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Incessant Shock Acceleration of Fast Ions Enhanced by Relativistic Effects

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Abstract

Interactions between nonthermal fast ions and an oblique shock wave are studied theoretically and numerically. Some of the fast ions can be repeatedly accelerated; owing to the relativistic effect that the particle velocity is limited by the speed of light c while the momentum can grow indefinitely, this acceleration is particularly enhanced when the shock speed v_{sh} and propagation angle θ_0 satisfy the relation $v_{sh} \sim c \cos\theta_0$. A total of 5000 fast ions with their initial Lorentz factors $\gamma = 4$ are followed with test particle simulations to study the evolution of their momentum and energy distributions. Some ions obtain energies greater than $\gamma \sim 100$.

Keywords:

particle acceleration, shock wave, ultrarelativistic ions, cosmic rays

1. Introduction

It has been long known that high-energy particles are produced in various astrophysical plasmas. In association with solar flares, ions can be accelerated up to $10^9 \sim 10^{10}$ eV and electrons to $10^7 \sim 10^8$ eV [1,2]. In supernova remnants, electrons with ~ 100 TeV are produced [3-5]. The observed highest energy of cosmic rays is ~ 10^{20} eV [6].

Particle simulations have shown that magnetosonic shock waves can accelerate particles with various nonstochastic mechanisms [7-20]. Quite recently, interactions of fast particles and shock waves have also been studied with theory, particle simulations, and test particle simulations [21-26]. It has been shown that fast ions can be incessantly accelerated to ultrarelativistic energies. Under certain conditions, owing to the relativistic effect, fast particles can move with the shock wave for long periods of time, and the acceleration is particularly enhanced [24-26]. In this paper, we study this acceleration mechanism. In Sec. **2**, we theoretically discuss this mechanism and derive the energy increase rate of a particle accelerated by this process. In Sec. **3**, with test particle simulations, we follow trajectories of 5000 fast ions and show how their momentum and energy distributions evolve. Section **4** gives a summary of our work.

2. Theory

We assume that a shock wave propagates in the x direction with a speed v_{sh} in an external magentic field $\boldsymbol{B}_0 = B_0(\cos\theta_0,\ 0,\ \sin\theta_0)$, where the subscript 0 indicates the upstream quantities.

We consider an energetic particle that enters the shock wave from the upstream region. Its speed is assumed to be faster than v_{sh}; hence, its gyro-radius is greater than the width of the shock transition region. This particle can return to the upstream region owing to the gyro-motion. Then, it gains energy from the transverse electric field E_y because it moves nearly parallel to E_y when it is in the shock region. Taking the scalar product of the relativistic equation of motion with the momentum $\boldsymbol{p}$, we readily obtain

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{p^2}{2}\right) = q_i \boldsymbol{p} \cdot \boldsymbol{E}, \tag{1}$$

where, q_i is the ion charge. We suppose that the particle enters the shock wave at $t = t_{in}$ and goes out to the upstream region at $t = t_{out}$. Then, integrating this equation along the unperturbed orbit from $t = t_{in}$ to t_{out}, we find the increase in the Lorentz factor as

$$\delta\gamma = \frac{2 q_i p_{1\perp} E_y}{(m_i c)^2 \Omega_{i1}} \sin\left(\frac{\Omega_{i1}(t_{\mathrm{out}} - t_{\mathrm{in}})}{2\gamma}\right), \tag{2}$$

where $p_\perp$ is the momentum perpendicular to $\boldsymbol{B}$, m_i is the ion rest mass, Ω_i is the ion gyro-frequency, and the subscript 1 denotes the quantities right behind the transition region. Here, we have neglected the electric field parallel to the magnetic field $E_\parallel$, which is weak in magnetohydrodynamic waves.

Time-averaged particle velocity in the x direction is given by $\langle v_x \rangle \simeq v_{0\parallel} \cos\theta_0$, where $v_{0\parallel}$ is the velocity along $\boldsymbol{B}_0$. Hence,

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a fast particle with

$$v_{0\|}\cos\theta_0 \simeq v_{sh} , \tag{3}$$

can move with the shock wave for some period of time. However, as the particle crosses the shock front, its $p_{\|}$ increases owing to the magnetic structure [22-26]. The particle therefore escapes from the shock wave to the upstream region. However, for a shock wave with

$$v_{sh} \sim c\cos\theta_0 , \tag{4}$$

fast ions cannot quickly go away ahead of the shock wave, because the particle speed is limited by the speed of light c. Hence, the acceleration processes can be repeated many times. For a fast particle barely entering the shock wave, the time period in which it is in the shock wave is quite short, $t_{out} - t_{in} \ll 2\pi\gamma/\Omega_{i0}$. Accordingly, its gyro-period is approximately given by $2\pi\gamma/\Omega_{i0}$. The fast ion suffers an energy jump (2) in each gyro-period. The energy increase rate average over relativistic gyro-period is therefore given as

$$\frac{1}{\Omega_{i0}}\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{g}{\pi}\frac{v_{sh}}{c}, \tag{5}$$

where g is a numerical factor smaller than unity. Here, we have eliminated E_y using the relation $E_y = (v_{sh}/c)(B_{z1} - B_{z0})$, which results from Faraday's law. Equation (5) indicates that γ linearly grows with time, if the time dependence of g is weak.

3. Simulation

To study long-time behavior of fast ions incessantly accelerated by an oblique shock wave, we have carried out test particle simulations [25,26]. In this method, we obtain the electric and magnetic fields of a shock wave from one-dimensional, relativistic, electromagnetic particle simulations. Then, assuming that the shock wave propagates steadily, we follow long-time trajectories of energetic particles in these fields.

The parameters of the particle simulation were as follows. The total system length was $L_x = 8192\Delta_g$, where Δ_g is the grid spacing. The total number of electrons was N_e = 576000. As space plasmas, the code contained helium ions as well as hydrogen ions, and the helium number density was 10 % of the hydrogen density. The ion-to-electron mass ratios were $m_H/m_e = 50$ and $m_{He}/m_e = 200$. The ratio of the electron gyro-frequency to the plasma frequency was $|\Omega_{e0}|/\omega_{pe} = 1.5$ in the upstream region. The Alfvén speed is thus $v_A/c = 0.20$, where v_A is defined using the mass density in the H-He plasma. The electron skin depth was $c/(\omega_{pe}\Delta_g) = 4$. The external magnetic field was in the (x, z) plane with $\theta_0 = 61°$. The time step was $\omega_{pe}\Delta t = 0.05$. We then excited a shock wave with $v_{sh} = 2.4v_A$, which is close to $c\cos\theta_0$. The profiles of B_z and E_y in this wave are shown in Fig. 1.

Using the wave fields propagating with the speed v_{sh}, we followed the trajectories of test energetic hydrogen ions which are initially in the upstream region. The number of these particles was N = 5000, and their initial energy was

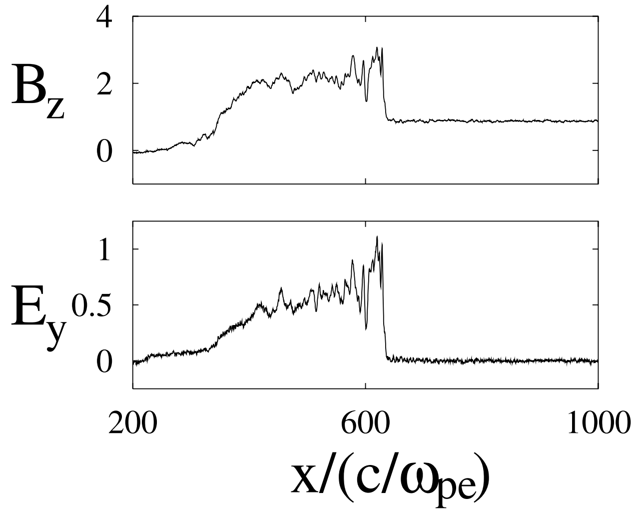

Fig. 1 Profiles of B_z and E_y in an oblique shock wave.

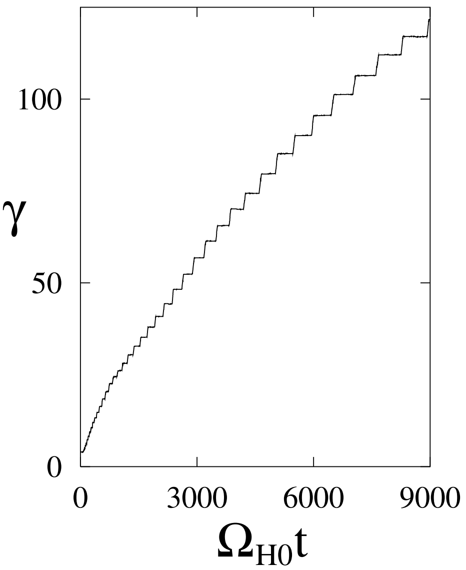

Fig. 2 Stepwise increase in γ of an incessantly accelerated fast ion.

taken to be $\gamma_0 = 4$; their initial energy distribution was $f(\gamma) = N\delta(\gamma - \gamma_0)$ with an isotropic momentum distribution. The plasma parameters were the same as those in the particle simulation.

Figure 2 shows time variation of γ of an incessantly accelerated ion. The energy increased stepwise from $\gamma_0 = 4$ to $\gamma_0 = 120$; when the calculation was terminated at $\Omega_{H0}t = 9000$, the acceleration was not finished.

Figure 3 displays energy distribution functions at $\Omega_{H0}t$ = 0 and at $\Omega_{H0}t = 9000$. By $\Omega_{H0}t = 9000$, 3.4 % of the fast ions have been accelerated to energies higher than $\gamma = 50$. The maximum energy is $\gamma \simeq 130$.

Figure 4 shows time evolution in the momentum space $(p_{\|}, p_{\perp})$. Since the initial particle energies are the same, γ_0 = 4, all the particles are on the half circle in the $(p_{\|}, p_{\perp})$ plane at $\Omega_{H0}t = 0$. We see from the lower panel ($\Omega_{H0}t = 9000$) that

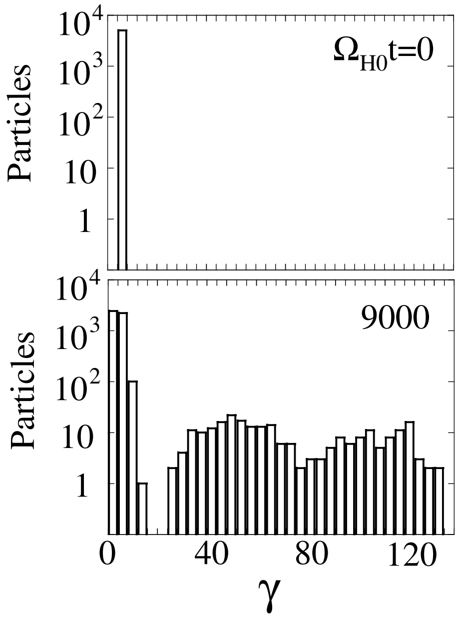

Fig. 3 Stepwise increase in γ of an incessantly accelerated fast ion.

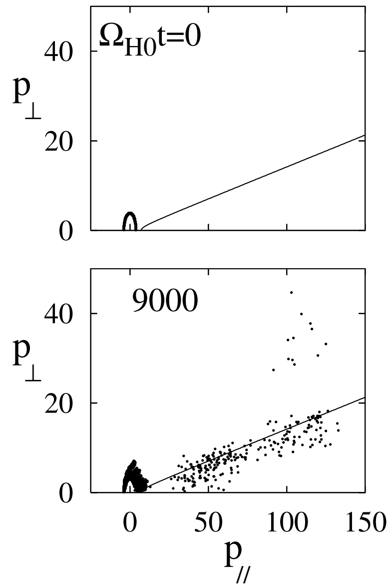

Fig. 4 Evolution of particles in the momentum space. Particles spread along the line $v_{0\|} = v_{sh}/\cos\theta_0$.

the particle distribution spreads along the line $v_{0\|} = v_{sh}/\cos\theta_0$, which is hyperbola in the $(p_\|, p_\perp)$ plane. Some particles have quite large $p_\perp$ at $\Omega_{H0}t = 9000$. They are in the shock wave at this moment.

Figure 5 shows the time variation of the total energy of these particles. Even around $\Omega_{H0}t = 9000$, it is increasing steadily.

4. Summary

We have studied the interactions between fast ions and oblique shock waves. When the shock propagation speed is $v_{sh} \sim c \cos\theta_0$, some fast ions are incessantly accelerated to ultrarelativistic energies. The energy increase rate for these particles was theoretically obtained. The evolution of 5000 fast particles was also investigated with test particle simulations. The acceleration mechanism discussed in this paper could be important around pulsars where the magnetic fields are strong.

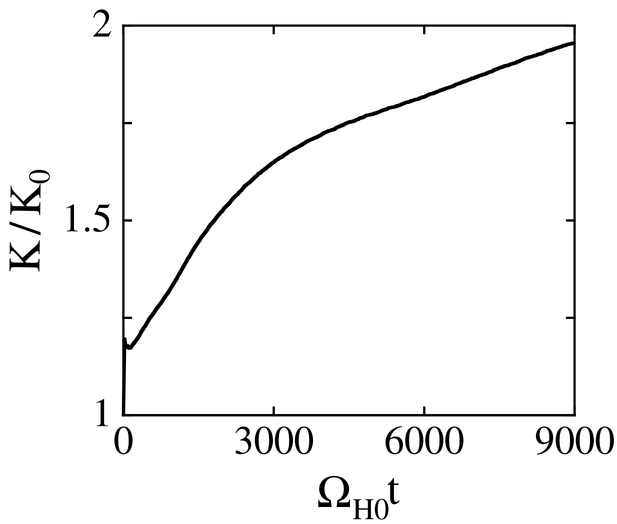

Fig. 5 Time variation of total energy K of a set of 5000 fast ions. Here, K_0 is the initial energy.

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