高マッハ数衝撃波の 3 次元 PIC シミュレーション：電子加速効率のパラメタ依存性

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3D PIC simulations of high-Mach-number shocks: Parameter dependence of the electron acceleration efficiency

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The diffusive shock acceleration (DSA) theory has provided a solution to observational evidences for efficient accelerations at collision-less shocks, as it predicts a power-law energy spectrum of particles having a spectral index that is close to the values suggested by multi-wavelength observations. As the DSA theory presumes pre-existing mildly energetic particles, pre-acceleration mechanisms are required to provide a seed population for DSA, particularly for electrons. The connection between pre-acceleration and DSA remains a critical issue in shock acceleration theory.

In order to deal with electron acceleration mechanisms in a self-consistent system, we examined 3D PIC simulations of a quasi-perpendicular, high-Mach-number shock. We successfully followed a long-term evolution, in which we found two different acceleration mechanisms coexist in the 3D strong shock structure. The Buneman instability was strongly excited ahead of the shock front in the same manner as have been found in 2D simulations. The shock surfing acceleration was found to be very effective in the present 3D system. In the transition region, the ion-beam Weibel instability generated strong magnetic turbulence in 3D space. Energetic electrons, which initially experienced the surfing acceleration, underwent the shock drift acceleration while being scattered by interacting with the turbulent fields. This pitch-angle scattering allowed the energetic particles stay in the upstream regions much longer than classical estimates from the adiabatic theory.

In this presentation, we discuss the 3D simulation is essentially important for the effective non-thermal electron acceleration by comparing with 2D simulations under the same upstream conditions: The in-plane upstream magnetic field case, in which the Buneman mode was weakly destabilized, resulted a faint heating in the turbulent area. On the other hand, the efficient SSA was realized in the out-of-plane case. The surfing-accelerated electrons, however, cannot undergo the subsequent stochastic SDA because of the weak turbulence level, which is due to limited growth of the ion Weibel instability in the 2D out-of-plane upstream magnetic field condition. We also discuss with 3D simulation runs under different upstream magnetic field obliquity. We found that super-luminal cases resulted limited acceleration efficiency as previously reported for magnetized relativistic shocks.