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Fluctuation dynamo in collisionless and weakly collisional, magnetized plasmas

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The amplification of cosmic magnetic fields by chaotic fluid motions is hampered by the adiabatic production of magnetic-field-aligned pressure anisotropy. This anisotropy drives a viscous stress parallel to the field that inhibits the plasma's ability to stretch magnetic-field lines. However, in high-β plasmas, kinetic ion-Larmor scale instabilities—namely, firehose and mirror—sever the adiabatic link between the thermal and magnetic pressures, reducing this viscous stress and thereby allowing the dynamo to operate. We identify two distinct regimes of the fluctuation dynamo in a magnetized plasma: one in which these instabilities efficiently regulate the pressure anisotropy so that it does not venture much beyond the firehose and mirror instability thresholds, and one in which this regulation is imperfect. Using kinetic and Braginskii-MHD simulations and analytic theory, we elucidate the role of these kinetic instabilities and determine how the fields and flows self-organize to allow the dynamo to operate in the face of parallel viscous stresses. In the case of efficient pressure-anisotropy regulation, the plasma dynamo closely resembles its more traditional $\mathrm{Pm} \sim 1$ MHD counterpart. When the regulation is imperfect, the dynamo exhibits characteristics remarkably similar to those found in the saturated state of the MHD dynamo. An analytical model for the latter regime is developed that exploits this similarity. The model predicts that the plasma dynamo ceases to operate if the ratio of field-aligned to field-perpendicular viscosities is too large, a behavior confirmed by numerical simulation. Leveraging these results, we construct a novel set of microphysical closures for fluid simulations that bridges these two regimes—one that exhibits explosive magnetic-field growth caused by a field-strength-dependent viscosity set by the firehose and mirror instabilities.

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