論文内容の要旨

Nonthermal Particle Acceleration in Collisionless Shock Waves

(無衝突衝撃波における非熱的粒子加速)

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Electron acceleration process in high Mach number collisionless quasi-perpendicular shocks is investigated in detail, using both theoretical and numerical approaches. It has been long known that nonthermal electrons are produced at collisionless shock waves in the heliosphere as well as in astrophysical environments. However, the detailed mechanisms accelerating these electrons remain yet to be answered.

Based on the existing particle acceleration theory called electron shock surfing acceleration, we show that the process indeed plays a key role in the injection of electrons to diffusive Fermi acceleration in high Mach number shocks. By performing one-dimensional particle-in-cell simulations of quasi-perpendicular shocks, it is demonstrated that the injection of electrons is achieved by the shock surfing followed by shock drift acceleration at shocks with Mach number typical of supernova remnant shocks. The simulation results are used to construct a theoretical model of the electron injection that can predict the injection efficiency of electrons. The model enables us to estimate the injection efficiency with realistic parameters. It is shown that the present model can indeed explain observed injection efficiencies very well.

We also investigate the effect of multidimensionality on the efficiency of particle acceleration in high Mach number shocks. The electron-ion electrostatic two-stream instability, known as the Buneman instability, is believed to play a role in the electron shock surfing acceleration. Two-dimensional particle-in-cell simulations show that the instability has smaller saturation level than previously thought because of the growth of many modes propagating oblique to the beam direction. We present a new estimate of the saturation

level of the Buneman instability, which suggests that the strong electron surfing acceleration can occur at supernova remnant shocks. On the other hand, the result indicates that electron acceleration to relativistic energy by the surfing acceleration is difficult at shock waves in the heliosphere.

Because of the presence of many oblique modes, the Buneman instability in multidimensions produces spatially isolated potential structures, which violates the assumption of one-dimensional potential originally made by the theory of the electron shock surfing acceleration. Electron acceleration, that is achieved by transport of electrons anti-parallel to the motional electric field, seems to be inefficient in such a condition. Contrary to this prediction, two-dimensional particle-in-cell simulations show that stochastic electron scattering plays a role. A periodic simulation model of the transition region of perpendicular shocks is used to investigate the interactions between electrons and turbulent electrostatic waves in weakly magnetized plasmas. It is shown that electrons stochastically scattered by large amplitude electrostatic waves see an effective force acting on them, leading to acceleration by an effective motional electric field. Therefore, energetic electrons are transported transverse to the beam direction.

The transport of energetic electrons anti-parallel to the motional electric field is actually important in a real shock transition region. A self-consistent high Mach number perpendicular shock is simulated by using a two-dimensional particle-in-cell code. Strong electron acceleration is actually observed even in multidimensions. Since the reflected ions drift oblique to the shock normal, the wave front of electrostatic waves produced by the Buneman instability also becomes oblique. Because of this, electrons stochastically accelerated by the turbulent electrostatic waves are transported to the upstream direction. As a result, they are ejected into the upstream region and suffer further acceleration by the upstream constant motional electric field. We conclude that the electron shock surfing acceleration is a robust process that actually survives in multidimensions. However, the theory of electron shock surfing acceleration should be modified to include the effect of multidimensionality.