Stochastic Shock Drift Acceleration of Electrons: Monte Carlo Simulations

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A Small Introduction

As acceleration mechanisms for electrons in shocks from low energies (less than keV) to high energies (more than MeV) are still poorly understood, we investigate stochastic shock drift acceleration (SSDA) (see, e.g., Amano 2022) as a potential mechanism for sufficient particle acceleration and electron beam formation. Diffusive shock acceleration (DSA) is capable of accelerating particles to high energies, but is inefficient at accelerating lower energy particles. Incorporating an efficient low energy particle acceleration mechanism, such as shock drift acceleration, bridges the gap between the energies of thermal electrons (less than 1 keV) and the required energies for efficient acceleration in DSA (100s of keV).

The Model

The 1D Monte Carlo model (Fig. 1) assumes a shock with a thickness of the order of an ion inertial length (d_i) and a hyperbolic tangent profile for the magnetic field at the shock. The turbulent region around the shock has approximately the same width as the shock ramp. The simulation has a finite box size corresponding to the estimated diffusion length of the injected particle population with free escape boundaries in the upstream and downstream. Particles are injected monoenergetically and isotropically to the plasma rest frame at the upstream simulation box boundary and traverse along the magnetic field lines.

Input Parameters

The physical input parameters of the shock for the simulation are estimated from radio observations of the 2023-10-03 coronal mass ejection and magneto-hydrodynamic modeling of the coronal magnetic field. The input parameters of the simulation are:

Upstream flow speed in the shock frame along the shock normal	$u_{x1} = 1400$ km/s
Upstream Alfvén speed	$V_A = 150$ km/s
Shock obliquity	$\theta_{Bn} = 87°$
Plasma beta	$\beta = 0.1$
Particle density	$n = 9 \cdot 10^7$ cm^{-3}
Particle injection energy	$E_{inj} = 1$ keV

Results

Fig. 2a shows the energy spectra of the upstream and downstream particle populations, where we can see particle acceleration from the injected 1 keV to more than 100 keV, hinting at SSDA being capable of accelerating electrons from low energies to high energies. Fig. 2b shows the residence times of particles in the simulation box, resulting in acceleration time scale of tens of seconds. Fig 3. shows time integrated histograms of particle energies parallel, anti-parallel, and perpendicular to the magnetic field. An electron beam away from the shock towards the upstream can be seen in Fig. 3c and 3d in the energy range of 2-10 keV. The simulation results in a bump-in-tail energy distribution upstream of and away from the shock shown in Fig. 3d.

References

Amano, T.: Electron Injection via Stochastic Shock Drift Acceleration: Theory, Simulation, and Observation, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-3277, https://doi.org/10.5194/egusphere-egu22-3277, 2022.
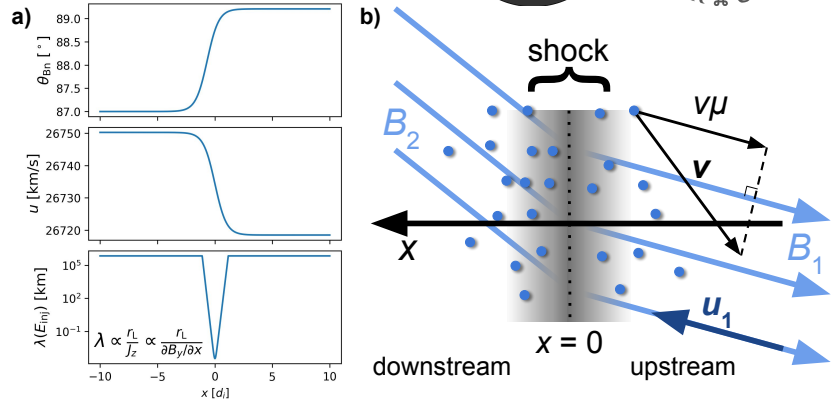
Figure 1: **a)** The shock obliquity θ_{Bn} profile, the flow speed u in the de Hoffmann–Teller frame (HTF) profile, and the mean free path λ profile of the simulation close to the shock assuming a hyperbolic tangent profile for the magnetic field. **b)** The one-dimensional stochastic shock drift acceleration Monte Carlo model geometry depicting the shock normal line x along which the 1D simulation is calculated, the magnetic field vectors $\mathbf{B}$, the HTF upstream flow speed u_1, the particle velocity $\mathbf{v}$ and pitch angle cosine μ, and the finite-thickness shock midpoint at $x = 0$.
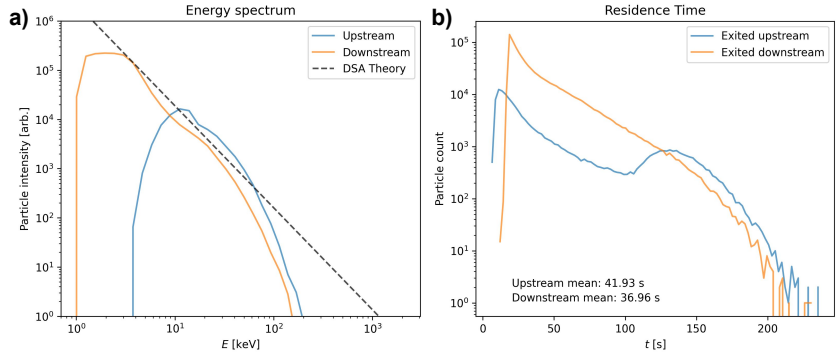

Figure 2: **a)** The particle intensity as a function of energy at the end of the simulation separately for particles that have escaped either upstream or downstream in the plasma rest frame. A theoretical power law distribution predicted by diffusive shock acceleration (DSA) for the input parameters is plotted for comparison. **b)** The particle residence time within the simulation box distribution separately for particles that have escaped either upstream or downstream.
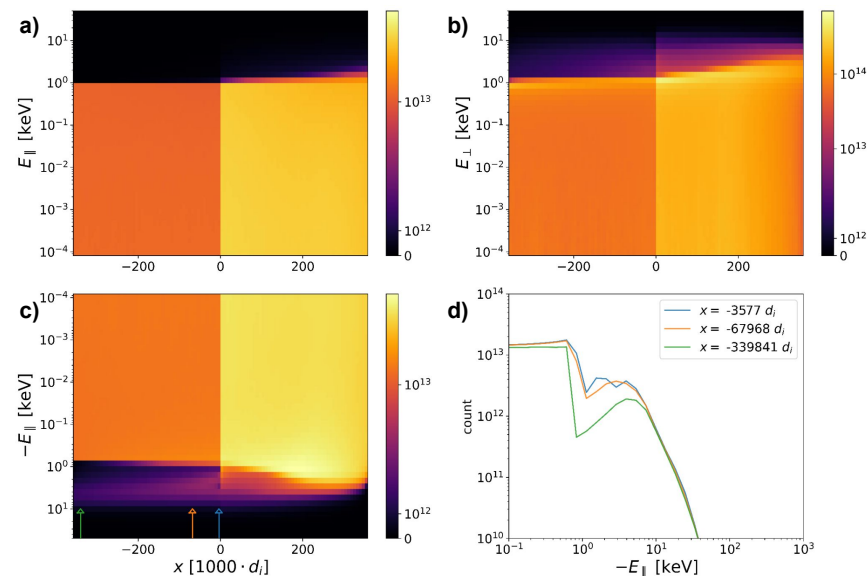

Figure 3: Time integrated distribution of particles as a function of position x along the shock normal and momentum **a)** parallel **b)** perpendicular **c)** anti-parallel to the magnetic field translated to energy in the plasma rest frame. Parallel (positive) direction is towards the positive direction of x. **d)** Time integrated distributions of particles as a function of anti-parallel energy at three locations in the upstream depicted with color-coded arrows in Fig. 3c.

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