Simulation studies of ion beam production by an oblique shock wave and associated instabilities

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It has been shown with theory and particle simulations [1-3] that nonthermal, energetic ions barely entering a shock wave can be further accelerated to higher energies by the transverse electric field in the shock wave because, while they are in the shock region, their gyromotions are nearly parallel to the transverse electric field. If these ions move with the shock wave for long periods of time, the acceleration processes can be repeated several times. The condition for the repeated acceleration is given by [2]

$$v_{\parallel} \cos\theta \simeq v_{\rm sh} \tag{1}$$

where $v_{\rm sh}$ is the shock propagation speed, $v_{\parallel}$ is the particle velocity parallel to the magnetic field, and θ is the shock propagation angle, i.e., the angle between the wave normal and external magnetic field. If the relation $v_{\rm sh} \sim c\cos\theta$ is satisfied, where c is the light speed, energetic particles could be indefinitely accelerated owing to the relativistic effects [3].
The above studies were concerned with the acceleration of nonthermal ions; that is, it was assumed that energetic ions were present from the beginning. We here study repeated interactions of thermal ions with an oblique shock wave and instabilities by these accelerated ions. When the thermal ions encounter the shock wave for the first time, some of them are energized by the reflection from the shock front. With attention to the fact that their parallel velocities in the upstream region immediately after the reflection are estimated as $v_{\parallel} \simeq 2v_{\rm sh}\cos\theta$, we predict that if $\theta = 45^{\circ}$, the reflected ions can be further accelerated by the shock wave with the mechanism discussed in Refs. [1-3] because the condition (1) is satisfied. Further, the theoretical expression for the maximum energy of the accelerated ion is obtained. We then perform two-dimensional (one space coordinate and three velocity components), fully kinetic, electromagnetic particle simulations. As predicted by the theory, some of the thermal ions are accelerated several times; the first energy gain is from the longitudinal electric field, and the following ones are from the transverse electric field. The parallel velocities of these ions also increase several times, which is due to the magnetic field [2], and thus these ions eventually move away to the upstream region. As a result of these processes, an ion beam parallel to the magnetic field is produced. The ion beam excites whistler waves, which slightly heat electrons.

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