On the rate of electron injection at collisionless shocks

*Takanobu Amano[1]

1. Department of Earth and Planetary Science, University of Tokyo

The acceleration of charged particles at a collisionless shock is conventionally understood in terms of the first-order Fermi acceleration, also known as the diffusive shock acceleration (DSA) mechanism. The nonthermal emission spectrum from relativistic electrons accelerated at strong astrophysical shocks is roughly consistent with the standard mechanism. However, it is well known that the DSA can not efficiently accelerate non-relativistic electrons because of the lack of scattering agents. There must be a mechanism that extracts a fraction of particles in the thermal pool and inject them into the relativistic energy range. Such a mechanism appears to be inactive at shocks of modest strength in the heliosphere, where relativistic electrons are usually not observed. The observations imply that the injection process must operate efficiently at strong astrophysical shocks, which should, however, be suppressed at weak and moderate shock strength.

Recent theoretical development and observational verification of the stochastic shock drift acceleration (SSDA) model [Katou & Amano 2019, Amano et al. 2020] have cast light on the electron injection problem. The model predicts that the injection into the relativistic energy range is possible only at high-speed and highly-oblique shocks. Therefore, it discriminates fast astrophysical shocks (such as young supernova remnant shocks with > a few thousand km/s) from heliospheric shocks (with typical speeds of a few to several hundred km/s). Such a success in explaining existing observations naturally raises the question of how many particles are then finally injected into the population of cosmic-ray electrons. We here make an attempt at a quantitative estimation of the electron injection rate within the framework of the SSDA model.

The SSDA theory at this moment is not sophisticated enough to predict the amount of the injected electrons by itself. We thus take a phenomenological approach using the information available from in-situ observations of the Earth's bow shocks reported in the past. The electron velocity distribution function (VDF) measured at the bow shock often exhibits the so-called flat-top VDF, which is nearly constant at low velocities up to some threshold and then decreases in a power-law from beyond that. There have been observational indications that the threshold velocity corresponds to the energy of the quasi-static cross-shock electrostatic potential in the de Hoffmann-Teller frame. Since the potential may be estimated from the flow kinetic energy of the shock, we can estimate the transition velocity between the flat and power-law parts. We adopt the flat-top VDF and assume that the power-law index is given by the SSDA theory. Under these assumptions, we have constructed a model that can estimate the injection rate as a function of macroscopic parameters of the shock (such as the shock speed).

The model shows that the electron injection rate naturally possesses a strong dependence on the shock speed, a tend independent of the shock obliquity. The higher shock speeds lead to much more efficient rates of electron injection. The shock obliquity may potentially strengthen the shock speed dependence even more. We find that a reasonable amount of electron injection rate may be reached with parameters relevant for young supernova remnant shocks. The validity of the model may, in principle, be tested using available in-situ spacecraft observations at planetary bow shocks.

Keywords: shock wave, plasma, particle acceleration