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Observation of a 'Cosmic-Ray-Modified' Interplanetary Shock

T. Terasawa[1], K. Maezawa[2], M. Hoshino[1], N. Shimada[1,3], T. Mukai[3], Y. Saito[3], T. Yamamoto[3], S. Kokubun[4], B. Wilken[5], and T. Doke[6]

[1] *Department of Earth and Planetary Physics, University of Tokyo, Tokyo 113-0033, Japan*
[2] *Department of Physics, Nagoya University, Nagoya 464, Japan*
[3] *Institute of Space and Astronautical Science, Sagamihara 229, Japan*
[4] *Solar Terrestrial Environment Laboratory, Nagoya University, Toyokawa 442, Japan*
[5] *Max-Planck-Institute for Aeronomy, Katlenburg-Lindau, D3411, Germany*
[6] *Advanced Research Center for Science and Engineering, Waseda University, Tokyo 169, Japan*

Abstract

We show that a propagating interplanetary shock observed on 21 Feb 1994 had the feature of a cosmic-ray-modified shock (CRMS), where the deceleration of the plasma flow in the shock frame started gradually from ~1 hour before the arrival of the shock and is explicable in terms of the increase of the 'cosmic-ray' pressures carried by energetic electrons (~ 40 keV) and protons (50 keV - 10 MeV). The ram pressure of the upstream solar wind showed large time variations, which we have concluded to be attributable to the nonlinear effect of the large amplitude Alfvén waves excited through the cyclotron resonant interaction with accelerated protons of several MeV.

1 Introduction:

It is widely believed that 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 the modification of shock characteristics. Such situation is described in terms of 'cosmic ray modified' shocks (CRMSs, hereafter). Drury and Völk (1981) treated the problem of CRMSs as an interaction between the background gas (flow velocity in the shock rest frame u, mass density ρ, pressure $P_{\rm g}$, and the ratio of specific heats $\gamma_{\rm g}$) and 'cosmic ray gas' (with pressure $P_{\rm c}$ and the ratio of specific heats $\gamma_{\rm c}$). The latter gas consists of 'cosmic ray' particles or nonthermal energetic particles, which are assumed to have an almost isotropic pitch angle distribution in the gas rest frame, so that these particles share the bulk velocity u with the gas. In the steady state, mass and momentum flux conservation relations are written as $\rho u = A$ and $Au + P_{\rm c} + P_{\rm g} = B$ with constants A and B. The characteristic spatial scale of the *foreshock* region, namely the region upstream of the shock front where $P_{\rm c}$ is non-negligible, is given by $\lambda \equiv \kappa/u_1$ (κ is a spatial diffusion coefficient for cosmic ray particles, and u_1 the flow velocity at the upstream boundary. See Figure 1.) In the steady state the ram pressure of the gas, $P_{\rm ram} \equiv \rho u^2 = Au$, is proportional to u.

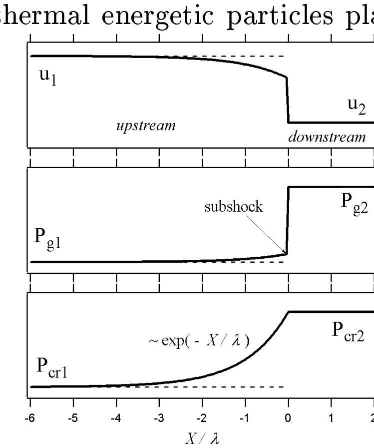

Figure 1: Structure of a steady CRMS (conceptual figure).

The spatial structure of CRMSs could become unsteady owing to various reasons: Drury and Falle (1986) showed that CRMSs are intrinsically unstable to the excitation of sound waves of the wave length smaller than the characteristic scale length λ. Zank et al. (1990) later extended this instability to the case of magnetosonic waves propagating oblique to the averaged magnetic field. On the other hand, parallel-propagating Alfvén waves can be self-consistently amplified to large amplitudes through the cyclotron resonant interaction with shock-accelerated particles. We show in this report that the latter waves were responsible for the significant modification of the foreshock structure of an interplanetary shock.

2 Observation:

At 09:03 UT on 21 February 1994 the GEOTAIL satellite encountered a fairly fast interplanetary shock (IPS) in the solar wind at (-27, -61, -2) R_E (earth radii) in the GSE coordinate, which was about 20 R_E upstream from the nominal bow shock position. The shock having a compression ratio$\sim$3.8, an Alfvén Mach number$\sim$5.8, and an upstream shock angle$\sim$68^o, propagated radially outward with $V_{\rm shock}$ $\sim$920 km/s in the observers' frame. Energetic particle fluxes increased exponentially toward the front of this IPS (Figure 2). Observed energy spectra in the upstream region had a power law shapes with index of 2.5-3. These features of energetic particles are explained in terms of the diffusive shock acceleration theory with a modification due to the downstream flow expansion (Shimada, 1998). (See also Terasawa et al., 1995; Koi et al., 1995; Shimada et al., 1998. For satellite instrumentation, see Kokubun et al. (1994), Mukai et al. (1994), and Doke et al. (1994).)

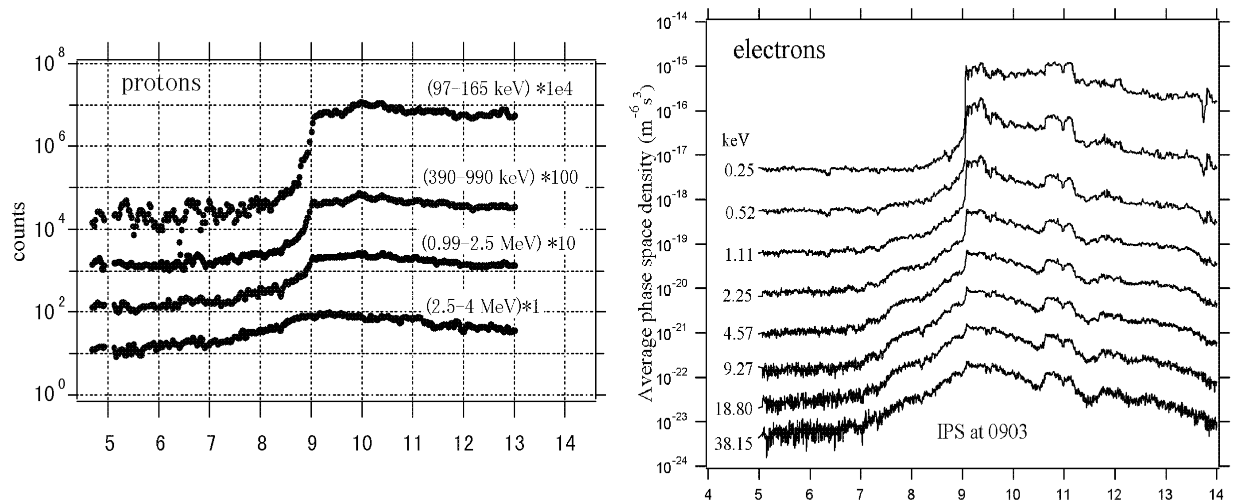

Figure 2: Observed increases of energetic protons (left panel) and electrons (right panel) accompanied with the passage of an interplanetary shock at 09:03 UT on 21 Feb 1994.

In Figure 3 we show the temporal variations of (a) the magnitude of the magnetic field $B_{\rm abs}$ (nT), (b) the solar wind plasma density $N_{\rm sw}$ (cm^{-3}), (c) the ion temperature $T_{\rm sw,p}$ (eV), and (d) the solar wind flow velocity $V_{\rm sw}$ (km/sec). These solar wind parameters showed gradual increases from $\sim$ 08:00 UT to the arrival of the IPS at 09:03 UT, when abrupt increases occurred in all of them. The velocity u in the shock rest frame ($\equiv V_{\rm shock} - V_{\rm sw}$) decreased by $\Delta u \sim -50$km/s. (The flow velocity $V_{\rm sw}$ in the observers' frame, on the other hand, increased by $|\Delta u|$). According to the steady state model as described in the introduction, the ram pressure decrease $\Delta P_{\rm ram}$ in the foreshock region, which is given by $\rho u \Delta u$, should be balanced with the increase of the 'cosmic ray pressure' + gas pressure. With the upstream values of ρ and u at 08:00 UT, we obtain $\Delta P_{\rm ram} \sim -1.3 \times 10^{-10}$ Pa.

The panel (e) of Figure 3 shows the variations of nonthermal electron pressure (250 eV-40 keV; a thin solid curve, $P_{\rm cre}$), nonthermal proton pressure (50 keV-10 MeV; a thin dotted curve, $P_{\rm crp}$), magnetic pressure (a thick dotted curve, $P_{\rm b}$), thermal proton pressure (a dashed curve, $P_{\rm thp}$). We have calculated these pressures of nonthermal particles from the integrated energy densities by assuming the specific heat ratio of 5/3. (Observational uncertainty in determining $P_{\rm cre}$ and $P_{\rm crp}$ is discussed in the appendix.) We see in Figure 3 (e) an approximate equi-partition of pressures, namely that all partial pressures $P_{\rm thp}$, $P_{\rm b}$, $P_{\rm crp}$, and $P_{\rm cre}$, are of the same order in the foreshock interval of ~08:00-09:00 UT. The summed pressure $P_{\rm sum}(\equiv P_{\rm thp}+P_{\rm b}+P_{\rm crp}+P_{\rm cre})$, which is shown by a thick dash-dotted curve in Figure 3 (e), increased from the far upstream value (3×10^{-11} Pa) to the value just upstream of IPS (1.3×10^{-10} Pa) by the amount $\Delta P_{\rm sum}\sim 1.0\times10^{-10}$ Pa. From the fact that this value of $\Delta P_{\rm sum}$ is close to the magnitude of the ram pressure change $|\Delta P_{\rm ram}|$ estimated above we conclude that this interplanetary shock belonged to the category of CRMSs.

However, looking at the observed time profile of $P_{\rm ram}=\rho u^2$ (a solid curve in Figure 3(f)), we notice that the behavior of this IPS was far from the expectation from the steady state model: While

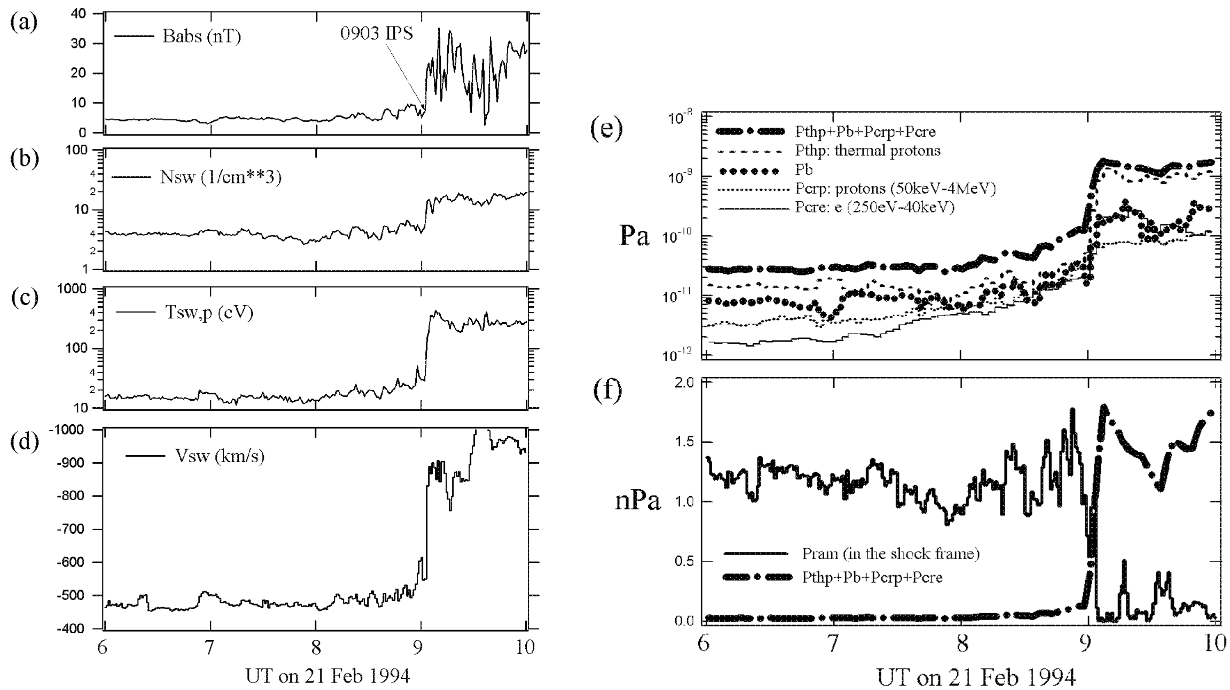

Figure 3: Temporal variations of plasma parameters and partial pressures.

the steady state model predicts that $P_{\rm ram}\propto u$, large variations in $P_{\rm ram}$ (time scale of ~5-15 min) did not give such a simple proportionality with u. As stated in the introduction, there are at least two possible origins for this unsteadiness: (i) the Drury-Falle type instability (or its extension to MHD), and (ii) the cyclotron resonant instability. While sonic or magnetosonic waves propagating *toward* the shock *oblique* to the averaged magnetic field are excited in the process (i), Alfvén waves propagating *away* from the shock in the plasma rest frame *parallel* to the averaged magnetic field are excited in the process (ii).

In the time profiles of plasma quantities shown in Figure 3 (a)-(d) we see variations of the time scale of ~5-15 min, for which we have made a detailed analysis: Firstly, from the minimum variance analysis of the magnetic field fluctuations, we have found that the waves propagated nearly *parallel* to the averaged magnetic field (within $\sim 15^{\rm o}$). Secondly, from the Poynting flux analysis of the magnetic field and plasma velocity fluctuations, we have found that the waves propagated *away* from the shock. These two findings are consistent with the process (ii) but not with (i). Assuming that the observed fluctuations were Alfvén waves from the process (ii), we estimate that their wavelength was $\sim$ 1.3-4$\times10^5$ km, with which protons of ~0.3-3 MeV satisfy the cyclotron resonance condition. If protons of this energy excited these Alfvén waves, their flux time profile should show resemblance to that of waves. The protons flux around this energy actually showed an order of magnitude increase in the foreshock interval (Figure 2), during which the fluctuations showed a significant amplification. It is therefore likely that the latter waves, resonantly excited Alfvén waves, were responsible to the unsteadiness of the foreshock region. Compressible fluctuations ($\delta|B_{\rm abs}|$ and $\delta N_{\rm sw}$) accompanying these large amplitude Alfvén waves ($\sim$ 50% of the averaged field strength) seem to be attributable to the nonlinear effect of these waves which had a nearly linear polarization. However, the origin of their linear polarization is not yet understood, since the cyclotron resonance instability typically produces circularly polarized waves. Hoshino (1987; 1988) showed that if circularly polarized Alfvén waves are spatially localized a self-focusing instability converts their polarization to linear. We are currently investigating whether similar process could produce the observed linear polarization under the foreshock condition of this IPS.

Why we had no evidence for the instabilities predicted by Drury and Falle (1986) or Zank et al. (1990)? Their instability might have been suppressed somehow in the environment of the observed IPS, or the perturbations owing to their instability might have existed but been simply masked by the products of the stronger cyclotron-type instability. To answer this question would be important for the general understanding of CRMSs, but requires further observational and theoretical studies.

Appendix:

We have calculated pressures of nonthermal electrons and protons from the integrated energy densities. One problem is possible underestimation of these energy densities of nonthermal particles owing to the limited energy coverage of the particle instruments. Figure 4 shows how the integrated energy densities depend on the maximum energies of the integration range, with the minimum energies being fixed (250 eV for electrons, and 50 keV for protons). As seen in the figure, the calculated energy density for protons seems to more or less saturates around several MeV, so that the effect of the underestimation seems not serious. The calculated energy density for electrons, on the other hand, does not stop increasing at 40 keV, the highest energy of the observation. If we linearly extrapolate it up to $\sim$10 MeV, the energy density of nonthermal electrons becomes at most comparable to that of nonthermal protons. It would be, therefore, not unreasonable to assume that the energy density of energetic electrons including those in the unobserved energy range were comparable to that of energetic protons but did not far exceed it.

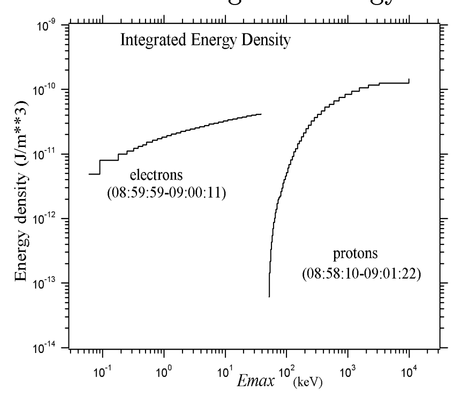

Figure 4: Dependence of energy densities of electrons and protons on the maximum energies of the integration ranges.

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