

Particle acceleration and generation of diffuse superthermal ions at a quasi-parallel collisionless shock: Hybrid simulations

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[1] A large scale one-dimensional hybrid simulation is performed to investigate the generation mechanism of diffuse superthermal ions at a high Mach number quasi-parallel collisionless shock. The shock exhibits a cyclic behavior and reforms periodically. The generation of the diffuse ions is associated with the reformation of the shock. At the beginning of the reformation cycle, a part of ions are reflected by the shock due to the existence of the cross shock potential. At the same time, an upstream wave is brought back by the upstream plasma and interacts with the shock. The upstream wave begins to steepen as it approaches the shock, and then a new shock front is formed. The reflected ions are trapped between the new and old shock fronts. They are accelerated every time they are reflected by the new shock front until the reformation cycle of the shock is finished and the particles escape from the shock. In this way, diffuse superthermal ions are generated in the quasi-parallel shock, which may be further accelerated to higher energy due to shock diffusive acceleration.

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1. Introduction

[2] The study of collisionless shocks is of much concern in space and astrophysical plasma. The shock can not only convert bulk energy of plasma irreversibly into thermal energy, but also account for the almost universally observed power law spectra of energetic particles from cosmic rays to gradual solar energetic particle events. The theory of diffusive shock acceleration has been successful in explaining the high energy tail of energetic particles associated with shocks [Axford *et al.*, 1977; Bell, 1978; Blandford and Ostriker, 1978]. At a quasi-parallel shock, the process of diffusive shock acceleration can be described as follows: the upstream ions reflected by the shock stream far upstream along the magnetic field, and then low-frequency plasma waves are excited due to plasma beam instabilities [Gary, 1991; Lu *et al.*, 2006]. The waves make the ions to be scattered across the shock several times. In this way, these ions can be accelerated to very high energies, forming a power law spectrum [Lee, 1983; Zank *et al.*, 2000; Li *et al.*, 2003; Giacalone, 2004; Zank *et al.*, 2007]. However, the diffusive shock acceleration theory is not concerned with the question of how a certain part

of the thermal particles are injected into the acceleration process. Thus, how a small fraction of seed particles are extracted from the thermal background plasma to generate superthermal ions for a further diffusive acceleration process remains unanswered.

[3] Hybrid simulations have been considered as a powerful tool to investigate the origin of diffuse superthermal ions as well as the details on the shock structure at quasi-parallel shocks, since the initial simulations were performed by Kan and Swift [1983] and Quest [1988]. In hybrid simulations, the ions are treated as particles, while the electrons are treated as a massless fluid. With hybrid simulations, Burgess [1989] further found that quasi-parallel shocks exhibit a cyclic behavior and reforms periodically. Since then, the reformation of quasi-parallel shocks has been confirmed by many authors. Scholer and Terasawa [1990] showed that the reformation process is initiated by an upstream wave as the wave crest is convected toward the shock. Winske *et al.* [1990] considered that the ion/ion beam instability between the incident ions and heated downstream ions to be responsible for the shock reformation. Scholer and Burgess [1992] attributed the reformation to the interaction of specularly reflected ions with upstream waves. At the same time, diffuse ions are always observed associated with these quasi-parallel shocks. Lyu and Kan [1990, 1993] attributed the diffuse ions to the leakage ions from the downstream of quasi-parallel shocks, whose tangential velocity is in phase with the tangential electric field produced by upstream and shock generated waves. Also by performing self-consistent hybrid simulations of a quasi-parallel shock, Scholer [1990] concluded that the major part of the diffuse ions are not due to the leakage of thermalized downstream ions. They

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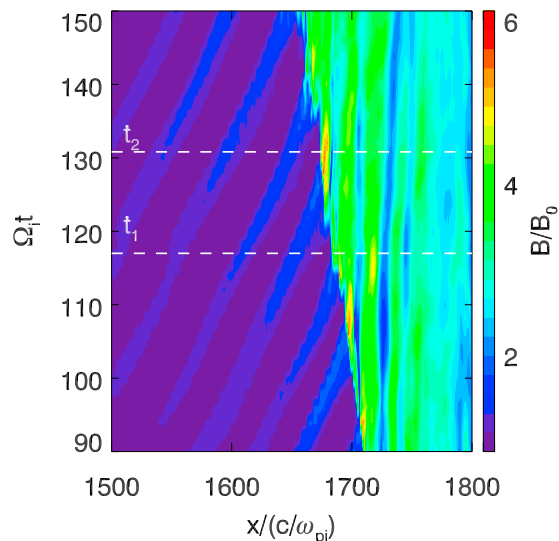


Figure 1. Contour plot of the total magnetic field $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$ from $\Omega_i t = 90$ to $\Omega_i t = 150$. The time period between the dashed lines denoted by t_1 and t_2 represent one reformation cycle (where $\Omega_i t_1 = 117$ and $\Omega_i t_2 = 131$).

proposed that the diffuse ions are accelerated from the thermal background plasma after these ions are reflected and then stay close to the shock for an extended period of time. *Kucharek and Scholer* [1991] further pointed out that grad B drift within the coplanarity plane is the main acceleration mechanism for the diffuse ions because of the existence of

the large noncoplanarity magnetic field component in the shock front. In this paper, we find that the reflected ions can be trapped by the old and new shock fronts, where the new shock front is formed when the upstream waves are convected to toward the shock. The trapped ions are accelerated every time they are reflected by the new shock front.

[4] The paper is organized as follows. In Section 2, we describe the hybrid simulation model. The simulation results are presented in Section 3. In Section 4, we discuss and summarize our results.

2. Simulation Model

[5] One-dimensional (1-D) hybrid simulations are performed in this paper to investigate the generation of diffuse superthermal ions at a quasi-parallel shock. Hybrid simulations treat ions as macroparticles, and electrons are assumed as massless fluid [Winske and Leory, 1985]. The particles are advanced according to the well-known Boris algorithm while the electromagnetic fields are calculated with an implicit algorithm. The simulations allow for one spatial direction (shock normal direction x), while the velocities and electromagnetic field are three-dimensional. The plasma consists of proton and electron components. Initially, protons satisfy a Maxwellian velocity distribution with a drift speed along the x direction. The shock is launched by reflecting the plasma at a rigid right boundary wall, and the formed shock propagates to the left. The angle between the upstream magnetic field and the shock normal is $\theta_{Bn} = \sin^{-1}(B_{z0}/B_0) = 30^\circ$ (where B_0 is the background magnetic field in the upstream). Particles are injected from the left

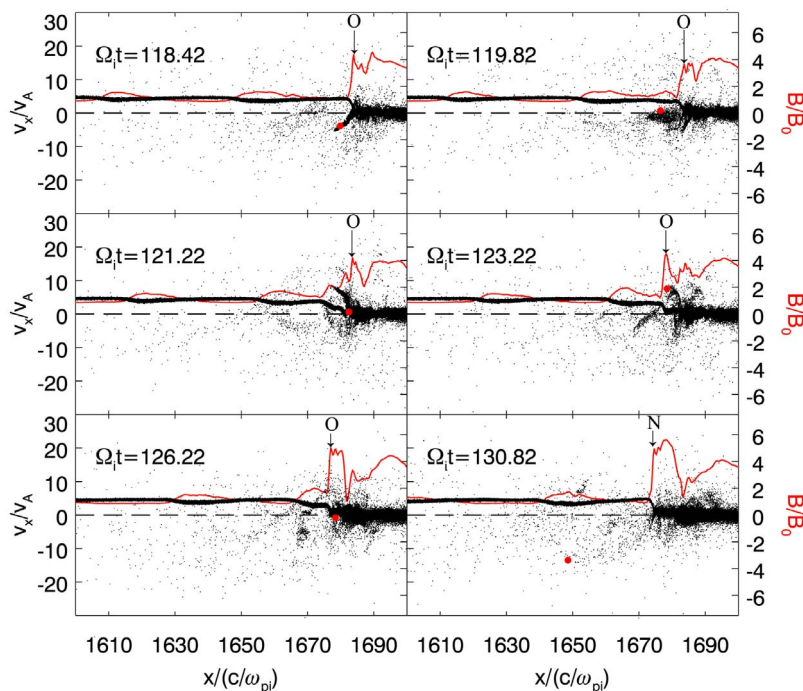


Figure 2. The time evolution of the ion phase space plots in the (x, v_x) plane, as well as the magnetic field B at $\Omega_i t = 118.42, 119.82, 121.22, 123.22, 126.22$ and 130.82 , which represents a selected self-reformation cycle between t_1 and t_2 denoted in Figure 1. In the figure, “O” denotes the overshoot position of the old shock, while “N” denotes the overshoot position of the new shock. The red dot is the typical particle, whose trajectory will be analyzed in Figure 4.

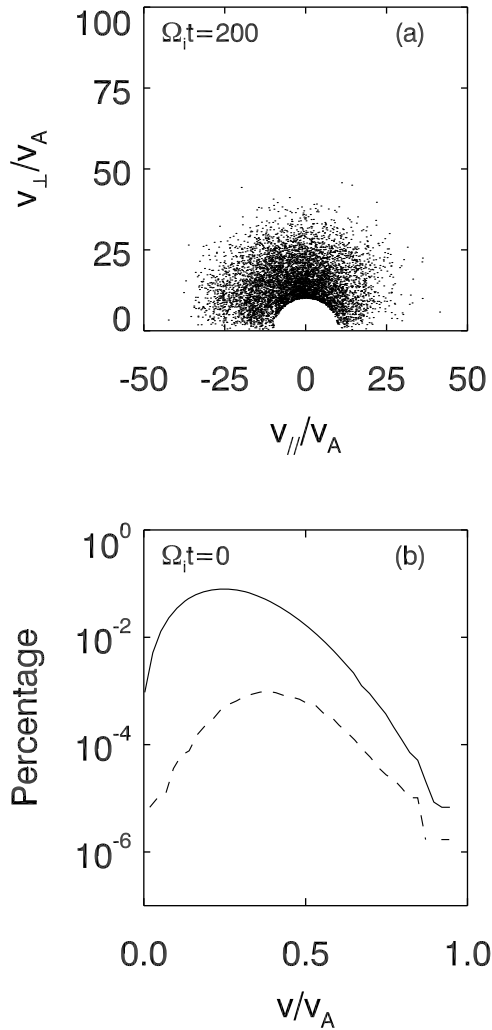


Figure 3. (a) The velocity distribution of the CT particles in the phase space (v_{\parallel} , v_{\perp}) at $\Omega_i t = 200$. The v_{\parallel} and v_{\perp} are the velocities parallel and perpendicular to the local magnetic field. (b) The velocity distribution of the ST ions (solid line) and CT ions (dotted line) at $\Omega_i t = 0$, when these particles are in the upstream and have not interacted with the shock. The distributions are normalized to the number of the ST particles.

boundary with a speed of $4.5V_A$ (where V_A is the Alfvén speed based on the upstream parameters), and the plasma beta upstream of the shock is $\beta_p = 0.1$. In the simulation, the number of grid cells is 6000 with the grid size $\Delta x = 0.3 c/\omega_{pi}$ (where c is the light speed, ω_{pi} is the ion plasma frequency based on the upstream number density, and c/ω_{pi} is the ion inertial length), which is sufficiently small to resolve the shock profile. The electron resistive length is chosen as $L_r = \eta c^2/(4\pi v_A) = 0.1c/\omega_{pi}$, which is much smaller than the grid size. Initially, there are 200 macroparticles in every cell. The time step is $\Omega_i \Delta t = 0.02$ (where Ω_i is the ion gyrofrequency).

3. Simulation Results

[6] In this paper, we at first show the evolution of the quasi-parallel shock, and then describe the generation of diffuse superthermal ions. Figure 1 illustrates the time

evolution of the total magnetic field $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$ from $\Omega_i t = 90$ to $\Omega_i t = 150$. The shock is propagating from the right to the left of the simulation box with an average velocity about $1.0V_A$. Because the plasma is injected from the left boundary with a velocity of $4.5V_A$, the upstream Alfvén Mach number is about $M_A = 5.5$ in the shock frame. As illustrated in the previous papers [Burgess, 1989; Scholer and Terasawa, 1990; Winske et al., 1990], the shock exhibits a cyclic behavior and reforms periodically. The period is about $12\Omega_i^{-1}$. Our results seem to support that the reformation of the shock is due to the interactions between the upstream waves and the shock, as proposed by Scholer and Terasawa [1990]. The wavelength of the upstream waves is about $40c/\omega_{pi}$.

[7] The reformation of the shock can be seen more clearly in Figure 2, which displays the evolution of the ion phase-space plots in the (x , v_x) plane, as well as the magnetic field B at one selected self-reformation cycle (from $\Omega_i t = 117$ to $\Omega_i t = 131$). At the beginning of the reformation cycle (around $\Omega_i t = 118.42$), a well-developed cold ion beam exists in front of the shock, and this beam extends about $10c/\omega_{pi}$. The cold ion beam is formed due to the specular reflection of the upstream ions by the shock. Almost all reflected ions occur during this period due to the existence of the steep ramp, where a strong electric field directed upstream is formed. At the same time, an upstream wave is brought back by the upstream plasma and interacts with the shock, which results in the steepening of the upstream wave and scattering of the ion beam. Detailed analysis shows that the waves have right-hand polarization in the plasma frame. According to the linear theory of the resonant ion beam instability and the relative speed between the ion beam and upstream plasma (about $9.0v_A$), we can calculate the wavelength of the excited waves is about $45c/\omega_{pi}$, which is consistent with our simulation results. Therefore, the upstream waves are excited by the resonant electromagnetic ion beam instability, as proposed by Quest [1988]. Then, the upstream wave is steepened into a wave crest, and a new shock front is formed. At last, the new shock front exceeds the old shock front and a reformation cycle is finished. The generation of superthermal ions can be obviously found during the reformation cycle of the shock.

[8] In order to trace the origin of these generated superthermal particles, we select the particles whose initial positions are between $x = 800c/\omega_{pi}$ and $x = 1680c/\omega_{pi}$ (we call them ST particles), and then follow their trajectories. These ST particles will interact with the shock. At $\Omega_i t = 200$, the shock is at $x \sim 1600c/\omega_{pi}$, and these ST particles have finished interacting with the shock about one reformation cycle ahead. We then collected the ions with velocities larger than $10V_A$ from these ST particles (we call them CT particles). Figure 3a shows the velocity distribution of the CT particles in the phase space (v_{\parallel} , v_{\perp}) at $\Omega_i t = 200$. The v_{\parallel} and v_{\perp} are the velocities parallel and perpendicular to the local magnetic field. These CT particles are almost isotropic, and the maximum velocity exceeds $40v_A$. Therefore, these superthermal ions can be called as diffuse particles. Figure 3b displays the velocity distribution of the ST ions (solid line) and CT ions (dotted line) at $\Omega_i t = 0$, when these particles are in the upstream and have not interacted with the shock. The distributions are normalized to the number of the ST particles.

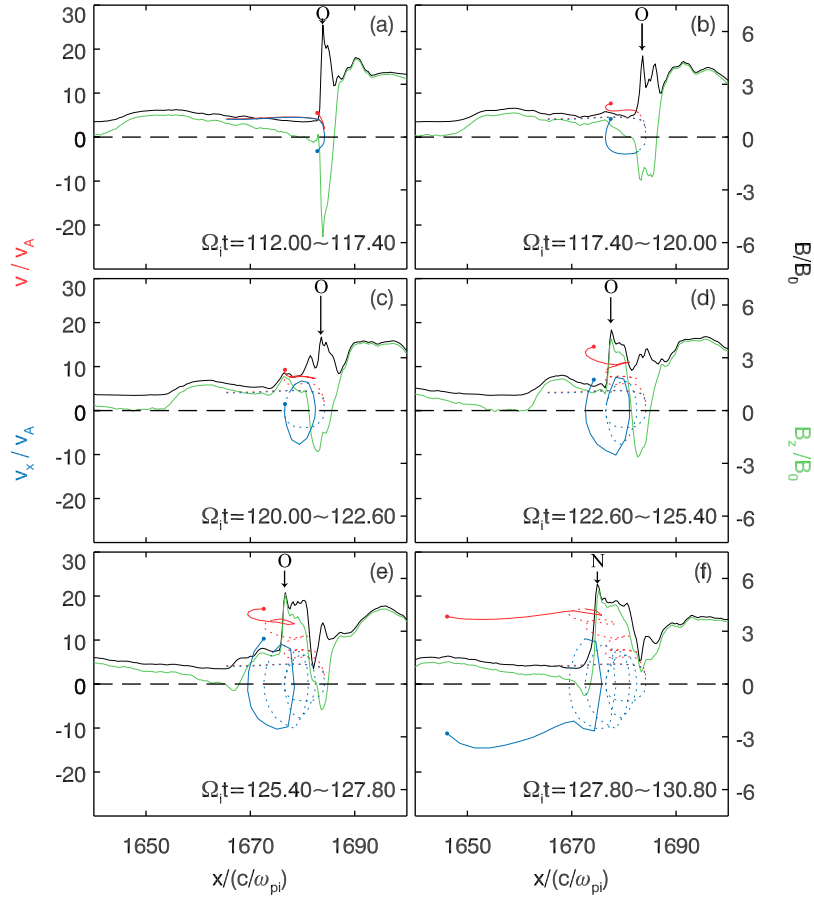


Figure 4. A typical ion trajectory in the (x, v_x) and (x, v) planes at (a) $\Omega_{it} = 112.00 \sim 117.40$, (b) $\Omega_{it} = 117.40 \sim 120.00$, (c) $\Omega_{it} = 120.00 \sim 122.60$, (d) $\Omega_{it} = 122.60 \sim 125.40$, (e) $\Omega_{it} = 125.40 \sim 127.80$ and (f) $\Omega_{it} = 127.80 \sim 130.80$. The red and blue lines represent v and v_x , respectively. The solid line describes the corresponding value at the selected periods, while the dotted line denoted the value before that period. The magnetic field B and the z component of the magnetic field B_z at $\Omega_{it} = 117.40, 119.20, 121.20, 126.80$ and 129.60 are also plotted in (a), (b), (c), (d), (e) and (f) for reference. The black and green lines represent B and B_z , respectively. This particle is also the one that shown by the red dots in Figure 2.

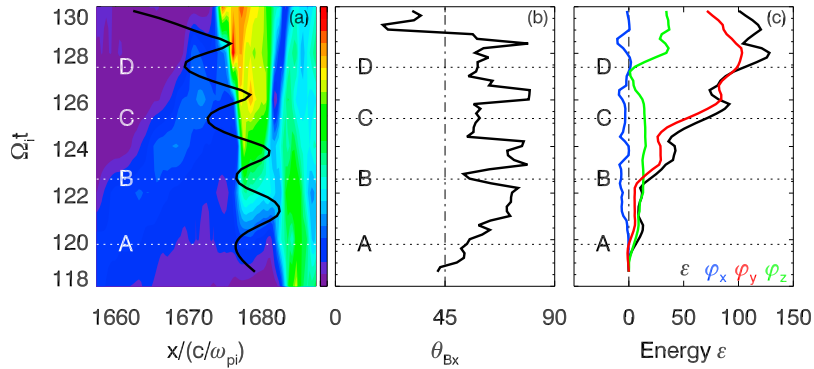


Figure 5. (a) Time versus position x , (b) time versus the angle θ_{Bx} between the local magnetic field and the x direction, and (c) time versus the particle energy ϵ , the potential difference gained due to the particle motion in the x , y and z directions, which are $\varphi_x = \int E_x v_x dt$, $\varphi_y = \int E_y v_y dt$ and $\varphi_z = \int E_z v_z dt$, respectively. In the figure, the points, where the particle is reflected by the new shock front, are denoted by A, B, C, and D. The contour of the total magnetic field in Figure 5 (a) uses the same color bar as in Figure 1.

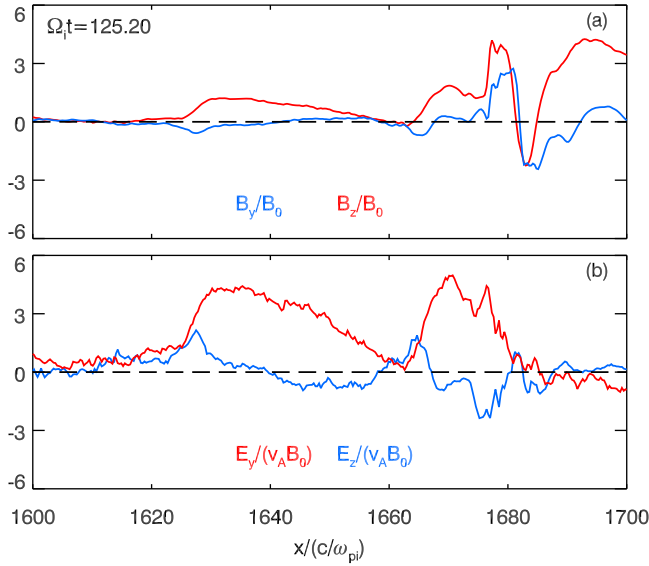


Figure 6. (a) The magnetic field B_y and B_z and (b) the electric field E_y and E_z at $\Omega_i t = 125.20$.

The velocity distribution of the CT ions at $\Omega_i t = 0$ is calculated with a backward integration. From Figure 3b, we can find that a large part of the corresponding diffuse ions can be accelerated out of the incident thermal distribution in the upstream, and there are about 1.2% upstream incident upstream ions can evolve into diffuse ions.

[9] In order to investigate the acceleration mechanism of the diffuse ions, we have marked every diffuse ion and then follow their trajectories. It is found that all diffuse ions come from the reflected ions, and then stay close to the shock for tens of ion gyroperiods. The similar results have also been obtained by *Scholer* [1990]. However, by following their trajectories, we can further know the reason why these reflected ions stay close to the shock for a long period. Figure 4 plot a typical ion trajectory in the (x, v_x) and (x, v_y) planes at different periods. The magnetic field B and the z component of the magnetic field B_z at $\Omega_i t = 117.4, 119.2, 121.2, 126.8$ and 129.6 are also plotted in the Figures 4a–4f for reference. At first, the particle is reflected by the shock and goes upstream. At the same time, we can find that an upstream wave is brought back by the upstream plasma and begin to interact with the shock. Then, the upstream wave steepens and forms a new shock front. The particle is trapped between the old and new shock fronts. Its velocity increases rapidly every time when the particle is reflected by the new shock front until it escapes after the reformation process of the shock is finished. Such an acceleration process is similar to the multiply reflected ion mechanism advocated by *Zank et al.* [1996]. Detailed analysis shows that almost all diffuse ions have similar acceleration process.

[10] The acceleration process of the typical diffuse ion can be demonstrated more clearly in Figure 5, which shows (a) time versus position x , (b) time versus the angle θ_{Bx} between the local magnetic field and the x direction, and (c) time versus the particle energy ϵ , the potential difference gained due to the particle motion in the x , y and z directions, which are $\varphi_x = \int E_x v_x dt$, $\varphi_y = \int E_y v_y dt$ and $\varphi_z = \int E_z v_z dt$,

respectively. Here, we can see again that the ion is accelerated when it is trapped between the old and new shock fronts. Its energy increases rapidly when it is reflected by the new shock front, where the angle between the local magnetic field and the x direction is larger than 45° . The energy gain of the particle mainly comes from the contribution of φ_y , or the y component of the electric field E_y seen by the particle. Figure 6 plots (a) the magnetic field B_y and B_z and (b) the electric field E_y and E_z at $\Omega_i t = 125.20$, which represents a typical shock profile. At the new shock front, where the particle is reflected and accelerated, there exists a large amplitude electric field E_y . Therefore, the trapped ion can be accelerated in the y direction, as shown in Figure 5. The electric field E_y is produced as the new shock front is convected toward the old shock front.

4. Discussion and Conclusions

[11] Shock diffusive acceleration is considered to be responsible for the almost universally observed power law spectra of energetic particles in space and astrophysical plasma. In the diffusive shock acceleration process, particles suffer multiple bounces back and forth when interacting with some turbulent shock profile. In this process, the particles can be accelerated to very high energy, which accounts for the observed power law spectra of energetic particles. However, this process requires a certain threshold be reached by the particles, i.e., a certain part of thermal particles are needed to be injected into some preaccelerations in order to the shock diffusive acceleration works efficiently [*Zank et al.*, 2001]. In a quasi-perpendicular shock, shock drift acceleration and surfing acceleration are considered to provide such preaccelerations [*Lee et al.*, 1996; *Zank et al.*, 1996; *Yang et al.*, 2009, 2011]. In this paper, with a 1-D hybrid simulation we studied the generation of superthermal diffuse ions in a quasi-parallel shock. Such an injection process in a periodically reformed shock can be described as follows: at the beginning of the reformation cycle, a part of ions are reflected by the shock. At the same time, a new shock front is formed as an upstream wave is brought back by the upstream plasma and interacts with the shock. The reflected ions are trapped between the new and old shock fronts. Every time, the ion is reflected by the new shock front, it is accelerated in the y direction due to the existence of a large amplitude electric field E_y in the new shock front. Such diffuse ions provide the seed particles for the further shock diffusive acceleration in a quasi-parallel shock.

[12] The generation of diffuse ions in quasi-parallel shocks has also been investigated previously by *Scholer* [1990]. They found that the reflected ions are accelerated when they stay close to the shock for tens of ion gyroperiods. In this paper, we further find that the reflected ions stay close to the shock for an extended period is due to they are trapped between the new and old shock fronts, where the new shock front is formed when the upstream waves are brought back by the upstream plasma. Every time, the ions are reflected by the new shock front, they are accelerated in the y direction by the electric field E_y . One thing that should be noticed is that a 1D hybrid model eliminates the possibility of a trapped ion to escape around the other directions of a structured shock, which may artificially increase the acceleration efficiency. This is our future investigation.

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