§10. Effects of Multi-dimensional Electromagnetic fluctuations on Energetic Particles in Magnetosonic Shock Waves

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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 electromagnetic fields in the shock wave [1]. For example, some ions are accelerated via reflection by magnetic and electrostatic fields at the shock front. The energies of reflected ions can be relativistic if the external magnetic field is strong such that $|\Omega_e|/\omega_{pe} > 1$, where $\Omega_e(< 0)$ and ω_{pe} are electron gyro and plasma frequencies, respectively.

Electrons are accelerated by a different mechanism. A magnetosonic shock wave propagating obliquely to a magnetic field can trap electrons and accelerate them. The energies of the accelerated electrons can be ultrarelativistic when $|\Omega_e|/\omega_{pe} > 1$ and the propagation speed of the shock wave v_{sh} is close to $c \cos\theta$, where 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. The reflected electrons are then trapped in the main pulse and are accelerated by the strong electric field there.

The trapped electrons significantly influence electromagnetic fields in a shock wave. In the two-dimensional (2D) simulations [2], the trapped electrons excite whistler-wave instabilities through interaction with whistler waves with finite wavenumbers along the shock front. As a result of nonlinear development of the instabilities, the 2D electromagnetic fluctuations along the shock front grow to large amplitudes. The 2D electromagnetic fluctuations can cause detrapping of energetic electrons from the main pulse and subsequent acceleration to much higher energies [3,4].

In the above works, the 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 because v_{sh} is much greater than the ion thermal velocity. Further, the reflected ions do not stay near the shock front, unlike the trapped electrons. Therefore, the effects of reflected ions on electromagnetic fields in a shock wave would be small, compared to those of trapped electrons

In this work, we studied how ions are influenced by the 2D electromagnetic fluctuations that the trapped electrons produce[5]. First, we analytically derived the condition for ions to be reflected from the shock front. It was predicted that the fraction of the reflected ions is enhanced by the 2D electromagnetic fluctuations. Next, we studied the effects of trapped electrons on ion motion in an oblique shock wave using 2D electromagnetic particle simulations. We followed the orbits of a large number of ions in the 2D simulation. We call these ions 2Ds ions. Furthermore, we calculated the orbits of the same number of test ions in the electromagnetic fields averaged along the shock front. That is, the test ions are not influenced by the 2D electromagnetic fluctuations. We call these test ions 1Dt electrons. Figure 1 shows that the number of reflected 2Ds ions (b) is greater than that of reflected 1Dt ions (c). It was also shown that the difference between the 2Ds ions and 1Dt ions increases with the amplitudes of the 2D electromagnetic fluctuations excited by the trapped electrons.

Thus, we have predicted that the ion reflection is enhanced by the 2D electromagnetic fluctuations and have confrimed this with the simulations.

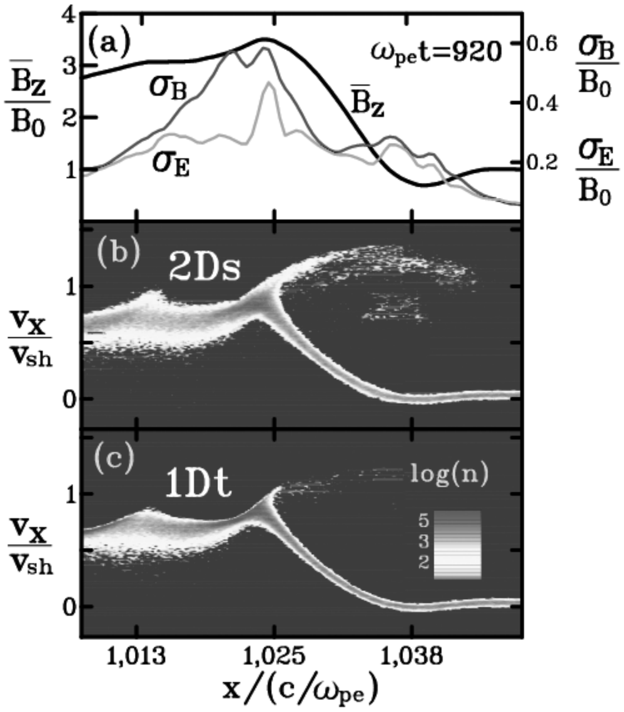

Fig. 1: (a) Profiles of 1D averaged magnetic field $\bar{B}_z$ (black line) and amplitudes of 2D electromagnetic fluctuations, σ_B (blue) and σ_E (red) near the shock front, (b) phase space (x, v_x) of 2Ds ions, (c) that of 1Dt ions. The ions with $v_x > v_{sh}$ are reflected from the shock front. The number of the reflected 2Ds ions is greater than that of the reflected 1Dt ions.

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