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Electron trapping and ion reflection by an oblique shock wave
斜め衝撃波による電子の捕捉とイオンの反射

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A magnetosonic shock wave propagating obliquely to an external magnetic field can trap some electrons and accelerate them to ultrarelativistic energies. The trapped electrons excite two-dimensional (2D) electromagnetic fluctuations with finite wavenumbers along the shock front. We study effects of the trapped electrons on ion motions through the 2D fluctuations. It is analytically shown that the fraction of ions reflected from the shock front is enhanced by the 2D fluctuations. This is confirmed by 2D (two space coordinates and there velocities) relativistic, electromagnetic particle simulations with full ion and electron dynamics and calculations of test ions in the electromagnetic fields averaged along the shock front.

1. Introduction

Electromagnetic particle simulations with full ion and electron dynamics have shown that a large-amplitude magnetosonic shock wave can promptly accelerate ions and electrons with different nonstochastic mechanisms caused by strong electromageitc field near the shock front [1]. In a magnetosonic shock wave, the electric potential and the magnetic field strength rapidly rise in the shock transition region. This can reflect some ions from the shock front and accelerated them. Electrons are accelerated by a different mechanism. A magnetosonic shock wave propagating obliquely to an external magnetic field with $|\Omega_e|/\omega_{pe} > 1$ can trap some electrons and accelerate them to ultrarelativistic energies when 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. They are then trapped in the main pulse and are accelerated by the strong electric field there [2].

The trapped electrons can significantly influence electromagnetic fields in a shock wave because the number of trapped electrons continually increases with time. In the 1D simulation [3], the trapped electrons strengthen the electric field parallel to the magnetic field, which can cause the electron deep trapping in the main pulse; once electrons get trapped, they cannot readily escape from the main pulse. In the 2D case, the trapped electrons excite the instabilities through the interaction with whistler waves with finite wavenumbers along the shock front [4]. As a result of the nonlinear development of the instabilities, the 2D electromagnetic fluctuations along the shock front grow to large amplitudes. It was demonstrated that the 2D electromagnetic fluctuations can cause detrapping of energetic electrons from the main pulse and subsequent acceleration to much higher energies [5].

In the above works, interactions between the reflected ions and the trapped electrons were not investigated. In a low beta plasma with $|\Omega_e|/\omega_{pe} > 1$, the fraction of the reflected ions is quite small. Therefore, the effects of reflected ions on electromagnetic fields in a shock wave would be small, compared to those of trapped electrons that can stay near the shock front for a long period of time. In fact, the 2D simulations showed that the amplitudes of instabilities excited by the reflected ions in the upstream region are much smaller than those by the trapped electrons in the main pulse region. In this paper, we study the effects of trapped electrons on ion reflection using theory and simulations.

2. Physical consideration 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

$$\boldsymbol{E}(x,y,t) = \bar{\boldsymbol{E}}(x,t) + \delta\boldsymbol{E}(x,y,t),$$
$$\boldsymbol{B}(x,y,t) = \bar{\boldsymbol{B}}(x,t) + \delta\boldsymbol{B}(x,y,t), \quad (1)$$

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.

Using a simple model that $\boldsymbol{E}$ and $\boldsymbol{B}$ do not depend on x and t in the shock transition region, we can approximately write the fraction of the reflected ions as

$$n_{ref}(y)/n_0 = \mathrm{erfc}[v_{ref}/(\sqrt{2}v_{Ti})], \quad (2)$$

where the complementary error function is defined as

$$\mathrm{erfc(p)} = (2/\sqrt{\pi})\int_p^\infty dt\,\exp(-t^2). \quad (3)$$

The critical velocity for the ion reflection v_{ref} is given by

$$v_{ref}(y) = \bar{v}_{ref} + \delta v_{ref}(y), \quad (4)$$

with

$$\bar{v}_{\rm ref} = v_{\rm sh} - \sqrt{\frac{2q\bar{E}_x\Delta}{m}}\left(1 + \frac{v_{\rm sh}^4}{8c^4}\frac{\bar{B}^4}{\bar{E}_x^4}\right), \qquad (5)$$

$$\delta v_{ref}(y) = \frac{\partial v_{ref}}{\partial \bar{\boldsymbol{E}}}\cdot\delta\boldsymbol{E}(y) + \frac{\partial v_{ref}}{\partial \boldsymbol{B}}\cdot\delta\boldsymbol{B}(y). \qquad (6)$$

We introduce the fraction of reflected ions in the 1D averaged field as $\bar{n}_{\rm ref}/n_0$. We then write the y-averaged value of n_{ref}/n_0 as

$$\langle n_{\rm ref}/n_0\rangle = \bar{n}_{\rm ref}/n_0 + \langle\delta n_{\rm ref}/n_0\rangle. \qquad (7)$$

Although the y-averaged $\delta v_{\rm ref}$ is zero, the y-averaged $\delta n_{\rm ref}$, $\langle\delta n_{\rm ref}\rangle$, is positive. When $\delta v_{\rm ref}$ can be written as

$$\delta v_{\rm ref} = \delta v_1\cos(k_y y + \alpha_y), \qquad (8)$$

where δv_1, k_y and α_y are constants, $\langle\delta n_{ref}/n_0\rangle$ can be approximated as

$$\left\langle\frac{\delta n_{ref}}{n_0}\right\rangle \simeq \frac{\bar{v}_{ref}}{2\sqrt{2\pi}v_{Ti}^3}\exp\left(-\frac{\bar{v}_{ref}^2}{2v_{Ti}^2}\right)|\delta v_r|^2 > 0. \qquad (9)$$

The equations (7) and (9) lead

$$\langle n_{ref}/n_0\rangle > \bar{n}_{ref}/n_0. \qquad (10)$$

The fraction of reflected ions in the 2D electromagnetic fields becomes greater than that in the 1D averaged fields, $\bar{\boldsymbol{E}}$ and $\bar{\boldsymbol{B}}$. Their difference increases as the amplitudes of the 2D fluctuations $\delta\boldsymbol{E}$ and $\delta\boldsymbol{B}$ in the shock transition region increase.

3. Simulation

We simulate an oblique shock wave using a 2D (two space coordinates and three velocities), relativistic, electromagnetic particle code with full ion and electron dynamics. We set $v_{\rm sh} = 0.95\cos\theta$, $\theta = 54°$, and $\Omega_{\rm e}/\omega_{\rm pe} = 5.0$. The shock wave traps some electrons and accelerates them. These electrons excite the 2D electromagnetic fluctuations. The total number of the simulation particles is $N \simeq 1.1\times10^9$. We follow the motions of 2.1×10^6 ions in the 2D simulation. We also compute the same number of test ion orbits in the 1D averaged field $\bar{\boldsymbol{E}}$ and $\bar{\boldsymbol{B}}$ obtained by the 2D simulation. The fraction of the reflected ions in the 2D simulation is $\langle n_{\rm ref}/n_0\rangle$, whereas that in the test particle calculation is $\bar{n}_{\rm ref}/n_0$.

Figure 13 shows the time evolution of electromagnetic fields and ion reflection. The maximum value of $\bar{B}_z$ (a), the fractions of reflected ions $\langle n_{ref}/n_0\rangle$ and of reflected test ions $\bar{n}_{ref}/n_0$ (the red and blue lines in (b), respectively), and the magnitude of the 2D fluctuations, $|\sigma_B|_{\rm st} + |\sigma_E|_{\rm st}$, averaged over the shock transition region (c) are plotted. Here, $|\sigma_B|_{\rm st}$ and $|\sigma_E|_{\rm st}$ are defined by

$$|\sigma_B|_{st} = \frac{1}{\Delta L_y}\sum_{j=x,y,z}\int_{x_m}^{x_m+\Delta}\int_0^{L_y} dy|\delta B_j(x,y,t)|, \qquad (11)$$

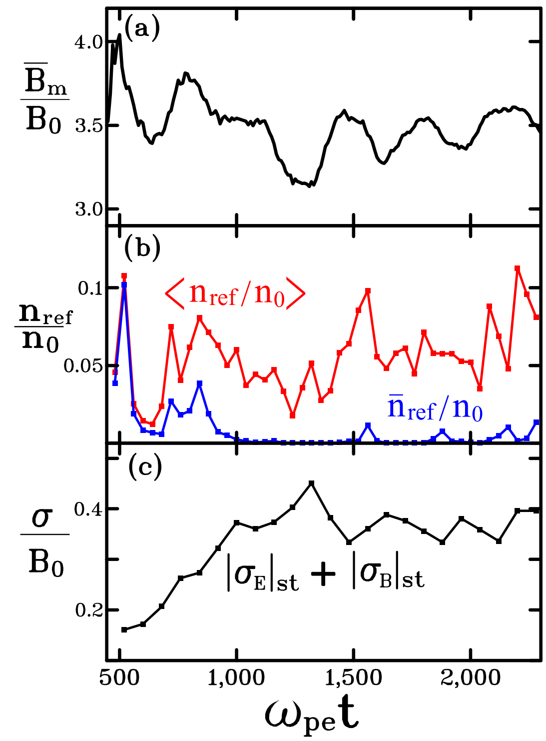

Fig. 1 Time variations of $\bar{B}_{\rm m}$, $\langle n_{\rm ref}/n_0\rangle$, $\bar{n}_{\rm ref}/n_0$, and $|\sigma_E|_{\rm st}+|\sigma_B|_{\rm st}$.

$$|\sigma_E|_{st} = \frac{1}{\Delta L_y}\sum_{j=x,y,z}\int_{x_m}^{x_m+\Delta}\int_0^{L_y} dy|\delta E_j(x,y,t)|, \qquad (12)$$

where x_m is the center of the main pulse and Δ is the width of the shock transition region. In the early stage $\omega_{\rm pe}t < 700$, $\langle n_{ref}/n_0\rangle$ is almost equal to $\bar{n}_{ref}/n_0$. However, after $\omega_{\rm pe}t > 700$, the former is much greater than the latter. The time evolution of their difference is similar to $|\sigma_B|_{\rm st} + |\sigma_E|_{\rm st}$, indicating that as the amplitudes of the 2D fluctuations become large, the ion reflection is enhanced. (More strictly, as suggested by eqs. (5) and (9), $\langle\delta n_{\rm ref}/n_0\rangle$ may depend on $\bar{B}_m$.)

4. Summary and Discussion

We have studied ion reflection by an oblique shock wave in which some electrons are trapped and excite 2D electromagnetic fluctuations. It is analytically shown that the fraction of the reflected ions in the 2D shock wave is greater than that in the 1D averaged fields. This is confirmed by the 2D particle simulations and test particle calculations. In the presentation, we will also show the difference between the 2D and 1D particles simulations.

References

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