

Pickup Ion Injection at Quasi-Parallel Shocks

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Abstract

The “injection problem” at quasi-parallel shocks is addressed for pickup ions. The cross-shock electrostatic potential reflects part of the pickup ion distribution incident on the shock efficiently, with some ions experiencing multiple reflections. The multiply reflected ions are sufficiently energetic that they can now be further energized by the diffusive shock acceleration mechanism.

1 Introduction:

Interplanetary shocks associated with co-rotating interaction regions (CIRs) and coronal mass ejections (CMEs) within some 5 AU are thought to accelerate ions up to energies of a few MeV/nuc. [see *Reames 1999* for a review]. Within this region of the solar wind, shocks are often quasi-parallel.

Considerable evidence has now accumulated which suggests that the accelerated ions seen in gradual solar energetic particle (SEP) events originated from *in situ* solar wind material [e.g., *Reames, 1999*]. This immediately raises a question of considerable importance for particle acceleration at shock waves, which is how particles are accelerated from the thermal core of the solar wind up to energies sufficiently large that they can be accelerated diffusively at a shock wave – the “injection problem”. For a particle to be accelerated diffusively at a shock by the first-order Fermi mechanism, the particle must be sufficiently energetic that it can scatter diffusively across all the micro- and macrostructure of the shock, experiencing compression between the converging upstream and downstream flows. This requires that particles satisfy $v \gg V_{sh}$ in the solar wind frame, where V_{sh} is the shock speed and v the particle speed [*Jokipii, 1987; Zank et al., 1996*]. The standard model of diffusive shock acceleration cannot address the injection problem (except at a phenomenological level) since the transport equation used to model the transport of energized particles is valid only for particle speeds $v \gg U_{SW}, V_A$, where U_{SW} is the solar wind speed and V_A is the Alfvén speed. The difficulty in extracting a thermal ion from the solar wind velocity distribution has long been recognized. *Gosling et al.* [1981], in an interesting and important paper, combined measurements from several instruments on the ISEE spacecraft to obtain an ion velocity distribution function $f(v)$ which extended from solar wind energies (~ 1 keV) to 1.6 MeV during the post-shock phase of an energetic storm particle (ESP) event. The downstream ESP ion

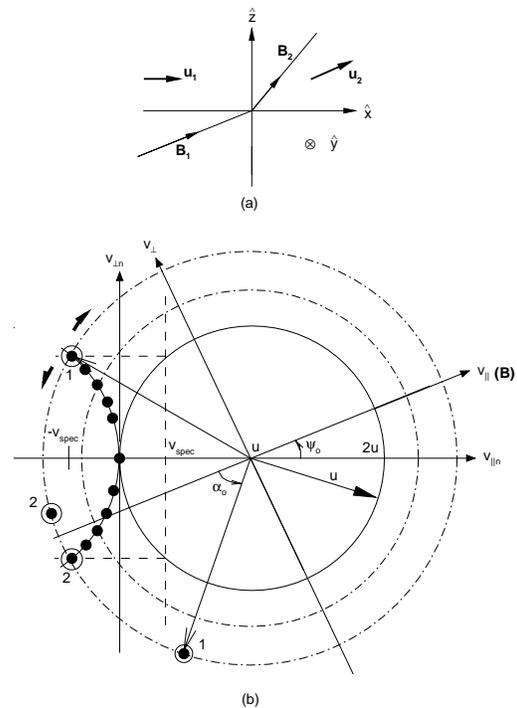


Figure 1: (a) The shock geometry. (b) The specular reflection of particles at a shock front in the stationary shock frame. The reflected particles form a series of nested shells, of which two are shown by the dash-dotted circles.

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population was almost isotropic in the solar wind frame and emerged smoothly from the thermal solar wind distribution. *Gosling et al.* [1981] estimated that $\sim 1\%$ of the solar wind ion population was accelerated to suprathermal energies.

More recently, the acceleration of pickup ions at shocks associated with CIRs has been described by *Gloeckler et al.* [1994]. These results, like those of *Gosling et al.* [1981], showed convincingly that pickup ions were accelerated directly from the “thermal pickup ion” distribution (essentially a thickened shell in velocity space) itself. Furthermore, the injection efficiency was much greater for pickup protons than for thermal solar wind protons. Specifically, *Gloeckler et al.* [1994] estimated that $\sim 0.5\%$ of the solar wind ion population was accelerated at the associated CIR shock (consistent with the estimate of *Gosling et al.*, 1981) whereas $\sim 40\%$ of the pickup hydrogen (H^+) population was accelerated. The injection mechanism for pickup ions injects pickup protons more efficiently than pickup helium (He^+) (which has an $\sim 16\%$ efficiency). Thus, the pickup ion injection mechanism appears to discriminate inversely with mass. However, He^+ is much more efficiently injected than are alpha particles (He^{++}), of which some $\sim 0.3\%$ are accelerated. Further support for the general efficiency with which pickup ions are injected at interplanetary shocks compared to solar wind ions has been provided by *Fränz et al.* [1999]. These authors suggest that at solar distances of 3 - 5 AU, He^+ pickup ions dominate the accelerated He ion population whereas all other ions show thermal abundances. This is consistent with the heliocentric radial distribution of neutral He which is ionized only very close to the Sun. At distances of 3 - 5 AU, pickup He^+ will contaminate the thermal He ion population. *Fränz et al.* [1999] suggest that their results show that pickup He^+ is energized preferentially compared to the thermal solar wind He ion population.

At quasi-perpendicular shocks, multiply reflected ion (MRI) acceleration or shock surfing [*Zank et al.*, 1996; *Lee et al.*, 1996] appears to provide sufficient injection energy. The mechanism introduced here addresses the injection problem at quasi-parallel shocks.

2 The Basic Model

At the ramp of of a quasi-parallel shock, the charge separation induced by the overshoot of the heavier ions as they decelerate leads to a jump in the electrostatic potential ϕ at the shock, which is given approximately by [*Goodrich and Scudder*, 1984]

$$e\phi \simeq \frac{\gamma_e}{\gamma_e - 1} [kT_e] \simeq \frac{1}{2} m u_1^2. \quad (1)$$

In (1), k denotes the Boltzmann constant, T_e the electron temperature, γ_e the electron adiabatic index, m the proton mass, and u_1 the upstream flow speed for the stationary shock. The square brackets denote the jump in the electron temperature between the upstream and downstream state. It then follows that those particles satisfying $v_x \leq V_{spec}$ in the shock frame are reflected at the shock, where

$$V_{spec}^2 \simeq \frac{2Z}{M} \frac{\gamma_e}{\gamma_e - 1} [kT_e] \simeq \frac{Zm}{M} u_1^2. \quad (2)$$

Z and M denote the charge and mass of the particle of interest, and V_{spec} is a measure of the amplitude of the electrostatic cross-shock potential. The pickup ion distribution in the solar wind

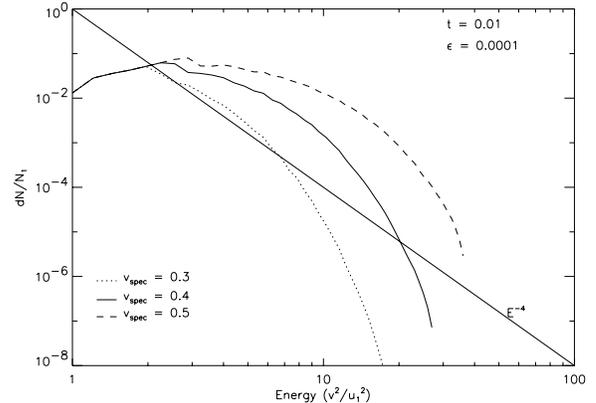


Figure 2: Energy spectra of transmitted particles for a set of specular reflection velocities V_{spec} . An E^{-4} line is drawn for reference.

may be approximated as a shell distribution in the solar wind frame. For pickup ions, the fraction of the incident pickup shell that is reflected can be expressed as

$$\mathcal{R} \simeq \frac{1}{2} \left(\frac{2Z}{M} \frac{\gamma_e}{\gamma_e - 1} \frac{[kT_e]}{u_1^2} \right)^{1/2} \simeq \frac{1}{2} \left(\frac{Zm}{M} \right)^{1/2}. \quad (3)$$

For H^+ , nearly 50% of the incident pickup ion shell can be reflected if we assume the crude scaling of (1). This is probably an overestimate of the injection efficiency but it is reasonably consistent with the 40% efficiency quoted by *Gloeckler et al.* [1994] for pickup H^+ .

Besides the cross-shock potential, particles can also be reflected by magnetic mirroring at quasi-parallel shocks. The shock geometry, the incident pickup ion shell, and the reflected beam are illustrated in Figure 1. Two coordinate systems are used: $v_{\parallel n, \perp n}$ refer to the shock normal coordinate system, and $v_{\parallel, \perp}$ to the magnetic field coordinates. For a quasi-parallel shock, these coordinate systems are not coincident. The angle between the shock normal and upstream magnetic field is ψ_0 . The reflected particles form a broad beam which we approximate by a set of δ -beams (depicted by \bullet), each effectively forming a narrow (ring) beam in velocity space. Each δ -beam drives a ring-beam instability which scatters reflected ions onto their own [partial] shell distribution. Account is taken of the difficulty in scattering through 90° , with the result that unless scattering is strong, the upstream reflected distributions are anisotropic. As the δ -beam scatters onto a series of nested shells, the ions that were reflected convect back into the shock. Once again, that fraction of the particles which finds itself in the phase space $v_{\parallel n} \leq V_{spec}$ will again experience specular reflection, and the entire cycle will be repeated.

The repeated specular reflection of ions at the electrostatic shock potential and their scattering by magnetic fluctuations in the region upstream of the shock provides a mechanism for energizing thermal pickup ions at quasi-parallel shocks, which we call Stochastic Reflected Ion (SRI) acceleration. The detailed algorithm and its numerical implementation may be found in *Zank et al.* [1999].

3 Discussion and Conclusions

A large fraction of the initial pickup ion distribution incident on the shock is reflected. The reflection results from two processes: the inability of an ion with a small velocity normal to the shock to overcome the cross-shock electrostatic potential and, secondly, a subpopulation of pickup ions on the shell distribution whose adiabatic moments force them to mirror at the compressed magnetic field of the quasi-parallel shock. The efficiency of reflection, which might be thought of as a measure of injection efficiency, is very high, and may be as much as 40-50%.

For purely parallel shocks (i.e., $\psi_0 = 0$), the transmitted differential energy spectrum in the fluid frame is an increasing function of energy, until it softens and rolls off in an exponential-like fashion. Both the spectral shape and the particle energy gain depend on the anisotropy of the reflected ion distribution when it re-encounters the shock and the amplitude of the cross-shock potential (expressed through the value of V_{spec}). An increase in the anisotropy of the upstream reflected and scattered ion distribution leads to a hardening of the energy spectrum. This occurs because more particles remain in the anti-flow direction hemisphere at the time the distribution re-encounters the shock, so allowing

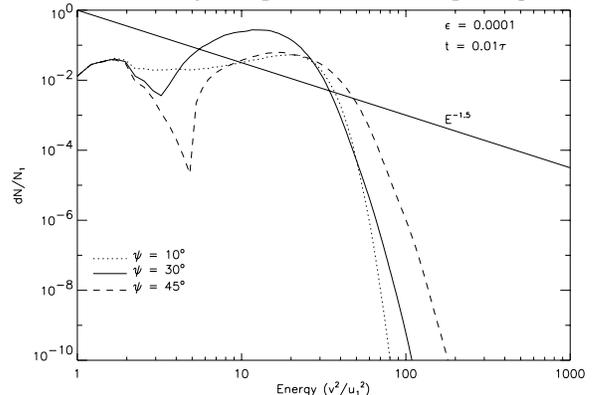


Figure 3: Energy spectra for particles transmitted through a set of quasi-parallel shocks with upstream magnetic fields oriented at 10° , 30° , and 45° to the shock normal.

more ions to experience multiple reflections. This suggests that the upstream turbulence responsible for scattering the ions should be strong enough to disrupt the reflected beam fairly rapidly so that a sizeable fraction of the beam is convected back to the shock but the scattering should proceed at a rate that is slow enough not to scatter the initial beam on to a filled shell distribution. The most dramatic hardening of the differential energy spectrum results from an increase in V_{spec} -Figure 2. Higher energies (up to ~ 40 -50 times the solar wind energy) are also obtained as V_{spec} is increased. For $V_{spec} \sim 0.7u_1$, the spectrum is completely flat (not shown). Finally, one can compute the expected wave spectrum generated by the reflected beam. The main enhancement in the wave/turbulence spectrum occurs at about the reflected pickup ion gyrofrequency and, in the spacecraft frame, falls off approximately as ω^{-2} . This feature is superimposed on the *in situ* upstream turbulence spectrum.

Quasi-parallel shocks can produce much harder spectra than comparable parallel shocks since ions can also experience specular reflection by mirroring at the magnetic field of the shock ramp. As the upstream magnetic field obliquity increases, two distinct peaks in the differential energy spectrum become increasingly prominent (Figure 3). The less energetic peak results from the repeated scattering of ions off the cross-shock potential and the higher energy peak is a consequence of mirroring. Very much larger ion energies are possible at quasi-parallel shocks. The two peaks in the transmitted spectrum can become indistinguishable as V_{spec} is increased. The reflected ion velocity space distribution (Figure 4) shows the presence of a cold beam and a more diffuse energetic ion population.

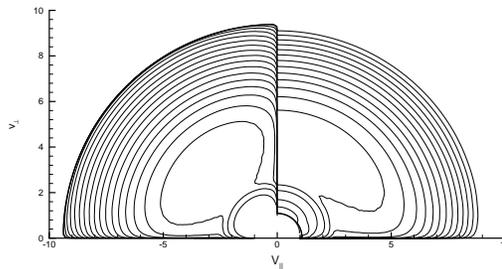


Figure 4: The velocity space distribution immediately upstream of the shock of particles reflected from a quasi-parallel shock (10°). The cold beam and the distribution anisotropy are evident.

The model presented here shows that thermal pickup ions can be energized to sufficiently high energies that they can then be accelerated further by the standard diffusive shock acceleration mechanism at a quasi-parallel shock. We suggest that a two-step mechanism is therefore responsible for the anomalous cosmic ray component.

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