Injection and acceleration of ions at collisionless shocks: Kinetic simulations

M. Scholer, H. Kucharek, Vladimir Krasnosselskikh, K.H. Trattner

Injection and Acceleration of Ions at Collisionless Shocks: Kinetic Simulations

M. Scholer[1], H. Kucharek[1], V. V. Krasnosselskikh[2], and K.-H. Trattner[3]

[1]*Max-Planck-Institut für extraterr. Physik, 85740 Garching, Germany*
[2]*LPCE-CNRS, 45045 Orleans, France*
[3]*Lockheed Martin Missiles and Space, Palo Alto, CA 94304*

Abstract.
Kinetic simulations of collisionless shocks have provided a wealth of information on injection and acceleration of thermal ions into a diffusive acceleration process. At quasi-parallel shocks upstream diffuse ions and the induced upstream turbulence are an integral part of the collisionless shock structure. Before injected into a diffusive acceleration process thermal ions are trapped near the shock and are accelerated to higher energies. The injection and acceleration process for thermal ions at quasi-perpendicular shocks depends on the possibility of these ions to recross the shock many times. A viable mechanism for injection is cross-field diffusion of the specularly reflected ions after they have crossed the shock into the downstream region. Determination of the cross-field diffusion coefficient in strong turbulence suggests that specularly reflected ions can recross the quasi-perpendicular shock and can get further accelerated. At more oblique shocks the same injection process as at quasi-parallel shocks can work: particles gain high enough velocities during their first shock encounter so that they can escape the shock along the magnetic field in the upstream direction. Because of the form of the pickup ion distribution in velocity space there seems to be no problem for accelerating these ions at either quasi-parallel, quasi-perpendicular, or perpendicular shocks.

INTRODUCTION AND BACKGROUND

Shocks ara an important site for particle acceleration in astrophysical settings. In particular the first order Fermi acceleration mechanism as formulated by Krimsky (1), Axford et al. (2), Blandford and Ostriker (3), and Bell (4) has been widely employed in cosmic ray physics. The diffusive shock acceleration theory is not concerned with the question how a certain part of the ambient particles is injected into the acceleration process, but starts with suprathermal seed particles, which can either be already present in the upstream flow or are injected at the shock. One of the important questions in ion acceleration at collisionless shocks is how ions are extracted from the thermal population and are injected into a subsequent acceleration process, which usually is assumed to be diffusive shock acceleration. By thermal population we mean here and in the following the upstream plasma, i.e., in case of the heliosphere the solar wind. This so-called injection problem is of great interest, since once we understand injection we may be able to predict the flux in the suprathermal energy range at the shock. Standard diffusive shock acceleration theory, with possible complications as adiabatic deceleration in the solar wind etc, will then predict spectral shapes and absolute fluxes of the accelerated particles. Most detailed information on ion acceleration comes from in situ measurements at the Earth's bow shock and, to a lesser extent, at interplanetary traveling shocks and shocks bounding corotating interaction regions. Shocks are usually divided into quasi-perpendicular and quasi-parallel depending on whether the angle between the upstream magnetic field and the shock normal, Θ_{Bn}, is $>$ or $<45°$, respectively. There is no principal difference in the Fermi acceleration mechanism between quasi-parallel and quasi-perpendicular shocks: diffusive shock acceleration only requires scattering between the upstream and the downstream region. The acceleration efficiency is determined by the diffusion coefficient in the shock normal direction, which consists of a contribution from the parallel (to the magnetic field) diffusion coefficient and a contribution from the perpendicular (cross-field) diffusion coefficient.

Ion distributions observed upstream of the quasi-parallel and of the quasi-perpendicular bow shock differ considerably (5). This may lead us to believe that the injection mechanism also differs for the two regimes. There are two problems with using in situ particle observations obtained upstream of the Earth's bow shock in order to delineate the seed particles: firstly, bow shock observations are complicated by the fact that the ion distributions from the region upstream of the quasi-perpendicular shock, like field-aligned beams, are convected by the solar wind into the quasi-parallel regime and can thus interact with the quasi-parallel bow shock. Secondly, observations can not give us information about the initial distribution which is subsequently further accelerated; one observes a more or less final state and it is not possible to distinguish between ions just having been injected or those which have been scattered between the upstream and downstream medium many times and partake in a Fermi acceleration process. The latter also holds for interplanetary shocks.

However, the question arises whether a distinction between injection and acceleration is at all possible. According to the view held by Malkov and Völk (6) "the problem of injection consists not so much in the source of the particles to be injected, but in the way to describe their acceleration out of the thermal distribution". A natural assumption for acceleration out of the thermal distribution is an extension of the diffusive acceleration theory down to thermal energies, i.e., that also part of the shock heated solar wind plasma can freely scatter across the shock many times. In the case of quasi-parallel shocks the upstream leaking thermal particles are simply the hot downstream ions which have an upstream directed velocity which exceeds the shock velocity (both taken in the upstream rest frame). This model has first been developed by Ellison (7) using Monte Carlo particle simulations, wherein particle trajectories are determined from a prescribed scattering law (elastic scattering). These simulations can model thermal particle injection and acceleration and determine simultaneously the average shock structure, including shock mediation by the accelerated particles. Predictions of this model for spectra and abundances agree favorably well with the observations at the quasi-parallel bow shock, which is maybe not too surprising, considering the fact that the scattering law contains several free parameters, as rigidity dependence and absolute value, which have to be adjusted. Ellison et al. (8) have extended their Monte Carlo model for oblique shocks by assuming that particles are scattered parallel and perpendicular to the field according to a hard sphere scattering law, i.e., the perpendicular diffusion coefficient is given by $\kappa_\perp = \kappa_{||}/(1+\eta^2)$ where η is related to the parallel mean free path $\lambda_{||} = 3\kappa_{||}/v$ by $\lambda_{||} = \eta r_g$ with r_g and v as the particle's gyroradius and velocity, respectively. The parameter η determines the scattering strength, and injection and acceleration becomes efficient when scattering is strong ($\eta << 10$).

The same idea, i.e., that also part of the shock heated solar wind plasma can freely scatter across a shock many times, has been put on an analytical basis by Malkov and Völk (6). They have extended the theory of diffusive particle acceleration to low particle energies, where the difference between the upstream and the downstream fluid frame is essential and where the particle distribution at the shock may become highly anisotropic. In their model for parallel shocks wave excitation and pitch angle scattering are treated self-consistently by assuming that pitch angle scattering is due to self-excited MHD waves propagating along the ambient magnetic field. These waves are excited in cyclotron resonance due to the pitch angle anisotropy of the backstreaming ions, i.e., by an electromagnetic ion/ion beam instability. Quasi-linear theory results in two coupled equations for the evolution of the particle distribution and the wave spectrum. The solution for the particle spectrum contains the source of the particles to be injected. As the source of the injected particles Malkov and Völk (6) also assume downstream heated particles with a velocity exceeding the shock velocity, although other sources can, in principle, be incorporated. To summarize: the Monte Carlo model (7) assumes that the heated downstream solar wind scatters according to a hard sphere scattering law and thus circumvents the injection problem; the model predicts absolute fluxes and spectra. Theory (6) is an extension of the diffusive acceleration theory valid in the suprathermal energy range.

INJECTION AND ACCELERATION AT QUASI-PARALLEL SHOCKS

First results on the direct injection of ions out of the incident thermal plasma at a collsionless shock into the Fermi acceleration mechanism were based on hybrid simulations of an exacactly parallel shock (9). In hybrid simulations the ions are treated as macroparticles and the electrons are represented by an inertialess electron fluid. Thus frequencies of the order of the ion gyrofrequency and smaller, and length scales of the order of the ion inertial length are treated correctly. Following the work by Quest (9), Scholer (10), Kucharek and Scholer (11) and Giacalone et al. (12) have performed hybrid simulations of quasi-parallel shocks which resulted in upstream diffuse proton densities of 3-4% of the incident solar wind proton density. Giacalone et al. (12) introduced artificially a high level of upstream magnetic field fluctuations, so that the injected ions were efficiently scattered back and forth between the upstream and downstream region. This led to the build up of a power law distribution of the diffuse particles in the low energy region as predicted by steady state diffusive acceleration theory. Trattner and Scholer (13, 14) included self-consistently He^{2+} in their shock simulations and found that a few percent of the upstream He^{2+} ions are extracted at the shock and are subsequently further accelerated.

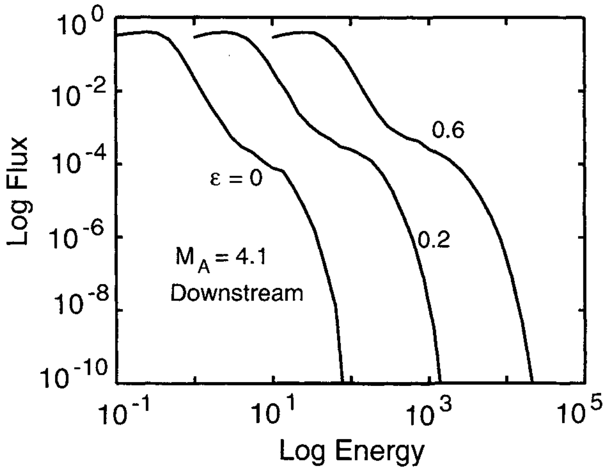

FIGURE 1. Differential flux (arbitrary units) of protons downstream of simulated shock ($\Theta_{Bn} = 5°$, Alfvén Mach number = 4.1)for 3 different values of upstream imposed magnetic field turbulence (from 15).

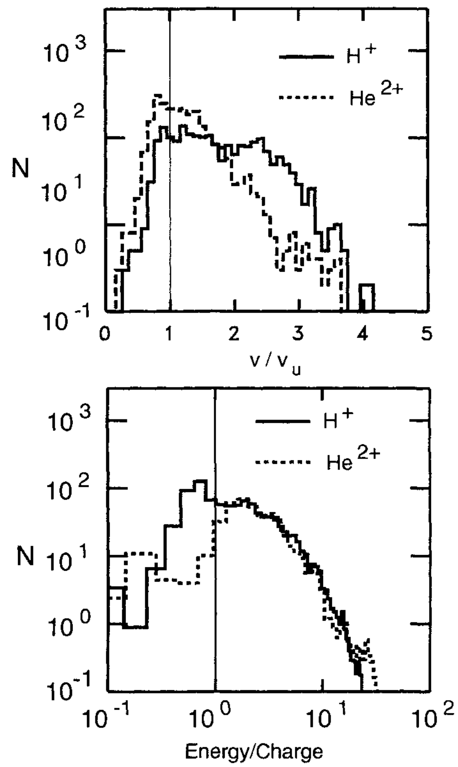

FIGURE 2. Histogram of number of H and He^{2+} ions versus velocity in units of shock velocity (upper panel) and energy per charge in units of shock ram energy (lower panel), when the particles cross for the first time a boundary 10 ion inertial length upstream of the shock (from 15).

Scholer et al. (15) performed quasi-parallel shock simulations for a wide range of parameters. In particular, they were concerned with the spectral shape of diffuse ions. Figure 1 shows downstream energy spectra (differential flux) in a log-log representation for 3 different values of upstream imposed turbulence (ε = total integrated upstream power in the magnetic field fluctuations). Energy is in units of the shock ram energy $E_p = m_p v_u^2/2$, where v_u is the upstream bulk speed relative to the shock and m_p the proton mass. One can see the heated downstream plasma at low energies and a second population with a high energy cut-off, which is simply due to the fact that the acceleration time is limited. The spectra of the accelerated particles can be expressed as exponentials in energy; the e-folding energy (normalized to the shock ram energy) increases with time (which can be transformed at the bow shock into magnetic field connection time) and with ε, the level of upstream turbulence. At the same solar wind ram velocity the e-folding energy increases with shock Mach number. Spectra of diffuse protons and alpha particles are known to exhibit e-folding energies which are about equal in energy per charge. In order to explain this in terms of the Fermi acceleration model it has been assumed in the past that there is no or very weak scattering beyond some distance upstream of the bow shock (free escape boundary). If the diffusion coefficients for protons and He^{2+} ions are identical at the same energy per charge steady state Fermi theory with a free escape boundary predicts for the spectra equal e-folding energies in energy per charge. However, Scholer et al. (15) have argued that the introduction of a free escape boundary is an artifact introduced in order to obtain exponential spectra by a steady state theory, since steady state shock acceleration theory in an infinite medium predicts power law distributions. In particular a Monte Carlo simulation is intrinsically steady state; in such a theory a spectral cut-off can only be obtained by a free escape boundary or some other loss process. Lee (16) has actually proposed cross-field diffusion to the flanks of the bow shock as a possible loss process leading to exponential spectra.

What can we learn from the hybrid simulations as far as injection is concerned? In order to obtain the "injection spectrum" we imagine a boundary close to the shock. We then determine the distribution of the solar wind ions which later in their life become diffuse upstream ions when they cross this boundary the first time in the upstream direction. Figure 2, taken from Scholer et al. (15), shows in the upper panel the number of backstreaming ions versus velocity in units of the shock ram velocity v_u (upstream bulk velocity in the shock frame) and versus energy per charge $(E/E_p)/Q$ (lower pane). In this run He^{2+} has been included self-consistently. The upper panel shows the following: a large contribution to the spectrum consists of ions, which have in the shock frame about shock ram velocity ($v/v_r \sim 1$), i.e., which are specularly reflected at the shock. However, the injection spectrum extends to several tens of the shock ram energy and is almost identical for both species when evaluated at equal energy per charge. Firstly, it is not necessarily the subsequent diffusive shock acceleration process, which determines the ordering in energy per charge; the injection spectrum exhibits already such an ordering. Secondly, injection is not from the hot downstream distribution. If it were so, the injection spectrum should not drop to zero at zero velocity. If heated downstream ions escape upstream the maximum intensity is expected to be at $v = 0$ in the shock frame which, as can be seen from Figure 2, is clearly not the case. Such a simplified kinematic leakage model does not take into account that the downstream particles are trapped in the large amplitude downstream waves originating upstream from the turbulence excited by the backstreaming ions. Malkov (17) has suggested a model where the large amplitude downstream waves efficiently trap the thermal ions and regulate their upstream leakage. We will come back to this model later.

One can gain more insight by investigating individual particle orbits from a typical quasi-parallel shock run. Figure 3 shows in the top panel the trajectory of a proton in $x - t$ space which ends up as a diffuse upstream ion. x is the direction normal to the shock. The heavy line is the shock position; upstream is to the left, downstream to the right. The unit of distance is the upstream proton inertial length λ_o (equal to the gyroradius for a beta =1 plasma) and the unit of time is the inverse proton gyrofrequency Ω^{-1}. Because of technical reasons the simulation frame is the downstream rest frame. In this frame the shock moves in the upstream direction. The thin line is the trajectory of a solar wind ion which moves toward the shock. It reaches the shock at $\Omega t \sim 80$ and stays for about 3 gyroperiods in the vicinity of the shock before escaping upstream. The lower panel shows a plot of perpendicular velocity $v_\perp$ versus parallel velocity $v_\parallel$ during this time interval. The particle reaches the shock and is reflected. Subsequently it's perpendicular velocity increases by about a factor 3. It then bounces back and forth between the shock and the upstream region, while the perpendicular energy continues to increase.

Analysis of many trajectories like the one shown in Figure 3 suggest that the acceleration process in the thermal and suprathermal energy range is not well described by a diffusive process. It is still true that the problem of injection consists not so much in the source of the particles to be injected, but in the way to describe their acceleration out of the thermal distribution; however, the simulations seem to tell us that diffusive theory is not an adequate description. This is not to say that there is no diffusive shock acceleration. The backstreaming ions are

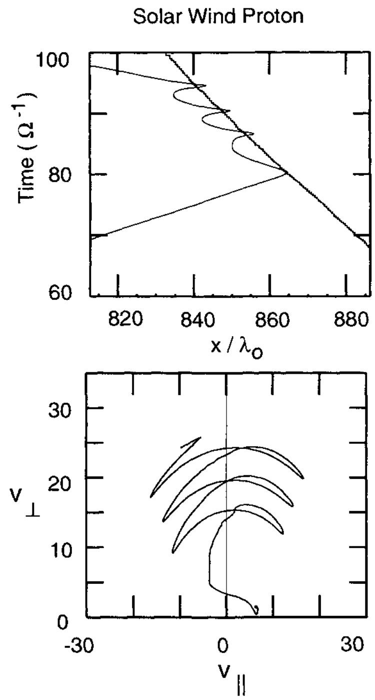

FIGURE 3. Trajectory of a solar wind proton which becomes energized at the shock in $x - t$ space (upper panel), and the perpendicular versus parallel velocity during this time interval (lower panel)

actually scattered in the upstream wave field, return to the shock, and are further accelerated. Figure 4 shows a trajectory of a proton over an extended time interval. After initial contact with the shock the particle moves upstream, interacts again with the shock for an extended time and moves again upstream. This stage can be described by standard diffusion theory, eventually taking into account the particles anisotropy. But what seems to be also important is the fact that the particle is not scattered from downstream, but is reflected at the shock ramp. In this energy regime the forces acting on the particles at the shock ramp, like shock potential and magnetic mirror forces, and thus the physics at the shock transition is of importance. A simple boundary condition, as the constancy of the particle streaming, does not necessarily describe correctly the ongoing physics. Likewise, a Monte Carlo model which assumes a step-like change in the velocities of the scattering centers, eventually mediated by the energetic particles, can not correctly describe the physics at the shock ramp.

The simulations discussed above suggest that the problem of injection and acceleration can be divided into three tasks: 1. Given the shock conditions, one has to determine the distribution of particles originating from the upstream flow which are reflected from the shock or es-

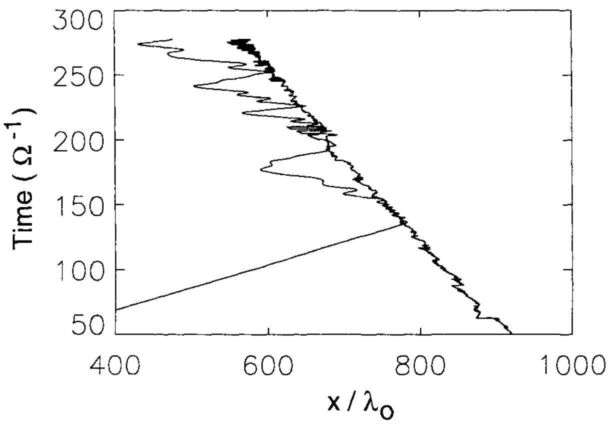

FIGURE 4. Trajectory of a diffuse ion showing multiple interactions with the shock and scattering in the upstream medium

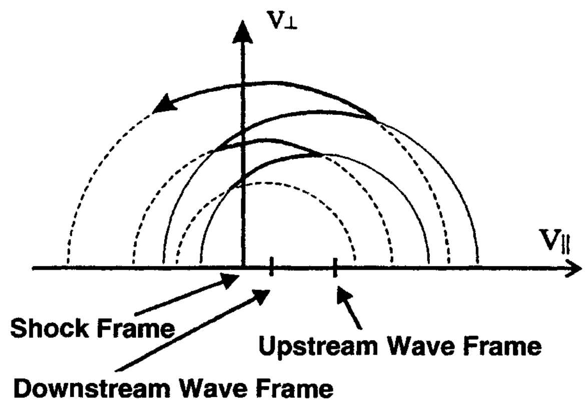

FIGURE 5. Schematic of the velocity space trajectory of a particle during repeated crossing of the shock front (from 18).

cape from downstream. 2. One follows trajectories of these particles when they have multiple encounters with the shock. 3. The particles have an energy which is high enough so that their interaction withe the shock can be described by standard diffusive shock acceleration theory, possibly modified due to anisotropies. A model for steps 2 and 3 has been developed within the framework of quasi-linear theory in (6). However, since phase-mixing is assumed in (6), this theory does probably not correctly describe step 2. A description of the possible physics concerned with step 2 based on hybrid simulation results has been given by Sugiyama and Fujimoto (18). The large-amplitude upstream and downstream waves lead to nonlinear phase-trapping of the particles injected in step 1: the pitch angle of non-resonant particles changes over a wide range within one gyroperiod. This leads to rapid crossing from upstream to downstream and vice versa. Since the energy in each wave frame is constant and the phase velocity changes drastically from upstream to downstream a particle moves, depending on whether it is upstream or downstream, on circles with different centers in $v_\perp - v_\parallel$ velocity space and moves to higher and higher velocities. This is schematically shown in Figure 5 (from 18). However, so far no theory has yet been developed for step 2 which results in a source function, which is then the input for a diffusive theory (step 3).

The theory developed in (17) for step 1 is a thermostat model, i.e., particles escape into the upstream region out of a hot downstream plasma. The large amplitude downstream waves filter the hot plasma in its leakage upstream by resonant interaction. The model is self-consistent: when the beam of escaping ions is weak, it excites only small amplitude waves and the leakage will be increased to produce stronger waves. Escaping ion intensity and turbulence amplitude rest at some definite and unique level. The theory developed by Malkov (17) is so far the only theory which quantitatively predicts the injection rate and the turbulence level as a function of Alfvén Mach number and shock compression ratio.

We propose as an alternative possibility to the model of leakage from a downstream thermostat a model for step 1, which is rather similar to the shock surfing mechanism developed for quasi-perpendicular shocks (19, 20). We assume that a solar wind ion is trapped at the shock ramp in its motion along the magnetic field and is accelerated perpendicular to the magnetic field by resonance in the upstream circularly polarized wave. The resonance condition is $\omega - k_\parallel v_\parallel = \pm\Omega$, where ω is the wave frequency, $k_\parallel$ the wave vector parallel to the upstream magnetic field, and $v_\parallel$ the parallel velocity of the particle. The acceleration can exist at the shock as long as the particles is trapped, i.e., $v_\parallel$ is constant and zero in the shock frame. In order for this to happen the force of the electromagnetic wave in the parallel direction toward the shock has to be balanced by some other force at the shock. This force can be either the cross-shock potential or the electromagnetic force in the shock ramp due to the increase in the tangential magnetic field component in quasi-parallel shocks. In order to have $v_\parallel$ constant a specific spatial dependence of the trapping force is required. Eventually the particle is detrapped and leaves the shock in the upstream or downstream direction. The maximum energy gain by this process is limited by the time the particle stays trapped. So far, this theory is not self-consistent, since it does not predict the injection rate and the relation to the upstream wave amplitudes. To summarize: the Malkov theory (17) for step 1 depends on the downstream region being a thermostat. It predicts which particles are detrapped in the downstream turbulence and escape upstream, leading to upstream turbulence and determining the downstream wave amplitudes and is a leakage model. In our model it is assumed that some solar wind ions perform a non-adiabatic motion when they reach the shock so that their parallel velocity is small. The particles stay trapped at the shock by the electric and magnetic forces in the shock ramp and by the electromagnetic force exerted by the incoming wave, and are accelerated in gyroresonance with the upstream waves convected into the shock.

We have only briefly mentioned composition. Theory (17) makes also predictions about the dependence of the injection rate on the mass to charge ratio of different species. However, since this theory relies on the downstream region being a thermostat, assumptions have to be made about the downstream thermal distribution function of the minor ions. Simulations have shown that depending on Mach number and beta (upstream thermal to magnetic field pressure) the minor ions are not thermalized on the same scale as the protons. Thus a thermostat model is not appropriate. In simulations of quasi-parallel collisionless shocks where the upstream plasma contains a few percent alpha particles as a minor component it is found that the alpha particle of the incident solar wind gyrate downstream as a coherent beam before being finally thermalized far downstream of the shock ramp (14). During the gyration this beam reaches occasionally the shock front and bunches of alpha particles escape upstream. They are subsequently scattered in the upstream waves and can interact again with the shock, thus gaining higher energies.

A final question is from where in velocity space the injected and accelerated particles originate. In the simulations in (14) the ions were sorted according to their initial velocity in the upstream rest frame (peculiar system). The thermal speed of the upstream plasma is v_{th}. Ions were subdivided into bins with equally spaced thermal speed and the ratio of diffuse ion density to the ion density in each subpopulation was determined. No diffuse ions originate from the core, i.e., from $0 < v < 0.5v_{th}$, whereas the ratio of diffuse ions to incident ions in the $v > 2v_{th}$ bin is, depending on the plasma beta, of the order of 40%. Thus diffuse ions originate from the outer region (in the peculiar system) of the distribution in velocity space.

INJECTION AT QUASI-PERPENDICULAR SHOCKS

An important question in shock acceleration studies is whether upstream thermal ions can be efficiently injected and accelerated at quasi-perpendicular shocks, i.e., shocks with $\Theta_{Bn} > 45°$. Backstreaming ions have been observed at the Earth's quasi-perpendicular bow shock; however, these ions seem to originate from locations such that $\Theta_{Bn} < 70°$ (21). When $\Theta_{Bn} > 70°$ specularly reflected ions at the Earth's bow shock are accelerated by the interplanetary electric field parallel to the shock surface and turned around under the influence of the Lorentz force. When they return to the shock they have gained sufficient energy to surmount the effective potential barrier that originally caused their reflection and they end up downstream. On the other hand energetic particles have actually been observed at quasi-perpendicular interplanetary traveling shocks and at the quasi-perpendicular foreward and reverse shocks bounding the corotating interaction regions. In order for charged particles to be efficiently accelerated by quasi-perpendicular shocks they must encounter the shock several times. One way for this to happen is by scattering rapidly enough that they diffuse against the downstream convection. Since the magnetic field is nearly perpendicular to the flow, the diffusion is across the magnetic field. Another way for particles to encounter the shock several times is by being trapped between the electrostatic potential and the upstream Lorentz force. The latter mechanism (shock surfing) has been proposed for acceleration of pickup ions at quasi-perpendicular shocks (19, 20). This mechanism can work for pickup ions, but not easily for thermal solar wind ions, since it requires that the ions have in the shock frame a velocity normal to the shock which is much smaller than the solar wind bulk velocity. This is the case for a fraction of the pickup ions at traveling interplanetary shocks as well as at the heliospheric termination shock.

Self-consistent particle simulations of collisionless shocks should results in the appropriate parallel and perpendicular scattering of thermal solar wind ions and possible injection and acceleration. However, these simulations have been performed almost exclusively in one or two spatial dimensions in such a way as to ignore the coordinate normal to the plane containing the asymptotic magnetic field. Jokipii et al. (22) and Jones et al. (23) have presented a general theorem according to which charged particles in fields with at least one ignorable spatial coordinate is effectively forever tied to the same magnetic line of force, except for motion along the ignorable coordinate. Thus, 1-D and 2-D kinetic simulations of quasi-perpendicular shocks can not give results on the injection and acceleration of thermal ions. Since at present long time 3-D simulations of shocksare not computationally feasible, Giacalone et al. (24) have introduced an ad hoc perpendicular diffusion in an 1-D hybrid simulation of perpendicular shocks. In these simulations pickup ions have been included self-consistently. Assuming a scattering time of about 20 times the inverse ion gyrofrequency upstream of the shock these authors found that only pickup ions are injected efficiently, whereas thermal solar wind ions are not.

The turbulence behind quasi-perpendicular shocks is produced by the combined distributions of transmitted solar wind ions and transmitted specularly reflected ions. The specularly reflected ions gyrate downstream as a gyrophase-bunched distribution. The combined distribution is susceptible to the Alfvén ion cyclotron instability and to the mirror mode instability. In order to determine the parallel and cross field diffusion coefficient in such a turbulence field Scholer et al. (25) have performed 3-D simulations of a system consisting initially of a core distribution and a gyrophase-bunched distribution. From the temporal development of the spatial variance over many particle trajectories a ratio of the perpendicular to parallel diffusion coefficient of $\kappa_\perp/\kappa_\| \sim 0.1$ has been derived, which is by an order of magnitude larger than the value predicted by hard sphere scattering, i.e., parallel scattering is considerably more effective than perpendicular scattering. Thus, it is expected that specularly reflected ions are rapidly pitch-angle scattered onto a sphere in velocity space. The perpendicular diffusion coefficient results in a perpendicular scattering time constant of $\Omega t \sim 20$. In the 1-D quasi-perpendicular shock simulations by Giacalone et al. (24) pitch angle scattering was prohibited, since in the 1-D setup the instability with k vectors parallel to the magnetic field can not be excited. However, since specularly reflected ions should rapidly pitch-angle scatter in a 2- or 3-D setup, they should behave as far as cross-field diffusion is concerned similarly as pickup ions. Thus, the cross-field scattering in the turbulence generated by the specularly reflected ions may be sufficient to inject and accelerate these ions at quasi-perpendicular shocks.

In oblique shocks, that is in a Θ_{Bn} range between $\sim 50° - 60°$, particles can get injected by the same mechanism that works at quasi-parallel shocks: we have pointed out that particles are trapped near the shock and gain energies of up to 10 times the shock ram energy before they move upstream and are possibly further accelerated by a diffusive acceleration mechanism. At these high energies particles can leave the shock in the upstream direction for shock normal - magnetic field angles exceeding 45°, can subsequently produce upstream waves, and can get backscattered. 1-D simulations of oblique shocks ($\Theta_{Bn} = 60°$) have indeed resulted in high energy backstreaming ions. These simulations have to be repeated at least in 2-D: in 1-D simulations only waves with **k** vectors parallel to the shock nomal are allows whereas **k** of maximum growth is expected to be parallel to the magnetic field.

INJECTION OF PICKUP IONS

The injection/acceleration of pickup ions by the shock surfing mechanism (19 20) was already mentioned earlier. Such a process cannot be modeled by hybrid simulations since the mechanism relies on the spatial scale of the shock potential being of the order of the electron inertial length. Full particle simulations are necessary to verify this acceleration mechanism. Pickup ions have a velocity distribution which is close to a spherical shell with a radius of solar wind speed around the solar wind velocity. Pickup ions are easily reflected from quasi-parallel shocks. The potential in a quasi-parallel shock helps to decelerate the solar wind; a large part of the pickup ion distribution has a velocity between zero and solar wind speed and can get reflected at the shock, as has been seen in 1-D hybrid simulations of Scholer and Kucharek (26). Injection at quasi-perpendicular shocks by cross-field diffusion is another possibility. Since a large part of the pickup ion distribution has a very small velocity in the shock normal direction these ions are able to recross the shock due to cross-field diffusion many times. This has been demonstrated in the hybrid simulations of Giacalone et al. (24) and in the Monte Carlo simulations of Ellison et al. (27).

SUMMARY

Self-consistent quasi-parallel collisionless shock simulations have shown that $\sim 2-4\%$ of the upstream ion are extracted during their interaction with the shock and are subsequently accelerated to higher energies. This may not sound as an important result, but in view of the large number of sceptics of such a process it is actually a rather important result. The simulations have shown that the injected and accelerated particles are an integral part of the quasi-parallel shock structure: the upstream diffuse ions excite waves via the electromagnetic ion/ion beam instability. These waves are convected into the shock and lead to dissipation. Detailed analysis of particle trajectories during the simulations allows determination of the processes which lead to injection and acceleration. Once we know these processes, we may be able to construct theoretical models. The models by Malkov (17) for the injection from downstream and the model by Malkov and Völk (6) for the diffusive process in the suprathermal energy range are particularly noteworthy.

The injection and acceleration process for thermal ions at quasi-perpendicular shocks depends on the possibility of these ions to recross the shock many times. A viable mechanism for injection is cross-field diffusion of the specularly reflected ions after they have crossed the shock into the downstream region. Determination of the cross-field diffusion coefficient in strong turbulence suggests that specularly reflected ions can recross the quasi-perpendicular shock and can get further accelerated. One-dimensional simulations of shocks cannot give results on injection of thermal particles, even when an ad hoc perpendicular scattering is introduced. The specularly reflected particles have to scatter fast in pitch angle, so that they have small velocities in the shock normal direction. Pitch angle scattering is absent or only weak in 1-D simulations of perpendicular shocks since the excitation of waves with wave vectors parallel to the magnetic field is excluded. We have to await fully 3-D simulations of quasi-perpendicular shocks in order to verify such an injection and acceleration mechanism. At more oblique shocks the same injection process as at quasi-parallel shocks can work: particles gain high enough velocities during their first shock encounter so that they can escape the shock along the magnetic field in the upstream direction.

We may almost state that pickup ions like to be accelerated, not only by shocks, but also by turbulent fields. In magnetic field turbulence, as for instance behind shocks, transit time damping can accelerate pickup ions, since these ions have velocities exceeding the Alfvén speed, the minimum speed needed for transit time damping to work (28). Pickup ions are reflected from quasi-parallel shocks: hybrid simulations of quasi-parallel shocks have shown that the reflection rate of pickup ions is large. They can subsequently partake in a diffusive acceleration process. At quasi-perpendicular shocks the surfing mechanism is a possible mechanism. Cross-field diffusion at quasi-perpendicular shocks can inject and accelerate ions at these shocks. As far as pickup ions are concerned the problem seems to be the determination of the dominant acceleration mechanism in a particular situation. Simulations and theory have to come up with better predictions on the dependence of the injection efficiency on the charge to mass ratios. Comparison with the excellent ACE composition observations may eventually discriminate between the various injection and acceleration processes for pickup ions.

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REFERENCES

1. Krimsky, G. F., *Dokl. Akad. Nauk. SSRR* **234**, 1306 (1977).
2. Axford, W. I., Leer, E., and Skadron, G., in *Proc. Int. Conf. Cosmic Rays 15th* **11**, 132 (1977).
3. Blandford, R. R., and Ostriker, J. P.,*Astrophys. J.* **221**, L29 (1978).
4. Bell, A. R., *Mon. Not. R. Astron. Soc.* **182**, 147 (1978).
5. Gosling, J. T., et al., *Geophys. Res. Lett.* **5**, 957 (1978).
6. Malkov,M. A., and Völk, H. J., *Astron. Astrophys.* **300**, 605 (1995).
7. Ellison, D. C., *Geophys. Res. Lett.* **8**, 991 (1981).
8. Ellison, D. C., Baring, M. G. and Jones, F. C.,*Astrophys. J.* **473**, 1029 (1996).
9. Quest, K. B., in *Proc. 6th Intern. Solar Wind Conf.*, NCAR Techn. Note **306**, 503 (1988).
10. Scholer, M., *Geophys. Res. Lett.* **17**, 1153 (1990).
11. Kucharek, H., and Scholer, M., *J. Geophys. Res.* **96**, 22195 (1991).
12. Giacalone, J. et al., *Geophys. Res. Lett.* **19**, 433 (1992).
13. Trattner, K.-J., and Scholer, M., *Geophys. Res. Lett.* **18**, 1817 (1991).
14. Trattner, K.-J., and Scholer, M., *J. Geophys. Res.* **99**, 6637 (1994).
15. Scholer, M., Kucharek,H., and Trattner, K.-H., *Ann. Geophys.* **17**, 583 (1999).
16. Lee, M. A., *J. Geophys. Res.* **87**, 5063 (1982).
17. Malkov, M. A., *Phys. Rev. E.* **58**, 4911 (1998).
18. Sugiyama, T., and Fujimoto, M., in *Proc. Int. Conf. Cosmic Rays 25th* **4**, 423 (1999).
19. Lee, M. A., Shapiro, V. D., and Sagdeev, R. Z., *J. Geophys. Res.* **101**, 4777 (1996).
20. Zank, G. P., et al., *J. Geophys. Res.* **101**, 457 (1996).
21. Paschmann, G., et al., *J. Geophys. Res.* **86**, 4355 (1981).
22. Jokipii, J. R., Kota, J., and Giacalone, J., *Geophys. Res. Lett.* **20**, 1759 (1993).
23. Jones, F. C., Jokipii, J. R., and Baring, M. G., *Astrophys. J.* **509**, 238 (1998).
24. Giacalone, J., Jokipii, J. R., and Kota, J., *J. Geophys. Res.* **99**, 2929 (1994).
25. Scholer, M., Kucharek, H., and Giacalone, J., in press *J. Geophys. Res.*, (2000).
26. Scholer, M., and Kucharek, H., *Geophys. Res. Lett.* **26**, 29 (1999).
27. Ellison, D. C., Jones, F. C., and Baring, M. G., *Astrophys. J.* **512**, 403 (1999).
28. Fisk, L. A., *J. Geophys. Res.* **81**, 4633 (1976).