Detrapping mechanism of ultrarelativistic electrons from an oblique shock wave

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Theory and simulations [1] have found that prompt electron acceleration to ultrarelativistic energies with $\gamma > 100$, where γ is the Lorentz factor, can occur in a magnetosonic shock wave propagating obliquely to an external magnetic field with $|\Omega_e|/\omega_{\rm pe}\gtrsim 1$, where $\Omega_e(< 0)$ and $\omega_{\rm pe}$ are the electron gyro and plasma frequencies, respectively. In such a wave, some electrons are reflected near the end of the main pulse of the wave and are trapped and energized in the main pulse region. Once electrons are trapped, they can hardly escape from the wave and are trapped deep in the main pulse region; the energetic electrons exist in the main pulse. This indicates that the number of trapped electrons increases continually with time, which has been shown by particle simulations [1]. In this trapping and acceleration mechanism, the electric field parallel to the magnetic field, $E_\parallel$, in the oblique shock wave and its integral along the magnetic field, $F = -\int E_\parallel ds$, play essential roles. In Ref. [2], it was pointed that if $\partial F/\partial t > 0$ at particle positions after the reflection, the parallel energies of the reflected electrons decrease, which causes deep trapping.

The mechanism of the increase in F is, however, unclear. Further, because the previous theory and simulations are one dimensional, it is important to study multidimensional effects on trapping and acceleration of electrons. We firstly investigate the effect of the trapped electrons on electromagnetic fields in a shock wave under the assumption that the wave is one dimensional. We derive theoretical expressions for F including the number of trapped electrons $n_{\rm t}$ as a factor. It is found that the magnitude of F increases with $n_{\rm t}$, which indicate that the trapped electrons are trapped deeper due to the electromagnetic fields that they produce themselves. The theoretical prediction is confirmed by one-dimensional, electromagnetic, particle simulations. We next perform two dimensional simulations. It is demonstrated that ultrarelativistic electrons exist even outside of the main pulse region. The electrons are once trapped in the main pulse and then detrapped from it owing to the electromagnetic fluctuations along the shock front. Unlike in the one-dimensional case, the magnitude of F does not always increases with time, which can enhance the detrapping. When the propagation speed of the shock wave is close to $c\cos\theta$, where θ is the angle between the external magnetic field and wave normal, the guiding center of the electrons move with the shock wave even after the detrapping. The electrons can, therefore, enter the shock wave several times owing to their gyromotions and gain energies at these times. As a result of these processes, many electrons are accelerated to much higher energies in the two-dimensional case than in the one-dimensional case.

[1] N. Bessho and Y. Ohsawa, Phys. Plasmas **6** 3076 (1999); *ibid.* **9**, 979 (2002).

[2] A. Zindo, Y, Ohsawa, N. Bessho, R. Sydora, and Y. Ohsawa, Phys. Plasmas **12** 052321 (2005).