PROCEEDINGS OF SCIENCE

What regulates electron injection in diffusive shock acceleration?

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Using fully kinetic particle-in-cell simulations, we study electron acceleration at non-relativistic quasi-parallel shocks for a wide range of shock speeds and magnetizations. We single out the necessary steps that lead to electron injection into diffusive shock acceleration, also presenting a minimal model that accounts for the trends observed in simulations. These scalings are key to understand the nonthermal phenomenology of a variety of heliophysical and astrophysical collisionless shocks.

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1. Introduction

Cosmic rays (CRs) are the main ingredients behind the origin of high-energy observable such as synchrotron radio, X-rays, and gamma-rays which are produced by most helio/astrophysical sources. Since the discovery of CRs, one of the main questions is how particles achieve this tremendous amount of energy that shows a power-law distribution over several decades in momentum/energy space. The pioneering work by Fermi [1] proposed that the particles can produce a power-law distribution if they are repeatedly scattered by moving magnetic islands. [2–4] showed that collision shocks can naturally manifest these environments which allow particles to gain energy when diffusing back and forth across the shock. This promising mechanism that is known as diffusive shock acceleration (DSA) is supported by several observations such as Earth's bow shock [e.g., 5], supernovae shock [e.g., 6], galactic [e.g., 7], or extra-galactic environments [e.g., 8].

In the past decades, several important aspects of proton acceleration were thoroughly detailed in literature [see e.g. 9–14]. Quasi-parallel shocks (the angle between the magnetic field and shock normal $\lesssim 50^o$) are found as a very efficient proton accelerator, which is also consistent with observations [e.g., the bipolar gamma-ray morphology in SN1006 can be naturally explained 6, 10, 15].

Although electron acceleration has been also studied for several decades, the mystery of electron acceleration has not been solved. A few works showed the development of electron power-law tail in both non-relativistic and relativistic regimes [e.g., 16–21]. However, no theory fully explains *the conditions under which electron start DSA and what determine the injection fraction in DSA. These are the main objective of this work.*

This proceeding is organized as follows. We outline our setup of kinetic simulations in §2. The main results are presented in §3 and summarized in §4.

2. Numerical Setup

We employ the massively parallel fully kinetic electromagnetic (EM) particle-in-cell (PIC) code, Tristan-MP [22] to simulate collisionless shock. Our simulations are performed in the upstream rest frame, where the left boundary represents the piston and the right boundary the upstream. To save computational time, we use an expanding right boundary, which expands up to $\approx 10^4\, d_{\rm i}$. For all runs the grid spacing $\Delta x = d_{\rm e}/10$, the time stepping $\Delta t = 0.045\omega_{\rm pe}^{-1}$, and particle per cell per species 200. The upstream plasma temperature is set to thermal Maxwellian distribution. The magnetic field is characterized by the Alfvénic speed ($v_{\rm A} = B_0/\sqrt{4\pi n_0 m_{\rm i}}$) and its inclination relative to shock normal is initialized to $\theta_{\rm Bn} = \cos^{-1}(B_{\rm x}/|\mathbf{B}|) = 30^o$ and is assumed to be in the $x - y$ plane. The shock is parameterized by the shock speed ($v_{\rm sh}$), the Alfvénic Mach number ($\mathcal{M}_{\rm A} = v_{\rm sh}/v_{\rm A}$), and the ion sonic Mach number ($\mathcal{M}_{\rm s} = v_{\rm sh}/v_{\rm thi}$, with $v_{\rm thi} = \sqrt{k_{\rm B}T_{\rm i}/m_{\rm i}}$ thermal speed of ions). The corresponding electron sonic Mach number depends on the used proton-to-electron mass-ratio $m_{\rm i}/m_{\rm e} \equiv m_{\rm R}$, which yields $\mathcal{M}_{\rm s,e} = \mathcal{M}_{\rm s}/\sqrt{m_{\rm R}}$. We have covered a range of plasma β (from $0.125 - 160$), which denotes the ratio of thermal pressure to magnetic pressure.

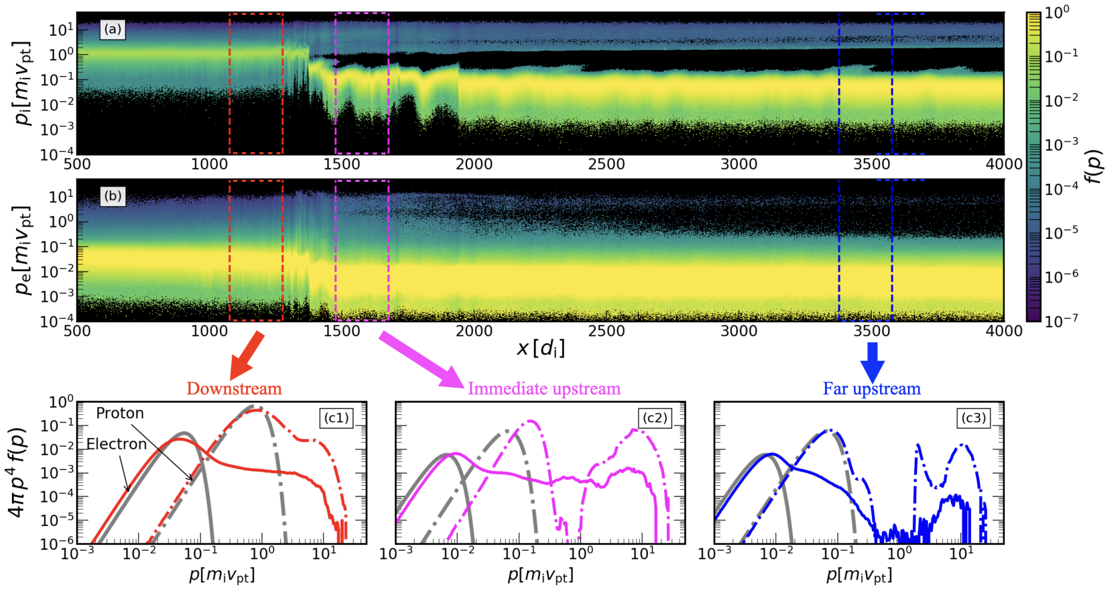

Figure 1: The $x - |p|$ phase-space distribution of protons (panel a) and electrons (panel b), and the spectra (panel c1–c3) from our benchmark shock simulation at $t = 275\,\omega_{ci}^{-1}$.

3. Results

To begin with, we show the snapshot of the particle distribution of our benchmark run ($v_{pt}/c = 0.1$, $\mathcal{M}_A = 20$, $\mathcal{M}_s = 40$, and $m_R = 100$) in Figure 1. Panels (a) and (b) represent the $x - p$ phase-space distribution of protons and electrons, which show the coexistence of the thermal and the energetic populations. Panels (c1)–(c3) display the spectra of protons (dash-dotted line) and electrons (solid line) in the three different regions marked in panels (a) and (b). In panel (c1), the grey lines represent the thermal distribution of downstream plasma obtained from hydrodynamic shock jump conditions by assuming equipartition between electrons and protons. The grey lines in panels (c2) and (c3) display the thermal Maxwellian distribution of far upstream plasma as set by the sonic Mach number.

The downstream spectra clearly show a power-law tail $f(p) \sim p^{-4}$ attached to the Maxwellian distribution for both species, similar to what is reported in the literature [e.g., 18, 23, 24]. The immediate-/far-upstream spectra contain more complex features due to a mixing among the return current, shock-reflected, and escaping populations. While the spectra show a nonthermal power-law distribution, they do not tell us whether the electrons actually have participated in DSA. Moreover, since the electron power-law tail starts well below the proton nonthermal tail, it may be relevant to ask do electrons need to achieve the proton injection momentum to participate in the DSA. Our developed theory successfully explains these questions, which we have verified by a detailed kinetic survey.

4. Summary

We have performed a survey of fully kinetic 1D PIC simulations to study electron acceleration at quasi-parallel non-relativistic shocks for different speeds, Alfvénic ($\mathcal{M}_{\rm A}$), and sonic Mach numbers ($\mathcal{M}_{\rm s}$). Our investigation shows that high Mach number quasi-parallel shocks ($\mathcal{M}_{\rm A} \gtrsim 10$) can efficiently accelerate electrons and protons. While the proton DSA efficiency is found to be quantitatively similar in different shock environments, we find that the electron DSA efficiency is quite sensitive. We thoroughly explore how the upstream conditions and the proton-to-electron mass ratio control the electron acceleration efficiency. We find that in high Mach number shocks ($\mathcal{M}_{\rm A} \gtrsim 10$), the electron DSA injection efficiency is about 1%, which decreases with the Mach numbers. The acceleration is faster in high-speed shocks and slower in low Mach number shocks. Results indicate that high-plasma β shocks can inject fresh electrons into DSA, which has crucial implications in galaxy-clusters studies. Thus, this study provides self-consistent prescriptions to interpret non-thermal radio, X-rays, and $\gamma-$ray emissions in galactic and extragalactic sources and also detail a theory of electron DSA.

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