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Effects of multi-dimensional electromagnetic fluctuations on ion reflection by an oblique shock wave
斜め衝撃波によるイオンの反射における多次元電磁揺動の効果

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The evolution of a large number of ions in a shock wave propagating obliquely to an external magnetic field is studied with a 2D (two space coordinates and three velocities) relativistic, electromagnetic particle code with full ion and electron dynamics. Furthermore, the motions of the same number of test ions in the electromagnetic fields averaged along the shock front are calculated. A comparison of the two groups of ions shows that 2D electromagnetic fluctuations, which are excited by the trapped electrons in the shock wave, enhance the reflection of ions from the shock front.

1. Introduction

Particle simulations have shown [1] that a magnetosonic shock wave propagating obliquely to an external magnetic field can trap some electrons and accelerate them to ultrarelativistic energies when an external magnetic field is strong such that $|\Omega_e|/\omega_{pe} > 1$ and the propagation speed of the shock wave v_{sh} is close to $c\cos\theta$, where Ω_e and ω_{pe} are the electron gyro and plasma frequencies, respectively, c is the speed of light and θ is the propagation angle of the shock wave. In such a wave, some electrons can be reflected near the end of the main pulse of a shock wave. Here, "main pulse" designates the first leading pulse in a shock wave. The reflected electrons are then trapped in the main pulse and are accelerated [1].

The one-dimensional (1D) particle simulation showed that once electrons get trapped, they cannot readily escape from the main pulse [2]. However, the two-dimensional (2D) simulation demonstrated that some electrons can be detrapped from it and can subsequently accelerated to the higher energies because of their gyromotions [3]. The detrapping is caused by the 2D electromagnetic fluctuations along the shock front, which are excited by the trapped electrons via interactions with whistler waves and grow to large amplitudes as a result of nonlinear development of the instabilities [4].

Because the 2D fluctuations excited by trapped electrons have large amplitudes near the shock front, they should significantly influence ion motion. It is well known that some ions can be accelerated through the reflection from the shock front [5]. We study the effects of the 2D fluctuations on ion reflection with 2D electromagnetic particle simulations and test particle calculations.

2. Condition for ion reflection

We consider a magnetosonic shock wave propagating in the x direction with a constant speed v_{sh} in the external magnetic field in the (x,z) plane $\boldsymbol{B}_0 = B_0(\cos\theta, 0, \sin\theta)$. We assume that electromagnetic fields vary along the x and y directions and write the electric and magnetic fields as

$$\begin{aligned} \boldsymbol{E}(x,y,t) &= \bar{\boldsymbol{E}}(x,t) + \delta\boldsymbol{E}(x,y,t), \\ \boldsymbol{B}(x,y,t) &= \bar{\boldsymbol{B}}(x,t) + \delta\boldsymbol{B}(x,y,t), \end{aligned} \tag{1}$$

where $\bar{\boldsymbol{E}}$ and $\bar{\boldsymbol{B}}$ are y-averaged $\boldsymbol{E}$ and $\boldsymbol{B}$, which we call 1D averaged fields. We call $\delta\boldsymbol{E}$ and $\delta\boldsymbol{B}$ 2D fluctuations.

In order to analytically obtain the condition for the ion reflection, we use a simple model that $\boldsymbol{E}$ and $\boldsymbol{B}$ in the shock transition region do not depend on x and t in the wave frame. As for the 2D fluctuations, we neglect the variation of $\delta\boldsymbol{E}$ and $\delta\boldsymbol{B}$ due to the change in y along the ion orbit in the shock transition region, which is consistent with the simulation results. Thus, we assume that ions feel the constant electromagnetic fields in the shock transition region, although the values of $\boldsymbol{E}$ and $\boldsymbol{B}$ depend on the position y at which ions enter the shock transition region. Then, we can obtain the condition for the ion reflection as

$$\tilde{v}_x > v_{ref}(y), \tag{2}$$

where $\tilde{v}_x$ is the ion velocity in the laboratory frame. The critical velocity for the ion reflection is defined as

$$v_{ref}(y) = \bar{v}_{ref} + \delta v_{ref}(y), \tag{3}$$

which depends on y. Here, $\bar{v}_{ref}$ and δv_{ref} are

$$\bar{v}_{ref} = v_{sh} - \sqrt{\frac{2q\bar{E}_x\Delta}{m}}\left(1 + \frac{v_{sh}^4}{8c^4}\frac{\bar{B}^4}{\bar{E}_x^4}\right), \tag{4}$$

$$\delta v_{ref}(y) = \frac{\partial v_{ref}}{\partial \bar{\boldsymbol{E}}} \cdot \delta\boldsymbol{E}(y) + \frac{\partial v_{ref}}{\partial \bar{\boldsymbol{B}}} \cdot \delta\boldsymbol{B}(y). \tag{5}$$

As v_{ref} decreases, the fraction of reflected ions increases.

3. Simulation

We carry out 2D (two space coordinates and three velocities), relativistic, electromagnetic particle simulations with full ion and electron dynamics. We simulate an oblique shock wave with $v_{sh} \simeq 0.95 \cos\theta$ in the external magnetic field with $\Omega_e/\omega_{pe} = 5$ and $\theta = 54°$. The total number of the simulation particles is $N \simeq 1.1 \times 10^9$. We follow the motions of 2.1×10^6 ions in the 2D simulation and call the ions the 2Ds ones. We also compute the test ion orbits in the 1D averaged fields, $\bar{\boldsymbol{E}}$ and $\bar{\boldsymbol{B}}$. We call the test ions as the 1Dt ions. The numbers of the 1Dt ions is the same as that of the 2Ds ions. The initial positions and velocities of the 1Dt ions are exactly the same as those of the 2Ds ions. A comparison between the two groups of ions elucidates the effects of the 2D fluctuations on ion motion.

Figure 1 (a) shows the x-profiles of $\bar{B}_z$ (black line), σ_B (blue line) and σ_E (red line) at $\omega_{pe}t = 520$, where σ_B and σ_E are the amplitude of $\delta\boldsymbol{E}$ and $\delta\boldsymbol{B}$ averaged over y. The phase spaces (x, v_x) of 2Ds ions and 1Dt ions are shown in Fig. 1 (b) and (c), respectively. The ions with $v_x > v_{sh}$ in the region $x > x_m$ are reflected from the shock front. The fraction of such particles in the 2Ds ions is almost equal to that in the 1Dt ions. This is because, at $\omega_{pe}t = 520$, the amplitudes of the 2D fluctuations, σ_B and σ_E, are small in the shock transition region, although they are large near the end of the main pulse.

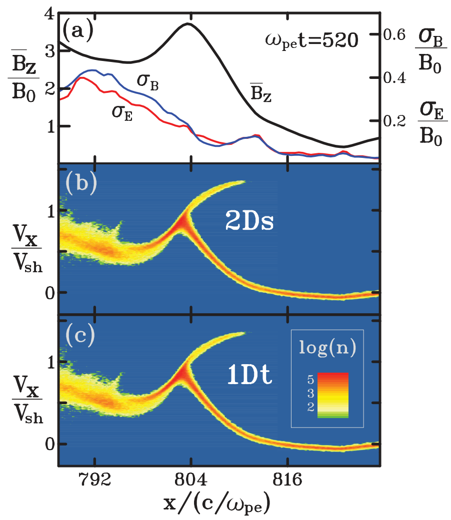

Fig. 1 Electromagnetic fields and ion phase space (x, v_x) at $\omega_{pe}t = 520$.

Figure 2 shows the same as Fig. 1 except at $\omega_{pe}t = 920$. Unlike at $\omega_{pe}t = 520$, the 2D fluctuations have large amplitudes near the center of the main pulse at $\omega_{pe}t = 920$. Because of these 2D fluctuations, there is a clear difference between the 1Dt and 2Ds ions. Some 2Ds ions are reflected from the shock front, whereas few 1Dt ions are.

According to eqs. (2)-(5), the ion reflection is enhanced as δE_x and δB increase. We observe δE_x and δB that the 2Ds ions felt before the reflection during the period from $\omega_{pe}t = 1000$ to 2000. Figure 3 shows the distributions of reflected 2Ds ions as functions of δE_x and δB, where the

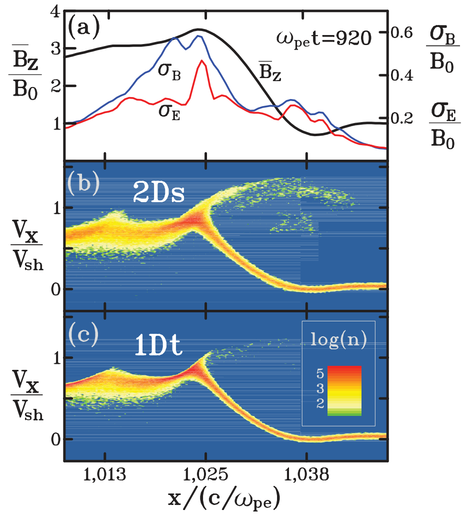

Fig. 2 The same as Fig. 1 except at $\omega_{pe}t = 920$.

values of δE_x and δB are averaged over the period from the time when the ions enter the shock transition region to the time when the ions are reflected. This figure confirms that many reflected ions felt the positive δE_x or the positive δB before the reflection.

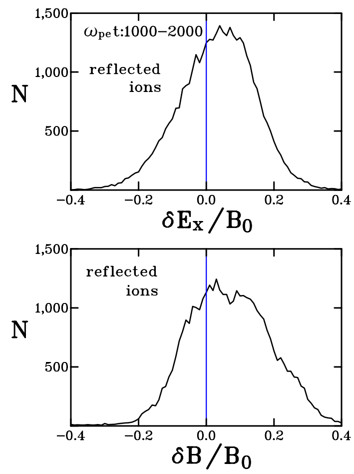

Fig. 3 Distribution of reflected ions as functions of δE_x and δB.

4. Summary

We have studied ion motion in an oblique shock wave with spatial attention to the effects of the 2D fluctuations excited by trapped electrons. The 2D particle simulations and test particle calculations demonstrated that the 2D fluctuations can enhance the fraction of reflected ions.

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