## §2. Effects of Multi-dimensional Electromagnetic Fluctuations on Energetic Particles in Magnetosonic Shock Waves

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Using 2D (two spatial coordinates and three velocity components) relativistic electromagnetic particle code with full ion and electron dynamics, we have studied ultrarelativistic electron acceleration by an oblique shock wave and formation of collisionless shock waves in a magnetized plasma.

(1) Electron acceleration by an oblique shock wave

A magnetosonic shock wave propagating obliquely to an external magnetic field can trap and accelerate electrons to ultrarelativistic energies when $v_{\rm sh}$ is close to $c\cos\theta$, where $v_{\rm sh}$ is the propagation speed of the shock wave, $c$ is the light speed, and $\theta$ is the propagation angle of the shock wave. Because of instabilities driven by the trapped electrons and nonlinear development of the instabilities, electromagnetic fluctuations along the shock front grow to large amplitudes[1]. These fluctuations can cause detrapping of electrons from the main pulse retaining their high energies. The electrons detrapped to the upstream region can then be further accelerated to higher energies as a result of their gyromotions[2].

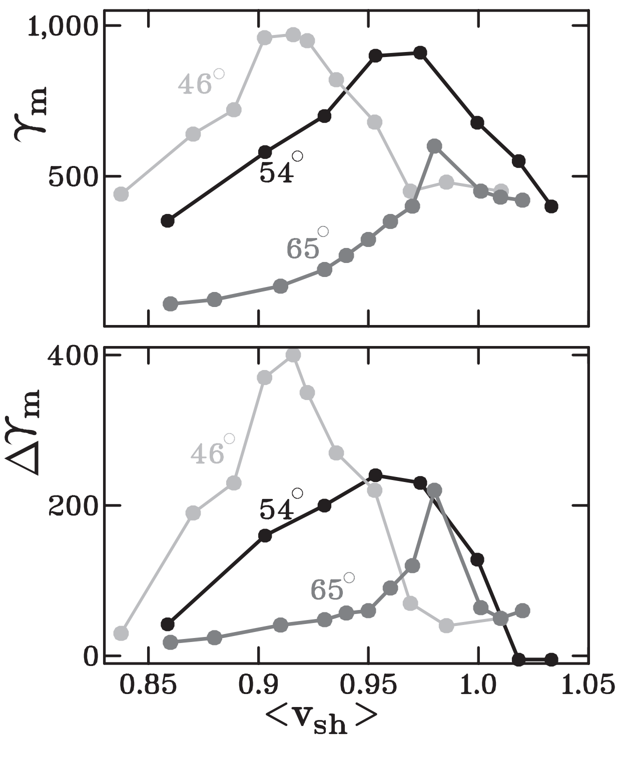


Fig. 1: Dependence of electron motions on the parameters $v_{\rm sh}$ and $\theta$

We have investigated the dependence of electron motions on the parameters $v_{\rm sh}$ and $\theta$ using 2D electromagnetic particle simulations [3]. The upper panel of Fig. 1 shows the maximum $\gamma$ of electrons, $\gamma_{\rm m}$, at $\omega_{\rm pe}t = 4500$, as functions $\langle v_{\rm sh}\rangle = v_{\rm sh}/(c\cos\theta)$ for $\theta = 46°$ (red), 54° (black), and 64° (blue). If $\theta$ is fixed, electron energies become maximum when $v_{\rm sh}$ is slightly smaller than $c\cos\theta$. If the value of $v_{\rm sh}/(c\cos\theta)$ is fixed, the maximum energy of electrons tends to increase with decreasing $\theta$ for the range $v_{\rm sh}/(c\cos\theta) < 1$. The lower panel of Fig. 1 shows the increment of $\gamma_{\rm m}$, $\Delta\gamma_m$, from $\omega_{\rm pe}t = 3000$ to 4500. This increment is caused by the subsequent acceleration after detrapping. The comparison between the two panels shows that the maximum $\gamma$ is caused by the subsequent acceleration. We have also examined the number of electrons that are detrapped to the upstream region and then suffer the subsequent acceleration. The number also becomes maximum when $v_{\rm sh}$ is slightly smaller than $c\cos\theta$.

(2) Formation processes of collisionless shock waves

Particle simulations have revealed that a magnetosonic shock wave can rapidly accelerate particles with various mechanisms [4]. However, formation processes of shock waves have not been fully understood. We study shock formation due to interactions between exploding and surrounding plasmas and evolution of modified two-stream instabilities using a 2D electromagnetic particle code [5].

After the exploding ions penetrate the surrounding plasma, a strong magnetic field pulse is formed near the front of the exploding plasma. Because of modified two-stream instabilities, 2D electromagnetic fluctuations grow to large amplitudes in this pulse. At $\Omega_{\rm i}t \simeq 1$, where $\Omega_{\rm i}$ is the ion cyclotron frequency, the pulse starts to split into two pulses. These pulses then develop into forward and reverse shock waves. We performed simulations for various values of the initial velocity of the exploding plasma and of the angle between the velocity and the external magnetic field. We then discussed the parametric dependence of the time for a strong magnetic-field pulse to start to split into two, the amplitudes of the generated pulses, and the properties of 2D magnetic fluctuations [6].

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