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Large-Scale Dynamos and Magnetic Helicity: Principles and Relevance to Coronae, Outflows, and Laboratory Plasmas

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Dynamos are studied by astrophysical, planetary, and fusion communities but the differences between dynamo types can be a source of confusion. To elucidate the relationship between the different dynamos, I divide dynamos into three categories e.g. [1]: 1. Nonhelical flow-driven dynamos which amplify fields on scales at or below the driving turbulence; 2. Helical flow-driven dynamos which amplify or sustain large scale magnetic fields in an otherwise turbulent flow. Traditional stellar, planetary, and Galactic dynamos aimed at explaining cycle periods and large-scale fields fit into this category; 3. Magnetically dominated helical dynamos, which sustain the large-scale magnetic field against resistive decay and evolve the magnetic geometry toward the lowest energy state. All three types occur in astrophysics whereas laboratory plasma dynamos in fusion devices are of type 3. Type 1 dynamos requires no helicity of any kind.

Focusing on type 2 and 3 dynamos, which both require a mean magnetic field aligned electromotive force, I will then discuss how different limits of a unified set of equations for magnetic helicity evolution reveal simple dynamos of both types. Dynamos that systematically amplify or sustain fields on spatial or temporal scales larger than those of the fluctuations involve a spatial or spectral transfer of magnetic helicity. (first apparent in Ref. [2] for type 2 dynamos.) Examples of steady-state vs. time dependent dynamos in the presence and absence of boundary terms and the influence on dynamo saturation will be discussed. For the simplest closed volume cases, type 2 dynamos involve the spectral segregation of opposite signs of magnetic helicity, while type 3 dynamos involve transport of net magnetic helicity from small to large scales.

The magnetic helicity framework and associated results are part of a growing body of work that reflects how magnetic helicity has emerged as a useful tool for understanding the operation and nonlinear evolution of large-scale dynamos (see [3] for a review). It is important to distinguish practical modeling of planetary and stellar dynamos, where the immediate aim is to specifically reproduce observations, from idealized studies of simple dynamos aimed at understanding the theoretical principles of nonlinear saturation. It is hoped that insights gained from the latter can eventually be incorporated into the former.

In this context, idealized type 2 MHD dynamo simulations of α^2 dynamos in periodic boxes by several groups e.g. [4, 5] have shown that when MHD turbulence is forced with sufficient kinetic helicity, the saturated magnetic energy spectrum evolves from having a single peak below the forcing scale to become doubly peaked, with one peak at the system (= largest) scale and one at theforcing scale. If we are eventually to understand the nonlinear saturation in a realistic helical dynamo with a practical theory, we should assess whether such a theoretical framework can first explain the saturation in simple numerical experiments. Toward this end, finite scale approximations to the dynamical evolution of the magnetic spectra have proven to be useful. Simple two scale dynamical models incorporating magnetic helicity evolution capture saturation quite well [6]. However, modeling the relative shift of the small-scale magnetic peak with respect to the small scale velocity peak at early times requires at least a three scale helical dynamo theory [7]. The three scale approach does show that the small-scale helical magnetic energy first saturates at very small scales, but then successively saturates at larger values at larger scales, eventually becoming dominated by the forcing scale. The transfer of the small-scale peak to the forcing scale is completed by the end of the kinematic growth regime of the large-scale field, and does not depend on magnetic Reynolds number R_M for large R_M. The three and two-scale theories evolve almost identically at late times, both consistent with the late time doubly humped “camel” magnetic spectra seen in simulations.

Next I will discuss how type 2 and type 3 dynamos can act together in a two-stage helical dynamo framework for growing the large-scale magnetic fields of coronal cycles, coronal holes, and astrophysical jets [8]. Jet and coronal hole fields are of large scale with respect to that of their anchoring rotators and in both stars and disks, and these fields are unlikely to result from simple flux accretion from the material that formed the rotator: In the sun, the solar cycle reversals prove that the field must be regenerated in situ. In disks ,the field can diffuse faster than it is accreted in the absence of in situ generation.

The two stage, large-scale field formation paradigm is this: First, a type 2 velocity driven helical dynamo amplifies fields of large enough scale that they buoyantly rise and supply magnetic helicity to the to the corona [9, 10] without being shredding by turbulent diffusion. Once in the corona, continued footpoint motions can further twist the field and inject more magnetic helicity. The loops respond by rising or opening to larger scales. Coronal mass ejection (CME) type events can be associated with this evolution if instability occurs. Such field evolution in the corona is in fact a type 3 dynamo. Disks and stars act as helicity injecting boundaries to their magnetically dominated corona, a circumstance directly analogous to Spheromak formation in the laboratory. In short, global fields of stars and disk involve a type 2 dynamo inside the rotator, which injects magnetic helicity into a type 3 dynamo in the corona. Note that we observe the exterior field, not the interior field for all astrophysical rotators except our Galaxy.

Finally, I will briefly mention some work on interface dynamos in supernovae [11]. For protosupernovae unlike the sun, the backreaction on the differential rotation is important in limiting the lifetime of the dynamo. These supernovae interface dynamos are explosive, not steady, and highlight processes that might account for the observed bipolar outflow asymmetry in explosive end states of stars.

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