§3. Particle Acceleration Due to Strong Electromagnetic Fields in Shock Waves

Ohsawa, Y., Toida, M., Sato, M., Takahashi, S. (Nagoya Univ.),
Ishiguro, S.

We have studied the electromagnetic structure of nonlinear magnetohydrodynamic waves and particle acceleration occurring in those waves, with theory and with fully kinetic, relativistic, electromagnetic simulations. Our work may be summarized as follows: 1) When a strong disturbance is given to a plasma, a large-amplitude Alfven wave packet is created and propagates behind a magnetosonic shock wave. We have shown with particle simulations that the wave packet can accelerate electrons to ultrarelativistic energies [1]. 2) In 2007, we investigated the parallel electric field in nonlinear magnetosonic waves in a single-ion-species plasma [2]. In 2008, we extended that work to three-component plasmas consisting of electrons, positrons, and ions; we have analytically obtained the parallel electric field in nonlinear magnetosonic waves and confirmed the theory with particle simulations [3]. These studies indicate that the parallel electric field can be strong in nonlinear magnetosonic waves. 3) We have investigated the shock formation processes for the case in which two plasmas collide with a high relative-velocity in an external magnetic field [4]. We have described the dependence of the formation of forward and reverse shock waves on the angle between the relative velocity and the external magnetic field. 4) With use of three-dimensional particle simulations with the number of simulation particles $N_i=N_e=1\times10^9$, we have studied the effect of ion composition on the ion acceleration in a shock wave in a two-ion-species plasma [5]. It has been found that the difference between the cutoff frequency ω_{+0} of the high-frequency magnetosonic wave and the resonance frequency ω_{-r} of the low-frequency mode plays a crucial role in determining the properties of ion acceleration. 5) By using a two-dimensional particle code, we have studied the evolution of a cylindrical shock wave and the trapping and acceleration of electrons in it. It has been shown that ultrarelativistic acceleration of electrons takes place in cylindrical shock waves as well as in planar ones [6]. Furthermore, high-energy electrons can be detrapped from the shock front owing to the curvature of the shock wave.

In the following, we briefly describe the study of the first subject: Evolution of Alfven wave packet and electron acceleration caused by the packet. Figure 1 shows magnetic-field profiles and electron phase spaces (x, γ), where γ is the Lorentz factor; the waves propagate in the x direction in an external magnetic field $\boldsymbol{B}_0$ in the (x,z) plane. In the top panel ($\omega_{pe}t$=4000), the front of a magnetosonic shock wave is around $x / (c/\omega_{pe}) = 1800$, and a large-amplitude Alfven wave packet is in the region $600 < x / (c/\omega_{pe}) < 1600$. We find ultrarelativistic electrons with Lorentz factors $\gamma \sim 100$ in the Alfven wave packet.

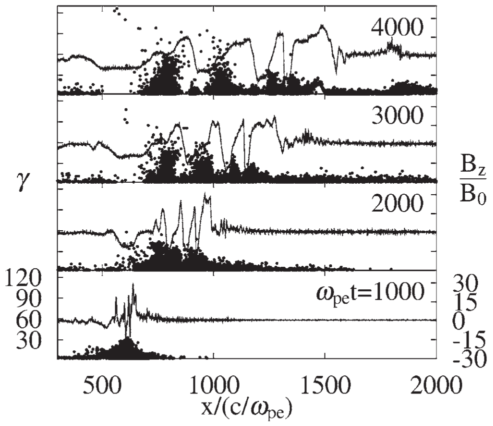

Fig. 1. Magnetic-field profiles and electron phase spaces.

Some electrons suffer three types of acceleration. Figure 2a shows the orbit of such particle in the (p_x, p_y) plane for $0 < \omega_{pe} t < 4000$, while Figs. 2b and 2c show expanded views of this orbit for $500 < \omega_{pe} t < 726$ and for $1128 < \omega_{pe} t < 1509$, respectively (the time of point A is $\omega_{pe} t = 1841$). This particle was accelerated firstly by a compressive small pulse behind the shock front for $500 < \omega_{pe} t < 1100$, secondly by the field-reversal in the front part of the Alfven wave packet for $1100 < \omega_{pe} t < 1500$, and thirdly by the layers with alternating magnetic polarity in and behind the wave packet for $\omega_{pe} t > 1800$, i.e., after point B.

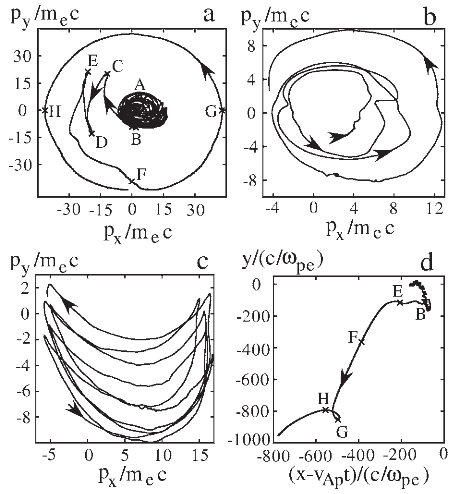

Fig. 2. Orbits of an accelerated electron in the (p_x, p_y) and (x-v_At, y) planes. Here, v_A is the Alfven speed.

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