Proceedings of ICRC 2001: 4222 © Copernicus Gesellschaft 2001

ICRC 2001

The injection problem at pickup proton-rich interplanetary quasi-parallel shocks

M. Scholer[1] **and H. Kucharek**[2]

[1]Centre for Interdisciplinary Plasma Science, Max-Palnck-Institut für extraterrestrische Physik, 85741 Garching, Germany
[2]Space Science Center, University of New Hampshire, Durham, NH 03824, USA

Abstract. We have performed a number of numerical experiments to study the interaction of interstellar pickup protons and helium ions with quasi-parallel stationary shocks. The collisionless shocks are modeled by the hybrid simulation method which treats the ions as macroparticles and the electrons as a massless background fluid. Solar wind protons, alpha particles, pickup H^+ and He^+ are included self-consistently. Particle splitting allows to follow the distribution function over many orders in magnitude. The pickup ion distributions are modeled as spherical shells in velocity space convected with the solar wind. Pickup ions are rather efficiently reflected; the reflection coefficient, measured as the ratio of incident to reflected ions, is at shocks with low contributions of pickup ions of the order of 50%. The preferred injection of pickup helium relative to solar wind alpha particles can lead to equal intensities of both species above a few times the ion velocity (normalized to shock velocity) at 4 - 5 AU. When the pickup proton intensity relative to solar wind protons increases the efficiency for injection of pickup protons decreases, while the reflection coefficient for less abundant pickup ions is only little effected. This leads to an overabundance of heavy ions relative to protons. The reflection coefficient of pickup ions is relatively independent of the angle between the magnetic field and the shock normal.

1 Introduction

Interstellar pickup ions, i.e., interstellar matter that penetrates into the solar system and is ionized in the inner heliosphere and picked up by the radially outward moving solar wind, are currently under intensive observational and theoretical investigation. Acceleration of these ions to high energies at the termination shock is most likely the process which produces the anomalous cosmic ray component (Fisk et al., 1974; Pesses et al., 1981). A number of mechanisms have been proposed which may inject pickup ions into an acceleration process at the quasi-perpendicular termination shock. They range from pre-acceleration by second order Fermi acceleration by the turbulence in the outer solar system (e.g., Chalov et al., 1997; Chalov and Fahr, 2000) to shock surfing (Lee et al., 1996; Zank et al. 1996) and direct injection into a diffusive acceleration process during times of a less oblique termination shock (Kucharek and Scholer, 1995). Furthermore, pickup ions have been observed to be efficiently injected into an acceleration process in corotating interaction regions, which are bounded by a forward and reverse shock pair (Gloeckler et al., 1994). Both, the termination shock as well as corotating shocks, are basically quasi-perpendicular shocks, i.e., the angle Θ_{Bn} between the shock normal and the upstream magnetic field is larger than 45°. Theoretical and numerical studies on pickup ion injection and acceleration at shocks has therefore concentrated in the past on perpendicular or quasi-perpendicular shocks. Giacalone et al. (1997) have proposed that in a first step pickup ions are accelerated at interplanetary traveling shocks in the inner heliosphere. It is proposed that these ions are then further accelerated at the termination shock to become the anomalous cosmic rays.

Interplanetary traveling shocks may be often exhibit a quasi-parallel configuration. Since quasi-parallel planetary bow shocks are known to have an extended foreshock region with so-called diffuse upstream ions, which are thought to be injected from the solar wind at the shock into a Fermi acceleration mechanism, it is expected that pickup ions are also efficiently injected into a diffusive acceleration mechanism at the quasi-parallel shocks: Since the shock potential is of the order of $\Phi \approx m_p v_{sh}^2/2$, where m_p is the proton mass and v_{sh} the shock (or upstream solar wind) speed and since pickup ions have a speed between zero and twice the solar wind speed the shock potential should be able to reflect about half of the pickup distribution, which subsequently could be further accelerated by multiple interaction with the shock. Recently Scholer and Kucharek (1999) have demonstrated by self-consistent hybrid simulations that pickup ions are indeed rather efficiently reflected at quasi-parallel interplane-

Correspondence to: M. Scholer (mbs@mpe.mpg.de)

tary traveling as well as at bow shocks. The reflection coefficient, measured as the ratio of incident to reflected ions, is more than one order of magnitude larger than the reflection coefficients for either solar wind protons or alpha particles, and is of the order of up to 40%. In the following we will expand on these simulations. In particular, we will compare the spectra of diffuse solar wind alpha particles and pickup helium ions in the inner solar system and then investigate how the reflection coefficient changes when going out into the outer heliosphere, i.e., when more and more pickup protons contribute relative to solar wind protons.

2 Numerical Simulations and Results

The simulations are done with a one-dimensional hybrid code with macroparticle ions and an inertialess electron fluid. The electron fluid is assumed to have a finite, but isotropic pressure. All variables are functions of time t and the spatial variable x, which is in the shock normal direction. The time is expressed in units of the inverse of the upstream proton gyrofrequency $\Omega_g = eB_o/m_p$, where e is the magnitude of the electron charge, m_p the proton mass, and B_o the upstream magnetic field magnitude. Distances are expressed in units of the proton inertial length $\lambda_o = c/\omega_p$ (c is speed of light, ω_p is ion plasma frequency in the upstream solar wind). The unit velocity is then the Alfvén velocity v_A, the number density is normalized to the solar wind density n_o. The calculations were done in a system of length $L_x = 1200\lambda_o$; the grid size is $\Delta x = 0.5\lambda_o$ and the time step is $\omega_p t = 0.02$. The solar wind alpha particles are included in the simulations self-consistently. We use a nominal ratio of 5% of alpha particle to proton density ratio n_α/n_p and a temperature ratio of $T_\alpha/T_p = 4$. Solar wind ions (protons and alpha particles) are split into two new particles with half the mass and charge every time a particle's energy surmounts certain energy steps. This allows us to follow the distribution function over many orders of magnitude, so that an absolute comparison of solar wind and pickup ion distribution functions becomes possible. Pickup protons are included self-consistently; the pickup He^+ ions are treated as test particles.

Figure 1 shows the distribution functions of solar wind alpha particles and pickup helium downstream of a shock with Alfvén Mach number $M_A = 6.5$ and $\Theta_{Bn} = 5°$. Here, a ratio of He^+/He^{2+} of 10^{-4} has been assumed. The log of the distribution function is plotted versus the particle velocity normalized to the shock velocity v_{shock}. As can be seen, although below $v/v_{shock} \sim 1$ the intensities of He^+ and He^{2+} differ by more than 6 orders of magnitude, the intensities above $v/v_{shock} \sim 2$ rapidly approach each other. At $v/v_{shock} \sim 10$ the He^+ intensity may exceed the He^{2+} intensity. It should be noted that all runs have been performed up to a time of $200\Omega_g^{-1}$, which at 1 AU would correspond in real time to about 3 min, i.e., the shock has just developed. At this point a direct comparison with measured distributions is not intended; also note that the shock is a standing high Mach number shock and not a traveling or CIR shock. Nevertheless, large increases in abundances between He^+ and He^{2+} can easily be achieved.

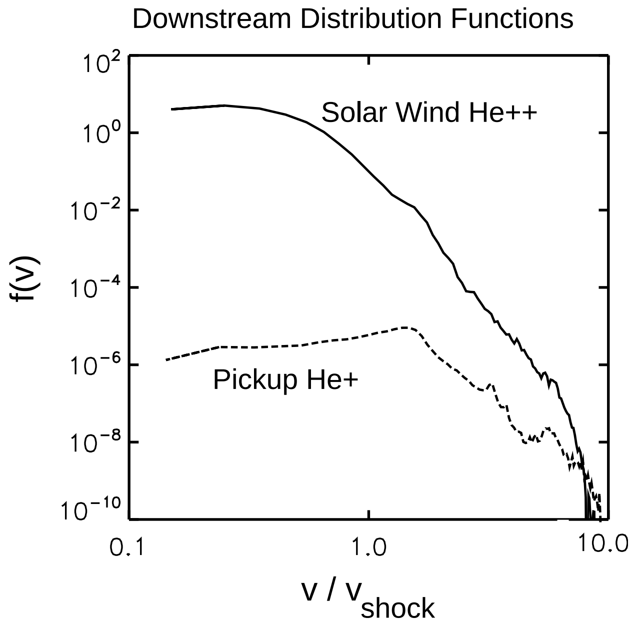

Fig. 1. The distribution function of solar wind alpha particles and pickup Helium at a quasi-parallel stationary shock with Mach number $M_A = 6.5$. A ratio of pickup He to solar wind alpha particles of 10^{-4} has been assumed.

We will now investigate how the reflection coefficient for pickup ions changes when the contribution of pickup protons is increased. At small pickup proton densities, as in the inner heliosphere, the diffuse ions are dominated by solar wind protons, although 50% of the pickup protons incident on a shock may get reflected and injected into a diffusive acceleration mechanism. These diffuse solar wind protons generate upstream propagating magnetosonic waves by an ion/ion beam instability, which are advected by the solar wind into the shock, and which are ultimately responsible for shock dissipation. When the pickup proton density is increased to values of 10 - 20 %, as expected in the outer heliosphere near the termination shock, the upstream suprathermal particles will eventually be dominated by pickup protons. The waves will then no longer be excited by the diffuse backstreaming solar wind protons but by reflected pickup protons. This will eventually modify the shock structure in such a way that the reflection coefficient for pickup protons decreases: the shock can no longer reflect half of the dominant incident population, i.e., the pickup protons. Figure 2 shows the result from various simulation runs in which the pickup proton to solar wind proton density ratio χ has been increased. Shown is the reflection coefficient defined as the number of ions incident on the shock to the number of ions which have been at the shock but subsequently crossed an upstream boundary (usually located at 20 proton inertial lengths upstream from the shock). As can be seen, the reflection coefficient

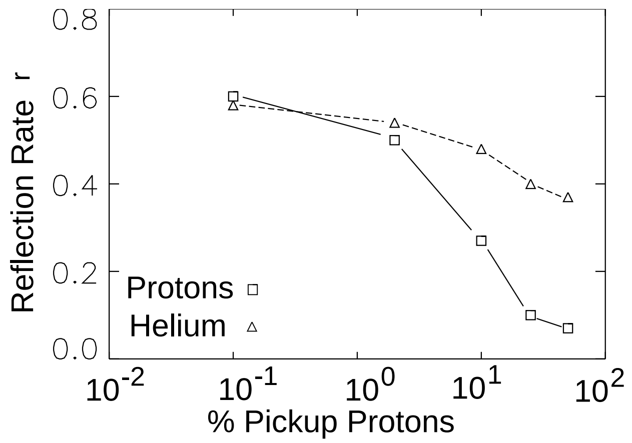

Fig. 2. The reflection coefficient of pickup protons and alpha particles at a stationary quasi-parallel shock as a function of the ratio of pickup protons to solar wind protons.

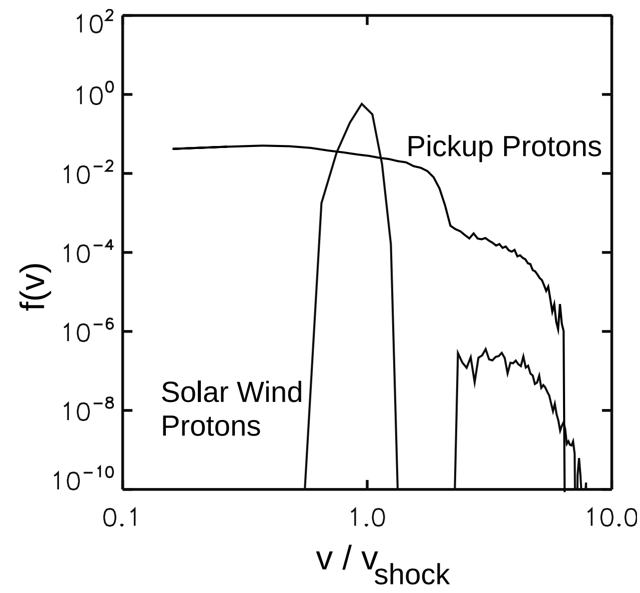

Fig. 3. The distribution function of solar wind alpha particles and pickup Helium at a quasi-parallel stationary shock with Mach number $M_A = 7$. A ratio of pickup protons to solar wind protons of 0.25 has been assumed.

decreases with increasing pickup proton to solar wind proton ratio χ from about 50% to about 10%, while the reflection coefficient of He^+ is only little effected. Note that the reflection coefficient for solar wind protons at pickup poor quasi-parallel shocks is of the order of $\sim 1\%$ or less. Since the reflection coefficient for He^+ ions does not change much, an increase in pickup proton density results in a decrease of the relative abundance of upstream diffuse protons to heavier ions, i.e., the diffuse protons are suppressed by about a factor 4. At $\chi > 0.1$ the diffuse protons are dominated by pickup protons. Figure 3 shows the distribution functions of solar wind and pickup protons upstream of a stationary quasi-parallel shock ($M_A \approx 7$) with $\chi = 0.25$. The diffuse upstream solar wind protons are well separated from the thermal solar wind distribution. Above twice the normalized velocity the diffuse pickup proton intensity exceeds the diffuse solar wind protons by more than two orders in magnitude.

Finally we have investigated how the reflection coefficient for pickup ions changes with increasing shock normal - magnetic field angle. Intuitively, larger Θ_{Bn} is expected to lead, in addition to reflection by the shock potential, to reflection by the magnetic mirror force. The combined action of the potential and the magnetic mirror effect should result in larger reflection rates. Figure 4 shows the dependence of the reflection coefficient for protons as a function of Θ_{Bn}. We have assumed that the pickup ions have a very low density, so that they can be considered essentially as test particles. As can be seen from Figure 4, the reflection coefficient is independent of Θ_{Bn} (or even decreases slightly with increasing Θ_{Bn}). The reason for the result that the reflection coefficient is independent of the magnetic field - shock normal angle Θ_{Bn} can be understood when investigating more closely the upstream magnetic field structure. Upstream of more oblique shocks the waves produced by the ion/ion beam instability steepen into large amplitude magnetic pulsations. These pulsations can have amplitudes of several times the upstream magnetic field magnitude. Thus the shock can no longer be considered as a staedy state transition with a step in magnetic field magnitude leading to mirroring of pickup ions. The importance of non-steady effects was also demonstrated by Winske et al. (1985) when investigating the reflection of Li^+ ions at the bow shock after they had been picked up by the solar wind. Whereas adiabatic theory predicts that most Li^+ ions are reflected at a $\Theta_{Bn} = 45°$ MHD shock, self-consistent simulations showed that most of the Li^+ ions were actually transmitted.

3 Conclusions

Pickup ions are easily injected at quasi-parallel shocks into a diffusive acceleration mechanism. The preferred injection of pickup helium relative to solar wind alpha particles can lead to equal intensities of both species above a few times the ion velocity (normalized to shock velocity) at 4 - 5 AU. When the pickup proton intensity relative to solar wind protons increases, the efficiency for injection of pickup protons decreases, while the reflection coefficient for less abundant pickup ions is only little effected. This leads to an overabundance of heavy ions relative to protons. The reflection coefficient for pickup ions is relatively independent of the angle between the magnetic field and the shock normal.

In future work detailed distribution functions of pickup and solar wind ions at interplanetary traveling shocks and CIR shocks have to be determined. This will possibly answer the question whether diffusive shock acceleration is capable to explain the large $\mathrm{He}^+/\mathrm{He}^{2+}$ abundance ratios in CIRs at 4 AU or whether statistical mechanisms have to be invoked. Large $\mathrm{He}^+/\mathrm{He}^{2+}$ abundance ratios of up to 17% have also

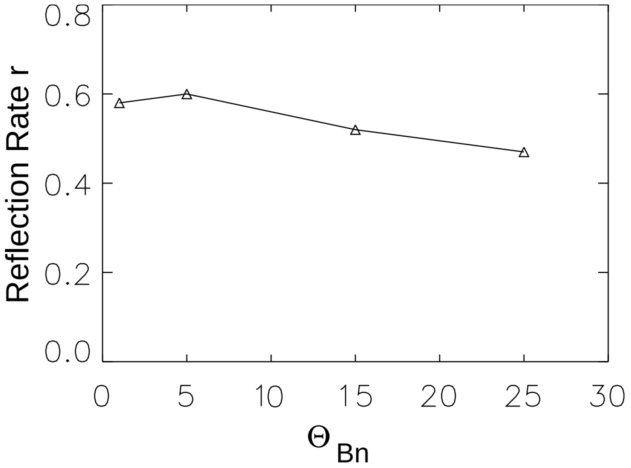

Fig. 4. The reflection coefficient of pickup protons at a stationary quasi-parallel shock as a function of the magnetic field - shock normal angle Θ_{Bn}.

been reported in CIRs at 1 AU (Chotoo et al., 2000). At shocks with a high pickup proton density contribution the upstream wave modes have to be investigated and have to be compared with those excited at shocks in the inner heliosphere where pickup ions are only a minority component. The present self-consistent simulations have only been run up to several hundred inverse proton gyrofrequencies, corresponding to a few minutes in real time. It is highly desirable to extend the simulations to longer running times in order to follow the distribution functions to higher energies.

References

Chalov, S. V., H. J. Fahr, and V. Izmodenov, Astron. Astrophys., 320, 659, 1997.

Chotoo, K., et al., J. Geophys. Res., 105, 23,107, 2000.

Chalov, S. V., and H. J. Fahr, Astron. Astrophys., 360, 381, 2000.

Fisk, L. A., B. Kozlovsky, and R. Ramaty, Astrophys. J., 190, L35, 1974.

Giacalone, J., et al., Astrophys. J., 486, 471, 1997.

Gloeckler, G., et al., Science, 261, 70, 1993.

Kucharek, H., and M.. Scholer, J. Geophys. Res., 100, 1745, 1995.

Lee, M. A., V. D. Shapiro, and R. Z. Sagdeev, J. Geophys. Res., 101, 4777, 1996.

Pesses, M. E., J. R. Jokipii, and D. Eichler, Astrophys. Lett., 246, L85, 1981.

Scholer, M., and H. Kucharek, Geophys. Res. Lett., 26, 29, 1999.

Winske, D., C. S. Wu, Y. Y. Lin, Z. Z. Mou, and S. Y. Guo, J. Geophys. Res., 90, 2713, 1985.

Zank, G. P., H. L. Pauls, L. H. Cairns, and G. M. Webb, J. Geophys. Res., 101, 457, 1996.