Proceedings of ICRC 2001: 3620 © Copernicus Gesellschaft 2001

ICRC 2001

The Earth's bow shock as a cosmic-ray-modified shock: GEOTAIL observation

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Abstract. We present a case study of a solar wind deceleration event caused by diffuse ions in the upstream region of the earth's bow shock, which can be interpreted in terms of 'Cosmic-Ray-Modified' shocks (CRMSs). We have confirmed that the basic property of CRMSs, the pressure balance among ram pressure, thermal/magnetic and 'cosmic ray' (here, the diffuse ions) subpressures: The solar wind ram pressure in the shock rest frame decreased by (1-2)$\times 10^{-10}$ Pa, which was approximately balanced by the sum of the thermal+magnetic subpressure increase of $\sim 3 \times 10^{-11}$ Pa and the increase of diffuse ion subpressure of $\sim 8 \times 10^{-11}$ Pa. We also discuss a possible intrinsic time variability of this bow shock and its foreshock region.

1 Introduction

Diffusive acceleration processes of nonthermal energetic particles play energetically important roles at various astrophysical shock environments. Once the energy density of accelerated particles becomes non-negligible, or even comparable to those of the background fields and plasma particles, we should take into account nonlinear modifications of shock characteristics. Such 'cosmic ray modified' shocks (CRMSs, hereafter) have been studied mainly from the theoretical side (e.g., Drury and Völk, 1981; Axford et al., 1982; Völk et al., 1984; Kang and Jones, 1990; Ellison et al., 1990, 2000). At the previous ICRC in Utah 1999, we presented a rare observation of CRMS property at a moderately strong interplanetary shock (Terasawa et al., 1999).

It has been known, on the other hand, that the earth's bow shock often shows the character of CRMSs: well ahead of the main shock ramp the upstream solar wind flow is decelerated by a few tens of km/s in the foreshock region where the diffuse suprathermal ions (10-10^2 keV) diffusively accelerated at the bow shock have non-negligible pressure (Formisano and Amata, 1976; Diodato and Moreno, 1977; Gosling et al., 1978; Bame et al., 1980; Bonifazi et al, 1980a, 1980b, 1983; Zhang, Schwingenschuh, and Russell, 1995). However, detailed studies of the CRMS nature of the bow shock have been prevented by the transient variations of the solar wind: It has not been clear how the deceleration of the solar wind flow correlates with the diffuse ion energy density. In this report we present a case study of an exceptionally clear example of the bow shock observation as a CRMS.

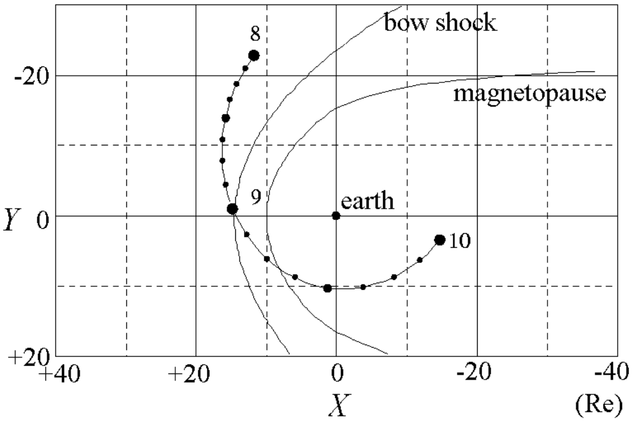

Fig. 1. The GEOTAIL orbit from 0 UT on 8 October 1995 to 0 UT on 10 October 1995. Nominal shapes of the bow shock and magnetopause are also drawn. The GEOTAIL crossing of the bow shock was near the subsolar point at $(X, Y, Z)_{\mathrm{GSE}}$=(13.8, 1.0, 1.1) $\mathrm{R_E}$.

2 Observation

We utilize datasets of energetic ions and solar wind ions from LEP/EAI and LEP/SWI experiments on GEOTAIL (Mukai et al., 1994), as well as magnetic field data from MGF experiment (Kokubun et al., 1994). Figure 1 shows the orbit of GEOTAIL for 48 hours: From 22:00 UT on 8 October 1995, the GEOTAIL spacecraft traversed the foreshock region of

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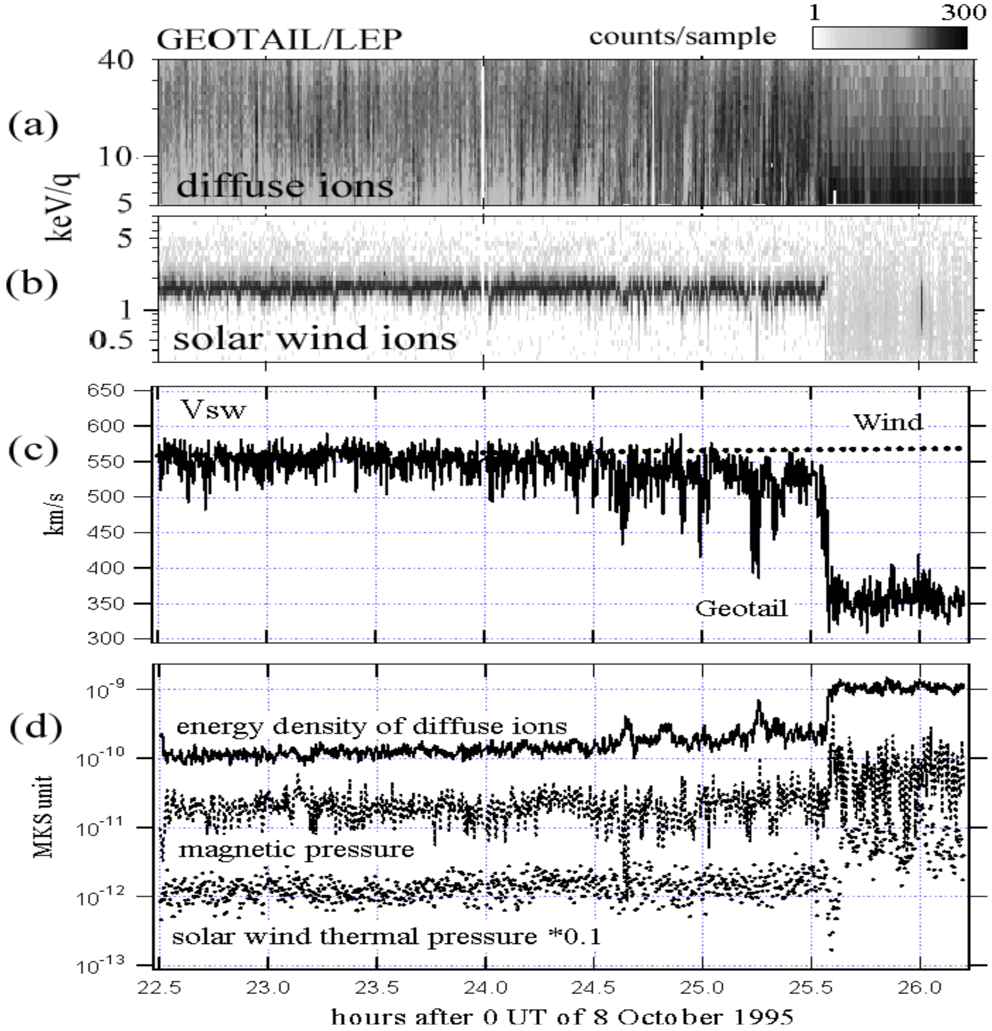

Fig. 2. Data are shown for the period from from 22:30 UT on 8 October ($t = 22.5$ h) till 02:15 UT on 9 October ($t = 26.25$ h): (a) Energy-versus-time plots of energetic ions (5-40 keV/q) and (b) for solar wind ions (0.3-8 keV/q) where counts per 12-sec sample are shown in a gray scale. (White stripes at $t \sim 24$ in both panels were due to a data gap.) (c) Solar wind velocities observed by GEOTAIL (solid line) and WIND (dotted line). (d) Energy density of diffuse ions (E_{DI}) and magnetic and proton thermal subpressures (P_B and P_{sw}). To avoid overlaps, $P_{sw}$is shifted down by one decade.

the nose bow shock over 3 hours. During this interval the solar wind was more or less steady and continuously monitored by the WIND spacecraft cruising about 130 $\mathrm{R_E}$ upstream of the GEOTAIL position (The estimated convection delay time of the solar wind from WIND to GEOTAIL was ~22 min.) Figure 2 (a) and (b) respectively show the energy-versus-time (E-t) plots of diffuse ions (propagating sunward) and solar wind ions observed aboard GEOTAIL. Figure 2 (c) shows changes of the solar wind velocity $V_{sw,\mathrm{GEOTAIL}}$ at GEOTAIL (a solid line) and $V_{sw,\mathrm{WIND}}$ at WIND (a dotted line) [1]. The GEOTAIL crossing of the bow shock at $t = 25.57$ h (01:34 UT) is evidenced by a sudden widening of the solar wind E-t plot (Figure 2 (b)) as well as a sharp drop in the solar wind velocity (Figure 2 (c)). Toward the bow shock, the upstream diffuse ions showed a gradual increase of their intensity, which is seen as the darkening of the gray scale in Figure 2 (a). (In the downstream region after $t = 25.57$ h there appeared darkest regions in the low energy end ($<\sim 10$ keV). They represent shock-heated solar wind ions, which we do not treat in this report.) In Figure 2 (c) we see that $V_{sw,\mathrm{GEOTAIL}}$ decreased by 10-150 km/s from the $V_{sw,\mathrm{WIND}}$ along with the increase of the diffuse ion intensity. We define the foreshock deceleration of the solar wind as $\Delta V_{sw} \equiv V_{sw,\mathrm{GEOTAIL}} - V_{sw,\mathrm{WIND}}$. To see the change of the diffuse ion intensity quantitatively, we calculate their

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[1] Around $t = 24.5$-25.0 h, there was a large velocity and magnetic field disturbance satisfying the Walén relation for anti-sunward propagating Alfvén waves. Since corresponding disturbance was not seen at GEOTAIL, they were likely Alfvén waves of solar origin having a limited longitudinal extent. We replaced observed $V_{sw,\mathrm{WIND}}$ with values linearly interpolated from those outside of this period.

energy density E_{DI} defined as,

$$E_{DI} = \int\int\int \frac{1}{2} m v^2 f(\boldsymbol{v}) d\boldsymbol{v} \qquad (1)$$

where $f(\boldsymbol{v})$ is the observed velocity space distribution function. Figure 2 (d) shows the change of E_{DI} (a solid line) as well as changes of the magnetic subpressure (P_B, a dashed line), and the thermal proton subpressure of the solar wind (P_{sw}, dots). E_{DI} and P_B (and weakly P_{SW}) showed gradual increases before their final jump at the bow shock. We calculate the subpressure exerted by the diffuse ions, P_{DI} as $(\gamma_{DI} - 1)E_{DI}$ assuming γ_{DI}=5/3.

Figure 3 (a) shows the scatter plot of ΔV_{sw} plotted against E_{DI}, which shows a clear negative correlation with the correlation coefficient 0.74. A regression line,

$$\Delta V_{sw} = -30.3\ (E_{DI}/10^{-10}\ \mathrm{J/m^3}) + 19.6\ \ \mathrm{km/s} \qquad (2)$$

is also drawn. In this figure the solar wind deceleration in the foreshock region becomes evident when E_{DI} exceeds $\sim 10^{-10}$ J/m^3 ($\sim$ 630 eV/cm^3). In Figure 3 (b) ΔV_{sw} is also compared with the normalized amplitude of the upstream waves, $\sigma_c / < |B| >$, where σ_c is the square root of the trace of the variance matrix R_{ij}, namely,

$$R_{ij} = \frac{1}{N} \Sigma_{k=1}^{N} (B_i - < B_i >)_k (B_j - < B_j >)_k \qquad (3)$$

and $< |B| >$ the 1-min average field intensity. In (3), i, j=x, y, z and k is the sequential number of the 3-sec data of the magnetic field ($k = 1, .., N = 20$). As seen in Figure 3 (b) the solar wind deceleration becomes significant when $\sigma_c / < B >$ exceeds ~ 0.4. Such a correlation between ΔV_{sw} and $\sigma_c / < B >$ was first noted by Bonifazi et al. (1983). However, while $|\Delta V_{sw}|$ in their case was $\sim$ 50 km/s at most, $|\Delta V_{sw}|$ in our case exceeds 100 km/s. We attribute this difference to the difference of the background solar wind velocity itself ($\sim$ 350 km/s in Bonifazi's case and $\sim$ 550 km/s in our case).

3 Discussion and Remarks

From the observed solar wind parameters, the change of the ram pressure of the solar wind, $\Delta(\rho_{sw} V_{sw}^2)$ in the observer's frame ($\sim$ the bow shock rest frame), is calculated to be $\sim -$(1-2) $\times 10^{-10}$ Pa just before the bow shock crossing. On the other hand, we obtain subpressure increases, ΔP_{DI}, ΔP_B, and ΔP_{sw} as $+0.8 \times 10^{-10}$ Pa, $+0.2 \times 10^{-10}$ Pa, and $+0.1 \times 10^{-10}$ Pa, respectively. (To calculate these increases we took values of P_{DI}, P_B, and P_{sw} at t = 22.5 h as their 'base' values.) Thus their summation, ΔP_{DI}+ΔP_B+ΔP_{sw} $\sim 1.1 \times 10^{-10}$ Pa, roughly compensated the ram pressure change [2]. This is what is expected for CRMSs ('Cosmic-Ray-Modified' shocks).

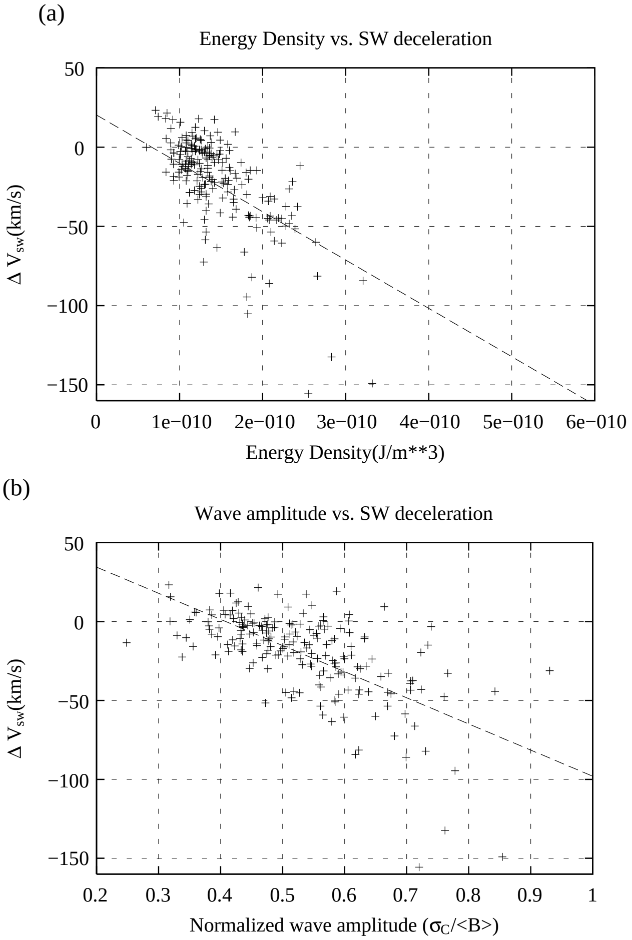

Fig. 3. (a) The amount of the solar wind deceleration (ΔV_{sw}, see text) is plotted against the energy density of diffuse ions (E_{DI}). (b) The same as (a), but the abscissa is the normalized amplitude of upstream waves ($\sigma_c / < |B| >$).

In the theoretical model of CRMSs the 'cosmic ray' subpressure increases gradually toward the shock front, so that the ram pressure decreases also gradually. However, in Figure 2 (c) we observed that the the ram pressure decrease was not smooth but accompanied with large variations, such as several impulsive decelerations of the solar wind seen at t = 24.63 h, 25 h, and 25.26 h, which were $\sim$ 20-60 min before the final bow shock crossing at t = 25.57 h. Corresponding to these deceleration events, there were temporal increases of the energy density of diffuse ions, E_{DI}, in Figure 2 (d). We might be able to argue that oscillatory motions of the bow shock surface produce these apparent impulsive variations of the upstream parameters while their instantaneous spatial profiles could be smooth. Another interpretation, however, is that the CRMSs are intrinsically 'turbulent' and accompanied with large impulsive variations of the velocity as well as the energy density of accelerated particles. (Such 'turbulence' could be caused by the instability studied theoretically

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[2] The subpressure of the solar wind electrons is not included, since the observation of the core part of the electron distribution is not available. However, since it is not unreasonable to assume that Δ(electron thermal subpressure) $\sim$ Δ(ion thermal subpressure) $\sim +0.1 \times 10^{-10}$ Pa in the order-of-magnitude discussion, the above subpressure summation was not seriously underestimated.

by many authors: e.g. Drury and Falle 1986; Zank et al., 1990). It is noted that similar ram pressure variations were seen in the extended foreshock region ($\sim$ 0.03 AU) of the interplanetary propagating shock (IPS) with CRMS features (Terasawa et al., 1999). For this IPS case the latter interpretation seems more likely, since oscillatory motions of the IPS surface, even if they could exist, unlikely caused the foreshock ram pressure variations in such extended spatial scale. It is hoped that more extensive studies of the earth's bow shock lead to further understanding of the time-dependent properties of CRMSs.

Acknowledgements. We thank the team members of the GEOTAIL particle and field measurement for their collaboration.

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