Theory and Observation of Nonthermal Electrons at Quasi-perpendicular Bow Shock

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The acceleration of energetic charged particles has been a topic of great interest both in space physics and astrophysics. In-situ observations of particles in space often find an extended non-thermal tail typically with a power-law in the energy spectrum. One of the most promising mechanisms to produce such non-thermal particles is the first order Fermi acceleration at shock waves. However, it is very well known that shock-associated enhancements of energetic electron fluxes are very rare at traveling interplanetary shocks (Lario et al. 2003, Dresing et al. 2016). On the other hand, relatively strong planetary bow shocks that stand in the solar wind sometimes produce energetic electrons (Gosling et al. 1989, Oka et al. 2006, Masters et al. 2013). Radio and X-ray synchrotron emissions from young supernova remnant shocks suggest that the acceleration of electrons is highly efficient at these shocks. The question is that what controls the shock acceleration efficiency for the non-thermal electrons.

Historically, the energetic electrons associated with shock crossings have been observed as spiky flux enhancements. With the unprecedented temporal resolution of particle measurement made by the MMS (Magnetospheric MultiScale) spacecraft, such a spike is now resolved to be a gradual flux increase from the upstream to downstream within a thin shock transition layer. This signature of supra-thermal electrons may potentially be understood with a recently developed theoretical model for the electron acceleration at quasi-perpendicular shocks.

The theory, which we call stochastic shock drift acceleration (SSDA), is based on the classical shock drift acceleration but takes into account the effect of stochastic pitch-angle scatterings. It assumes that a fraction of particles are trapped within the shock transition region because of strong pitch-angle scatterings. The trapped particles experience a nearly constant fractional energy gain per unit time via the magnetic mirror force (or equivalently, the gradient-B drift in the direction of the motional electric field). The SSDA theory predicts a power-law energy spectrum with its spectral index determined solely by the magnetic field gradient scale length. The energetic particle intensity profile within the shock transition layer should increase gradually toward downstream. These features are qualitatively consistent with some of the shock crossings observed by MMS.

In this study, we conduct quantitative comparisons between the theory and MMS observations of high Mach number quasi-perpendicular shocks. The electron energy spectra at the shock may well be represented by a power law from just above the thermal energy (~0.2keV). We find that the cut-off energies of the power-law component sometimes exceed the upper limit of the FPI instrument (~30 keV). A bursty appearance of high-frequency whistler waves (with frequencies around 0.1-0.5 times electron cyclotron frequency) is a typical signature of such strong shocks, suggesting that pitch-angle scatterings are going on for the accelerated electrons. Assuming the diffusion-convection equation for the energetic electrons, we may estimate the pitch-angle scattering coefficients from the observed profiles of the particle intensity. We will discuss the consistency between the theory of SSDA and MMS observations.