Particle acceleration and heating in plasma universe: collisionless shock waves and magnetic reconnection

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Explosive plasma phenomena such as supernova shocks, pulsar wind nebulae, gamma-ray bursts, solar flares, and Earth's substorms are known to produce non-thermal high-energy particles whose energies exceed extremely the thermal temperature. Among many acclaimed research into particle acceleration processes, magnetic reconnection and collisionless shock waves are often suggested to play specifically an important role on the production of high-energy particles and hot plasmas. We review the non-thermal particle acceleration and plasma heating in collisionless magnetic reconnection and shock waves in various plasma environments based on recent progresses of particle-in-cell simulations.

It is often discussed that the so-called diffusive shock acceleration/Fermi shock acceleration is a main player of the production of non-thermal high-energy particles in plasma universe, and that particles can gain energy stochastically during head-on and head-tail collisions of particles with MHD turbulence. Although ions can be easily energized during such a process, the production of relativistic electrons remains a puzzle for theory. A pre-heating/pre-acceleration process up to mildly relativistic energies are needed for the effective electron Fermi acceleration, and the key issue is the existence of strong instabilities in electron-scale with large amplitude waves. We review that recent particle-in-cell (PIC) simulations have not only confirmed this strong heating but have also found electron acceleration mechanisms that produce the supra-thermal, relativistic electrons [1]. The roles of those plasma instabilities and particle accelerations are argued as the function of on Mach number from non-relativistic to relativistic shock waves [2].

In addition to the shock physics, we also review the plasma heating and particle acceleration by collisionless magnetic reconnection as one of fundamental processes of the energy conversion from the magnetic field energy to the kinetic plasma energy. The most elementary process of particle energization is known to occur in the magnetic diffusion region with weak magnetic fields where the charge particles can be directly accelerated by an inductive reconnection electric field through meandering/Speiser motion. However, the size of the diffusion region is much small than the total system of reconnection, and the amount of non-thermal particles produced by this process is thus not necessarily large. The production of high-energy particles with large flux in reconnection is still a puzzle. Recently it is argued that the plasma sheet is unstable for multiple plasmoids generation for high Lundquist numbers [3], and we argue that the similar magnetic reconnection structure with the multiple magnetic islands can naturally happen in a wide variety of magnetically active regions such as high Mach number shocks and accretion disks gravitationally bounded around central objects [4]. We discuss that the acceleration efficiency can be strongly enhanced by the stochastic interaction of energetic particles with the multiple magnetic islands under the plasmoid-dominated reconnection [5].

Finally, we propose that localized large-amplitude waves and/or small-scale magnetic reconnection imbedded in macroscopic plasma phenomena would efficiently generate very high energy particles in many plasma environments.

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