統計的衝撃波ドリフト加速理論の観測的検証
Experimental Test for Stochastic Shock Drift Acceleration Theory

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High-energy charged particles are ubiquitous in space. They have energies orders of magnitude higher than the thermal energy and often exhibit a power-law distribution in a wide energy range. The collisionless shock is one of the leading mechanisms that may produce such high-energy non-thermal particles. Indeed, radio, X-ray, and gamma-ray observations strongly suggest that shock waves associated with supernova remnants, pulsar winds, relativistic jets in active galactic nuclei and gamma-ray burst are accelerating relativistic electrons. On the other hand, in-situ observations in the heliosphere (at planetary bow shocks, or interplanetary shocks driven by coronal mass ejections) have shown that the acceleration of electrons is, in general, weak or even absent in many of the shock crossings.

We have recently proposed a theory for electron acceleration at shocks that may resolve the observational controversy. The theory referred to as stochastic shock drift acceleration (SSDA) assumes stochastic pitch-angle scattering during electrons are interacting with a collisionless shock. The energy gain comes from the gradient-B drift (due to the magnetic field compression in the shock transition layer) in the direction anti-parallel to the convection electric field and is not associated with the assumed scattering. The scattering is, however, essential to confine the accelerated electrons in the shock transition layer for a long time, because, otherwise they would quickly escape from the system. In other words, the theory assumes that the electron transport obeys the diffusion-convection equation with an energy gain term determined only by the magnetic field gradient. It successfully explains the formation of a power-law energy spectrum, with a maximum energy cut-off determined by the rate of pitch-angle scattering. We here present the result of an experimental test using NASA's MMS (Magnetospheric MultiScale) spacecraft observation of an Earth's bow shock crossing event on December 9, 2016.

In particular, we have checked the following points that are predicted by the theory: (1) exponential increase in energetic particle intensity toward downstream within the shock transition layer, (2) nearly isotropic pitch-angle distribution. We find that both are reasonably satisfied in a thin layer (~7 sec. or ~350 km assuming a shock propagation speed of ~50 km/s) within the shock transition region. The result is then used to estimate the rate of pitch-angle scattering as a function of energy. We find that the pitch-angle scattering rate increases as increasing the particle energy from just above the thermal energy up to a few keV, beyond which it saturates to a nearly constant value. We find that the observed maximum energy cut-off (~30 keV) in the electron energy spectrum is consistent with that predicted by the theory based on the observed pitch-angle scattering rate. All of these results strongly indicate that the observed non-thermal electrons are accelerated by the SSDA.

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