TURBULENT RECONNECTION IN ASTROPHYSICAL PLASMAS AND QUANTUM FLUIDS

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Abstract Understanding the origin and the mechanism of reconnection process in collisionless media such as astrophysical plasmas and superfluids remains one of the major challenges in physics. By comparing the induction equation for astrophysical plasmas with the smoothed vorticity equation for superfluids, the possible role of turbulence in triggering collisionless reconnection is highlighted.

Collisionless reconnection

Spontaneous topology change induced by the phenomenon of reconnection can be found in various systems in nature. Vortex filament reconnection in ordinary fluids is an example, in which two filaments with different vortex sense meet at a spatial point and reconnect the filaments to each other (Fig. 1). The reconnected filaments have a strong curvature and jet flow is formed, streaming away from each other to relax the filament curvature. Reconnection events can also be found in different kinds of media such as superfluid (as realized by the low-temperature liquid helium state), plasmas and magnetic fields in laboratory, space, and astrophysical systems, and liquid crystal directors [1]. In particular, the superfluid and the astrophysical plasma are collisionless medium in that binary collisions of particles are lacking due to Bose-Einstein condensation and extremely low density, respectively. The collisionless medium has no viscosity, i.e., such a medium has no friction. Naively speaking, collisionless state forbids reconnection to occur because the topology of field line configuration must be conserved, as formulated in Kelvin's circulation theorem or Alfvén's frozen-in magnetic field theorem. In reality, however, reconnection events are observed both in superfluids and in astrophysical plasmas. In search of the origin and the mechanism of collisionless reconnection, a comparison study is given here between the induction equation for collisionless plasmas and the vortex equation in superfluids [2].

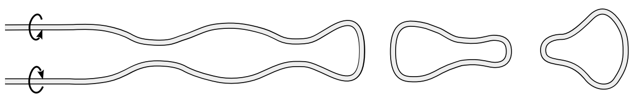

Figure 1. Sketch of the Crow instability in which anti-parallel vortex filaments develop into vortex rings through reconnection in an ordinary fluid with finite viscosity. Reproduced from Ref. [2].

Magnetic reconnection

Magnetic reconnection represents the breakdown of the frozen-in magnetic field. The motion of the magnetic field lines is described by the induction equation. In the two-fluid approximation regarding electrons and ions as distinct fluids, the induction equation is evaluated using the generalized Ohm's law [3], and is expressed as

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B} + \nabla \times \left(\frac{1}{n_\mathrm{e} e} \boldsymbol{j} \times \boldsymbol{B} - \frac{1}{n_\mathrm{e} e} \nabla \cdot \mathsf{P}_\mathrm{e} + \frac{1}{\epsilon_0 \omega_\mathrm{pe}^2} \frac{\partial \boldsymbol{j}}{\partial t} \right). \tag{1}$$

The left-hand side describes time evolution (or time derivative) of the magnetic field $\boldsymbol{B}$. The right-hand side describes different processes that contribute to the magnetic field evolution. The first term represents the convection of the field by the flow velocity $\boldsymbol{u}$ in the direction perpendicular to the field. The second term represents the diffusion of the field due to the finite resistivity η. Here, the resistivity may be anomalous caused by wave-particle scattering in the plasma [4]. The third term with the curl operator is effective on smaller spatial scales of the order of the electron to ion gyroradii. In near-Earth space (interplanetary space) the electron gyroradius is of the order of 10 km and the ion gyroradius 100 km. Three terms inside the bracket in the third term represent the electric fields arising from particle motions. The first small-scale term is the Hall electric field due to the separate motions of electrons and ions, and is determined by the electron number density n_e, the charge e, the current $\boldsymbol{j}$, and the magnetic field $\boldsymbol{B}$. The second small-scale term is the electric field due to the pressure anisotropy (with respect to the large-scale magnetic field) or stress of the electron fluid such as ambipolar electric field, and is determined by the electron pressure tensor P_e. The last small-scale term is the electric field due to the inertia of electrons in the time-varying current with the permittivity of free space ϵ_0 and the electron plasma frequency ω_pe as coefficients. Although any of these four processes (the anomalous resistivity, the Hall effect, the electron pressure tensor, and the electron inertia) may trigger magnetic reconnection [5], it is important to notice that wave-particle scattering in plasma turbulence is a likely candidate to trigger magnetic reconnection.

Quantum vortex reconnection

The fluid equation (in the form of compressible Euler equation) can be obtained for superfluids through the Madelung transformation of the Gross-Pitaevskii equation [2]. The superfluid is a potential flow derived from the gradient of the quantum mechanical phase, and the flow is necessarily irrotational with the vanishing vorticity $\boldsymbol{\omega} = \nabla \times \boldsymbol{u} = 0$. Quantum vortex filaments exist nevertheless. The reason is that the topological defect such as the local breakdown of superfluidity occurs in the core of the filaments. The uniqueness of the wavefunction phase imposes the quantization of the flow circulation to the Planck constant h divided by the particle mass m, $\Gamma = \oint \boldsymbol{u}\, \mathrm{d}\boldsymbol{\ell} = hL/m$ ($L = 1, 2, \cdots$). The vorticity equation is therefore trivial ($\boldsymbol{\omega} = 0$). However, by bundling many vortex filaments, it is possible to construct a non-trivial vortex equation. By decomposing the vorticity into the smoothed (or bundle-averaged) field $\bar{\boldsymbol{\omega}}$ and the small-scale fluctuations $\delta\boldsymbol{\omega}$, one may incorporate the concept of turbulent viscosity into the smoothed vorticity as

$$\frac{\partial \bar{\boldsymbol{\omega}}}{\partial t} = \nabla \times (\bar{\boldsymbol{u}} \times \bar{\boldsymbol{\omega}}) + \nu_{\mathrm{T}} \nabla^2 \bar{\boldsymbol{\omega}}, \tag{2}$$

That is, if the quantum fluid is set to fully-developed turbulence, one may apply the notion of the turbulent or eddy viscosity ν_{T} appearing in the one-point closure model or the Reynolds stress model.

Concluding remarks

The superfluid vorticity is zero on the microscopic scale, yet, the bundle treatment of vorticities enables one to compare the vorticity equation with the induction equation for collisionless plasmas. Turbulence is closely related to collisionless reconnection. The scenario of turbulent reconnection is one of the possible mechanisms of magnetic reconnection in collisionless plasmas as well as macroscopic vortex reconnection in quantum fluids. In this scenario, turbulent fluctuations are excited first, and then reconnection is induced by turbulence (Fig. 2). Various methods exist to evaluate the turbulent diffusivity. For collisionless plasmas, one may evaluate the anomalous resistivity by modeling the wave mode, the particles, and the resonant types [4, 6]. Or one may also derive the transport coefficients from the fundamental fluid equations (hydrodynamics, magnetohydrodynamics) on the basis of elaborated closure theory such as Direct Interaction Approximation (DIA) and Two-Scale Direct Interaction Approximation (TSDIA) [7, 8, 9].

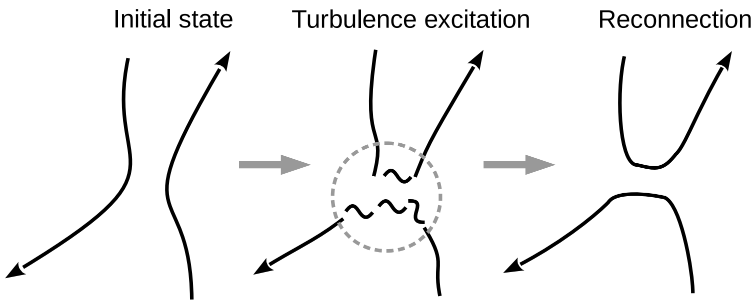

Figure 2. Sketch of turbulent reconnection.

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