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Acceleration of Energetic Ions by Oblique Magnetosonic Shock Waves

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Abstract

Enhanced acceleration of energetic ions by an oblique shock is studied by means of a fully relativistic, fully electromagnetic particle code with full ion and electron dynamics. It is found that some of the energetic ions that move with a shock can be accelerated many times. The acceleration takes place when the particle velocity becomes parallel to the transverse electric field in the shock.

Keywords:
particle acceleration, energetic particle, oblique shock wave

1. Introduction

Large-amplitude magnetosonic waves can accelerate some ions to high energies [1-9]. Their speeds can be comparable to or greater than the Alfvén speed. These results have been applied to solar physics to account for the prompt ion acceleration to relativistic energies, $10^9 \sim 10^{10}$eV [10]. In the present paper, we will examine the question; whether or not shock waves have mechanisms accelerating particles to higher energies. In fact, cosmic rays with much higher energies ($\lesssim 10^{20}$eV) are often observed and have been one of the most important issues in plasma physics and astrophysics.

In a turbulent plasma where nonlinear magnetosonic waves are present, high-energy ions that have been accelerated by a certain pulse will encounter many different magnetosonic pulses after the first acceleration. In the previous paper by Maruyama et al. [11], interactions of such high-energy ions with magnetosonic waves propagating perpendicular to a magnetic field were studied. They reported that some of the energetic ions can be further accelerated. The acceleration mechanism is quite different from that for thermal ions. Because the speeds of energetic ions are higher than the shock speed, they can go back to the upstream region by the gyro-motion after entering the shock region. They can gain energies when they are in the shock region and their velocities become nearly parallel to the transverse electric field formed in the magnetosonic shock. The maximum energy they can gain increases with increasing initial energy (energy before the encounter with the shock). It is to be noted that, for a perpendicular shock, they eventually move to the downstream region after these interactions.

In this paper, by using a particle simulation code, we study interactions of energetic ions with a magnetosonic shock wave propagating obliquely to a magnetic field. It will be found that some of the energetic ions can be further accelerated by the mechanism discussed in the previous paper [11]. A distinguish feature for the oblique shock is that it can trap some energetic ions; thus, the acceleration mechanism can operate many times on them.

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2. Effects of Parallel Motion

In a perpendicular shock, particles cannot move with a shock for a long time. In an oblique shock, however, some particles could move with a shock, by drifting along the field line. Let $v_{\|}$ be the velocity parallel to the magnetic field $\boldsymbol{B}$, θ the angle between the wave normal and $\boldsymbol{B}$, $v_{\rm sh}$ the shock speed, then the particles with

$$v_{\|} \cos\theta \sim v_{sh} \qquad (1)$$

can move with the shock. We will show by simulations that, of the ions that satisfy the above relation, some can gain energies many times from the shock; because they move with the shock, the acceleration mechanism discussed in Ref. [11] can work many times on each particle. They obtain energies when their velocities become parallel to the transverse electric field in the shock. Obviously, in perpendicular shocks, no particles satisfy the relation (1).

Even if the shock is oblique, very few ions would satisfy the relation (1) if there are no energetic ions; because usually the shock speed is much greater than the ion thermal speed, $v_{\rm sh} \gg v_{\rm Ti}$. However, if there are energetic ions in a plasma, we will have an appreciable number of ions that can move with a shock wave, holding the relation (1). Accordingly, this acceleration mechanism can take place in oblique shocks in a plasma having nonthermal energetic ions.

The gyro-radii of energetic ions are supposed to be greater than the shock width (or the pulse width). Thus, the field quantities can significantly change within the gyro-radii. The quantities θ and $v_{\|}$ at the position of each particle will vary with time as it gyrates. The relation (1) should therefore be interpreted as an average over a gyration.

3. Simulation

We use a one-dimensional (one space coordinate and three velocity components), relativistic, electromagnetic, particle simulation code with full ion and electron dynamics. The system length is $L_x = 4096\ \Delta_{\rm g}$, where $\Delta_{\rm g}$ is the grid spacing. The system is bounded [3,12]; the particles are confined in the region $100 < x/\Delta_{\rm g} < 3996$, being specularly reflected at $x/\Delta_{\rm g} = 100$ and $x/\Delta_{\rm g} = 3996$. The total number of electrons is $N_{\rm e} = 288{,}000$. As space plasmas, the code contains (majority) hydrogen ions with mass $m_{\rm H}$ and charge $q_{\rm H}$ and (minority) helium ions with mass $m_{\rm He}$ and charge $q_{\rm He}$. The mass density of He ions is taken to be 40 percent of that of H ions. The ion-to-electron mass ratio is $m_{\rm H}/m_{\rm e} = 50$. The electron cyclotron frequency in the upstream region is $\omega_{\rm ce}/\omega_{\rm pe} = 1.5$, where $\omega_{\rm pe}$ is the spatially averaged plasma frquency. The Alfvén speed is $v_{\rm A}/c = 0.196$, where c is the speed of light. Even though the code has a small number of He ions as well as H ions, the orbits shown in this paper will be those of H ions. (The orbits of energetic He ions are similar to those of H ions.) More detailed description of the simulation method can be found in Ref. [11].

Initially we have energetic ions as well thermal ions. In the upstream region, the thermal ions and electrons have Maxwellian distribution functions, which are uniform in space. The energetic ions have an isotropic distribution function such that $f(\gamma) = n_{\rm en}\delta(\gamma - \gamma_0)$, where γ is the Lorentz factor and γ_0 is the initial value. We excite a shock wave in an external magnetic field $\boldsymbol{B}_0 = (B_{x0}, 0, B_{z0})$. It propagates in the positive x direction; thus the x component of the magnetic field is constant, while the y and z components vary with time and space. In the following, we will show a case with the propagation angle $\theta = 60°$; that is, $B_{z0}/B_{x0} = \tan 60°$.

Figure 1 displays profiles of the transverse electric field E_y in a shock at various times. The propagation speed is $v_{\rm sh} = 1.92\ v_{\rm A}$. We also show there a phase space plot (x, γ) of energetic ions. Initially, they are uniformly distributed in space with $\gamma_0 = 2.0$. Here, the ions that were in the region $363 < x/(c/\omega_{\rm pe}) < 447$ at $t = 0$ are shown; they expand in space because of the gyro-motion. We find especially high-energy ions near the shock wave. The maximum value of γ increases with time.

We show in Fig. 2 time variations of the position x (upper panel) and energy γ (lower panel) of an energetic ion that is accelerated three times. The position of the shock front is represented by the dotted line; the upstream region is above this line. After the encounter with the shock, the particle moves with the shock. The energy γ increases rapidly when the particle enter the shock region for the first time. It then goes out to the upstream region; after a while it enters the shock region again, and the energy increases. The acceleration is repeated. The simulation was terminated before this process is finished, because the shock wave nearly reached the plasma boundary. If the system length is longer, then this process would have continued for a longer time.

It is important to note that, when the particle is in the upstream region, the average velocity in the x direction is obviously smaller than the shock speed. The velocity v_x is increased when it encounters the shock. It is caused by the change in the magnetic field, which will be briefly discussed in the next section.

4. Summary and Discussion

We have studied interactions with energetic ions and an oblique shock wave by means of particle simulations. It is found that some energetic ions can move with a shock and can be accelerated many times by the transverse electric field in the shock. The present result indicates that, once particles have high energies, they can be further accelerated many times by other magnetosonic waves. Its mechanism is different from the one for thermal ions.

Even if the initial parallel velocity is smaller than that given by Eq. (1), some particles can move with the shock. It is because $v_{\parallel}$ of energetic ions can be increased upon the collision with the shock. To see this, we assume that, for simplicity, we have magnetic field and particle orbit shown in Fig. 3. Then, the change in the magnetic field along the particle orbit would be given by

$$\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t} = (\boldsymbol{B}_1 - \boldsymbol{B}_0)\,[\,\delta(t - t_{\mathrm{in}}) - \delta(t - t_{\mathrm{out}})\,], \qquad (2)$$

where $\boldsymbol{B}_0$ and $\boldsymbol{B}_1$ are the magnetic fields in the upstream and shock regions, respectively. The particle is supposed to enter the shock region at $t = t_{\mathrm{in}}$ and return to the upstream region at $t = t_{\mathrm{out}}$. Further, in the following equation

$$\frac{\mathrm{d}(\boldsymbol{B}\cdot\boldsymbol{p})}{\mathrm{d}t} = \boldsymbol{B}\cdot\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} + \boldsymbol{p}\cdot\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}, \qquad (3)$$

we may neglect the first term on the right-hand side, if the Lorentz force is greater than the electric force (this is the case for energetic particles). Then, integrating Eq. (3), we find that, after returning to the upstream region, the parallel momentum is increased by an amount

$$\delta p_{\parallel} = [\boldsymbol{p}_{\perp}(t_{\mathrm{out}}) - \boldsymbol{p}_{\perp}(t_{\mathrm{in}})\,]\cdot \boldsymbol{B}_0 / B_0 \qquad (4)$$

Here, $\boldsymbol{p}_{\perp}$ denotes the momentum perpendicular to $\boldsymbol{B}_1$. One can readily see from Fig. 3 that the right-hand side is always positive; thus, $\delta p_{\parallel} > 0$. This effect will make it easier for shock waves to trap some ions. At the same time, it may act as a detrapping mechanism; thus it may put the upper limit of the maximum energy of those trapped ions. If $c\cos\theta \sim v_{\mathrm{sh}}$, however, relativistic particles with $v_{\parallel} \simeq c$ would not be quickly detrapped.

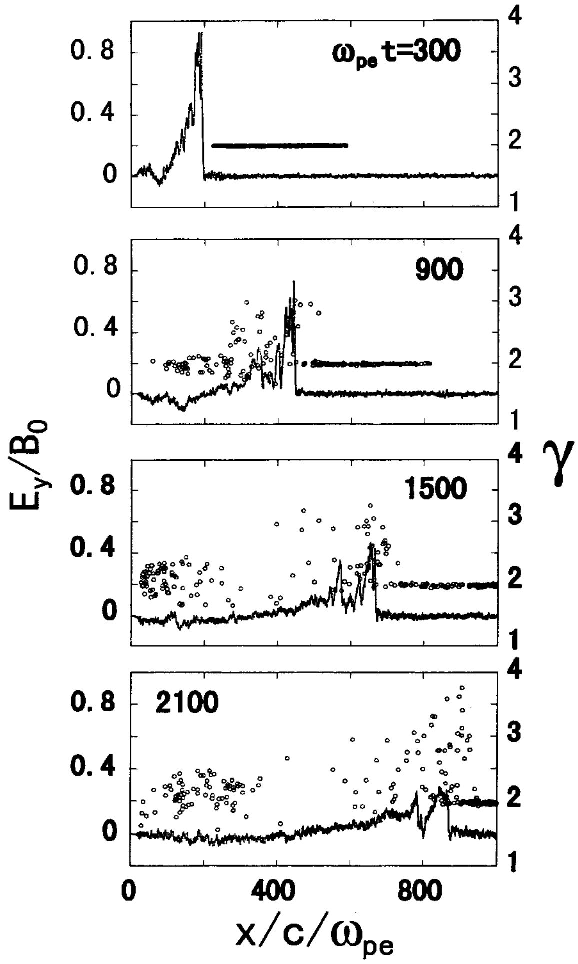

Fig. 1 Profiles of transverse electric field E_y and phase space plots (x, γ) of energetic ions. The dots represents energetic ions.

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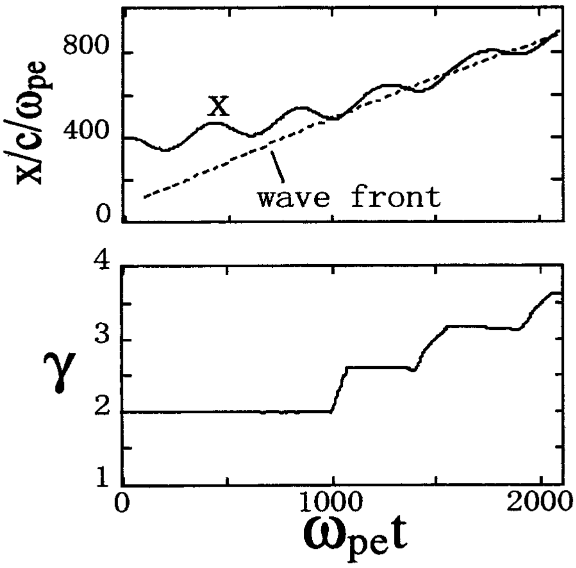

Fig. 2 Time variations of the x position of an accelerated energetic ion (solid line in the upper panel) and the Lorentz factor γ (lower panel). In the upper panel the x position of the shock front is also shown by the dotted line.

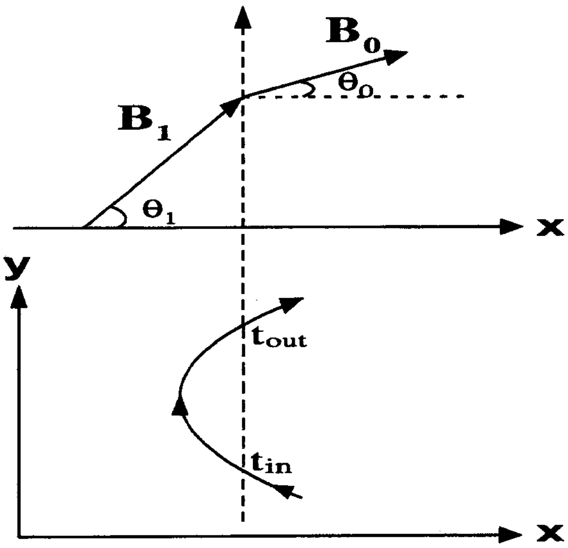

Fig. 3 Schematic diagram of magnetic field and particle orbit. Here, $\boldsymbol{B}_0$ and $\boldsymbol{B}_1$ are constant. An energetic ion enters the shock region at $t = t_{in}$ and goes out at $t = t_{out}$.

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