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Energy pathways driven by Kelvin-Helmholtz instability

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Understanding how energy is dissipated in non-collisional or weakly collisional plasmas is a central challenge in plasma physics. Turbulence has gained increasing recognition as a key driver of energy transfer across scales, from large fluid-like motions down to kinetic scales where energy is ultimately dissipated. This cascade process plays a crucial role in the heating and dynamics of various space plasmas, including the solar wind, planetary magnetospheres, and the heliosheath[1]. As energy cascades to sub-ion scales, kinetic effects become increasingly dominant, involving complex interactions such as wave-particle interactions, reconnection, and Landau damping[2]. Despite significant advances in the field, the precise mechanisms through which turbulence dissipates energy and contributes to plasma heating remain poorly understood[3].

In this framework, a significant role is played by Kelvin-Helmholtz instability (KHI), a fundamental plasma instability driven by velocity shears and ubiquitous in both fluids and plasmas. Contrary to neutral fluids which are always unstable to KHI, in a magnetized environment, the magnetic field plays a crucial role acting as a stabilizer. As a driver of large-scale vortices along the boundary, KHI structures contribute to mass and momentum transport, enabling plasma mixing that would otherwise be limited in a highly magnetized environment[4]. Moreover, as the instability evolves, the nonlinear interaction of modes produce an energy cascades from large-scale vortices to smaller kinetic scales, where dissipation mechanisms such as wave-particle interactions and reconnection heat the plasma. The nonlinear evolution of KHI-generated vortices can trigger secondary processes, such as the formation of thin current sheets, magnetic reconnection, and the onset of turbulence[5].

Both numerical simulations and in situ observations have revealed the role of vortex-induced turbulence and reconnection[6,7], as well as enhanced energy transfer across scales and distortions in velocity distribution functions in terms of field-aligned beams[8, 9, 10, 11]. Despite these advances, the precise pathways through which KHI facilitates energy conversion, particle energisation, as well as the channels through which the available free energy is dissipated remain elusive. It is therefore crucial to understand the nonlinear evolution of KHI and its contribution to energy conversion to shed more light on how energy is eventually dissipated in weakly collisional plasmas. These results would be also critical to better understand the coupling of solar wind to planetary magnetospheres. Using cutting-edge Magnetospheric MultiScale (MMS) spacecraft data, we explore energy conversion pathways in KHI at Earth's magnetopause during southward interplanetary magnetic field conditions. At ion scales, compressional waves and enhanced energy conversion between flow and thermal energy are observed within vortices, associated with both local non-thermal features and perpendicular temperature anisotropies. A net transfer into fluid flow energy through compressional channels is also evident. In contrast, at the vortex boundaries, enhanced magnetic fluctuations coincide with peaks in ion agyrotropy and a net energy transfer into thermal energy. Interestingly, the nature of the energy conversion channels inside the vortices appears to depend on their evolutionary stage: rolled-up vortices convert flow energy into free random energy, while earlier-stage vortices convert thermal energy into flow energy. Our findings provide insights into how shear flow energy is ultimately dissipated into heat, revealing the complex dynamics of KHI-driven turbulence.

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