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Uncovering Electron Acceleration Mechanisms in Quasi-Parallel Shocks using First-Principles Simulations

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Collisionless shocks are widely recognized as powerful particle accelerators in space and astrophysical environments, contributing significantly to the nonthermal energy budget across the universe. A fundamental challenge is understanding how collisionless shocks, where Coulomb interactions are negligible, accelerate thermal particles into a nonthermal energy state, leading to a power-law distribution spanning several orders of magnitude in energy. While the primary acceleration mechanism, diffusive shock acceleration (DSA), is well established, no existing theory succeeds in explaining the electron injection process into DSA.

To investigate this, we have conducted a comprehensive study of electron acceleration in non-relativistic quasi-parallel shocks using first-principles kinetic Particle-In-Cell simulations. Our investigation covers an unprecedented range of shock parameters: shock speeds 0.067–0.267c, Alfvén Mach numbers 5–40, sonic Mach numbers 5–160, and proton-to-electron mass ratios 16–1836. We identify the conditions required for electron injection into DSA and the acceleration efficiency of these nonthermal (cosmic ray) electrons for different shock parameters.

In this talk, I will present the key results from our investigation. I will focus on the mechanisms of electron acceleration and the critical role of self-generated plasma instabilities in electron injection and nonthermal energy evolution. I will also introduce a minimal model to illustrate these results. Our study provides essential insights for developing subgrid models of nonthermal processes at shocks, which are important for the accurate interpretation of nonthermal radiation, including radio, X-ray, and gamma-ray emission from Earth's bow shock to supernova remnants and other galactic/extragalactic sources.

Collaboration(s)

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