SH 4.4.01

Implications of Pickup Ion Reflection at the Quasi-perpendicular Termination Shock for the Shock Structure and Anomalous Cosmic Ray Modulation

J.A. le Roux[1], H. Fichtner[2], and G.P. Zank[1]

[1] *Bartol Research Institute, University of Delaware, Newark, DE 19716, USA*

[2] *Intitut für Theoretische Physik, Ruhr-Universität Bochum, Bochum, Germany*

Abstract

We present self-consistent calculations of the long-term temporal behavior of the multiply reflected ion acceleration of pickup protons at the quasi-perpendicular termination shock, and the termination shock structure.

1 Introduction:

Zank et al. (1996) and Lee et al. (1996) revived the multiply reflected ion (MRI) or shock surfing acceleration mechanism of Sagdeev (1966) and applied it to study the reflection and acceleration of pickup ions (PUIs) at quasi-perpendicular shocks. Using a test particle approach, they showed semi-analytically and analytically, respectively, that the MRI mechanism naturally reflects PUIs more efficiently than solar wind thermal particles, reflects lighter PUIs more efficiently than the heavier ones, and accelerates PUIs to high energies (up to ~ 0.2 MeV). In addition, Zank et al., (1996) showed that MRI acceleration produces a power law spectrum for PUIs that is harder than expected from diffusive shock acceleration. All these aspects are consistent with the observations of PUI spectra by Gloeckler et al. (1994). The MRI theory was confirmed by fully self-consistent hybrid simulations (Lipatov and Zank, 1999). The hybrid model, however, is too computer intensive to deal with MRI acceleration on a time scale much longer than the characteristic MRI acceleration time (~ ½ hour). Here, we incorporate the main aspects of the MRI theory of Zank et al. (1996) into a time-dependent HD solar wind and PUI model. This allows us to study self-consistently the temporal behavior of the MRI reflection and acceleration of PUIs at the quasi-perpendicular termination shock (TS), and of the TS structure over a much longer period of several years.

2 The Model:

At the quasi-perpendicular TS the cross shock potential ϕ is estimated by Zank et al. (1996) as

$$Ze\phi \approx Z\eta \frac{1}{M_{A1}^{2}}(s-1)mu_1^2 \tag{1}$$

where Ze is the charge of the PUI, M_{A1} is the upstream Alfvénic Mach number, s is the TS compression ratio, m is the proton mass, and u_1 is the upstream flow speed. The parameter $\eta \geq 2$ takes into account contributions to ϕ from the deflection of PUIs at the TS by the foot of reflected PUIs which slows down the incoming flow, and from the jump in the electron pressure across the TS. The PUIs are reflected when they fulfill the condition $1/2Mv_x^2 \leq Ze\phi$ where v_x is the velocity component normal to the shock front, and M is the PUI mass. It then follows that those PUIs will be specularly reflected at the TS for which $v_x \leq V_{spec}$ where

$$V_{spec} = \left[2\eta \frac{Zm}{M}\frac{u_1^2}{M_{A1}^2}(s-1)\right]^{1/2} \tag{2}$$

If we simply assume that the upstream PUI distribution is an isotropic spherical shell in velocity space with radius u_1, then the fraction R_{refl} of the PUI distribution reflected by the cross-shock potential is

$$R_{refl} = \frac{1}{2}\frac{V_{spec} + v_{sh}}{u_1} H(V_{spec} + v_{sh}) \tag{3}$$

where v_{sh} is the TS velocity in the observer frame. The reflected PUIs are trapped upstream by the Lorentz force and the shock potential until the PUIs gain enough energy from the motional electric field to overcome the potential. The maximum velocity parallel to the shock surface some PUIs reach is given by

$$v_{\max} = \frac{\eta}{x}\left(\frac{m}{m_e}\right)^{1/2} V_{A1}(s-1) \tag{4}$$

where x is a parameter determining the amount of electron inertial lengths that equals the width of the TS ramp, and m_e is the electron mass. After assuming that $f_{MRI}(\mathrm{v}) \propto v^{-3}$ (Zank et al., 1996) where f_{MRI} is the distribution function of PUIs that are MRI accelerated, and v is the particle speed, we find that the rate of increase in the PUI energy density is $1/2Mu_1^2 Q_{MRI}$ where Q_{MRI} is the production rate of MRI accelerated PUIs given by

$$Q_{MRI} = \frac{1}{2}\frac{u_1 n_{PUI} R_{refl}}{\ln(\varepsilon)(\Delta r)}(\varepsilon^2 - 1) \tag{5}$$

where $\varepsilon = v_{max}/u_1$, n_{PUI} is the PUI density just upstream of the TS, and (Δr) is the width of Q_{MRI}. With the assumption that the rate at which the upstream solar wind flow looses energy during MRI acceleration is balanced by the rate of "thermal" energy gain by the PUIs, the HD momentum equation of the solar wind and PUI fluid needs the addition of a loss term $L = -mu_1 Q_{MRI}$. The HD fluid equations that describe the collective behavior of solar wind protons, electrons, and PUI protons in a one fluid approach are given by

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho u) = mQ_{ph} \tag{6}$$

$$\frac{\partial \rho u}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho u^2) = -\frac{\partial P}{\partial r} - muQ_{ce} - mu_1 Q_{MRI} \tag{7}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho u^2 + \frac{P}{\gamma - 1}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 u\left(\frac{1}{2}\rho u^2 + \frac{\gamma}{\gamma - 1}P\right)\right] = -\frac{1}{2}m\left[u^2 H(r_{sh} - r) + v_{rms}^2 H(r - r_{sh})\right] Q_{ce} \tag{8}$$

where ρ is the total mass density, P is the total particle pressure, u is the radial solar wind speed assumed to be the same for all three species, $\gamma = 5/3$ is the adiabatic index for the combined fluid, r is radial distance from the Sun, and r_{sh} the radial distance to the TS. Also, Q_{ce} and Q_{ph} are the production rates for PUI protons due to charge exchange of the inflowing interstellar neutral hydrogen with the solar wind, and the photo-ionization of the neutrals by solar radiation, respectively. For more details, see le Roux and Fichtner (1997). Equations (6)-(8) are solved numerically and the expressions in equation (2)-(5) are updated after each time step to allow us to follow the temporal behavior of the reflection and acceleration of the PUIs, and the TS structure.

3 The Results:

In Figure 1 we show calculated solar wind speed as a function of r in the ecliptic plane in the upwind direction. The dashed curve denotes the initial solution in the absence of MRI PUI acceleration, while the solid curve is a typical solution when MRI acceleration at the TS is included. The dashed curve, originally calculated with the TS at ~ 81 AU, is shifted inward to compare with the MRI case. Without MRI effects, the TS has a compression ratio $s \approx 3.1$ due to the presence of "hot" PUIs in the solar wind which dominate the solar wind dynamically beyond the ionization cavity, and lowers the Mach number upstream to ~ 3.4. The TS structure in the solid curve features a foot (shock precursor), and ramp (subshock). The foot is due to the MRI accelerated PUIs that partially mediate the TS so that for the ramp $s \approx 2.6$. The loss in upstream solar wind ram pressure reduces the TS distance from ~ 81 AU to ~ 76 AU. This result was obtained by

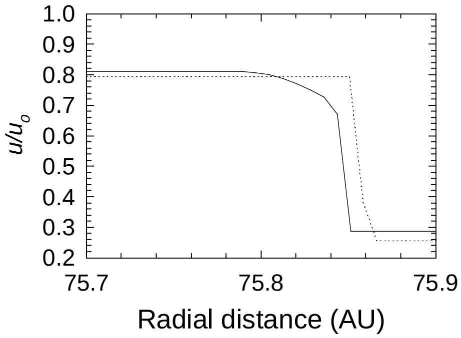

Figure 1: Simulated solar wind speed u normalized to u_0 = 400 km s^{-1} as a function of radial distance in the ecliptic plane. Dashed curve is the initial solution without MRI PUI acceleration. Solid curve is a typical solution with MRI effects included.

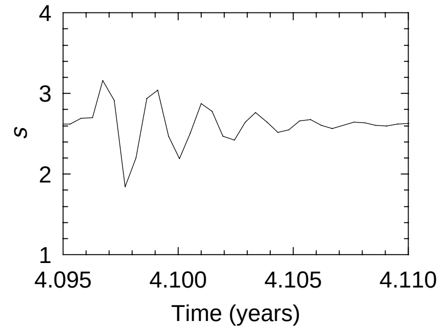

Figure 2: Compression ratio s of the TS ramp as a function of time during a typical PUI reflection cutoff event over a period of ~ 5.5 days.

assuming that the ramp width of the TS equals one electron inertial length (x = 1 in equation (4)).

A very interesting aspect of this model is the highly time-dependent nature of the PUI reflection process as calculated over an 11-year period. The reflection process periodically cuts off quite frequently during the first year, progressively less so from year 1 to year 5, and after that once per year on average. The reason is that the TS is on average always moving inward during this period, at first more quickly, but slowly later on in response to the MRI acceleration process that reduces the upstream ram pressure. Since at large r upstream $P \propto 1/r$ because PUI protons dominate, and $\rho \propto 1/r^2$ because of thermal protons, the inward moving TS always encounters an increasing upstream Mach number ($M_{s1} \propto 1/r^{0.5}$). It is this rate of increase in M_{s1} that controls the frequency of the sporadic reflection cutoff events. Based on the TS motion, we estimate that the TS will finally come to rest at a later time at ~ 75 AU.

Such a sporadic cutoff event is demonstrated in a series of figures (Figures 2-4) covering a period of ~ 5.5 days. After a sufficient buildup in M_{s1}, the event is initialized by a sudden increase in s of the TS ramp (1st peak in Figure 2). Consequently, the TS is pushed outwards, reaching a maximum $v_{sh} \approx +30$ km s^{-1} (1st peak of solid curve in Figure 3). According to equation (4), an outward moving TS ($v_{sh} > 0$) results in an increased fraction of reflected PUIs at the TS. This effect is visible as the first peak of R_{refl} in Figure 4. In response, more PUIs are accelerated by the MRI mechanism (larger loss term in equation (7)), and the TS weakens again (decrease in s after the first peak in Figure 2). The weakening is more pronounced than the previous strengthening, and the TS moves inward relatively quickly with a maximum velocity $v_{sh} \approx -100$ km s^{-1} (Figure 3). At this point, $|v_{sh}| > V_{spec}$ in Figure 3 and $R_{refl} = 0$ in equation (3), and Figure 4. This indicates that all PUIs overcome the shock potential. With the MRI acceleration process being interrupted, the TS recovers its strength again (2nd peak in s in Figure 2). From this point in time onwards, the whole cycle repeats for another few times until it dies out. Each cycle has a duration of ~ 1 day so that the event lasts for ~ 5 days. These cutoff events and the copious weaker events all have a duration of ~ 5-10 days.

In the sporadic reflection cutoff events R_{refl} peaks as high as ~ 19%, but overall, fluctuations in R_{refl} occur around a mean value of ~ 10.8%. Also, s of the TS ramp varies substantially in these events. It can be as large as ~ 3.2 and as small as ~ 1.8 (Figure 2). The ramp, although temporarily considerably weakened, is never totally mediated by the MRI accelerated PUIs. The subsequent fast inward motion by the strongly weakened TS due to the reduced upstream ram pressure always leads to a cutoff in the reflection process so that MRI acceleration temporarily ceases. This allows the TS to recover its strength before it becomes totally mediated by the MRI accelerated PUIs.

Initially, we find that PUIs reach a maximum energy of ~ 0.14 MeV by MRI acceleration. In the ensuing self-consistent calculations, the maximum energy decreases to ~ 81 keV on average as the TS is weakened

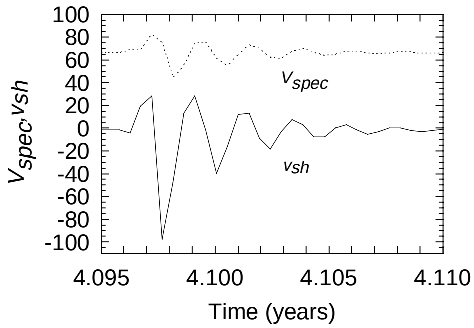

Figure 3: The maximum reflection velocity V_{spec} and TS velocity v_{sh} as a function of time for the same period as in Figure 2.

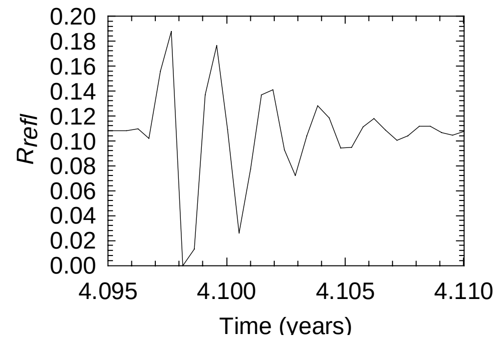

Figure 4: The fraction of reflected PUI protons as a function of time for the same period as in Figure 2.

by the MRI acceleration process. Inside the sporadic reflection cutoff events the maximum energy undergoes strong fluctuations. Typically, the maximum energy can be temporarily as high as ~ 0.17 MeV and as low as ~ 16 keV. Despite the seeming linear dependence on s, the largest increase(decrease)in v_{max} coincides with a decrease(increase) in s, suggesting that v_{max} depends more strongly on changes in V_{A1} (equation (4)).

4 Summary and Conclusions:

Self-consistent calculations of MRI reflection and acceleration of PUI protons at the perpendicular TS show that the TS is on average significantly mediated by the accelerated PUIs ($s \approx 2.6$ instead of ~ 3.1 for the no MRI acceleration case). On average, ~ 11% of PUI protons are reflected at the TS and they reach a maximum energy of ~ 81 keV, thereby forming a potential pool of pre-accelerated PUIs for further acceleration by diffusive shock acceleration to become anomalous cosmic ray protons. Based on standard quasi-linear theory for parallel diffusion, we find that the near-isotropy condition for standard diffusive shock acceleration theory at the quasi-perpendicular TS (Jokipii, 1987) is fulfilled at 81 keV if $\delta B/B \approx 0.8$ where δB is the average magnitude of the field fluctuations, and B is the mean field. MRI PUI acceleration causes the TS to move effectively toward the Sun. In a solar wind dominated by the PUI pressure, the TS then experiences an increasing upstream Mach number which results in strong sporadic and copious weaker temporal events lasting ~ 5-10 days. These strong events are characterized by a short-lived cutoff in the reflection of PUIs and their acceleration, and a TS momentarily almost fully mediated by MRI accelerated PUIs. The cutoff events occur with a frequency tied to the average velocity of inward motion of the TS.

References

Gloeckler, G. et al. 1994, JGR, 99, 17637

Jokipii, J.R. 1987, ApJ, 313, 842

Lee, M.A., Shapiro, V. D., & Sagdeev 1996, JGR, 101, 4777

Le Roux, J.A., & Fichtner, H. 1997, JGR, 102, 17365

Lipatov, A.S., & Zank, G.P. 1999, Phys. Rev. Lett., 82, 3609

Sagdeev, R.Z. 1966, Rev. Plasma Phys., 4, 23

Zank, G.P., Pauls, H. L., Cairns, I. H., & Webb, G. M. 1996, JGR, 101, 457