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Dynamo in weakly collisional non-magnetized plasmas impeded by Landau damping of magnetic fields

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The energy density corresponding to the microgauss magnetic field permeating the Universe at galaxy cluster scales is comparable to that of the turbulent flows. This approximate equipartition of magnetic and directed kinetic energies is consistent with the field being generated and maintained by a turbulent dynamo. Because of the multiscale and inherently three-dimensional nature of dynamos, they have almost exclusively been studied within the framework of magnetohydrodynamics (MHD), with notable exceptions using kinetic-fluid hybrid approaches[1,2].

We perform fully kinetic simulations[3,4] (i.e. protons and electrons are kinetic at physical mass-ratio) of flows known to produce dynamo in magnetohydrodynamics (MHD), considering scenarios with low Reynolds number and high magnetic Prandtl number, relevant for galaxy cluster scale fluctuation dynamos. The simulations employ the kinetic-Maxwell solver[5] of the Gkeyll[6] plasma physics simulation framework, which applies a discontinuous Galerkin method to solve the kinetic equation. Inter- and intraspecies Coulomb collisions are modeled by a conservative Lenard-Bernstein operator[7].

We first consider the time-dependent Galloway-Proctor[8] (GP) flow that produces a fast dynamo and has a low critical magnetic Reynolds number. We choose plasma parameters corresponding to a magnetic Reynolds number Rm=13 and magnetic Prandtl number of Pm=20, assuming a Spitzer resistivity and a collisional viscosity. We initialize the simulation with isothermal Maxwellian species with a subsonic flow corresponding to the GP flow, while currents are deposited as electron flows, consistent with the initial random magnetic perturbations. The time dependent flows are sustained using forcing on the ions, applied directly on the acceleration term in the kinetic equation.

For a physically identical setup, resistive MHD simulations using the Pencil Code[9] produce dynamo with exponentially growing magnetic field energy after one turnover time. However, in the kinetic simulations we find that Landau damping of magnetic fluctuations on the electrons leads to a rapid decay of magnetic perturbations, impeding the dynamo. This collisionless damping process operates on spatial scales where electrons are nonmagnetized, reducing the range of scales where the magnetic field grows in high magnetic Prandtl number fluctuation dynamos.

In magnetic diffusion tests we demonstrate that Gkeyll simulations accurately reproduce both the collisional limit, where magnetic field diffusion is caused by Spitzer resistivity, as well as the collisionless limit, where magnetic field decay is caused by Landau damping[10]. We show that the electric field causing the field dissipation is balanced by electron viscous stress, implying that isothermal electron fluid models would not be suitable to capture the phenomena. We also show how the effect of Landau damping diminishes as the plasma becomes magnetized.

Finally, we consider the implication of Landau damping on fluctuation dynamos with asymptotically large Pm. When magnetic fields in the universe were comparable to typical seed field estimates (assuming Biermann battery), the typical electron Larmor radius was comparable to the electron mean free path, allowing for magnetic perturbations to be Landau damped on kinetic scales. When electrons are not magnetized down to the resistive scale, the magnetic energy spectrum is expected to be limited by the scale corresponding to magnetic Landau damping or, if smaller, the electron gyroradius scale, instead of the resistive scale.

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