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Stochastic Shock Drift Acceleration as the Mechanism for Electron Injection into Diffusive Shock Acceleration at Collisionless Shocks

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The acceleration of high-energy particles is seen commonly in many phenomena in heliophysics and astrophysics. One of the leading candidates for the particle acceleration mechanisms is the diffusive shock acceleration (DSA) process that is believed to operate at collisionless shock waves. Indeed, the current standard paradigm is that DSA at galactic supernova remnant (SNR) shocks produces cosmic rays with energies up to $10^{15.5}$ eV. While the majority of cosmic rays are protons, a lot more information is available from cosmic-ray electrons in remote particle acceleration sites because of their higher radiative efficiency. Understanding the electron acceleration is thus crucial to investigate the physics of particle acceleration at the shocks. However, it is well known that DSA cannot explain the acceleration of low-energy electrons because they are not efficiently scattered by turbulence. There must be a pre-acceleration mechanism that extracts a fraction of electrons from the thermal pool and injects them into the particle acceleration cycle. This is the so-called electron injection problem and has been a subject of substantial debate over the decades.

We have recently proposed a novel particle acceleration mechanism called stochastic shock drift acceleration (SSDA) as a probable electron injection mechanism [Katou & Amano, 2019]. This is based on the classical shock drift acceleration (SDA) but in the presence of stochastic pitch-angle scattering. SDA for low-energy electrons conventionally considers that the interaction of electrons with the shock with the adiabatic approximation. On the other hand, recent kinetic simulations and in-situ observations of Earth's bow shock indicate that pitch-angle scattering may be efficient enough to violate the assumption of adiabaticity [Oka et al., 2017, Matsumoto et al. 2017, Kobzar et al. 2021]. In the presence of scattering, SSDA provides much more efficient energy gain because of better confinement of the particles in the acceleration region.

In contrast to the classical SDA, a power-law type energy spectrum may be obtained through SSDA, consistent with in-situ observations. The theory predicts that there should be the maximum energy beyond which the power law will cutoff. Given the macroscopic shock parameters, the cutoff energy depends only on the efficiency of pitch-angle scattering. We demonstrated that the theoretical predictions and in-situ measurements of waves and particles at Earth's bow shock are fully consistent with each other [Amano et al. 2020], indicating that SSDA is indeed a promising mechanism for electron injection. This motivates us to conduct a more sophisticated theoretical and numerical analysis.

In this paper, we will present a consistent derivation of the diffusion-convection equation from a transport equation that generalizes the one used in the original paper [Katou & Amano 2019]. This allows us to take into account the spatial dependence of the accelerated particle spectrum explicitly, both inside and outside the shock transition layer. We find that both SSDA and the conventional DSA are obtained from the same transport equation as solutions in different limiting cases. SSDA is realized when the diffusion length is comparable to the shock thickness. It gives a steeper-than-DSA spectrum, which is not necessarily a single power-law depending on the momentum-dependence of the diffusion coefficient. As increasing the energy, the diffusion length is likely to increase and may eventually become significantly larger than the shock thickness. This case corresponds to DSA, which gives the canonical spectral index. In other words, SSDA and DSA are approximate solutions for low-energy and high-energy electrons, respectively. They may be smoothly connected with each other if certain physical conditions are satisfied. Given a model for the scattering efficiency, the electron injection occurs favorably at higher Alfven Mach number and more oblique shocks. We will discuss possible wave generation mechanisms, which are indispensable for the proposed injection scheme. Applications to various shocks will also be discussed.

References

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