Vortex-magnetic interactions of flux tubes in magnetohydrodynamics

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The complex interplay between vortices and magnetic fields fundamentally shapes the magnetohydrodynamics (MHD). At high Reynolds numbers, both vorticity and magnetic fields are nearly frozen into the charged fluid, moving with it like non-diffusive dyes. In MHD, the motion of the charged fluid is driven by the competition between vorticity-induced flows and Lorentz forces from the magnetic field, resulting in coherent structures and vortex dynamics distinct from those in hydrodynamics[1].

Using magnetic flux tubes of varying strengths imposed on a pair of anti-parallel vortex tubes, we investigate the interaction between vorticity and magnetic fields across a wide range of interaction parameters *N*—a dimensionless measure of the relative strengths of inertial and Lorentz forces[2]. Initially, both the vorticity and magnetic field are confined to the same tubular regions of the fluid (Figure 1a). For small interaction parameters, classical vortex dynamics dominate, and the vortex tubes, carrying the magnetic flux tubes, undergo a vortex-magnetic joint reconnection akin to classical vortex reconnection[3] (Figure 1b). This process leaves remnants of the original tubes as threads and triggers a dynamo effect, leading to an increase in magnetic energy. At moderate interaction parameters, the fluid oscillates between vorticity-induced attraction and magnetic damping, resulting in instabilities and nonlinear interactions that generate secondary filaments and energy cascade (Figure 1c). At high interaction parameters, the interaction between anti-parallel flux tubes is suppressed, causing the tubes to align axially. The magnetic field disrupts the vortex core, rapidly converting magnetic energy into kinetic energy. (Figure 1d).

This study reveals how the interplay between vorticity and magnetic fields in MHD is governed by the relative strengths of inertial and Lorentz forces, uncovering distinct energy transfer mechanisms and coherent structure dynamics. These findings advance our understanding of MHD turbulence and have implications for astrophysical plasmas.

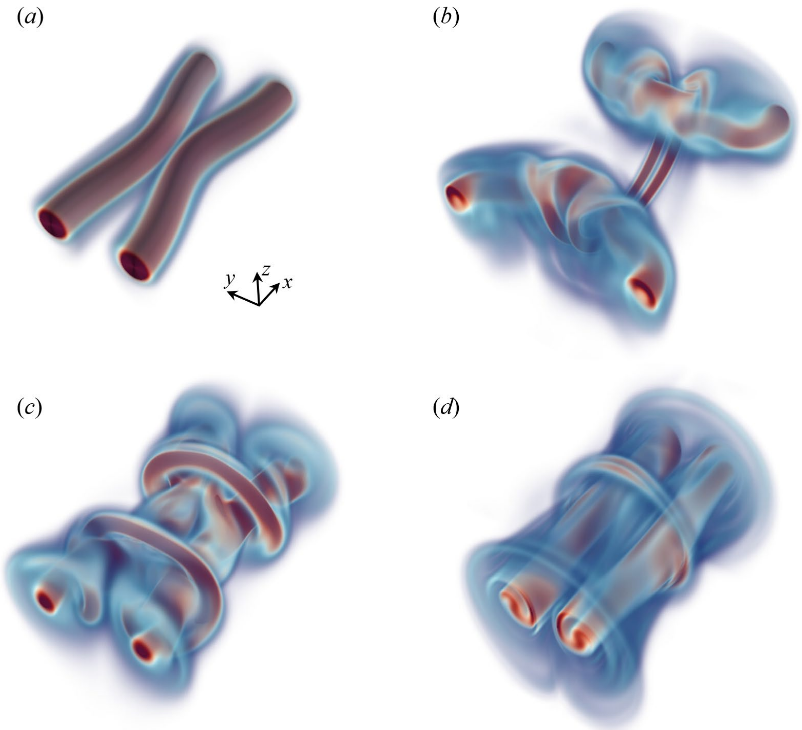

Figure 1: Vorticity modulus of simulated interacting flux tubes in MHD: (*a*) initial configuration, (*b*) reconnection at low interaction parameters *N*, (*c*) cascade at moderate *N*, and (*d*) damping at high *N*.

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[1]Shen et al., *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2405351121 (2024)
[2]Kivotides, *Phys. Rev. Fluids* **3**, 033701 (2018)
[3]Yao and Hussain, *Annu. Rev. Fluid Mech.* **54**, 317-347 (2022)