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PIC Simulation of a Relativistic Shock Propagating to Electron, Proton, and Heavy Ion Plasmas

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Chemical abundances in cosmic rays (CRs) are crucial for understanding their origin and acceleration mechanisms. Shock waves formed in high-energy astrophysical phenomena are promising mechanisms for CR acceleration. The chemical composition of the medium through which the shock propagates differs in each high-energy astrophysical phenomenon. Observational experiments of CRs show that the chemical composition of cosmic rays exhibits enhancements compared to solar abundances. This could be attributed to the chemical composition of their origin and even the potential dependence of acceleration efficiency on ion species. Previous particle-in-cell (PIC) simulations of relativistic shocks have primarily focused on plasmas with a single ion species. However, in relativistic shocks propagating through multispecies-ion plasmas, the acceleration mechanisms of each ion and electron remain unclear. In this study, we present the first PIC simulation of a relativistic shock propagating in an electron-proton-helium plasma. We find that even in an environment with a solar-like chemical composition, helium ions, despite their lower initial abundance, can be accelerated as efficiently as protons and may even dominate the high-energy region of the cosmic-ray energy spectrum at the source. Additionally, we analytically derive the injection fraction of helium ions, which is consistent with our simulation results. We also find that the acceleration fraction depends on the upstream helium ion fraction. Since ions with the same charge-to-mass ratio follow similar trajectories, our results can be extended to other heavy elements. Our findings are consistent with the chemical composition of ultra-high-energy CRs observed by the Telescope Array and Auger (Batista et al. 2019). Finally, we discuss the implications of high-energy heavy ions for high-energy neutrino emissions.

Collaboration(s)

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