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Tides induced magnetic field in the solar system

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Abstract

The elliptical instability can take place in planetary cores and stars elliptically deformed by gravitational effects, where it generates large-scale three-dimensional flows assumed to be dynamo capable. In this work, we present the first magneto-hydrodynamic (MHD) numerical simulations of such flows, using a finite-element method. We first validate our numerical approach by comparison with kinematic and dynamic dynamos benchmarks of the literature. We then systematically study the magnetic field induced by various modes of the elliptical instability from an imposed external field in a triaxial ellipsoidal geometry, relevant in a geo- and astrophysical context. Finally, we present our first steps towards demonstrating the existence of a tidal dynamo. Results for the solar system are presented and discussed.

1. Introduction

Many celestial bodies possess their own magnetic field, either by induction from an external field, or by a natural dynamo mechanism. On Earth today, the magnetic field is very likely generated by thermo-chemical convective motions within its conductive liquid core, driven by the solidification of its inner core. However, the origin of the magnetic field in the Early Earth, in the Moon or in Ganymede is more uncertain, and leads to the consideration of alternative dynamo mechanisms [1]. The recent discovery of fast magnetic reversals on the extra-solar star Tau-boo [2], which may be related to strong tidal effects due to the presence of a massive close companion, also requires to re-evaluate classical models of convective dynamos. Indeed, even when the dynamo is of a convective origin, the role of other driving mechanisms can be very important in the organization of fluid motions.

The elliptical instability is an instability affecting any rotating fluid whose streamlines are elliptically deformed [3]. A fully three-dimensional turbulent flow is excited in the bulk as soon as (i) the ratio between the ellipticity β of the streamlines and the square root of the Ekman number E is larger than a critical value of order one and (ii) a difference in angular velocity exists between the mean rotation of the fluid and the elliptical distortion. In a planetary context, the ellipticity of streamlines is related to the tidal deformation of the planetary layers. A differential rotation is generically present between the core fluid and the dynamic tides in non-synchronized systems; it also appears between the static bulge and the core fluid because of librations in synchronized ones. The elliptical instability is then refereed to as tide driven elliptical instability (TDEI) and libration driven elliptical instability (LDEI), respectively. So far, MHD simulations of planetary dynamos have been performed in spherical, and recently spheroidal, geometries, which allows relatively fast computations (spectral methods) but also prevents any elliptical instability. To study its MHD consequences, we have thus developed the first numerical MHD simulations in a triaxial ellipsoidal geometry, using a finite element method.

2. Validation of the model

Our numerical model has been validated against different MHD test-cases. First, kinematic dynamo validations have been successfully obtained on both Ponomarenko and Von Karman driving flows. The validation has then been extended to dynamic dynamos considering the usual convective numerical benchmark of [4]. The classical spin-over mode of the elliptical instability has then been considered because analytical and experimental results are available in the literature [5, 6]. An excellent quantitative agreement is found on both the reduction of the growth rate due to the Joule damping and on the amplitude of the induced magnetic field and of the MHD flow at saturation. These various tests confirm that our numerical model correctly sim-

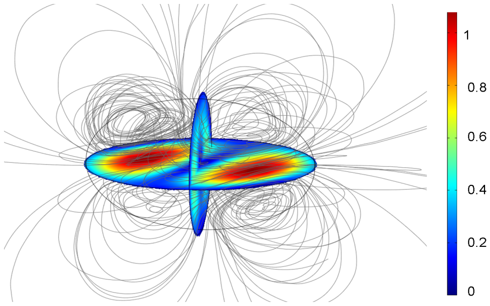

Figure 1: MHD numerical simulations of the mode (1,3) of the TDEI in a triaxial ellipsoid, with an uniform magnetic field imposed along the rotation axis. The norm of the induced magnetic field (normalized by its maximum value) is represented on slices at the saturation of the mode (1,3). Magnetic field lines are also shown.

ulates both the induced field and its retroaction on the flow.

3. Induced magnetic field by complex modes of the elliptical instability

We are now in a position to go further in studying induction by more complex elliptically driven flows, as relevant for planetary applications [7]. Apart from the spin-over mode, no theoretical global approach has yet been developped for other modes of the elliptical instability. Combining our numerical simulations with a local WKB analysis, we study the threshold and the induced magnetic field for the so-called $(1,3)$ mode of TDEI (figure 1), excited when the polar flattening is taken into account, and for various modes of the LDEI, expected in synchronized moons [7]. We show for instance that the induced field by LDEI generates magnetic fluctuations in the vicinity of Europa [8, 9], and could provide an alternative explanation for the signal measured by the Galileo mission, in addition to the plasma currents model usually considered in the literature [8].

4. On-going studies

Following our induction studies, the next step of our numerical study is to determine whether or not the elliptical instability is dynamo capable. To answer this question, and starting from an induction configuration, we can suddenly shut down the externally imposed magnetic field and report the decay/growth rate of the induced magnetic field as a function of the magnetic Reynolds number. These first results are encouraging and the expected dynamo ability of the elliptical instability could explain the magnetic field of the Moon [10] or the fast magnetic signal of the star Tau-boo [2].

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