The Effect of Cosmic Rays on the Propagation of Shock Waves in the Outer Heliosphere

W.K.M. Rice and G.P. Zank

Bartol Research Institute, University of Delaware, Newark, DE 19716, USA

Abstract

In previous work it has been shown that the propagation of shocks waves in the outer heliosphere is strongly effected by the inclusion of pickup ions (PIs) in the heliospheric model. We present results showing how the inclusion of a magnetic field can further effect shock wave propagation. Galactic and anomalous cosmic rays are then also included in the heliospheric model and results illustrating their effect are presented. The anomalous cosmic rays are assumed to be produced by injection at the interplanetary shock fronts and the galactic and anomalous cosmic rays, due to different energy ranges, are taken to have different adiabatic indices and diffusion coefficients.

1 Introduction:

Using a one dimensional gasdynamic model Zank & Pauls (1997) showed that pickup ions (PIs) have a significant effect on the propagation of shock waves in the outer heliosphere. This was shown to be due to the PIs decelerating the solar wind and producing an ion population whose internal energy dominates that of the solar wind (Holzer, 1972; Isenberg, 1986; Zank et al., 1996). Consequently the solar wind temperature, and hence the sound speed, is greater in the outer heliosphere when PIs are included (Zank et al., 1995, 1996). Weak shocks waves propagate at, approximately, the sound speed and hence propagate faster when PIs are included than when they are ignored.

When a magnetic field is included weak shock waves propagate at the fast magnetosonic speed, a combination of the sound speed and the Alfvén speed. The inclusion of cosmic rays changes the sound speed for long wavelength waves (Axford, Leer & McKenzie, 1982) and hence will also change the shock propagation speed. In the presence of PIs, however, the gas pressure is significantly greater than the cosmic ray pressure within 40 AU and this effect is quite small. The major effect of cosmic rays is that their pressure gradient can accelerate or decelerate the solar wind particles, modifying the shock structure (Axford, Leer, & McKenzie, 1982; Drury & Volk, 1981; Donohue, Zank, & Webb, 1994). Within the heliosphere the galactic cosmic rays have a very small pressure gradient and do not noticeably modify the interplanetary shock structure. The anomalous cosmic rays, which we assume are produced by injection at the interplanetary shock fronts (Zank, Webb, & Donohue, 1993), can have a significant pressure gradient (depending on the injection efficiency and the diffusion coefficient) and can noticeably modify the shocks.

The model that we use is a one-dimensional, spherically symmetric, MHD model. The cosmic rays are assumed to have a negligible density and contribute only a pressure. The equations are

$$\partial_t \rho + 1/r^2 \partial_r (\rho u r^2) = 0 \tag{1}$$

$$\partial_t (\rho u) + 1/r^2 \partial_r (\rho u^2 r^2) + \partial_r P_g + \partial_r P_{cg} + \partial_r P_{ca} + B^2/(\mu_o r) + B/\mu_o \partial_r B = Q_M \tag{2}$$

$$\begin{aligned} &\partial_t \left(\frac{1}{2}\rho u^2 + \frac{P_g}{\gamma_T - 1} + \frac{P_{ca}}{\gamma_T - 1} + \frac{P_{cg}}{\gamma_R - 1} + \frac{B^2}{2\mu_o} \right) + \frac{1}{r^2}\partial_r \left[\left(\frac{1}{2}\rho u^2 + \frac{\gamma_T P_g}{\gamma_T - 1} \right) u r^2 + \right. \\ &\left. \frac{r B^2}{\mu_o} + \frac{r^2 B}{\mu_o}\partial_r B + \frac{\gamma_T P_{ca}}{\gamma_T - 1} u r^2 + \frac{\gamma_R P_{cg}}{\gamma_R - 1} u r^2 - \frac{\kappa_a r^2}{\gamma_T - 1}\partial_r P_{ca} - \frac{\kappa_g r^2}{\gamma_R - 1}\partial_r P_{cg} \right] = Q_E \end{aligned} \tag{3}$$

$$\partial_t P_{cg} + \left(u - 2\kappa/r \right) \partial_r P_{cg} + \gamma_R \left(\partial_r u + 2u/r \right) P_{cg} - \partial_r \left(\kappa \partial_r P_{cg} \right) = 0 \tag{4}$$

$$\partial_t P_{ca} + \left(u - 2\kappa/r \right) \partial_r P_{ca} + \gamma_T \left(\partial_r u + 2u/r \right) P_{ca} - \partial_r \left(\kappa \partial_r P_{ca} \right) = -\alpha \partial_r u \tag{5}$$

$$\partial_t B + 1/r \partial_r (r u B) = 0 \tag{6}$$

where ρ, P_g, B, and u denote the solar wind density, gas pressure, magnetic field strength and, radial flow velocity. P_{ca} and P_{cg} are the anomalous and galactic cosmic ray pressures and κ_a and κ_g are their respective diffusion coefficients. The values used for these diffusion coefficients are 8 $\times$ 10^{15} and 5 $\times$ 10^{18} m^2 s^{-1} respectively. The value of the anomalous cosmic ray diffusion coefficient was chosen to be close to the Bohm limit for a 1 MeV proton. Here γ_T and γ_R are the thermal and relativistic specific heat ratios with γ_T taken to be 5/3 and γ_R to be 4/3. Q_M and Q_E are the momentum and energy source terms associated with the deposition, through charge exchange, of PIs in the solar wind (Zank & Pauls, 1997; Rice & Zank, 1999). The term on the right hand side of equation (5) is a term that simulates particle injection at the interplanetary shock fronts (see Zank, Webb, & Donohue, 1993) and α is zero everywhere except at the shock fronts. Since PIs are most efficiently accelerated, α depends on the neutral density (when the neutral density is low very few PIs are present at small radial distances) and on the gas pressure. At large radial distances PIs dominate the internal energy of the solar wind. The equations are solved using a time explicit Eulerian hydrodynamic code (Pauls, Zank, & Williams, 1995) and an example of the steady state solutions, and the initial conditions, can be found in Rice & Zank (1999).

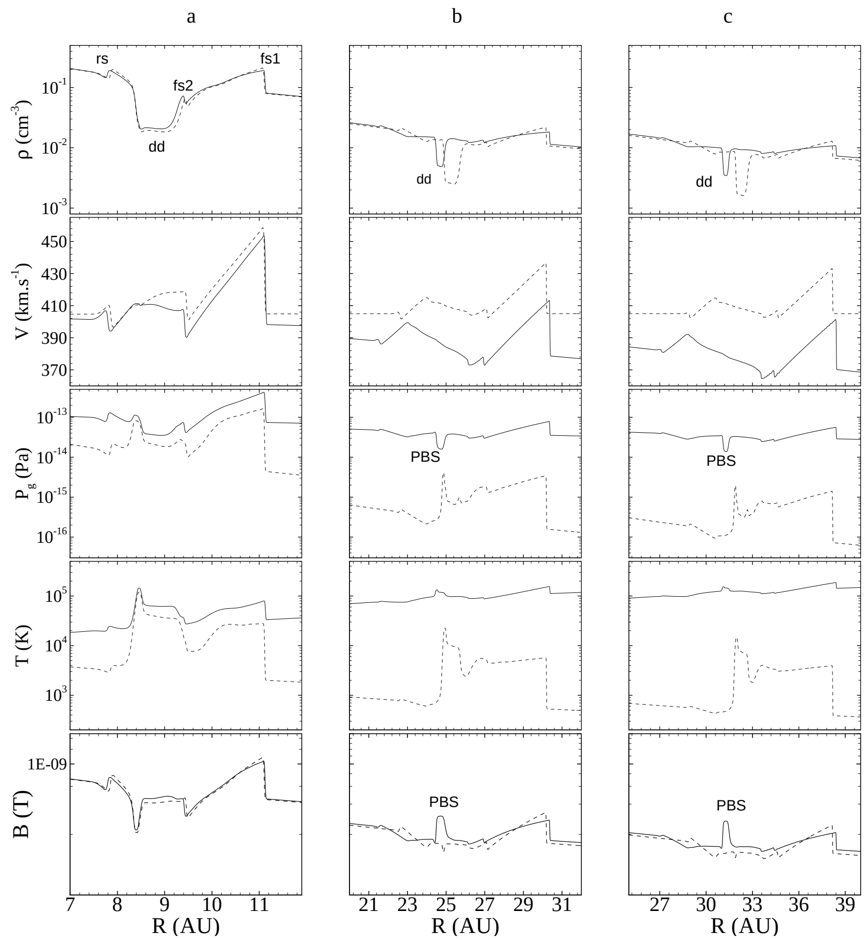

Figure 1: Comparison between a stream driven wave propagating through a PI mediated solar wind (solid lines) and an adiabatic solar wind (dashed lines).

2 Simulations:

Shock waves are introduced by changing the values of the plasma parameters at 1 AU. The wave considered may be thought of as a stream driven wave. This is modeled by increasing the velocity (400 to 800 km s^{-1}), reducing the density (10 to 2 cm^{-3}) and increasing the temperature (5 $\times$ 10^4 to 20 $\times$ 10^4 K). These new values are held at 1 AU for 39.6 hours after which the parameters are returned to their original values. We consider this initial condition for 3 different heliospheric models; a magnetized solar wind without PIs, a magnetized solar wind with PIs and a magnetized solar wind with PIs and with cosmic rays.

Figure 1 shows a comparison between a stream driven wave propagating through a magnetized solar wind with PIs (solid lines) and one without PIs (dashed lines). Apart from cosmic rays, which are not present in these models, all the plasma parameters are plotted. The gas pressure and temperature plots show that, in the outer heliosphere, the pressure and temperature are much greater in the presence of PIs than when they are ignored. From the density and velocity plots one can see two forward shocks (marked fs1 and fs2 in Figure 1a) and a reverse shock (marked rs in Figure 1a). It is clear that these shocks separate at a greater rate when PIs are included than when they are ignored. The structure is reasonably similar in both cases although the shocks in the PI case seem weaker than in the adiabatic case. Zank & Pauls (1997), using a gasdynamic model, found a much greater difference between the PI case and the case where PIs are ignored. In the absence of a magnetic field the shock speed depends only on the sound speed which is much smaller in the outer heliosphere when PIs are ignored than when they are included.

In a magnetized solar wind the shock speed depends on both the sound speed and on the Alfvén speed (which is virtually independent of PIs) and hence the difference between the shock speeds in the two cases is not as great as it is in the gasdynamic case. An MHD heliospheric model also allows for the presence of pressure-balanced structures (PBSs) (Burlaga, 1995). The structure marked PBS in the magnetic field and pressure plots of Figure 1 is coincident with the density depression (marked dd in the density plots of Figure 1). The total pressure (magnetic plus gas) across this structure remains approximately constant, as does the temperature. This may be an indication of a PBS. It is clear that this PBS is more easily distinguished in the presence of PIs than in their absence (see Burlaga et al., 1994).

Figure 2 shows a comparison between a PI mediated, magnetized solar wind without cosmic rays (dashed lines) and one with cosmic rays (solid lines). The dashed lines in Figure 2 correspond to the solid lines in Figure 1. In Figure 2 the solar wind density, velocity, pressure and magnetic field strength are plotted together with the cosmic ray pressure. The cosmic rays consist of a galactic and an anomalous component. The galactic cosmic rays have a small pressure gradient and although they do decelerate the solar wind slightly (by about 5 km s^{-1} at 50 AU), they do not significantly affect the shock propagation characteristics. If the shocks had a higher Mach number they could possibly modify the galactic cosmic ray profile which would change the pressure gradient and could, in turn, modify the shock structure (Axford, Leer, & McKenzie, 1982; Drury & Volk, 1981). The anomalous cosmic rays are, however, assumed to be produced by injection at the shock fronts and their pressure gradient depends on the injection efficiency (the α term in equation 5) and on their diffusion coefficient (which differs from the galactic cosmic ray diffusion coefficient).

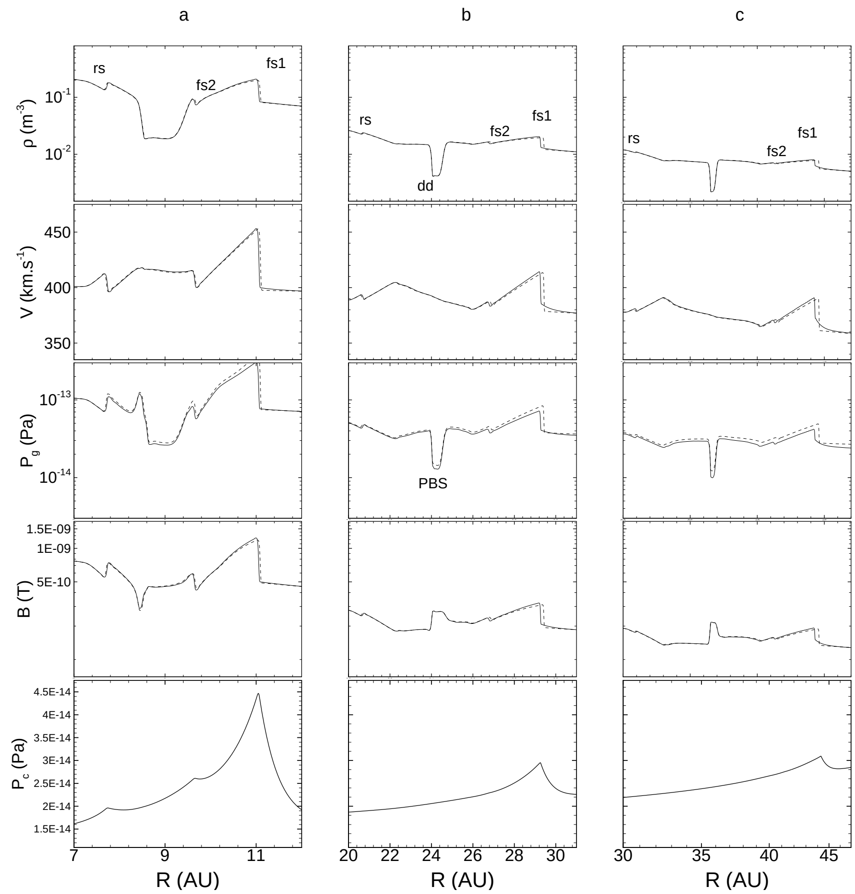

Figure 2: Comparison between a stream driven wave propagating through a PI mediated heliosphere containing cosmic rays (solid lines) and one without cosmic rays (dashed lines).

In Figure 2a there are 3 peaks in the cosmic ray pressure corresponding to injection at the two forward shocks (fs1 and fs2) and at the reverse shock (rs). The two smaller peaks are absent in Figures 2b and 2c because fs2 and rs become so small that the assumed injection efficiency becomes negligible. In Figures 2b and 2c, the first forward shock (fs1) in the presence of cosmic rays lags the equivalent shock when cosmic rays are ignored. The same is true of the second forward shocks (fs2) although the difference is not quite as great as it is for fs1. The reverse shocks seem to be almost coincident at all three times. In Figures 2b and 2c it is also clear that fs1 is quite different in the two cases. Although the second forward shock (fs2) does not exactly coincide in the two cases, it does not seem to be significantly effected by the cosmic rays. Since the anomolous cosmic rays, beyond about 20 AU, are absent around fs2 and rs but significant around fs1, this would indicate that they are modifying the forward shock's propagation characteristics and that the galactic cosmic rays do not play a significant role. Figures 2b and 2c show that fs1 is weaker in the presence of cosmic rays than in their absence. The velocity and pressure plots of Figures 2b and 2c also show changes upstream of fs1. The reason for this is that the injection mechanism removes internal energy from the solar wind and adds it to the cosmic rays. The resulting cosmic ray pressure gradient acts to decelerate the solar wind upstream of the shock creating an extended foreshock. For certain shock Mach numbers the cosmic rays can completely smooth the shock (Axford, Leer, & McKenzie, 1982; Drury & Volk, 1981). However, in this case a subshock is still needed to connect the upstream and downstream states. The actual effect of the cosmic rays will depend on the injection efficiency and on their diffusion coefficient since this will determine the anomolous cosmic ray pressure gradient.

3 Conclusion and Discussion:

Unlike a gasdynamic solar wind model, the inclusion of PIs in a magnetized heliospheric model does not significantly change the propagation characteristics of interplanetary shocks. The PIs do, however, make the plasma $\beta > 1$ and hence, although the differences are small, it is the PIs that dominate the shock propagation properties. It was also seen that the presence of PIs allows PBSs to be more easily observed.

The addition of cosmic rays to a PI mediated heliospheric model was found to change the shock propagation characteristics if anomalous cosmic rays were accelerated at the interplanetary shock fronts. This was done by exchanging internal energy between the solar wind and the cosmic ray gas. The resulting anomolous cosmic ray pressure gradient was found to decelerate the solar wind upstream of the shock creating a foreshock and changing the shock characteristics. Galactic cosmic rays were found not to effect the shocks significantly but may start to do so at larger radii once the cosmic ray and gas pressures become comparable.

Acknowledgements. This work was supported in part by NSF award ATM-9713223, a NASA award NAGS-6469, a NASA Delaware Space College grant NGTS-40024, and JPL contract 959167.

References

Axford, W.I., Leer, E., & McKenzie, J.F. 1982, A&A **111**, 317
Burlaga, L.F., et al. 1994, J. Geophys. Res. **99**, 15.523
Burlaga, L.F.1995, Interplanetary Magnetohydrodynamics (Oxford Univ. Press)
Donohue, D.J., Zank, G.P., & Webb, G.M. 1994, ApJ **424**, 263
Drury, L.O'C., & Völk, H.J. 1981, ApJ **248**, 344
Holzer, T.E. 1972, J. Geophys. Res. **77**, 5407
Isenberg, P.A. 1986, J. Geophys. Res. **91**, 9965
Pauls, H.L., Zank, G.P., & Williams, L.L. 1995, J. Geophys. Res. **100**, 21,595
Rice, W.K.M., & Zank, G.P. 1999, J. Geophys. Res., in press
Zank, G.P., Webb, G.M., & Donohue, D.J. 1993, ApJ **406**, 67
Zank, G.P., Cairns, I.H., & Webb, G.M. 1995, Adv. Space. Res. **15(8/9)**, 453
Zank, G.P., Pauls, H.L., Cairns, I.H., & Webb, G.M. 1996, J. Geophys. Res. **101**, 457
Zank, G.P., & Pauls, H.L. 1997, J. Geophys. Res. **102**, 7037