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Three-dimensional Particle-In-Cell simulations for high Mach number collisionless shocks

T. Amano[1], Y. Matsumoto[2], T. Katou[1], M. Hoshino[1]
[1] Department of Earth and Planetary Science, University of Tokyo,
[2] Department of Physics, Chiba University
e-mail: amano@eps.s.u-tokyo.ac.jp

High-energy charged particles that are out of the thermal equilibrium distribution are ubiquitous in space and astrophysical plasmas. Once such non-thermal particles are generated, the collisionless nature of the system allows them to survive for a long time without losing energies. The non-thermal population is typically negligible in terms of density, but the energy density is not necessarily small because of extremely high individual particle energies. The pressure exerted by the non-thermal particles may thus play a significant role even for the macroscopic dynamics of the system. The fundamental question is then, how such high-energy non-thermal particles are generated in the Universe. The most well-accepted scenario is the first-order Fermi acceleration at collisionless shocks that will produce a power-law type energy spectrum, roughly consistent with observations. The mechanism essentially transfers a fraction of the available free energy (as the flow kinetic energy of the shock) to the accelerated particles. However, the efficiency of this energy conversion rate is not predicted by the theory. The question can only be answered by understanding the highly nonlinear plasma dynamics occurring within the collisionless shock internal structure that picks up only a fraction of particles out of the thermal pool and accelerates them to the non-thermal energies.

We here present our recent three-dimensional (3D) Particle-In-Cell (PIC) simulation results for high Mach number collisionless shocks relevant to supernova remnants (SNR), with the magnetic filed nearly perpendicular to the shock normal [1]. We found that the electron acceleration within the shock transition region occurs mainly with two different mechanisms. The one that occurs first is the so-called shock surfing acceleration (SSA) mechanism [2] that involves large-amplitude electrostatic waves generated by the Buneman instability. The SSA operating in 3D appears surprisingly similar to its 2D counterpart [3] and provides a quite rapid (time scale on the order of the electron gyroperiod) way to generate non-thermal electrons. As the Buneman instability is excited in the leading edge (or the upstream side) of the shock transition region, the cold electrons entering into the shock first experience the rapid energization. The pre-accelerated particles then suffer further energization via the shock drift acceleration (SDA). This two-step acceleration was discussed previously based on one-dimensional (1D) PIC simulation results [4]. However, the 3D simulation revealed that the SDA now becomes much more efficient because of the magnetic turbulence generated by the Weibel instability [5]. The classical SDA is an adiabatic process, and its energy gain is deterministic. In contrast to this, the Weibel-generated turbulence introduces the stochasticity in the dynamics of electrons, which makes it possible to confine a fraction of particles within the shock transition region longer than expected from the adiabatic theory. The process, which we call the stochastic SDA, combined with the preceding SSA provides an efficient means to accelerate electrons to relativistic energies. By comparing with two-dimensional (2D) simulations, we found that such an efficient electron acceleration is realized only in fully 3D because the reduced dimensionality in 2D simulation does not allow the two different mechanisms to coexist.

We have also developed a theory of the stochastic SDA. The model predicts that a power-law type energy spectrum will be produced in the steady state. The spectral index does not depend on the details of the scattering, such as the wave characteristics or the rate of scattering. This property makes it possible to apply the same theory to moderate Mach number shocks such as earth/planetary bow shocks, for which in-situ observations are available. Instead of the Weibel-generated turbulence, high-frequency whistler waves may play the role for the scattering in the earth bow shock [6]. A theoretical interpretation of the recent high temporal resolution in-situ measurements of the bow shock by the Magnetospheric Multiscale (MMS) spacecraft [7] will be presented.

References

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