origin of this density reduction, which is currently not understood, should be studied in terms of global 3D modeling of the dilute solar wind and magnetosphere interaction.

Both upstream and downstream of the bow shock we observed double proton streams in velocity space, separated by the local Alfvén velocity. We believe that this observation is an extreme version of 'double ion streams' in the solar wind found by Feldman et al. [1973a; 1973b] (see also a review, *Feldman and Marsch*, 1997). While double streams would be a natural consequence when Coulomb collisions become rare as the density decreases [e.g., *Livi and Marsch*, 1987], further theoretical treatment is needed, for example, to understand the physical mechanism of the 'Alfvén velocity regulation' of the peak separation.

Enhanced strahl electrons observed for several hours surrounding the solar wind density minimum are similar to previous ISEE 3 observations [*Phillips et al.*, 1989]. These authors attributed the origin of strong anisotropy to the lack of isotropization via Coulomb self-collisions (with some additional wave-particle interaction processes). Since similar mechanisms were suggested both for double ion streams and enhanced strahl electrons, Phillips et al. conducted a search for the correlation between these two phenomena. Clear-cut identification of double ion streams, however, was not possible because only low count rates were obtained during such events by particle sensors with relatively small geometric factors (G). In this letter, owing to modern ion sensors of large G, we have been able to establish that both double proton streams and enhanced strahl electrons occurred during the same low density event. A remaining puzzle, however, is the relative timing of these two phenomena: While double proton streams occurred only for 1-3 hours close to the density minimum, the enhancement of the electron anisotropy lasted for ∼15 hours. A quantitative model is needed to understand this differece in behavior between ions and electrons. Finally, from the plasma physical point of view, this May 1999 event also provides an interesting opportunity to study an extremely low Mach number shock. How the double peaked distribution of protons survived through the low Mach number bow shock transition is another question worth investigating.

It is further noted that the ion and electron temperatures in the plasma sheet during short encounters ∼12 hours after the solar wind density minimum were similar to those usually observed during active periods. How the plasma sheet, or the magnetotail itself, was maintained during the extremely low density solar wind period is an interesting problem, which is beyond the scope of this investigation.

Acknowledgments. We are grateful to R. P. Lepping and K. W. Ogilvie for their permission to use the magnetic field and plasma data sets from the WIND satellite.

References

Feldman, W. C., et al., Double ion streams in the solar wind, *J. Geophys. Res., 78,* 2017-2027, 1973a.

Feldman, W. C., et al., On the origin of solar wind proton thermal anisotropy, *J. Geophys. Res., 78,* 6451-6468, 1973b.

Feldman, W. C., and E. Marsch, Kinetic phenomena in the solar wind, in *Cosmic Winds and the heliosphere*, edited by J. R. Jokipii et al., p.p. 617-676, Univ. Arizona Press, 1997.

Frank, L. A., et al., The comprehensive plasma instrumentation (CPI) for the GEOTAIL spacecraft, *J. Geomag. Geoelectr., 46,* 23-37, 1994.

Gosling, J. T., et al., A sub-Alfvénic solar wind: Interplanetary and magnetosheath observations, *J. Geophys. Res., 87,* 239-245, 1982.

Kasaba, Y., et al., Magnetosheath electrons in anomalously low density solar wind observed by GEOTAIL, *Geophys. Res. Lett.,* 2000, in press.

Kokubun, S., et al., The GEOTAIL magnetic field experiment, *J. Geomag. Geoelectr., 46,* 7-21, 1994.

Lepping, R. P., et al., The WIND magnetic field investigation, *Space Sci. Rev., 71,* 207-229, 1995.

Livi, S., and E. Marsch, Generation of solar wind proton tails and double beams by Coulomb collisions, *J. Geophys. Res., 92,* 7255-7261, 1987.

Mukai, T., et al., The low energy particle (LEP) experiment onboard the GEOTAIL satellite, *J. Geomag. Geoelectr., 46,* 669-692, 1994.

Ogilvie, K. W., et al., SWE, A comprehensive plasma instrument for the WIND spacecraft, *Space Sci. Rev., 71,* 55-77, 1995.

Phillips, J. L., et al., Anisotropic thermal electron distributions in the solar wind, *J. Geophys. Res., 94,* 6563-6579, 1989.

T. Terasawa and M. Hoshino, Department of Earth and Planetary Science, Faculty of Science, University of Tokyo, Tokyo 113-0033, Japan. (e-mail: terasawa@eps.s.u-tokyo.ac.jp; hoshino@eps.s.u-tokyo.ac.jp)

Y. Kasaba, K. Tsubouchi, T. Mukai, Y. Saito, and A. Nishida, Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229-8510, Japan.

L. A. Frank, W. R. Paterson, and K. Ackerson Department of Physics and Astronomy, University of Iowa Iowa City, IA 52242-1479

H. Matsumoto and H. Kojima, Radio Atmospheric Science Center, Kyoto University, Gokasho, Uji 611-0011, Japan.

H. Matsui, and M. Fujimoto, Tokyo Institute of Technology Ookayama, Meguro, Tokyo 152-8551, Japan.

D. Larson, R. Lin, and T. Phan, Space Science Laboratory, University of California, Berkeley, CA 94720

J. Steinberg, D. McComas, and R. Skoug, D466, Los Alamos National Laboratory, Los Alamos, NM 87545

(Received April 14, 2000; accepted June 23, 2000)