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Ion dynamics at supercritical quasi-parallel shocks: Hybrid simulations

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By separating the incident ions into directly transmitted, downstream thermalized, and diffuse ions, we perform one-dimensional (1D) hybrid simulations to investigate ion dynamics at a supercritical quasi-parallel shock. In the simulations, the angle between the upstream magnetic field and shock nominal direction is $\theta_{Bn} = 30^\circ$, and the Alfven Mach number is $M_A \sim 5.5$. The shock exhibits a periodic reformation process. The ion reflection occurs at the beginning of the reformation cycle. Part of the reflected ions is trapped between the old and new shock fronts for an extended time period. These particles eventually form superthermal diffuse ions after they escape to the upstream of the new shock front at the end of the reformation cycle. The other reflected ions may return to the shock immediately or be trapped between the old and new shock fronts for a short time period. When the amplitude of the new shock front exceeds that of the old shock front and the reformation cycle is finished, these ions become thermalized ions in the downstream. No noticeable heating can be found in the directly transmitted ions. The relevance of our simulations to the satellite observations is also discussed in the paper. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4752219]

I. INTRODUCTION

Collisionless shocks are of fundamental importance in the research of space plasma physics, because they are crucial in accelerating and heating particles. According to the shock angle θ_{Bn}, which is defined as the angle between the upstream magnetic field and the shock normal direction, the collisionless shocks can be categorized into two main types: quasi-parallel ($\theta_{Bn} < 45^\circ$) shocks and quasi-perpendicular ($\theta_{Bn} > 45^\circ$) shocks.[1] In a quasi-perpendicular shock, the reflected ions by the shock gyrate in the magnetic field around the foot region, and subsequently penetrate the shock potential to the downstream with high tangential velocities.[2,3] Then, a quasi-perpendicular shock has relatively simple structure. In a quasi-parallel shock, the reflected ions are considered to have upstream directed guiding center velocities, thus can escape to the far upstream and excite large amplitude upstream waves.[4–6] Therefore, the transition region from the upstream to the downstream in a quasi-parallel shock is obscured.

The ion dynamics in supercritical quasi-parallel shocks have been thoroughly investigated by many pervious studies.[7–9] With one-dimensional (1D) hybrid simulations, Quest *et al.*[10] pointed out that the incident upstream ions can be nearly specularly reflected and then form ion beams in the upstream. The ion beam can excite plasma waves in the upstream, and the incident ions are considered to be heated by such waves.[11] In 1D hybrid simulations with an extended simulation domain, several authors have reported the cyclic behavior of the shock front in supercritical quasi-parallel shocks, where the shock periodically reforms, and the reflected ions are indicated to be crucial in such a process.[4,12–14] Scholer and Terasawa[15] found that the reflected ions in supercritical quasi-parallel shocks are quickly trapped between the shock and the upstream wave crests, which are convected toward the shock by the incident upstream plasma. They concluded that the reflected ions will not escape to the far upstream because of the large component of the tangential magnetic field with respect to the shock normal direction in the upstream. Instead, together with the slowed down incident upstream ions, these reflected ions constitute the downstream thermalized distribution during the reformation of the shock. Scholer[16] further found that a part of incoming thermal ions originating in a certain part of phase space can stay with the shock for an extended period after they are reflected by the shock, which lead to a considerable energy increase and form superthermal diffuse ions.[16] In this paper, ion dynamics are investigated by separating the incident upstream ions in 1D hybrid simulations of a supercritical quasi-parallel shock into three parts: the directly transmitted, downstream thermalized, and diffuse ions.

The paper is organized as follows. In Sec. II, we describe the hybrid simulation model. The simulation results are presented in Sec. III. In Sec. IV, we discuss and summarize our results.

II. SIMULATION MODEL

One-dimensional (1D) hybrid simulations are performed in this paper to investigate the ion behaviors at a quasi-parallel shock. Hybrid simulations treat ions as macroparticles, and electrons are assumed as massless fluid.[17,18] 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

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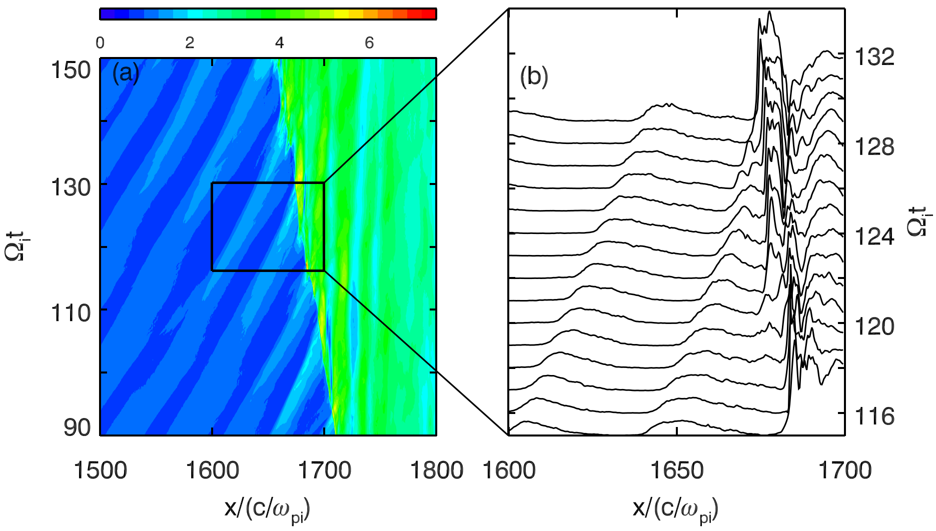

FIG. 1. (a) The evolution of total magnetic field B from $\Omega_i t = 90$ to $\Omega_i t = 150$; (b) its detailed profile in one particular reformation cycle between $\Omega_i t = 116$ and $\Omega_i t = 130$ with the interval between each two nearest curve equaling $2\Omega_i^{-1}$, and the first curve is at $\Omega_i t = 116$.

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 $\theta_{Bn} = \sin^{-1}(B_{z0}/B_0) = 30^0$ (where B_0 is the magnetic field in the upstream). Particles are injected from the left boundary with a speed of 4.5 V_A (where V_A is the Alfven speed based on the upstream parameters), and the upstream plasma beta is $\beta_p = 0.1$. In the simulations, the number of grid cells is 6000 with the grid size $\Delta x = 0.3c/\omega_{pi}$ (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). Initially, there are 200 macroparticles in every cell. The time step is $\Omega_i \Delta t = 0.02$ (where $\Omega_i = eB_0/m$ is the ion gyro-frequency).

III. SIMULATION RESULTS

As evidenced in previous studies, the quasi-parallel shock in our simulations presents a cyclic behavior, where the shock reforms itself periodically. The evolution of the shock is shown in Figure 1. Fig. 1(a) plots the total magnetic field B from $\Omega_i t = 90$ to $\Omega_i t = 150$, and Fig. 1(b) plots the detailed profiles of the magnetic field B in one selected reformation cycle, which is from $\Omega_i t = 116$ to $\Omega_i t = 130$ with the interval $2\Omega_i^{-1}$. The shock is propagating from the right to the left in the simulation domain with a velocity about one Alfven speed. Therefore, the Alfven Mach number of the shock is $M_A \sim 5.5$. At the same time, the upstream waves, which are considered to be excited by the reflected ions due to the ion-ion beam instability, are convected back to the shock by the upstream plasma, and their amplitude increases when approaching the shock. When the amplitude exceeds that of the shock, a new shock front is formed and a reformation process is finished. Such a reformation process takes place periodically, as demonstrated in previous studies.[4,12]

Figure 2 shows the ion phase space (v_x, x) at $\Omega_i t =$(a) 118.42, (b) 124.62, and (c) 130.82, which is selected from one reformation cycle. The total magnetic field B is also plotted in the figure. At the beginning of the reformation cycle, part of the upstream ions is specularly reflected by the shock and forms a cold ion beam just before the shock. Detailed analysis shows that the ion reflection occurs at the beginning of the reformation cycle, when the shock has a steep ramp. These reflected ions may return to the shock, or trapped between the old and new shock fronts.

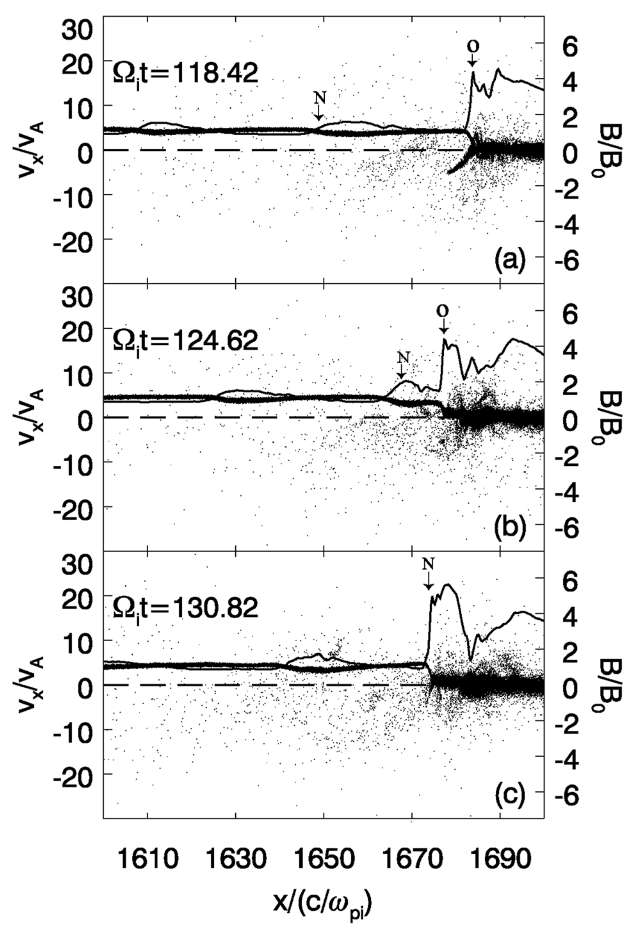

FIG. 2. The ion phase space (v_x, x) distribution at $\Omega_i t =$(a) 118.42, (b) 124.62, and (c) 130.82, which is selected from one reformation cycle. The total magnetic field B is also plotted in the figure for reference. The labels "O" and "N" denote the position of the old and new shock fronts, respectively.

In order to investigate the ion behaviors at the quasi-parallel shock with more details, we divide upstream ions into three groups. At first, we separate the upstream ions into reflected and directly transmitted ions. After being reflected, the reflected ions are in the upstream of the shock (their positions are located in front of the ramp, where $|\partial B/\partial x|$ has the maximum value), and at the same time their velocities in the $-x$ direction is larger than the shock propagating speed. The reflected ions are then separated into diffuse and downstream thermalized ions. Because the ion reflection occurs at the beginning of the reformation cycle, we define diffuse ions as the particles, which are in the upstream of the new shock front at the end of the reformation cycle ($x < 1675c/\omega_{pi}$ at $\Omega_i t = 130.22$), while downstream thermalized ions as the particles downstream of the new shock front ($x > 1675c/\omega_{pi}$ at $\Omega_i t = 130.22$). The diffuse ions have isotropic distribution, and can be accelerated to higher energy than that of the downstream thermalized ions, as described later. Figure 3 plots the phase space (v_x, x) for (a) diffuse ions, (b) downstream thermalized ions, and (c) directly transmitted at different times. The total magnetic field B is also plotted in the figure for reference. We follow the upstream ions which are located between $x = 1620c/\omega_{pi}$ and $x = 1684c/\omega_{pi}$ at $\Omega_i t = 116.22$. These particles can interact with the shock front in one reformation cycle. When crossing the shock, the bulk velocity of the transmitted ions in the x direction decreases, and no noticeable heating can be found in the downstream. In contrast, the reflected ions can be accelerated during their reflection by the shock. The reflection occurs at the beginning of the reformation cycle and forms a cold ion beam in the upstream. Part of the reflected ions is trapped between the old and new shock fronts for an extended time period. At last, these particles escape to the upstream of the new shock front at the end of the reformation cycle, and become superthermal diffuse ions. The other reflected ions may return to the shock immediately or be trapped between the old and new shock fronts for a short time period, and become downstream ions when the amplitude of the new shock front exceeds that of the old shock front. Such a process provides a mechanism to heat the upstream plasma in a quasi-parallel shock. Figure 4 plots the downstream temperatures of the downstream thermalized and directly transmitted ions, and the magnetic field B/B_0 is also plotted for reference. The temperature is the average value in the x, y, and z directions, and is normalized by the upstream temperature T_0. Obviously, the temperature of the downstream thermalized ions is much larger than that of the transmitted ions, and it provides the main dissipation of the shock.

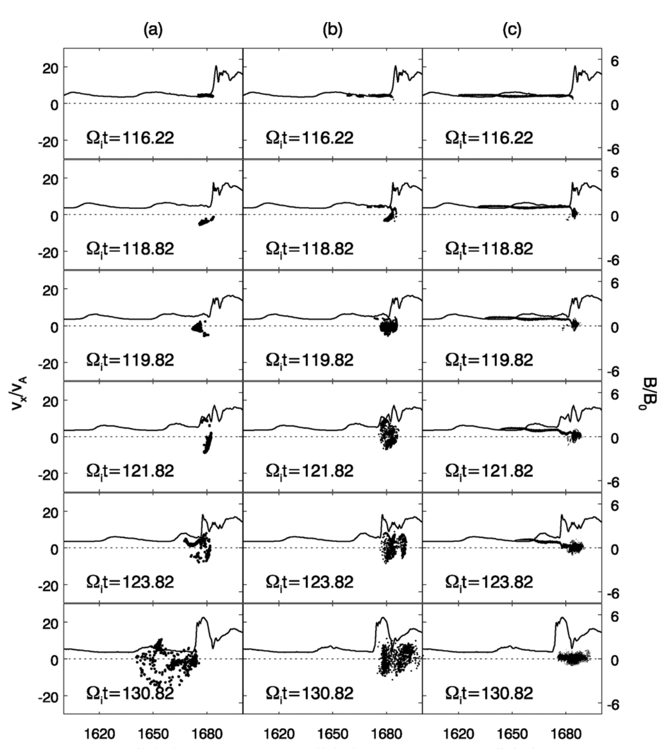

FIG. 3. The ion phase space (v_x, x) for (a) diffuse ions, (b) downstream thermalized ions, and (c) directly transmitted ions at different times. The total magnetic field B is also plotted in the figure for reference.

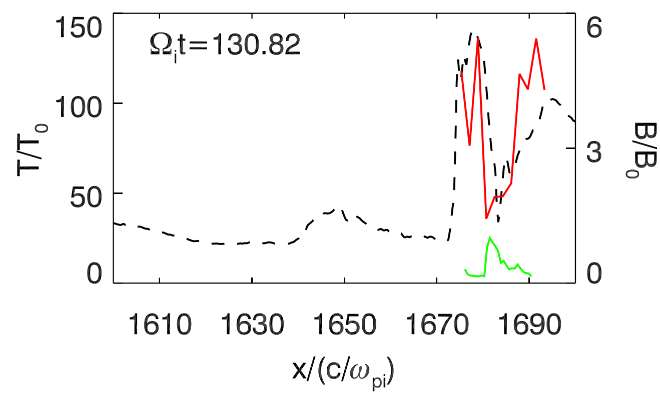

FIG. 4. Plots of the downstream temperatures of the downstream thermalized and directly transmitted ions, in which the magnetic field B/B_0 is also plotted for reference. The temperature is the average value in the x, y, and z directions, and is normalized by the upstream temperature T_0. In the figure, the dashed line denotes the magnetic field. The red and green lines denote the temperatures of the downstream thermalized and directly transmitted ions, respectively.

Figure 5 describes the ion phase space (v_x, v_y) and (v_x, v_z) for (a) diffuse ions, (b) downstream thermalized ions, and (c) directly transmitted ions at $\Omega_i t = 130.82$. As in

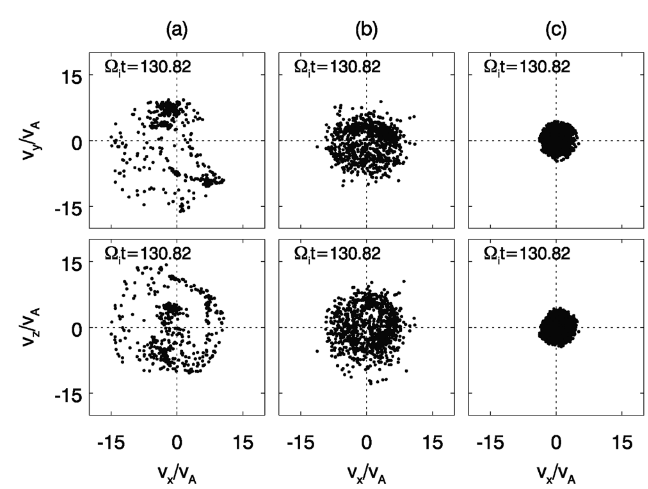

FIG. 5. The ion phase space (v_x, v_y) and (v_x, v_z) for (a) diffuse ions, (b) downstream thermalized ions, and (c) directly transmitted ions at $\Omega_i t = 130.82$.

Fig. 3, we follow the upstream ions which are located between $x = 1620c/\omega_{pi}$ and $x = 1684c/\omega_{pi}$ at $\Omega_i t = 116.22$. The diffuse ions have isotropic distribution, and they have higher energy than that of the downstream thermalized ions. These diffuse ions may be further accelerated by diffusive shock acceleration, while no obvious heating can be found in the ions, which directly transmit from the upstream to the downstream. The percentages of directly transmitted, downstream thermalized, and diffuse ions are about 92%, 7%, and 1%.

IV. CONCLUSIONS AND DISCUSSION

In this paper, by dividing the upstream ions into directly transmitted, downstream thermalized, and diffuse ions, we investigate ion dynamics in a supercritical quasi-parallel shock with 1D hybrid simulations. The shock reforms periodically, and the ion reflection occurs at the beginning of the reformation cycle. Part of the reflected ions can be trapped between the old and new shock fronts for an extended time period. Theses ions can escape to the upstream and form superthermal diffuse ions, which may be further accelerated by diffusive shock acceleration. The other reflected ions may return to the shock or trapped between the old and new shock fronts for a short time period, and form the thermalized ions in the downstream when the amplitude of the new shock front exceeds that of the old shock front. No noticeable heating can be found in the directly transmitted ions.

Scholer and Terasawa[15] found that in a supercritical quasi-parallel shock the reflected ions, together with the slow down incident ions, constitute the downstream thermalized distribution during the reformation of the shock. We further find that the dissipation of the shock is mainly provided by the reflected ions, which return to the shock immediately or are trapped between the old and new shock fronts for a short time period. They become downstream thermalized ions when the reformation cycle is finished. With ISEE 2 measurements, Gosling *et al.*[19] found that in addition to the superthermal diffuse ions, there are still two distinct populations downstream of quasi-parallel shocks: a cold core and a tenuous thermalized component. The thermalized component consists of about 10%–20% of the downstream ions. They also suggested that the core comes from directly transmitted solar wind ions, and the thermalized component is comprised of ions which are originally reflected by the shock. In our simulations, we divide the ion distributions into three components: directly transmitted, downstream thermalized, and diffuse ions. There is no obvious heating for the directly transmitted ions, and the downstream thermalized ions are reflected and then heated by the shock. The downstream thermalized ions contain about 7% of the total ions, and the dissipation of the shock is mainly provided by these ions. The results are consistent with the observations by Gosling *et al.*[19]

In our 1D simulations of the quasi-parallel shock, the Alfven Mach number is about 5.5, and the dissipation of the shock is provided by the downstream thermalized ions. Other dissipation mechanisms may also work, for example, the interface instability when the Alfven Mach number is sufficiently large ($M_A \geq 7$),[13,20] and the scattering of the turbulence, which is inhibited in 1D simulations. Their roles in the dissipation of a quasi-parallel shock are our future investigations.

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