

Universal Scaling Law for Particle Energization in Collisionless Plasmas

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Particles are energized — heated and accelerated to nonthermal energies — in laboratory, space, solar, and astrophysical plasmas. Although shocks and magnetic reconnection are recognized as key processes, the detailed mechanisms and the partitioning of energy between ions and electrons remain unresolved. Using coupled theoretical and observational scaling analyses, we show that a simple relation, $\Delta\varepsilon = qVBL$, captures plasma energization in a universal way, where $\Delta\varepsilon$ is the particle energy gain, q the particle charge, V the bulk flow speed, B the magnetic field strength, and L a characteristic length scale of energization. Different choices of L lead to distinct predictions: the system size gives the maximum particle energies, while a kinetic scale predicts heating (temperature increase ΔT) in shocks and reconnection, for both ions and electrons. Our results suggest broad applicability, from solar flares to supernova remnants and planetary magnetospheres, despite some assumptions and limitations. In addition, the scaling captures the essential MHD trends while revealing systematic deviations that point to kinetic effects beyond fluid models, highlighting promising directions for theoretical and simulation studies.

