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Flows driven by libration, precession, and tides in planetary cores*

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Understanding the flows in planetary cores, i.e., the large liquid iron oceans hidden in the central part of terrestrial planets, is a tremendous interdisciplinary challenge, at the frontier of fundamental fluid dynamics and planetary sciences. Beyond buoyancy driven flows that constitute the standard model for core fluid dynamics, an increasing amount of research has focused on the rotational dynamics of these spinning systems, periodically perturbed by tides, precession, and libration. Although of small amplitude, those harmonic forcings are capable of exciting resonant instabilities in planetary cores, providing alternative routes towards turbulence and magnetic field generation. In this paper I provide an overview of some recent works on this field, focusing on the mechanisms of tide and libration driven elliptical instabilities. Combined laboratory experiments and pioneering numerical simulations have allowed a full description of the stability and linear state of these flows, as well as the investigation of some convincing planetary applications. Open questions now remain regarding the nonlinear saturation of the excited flows as well as their dynamo capability. These will undoubtedly be the focus of future research, in the context of intense activity in planetary exploration of our solar system and others, which highlights the need to go beyond the standard convective models.

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I. SOME CHALLENGES AND OPEN QUESTIONS IN THE FLUID DYNAMICS OF PLANETARY CORES

A large number of celestial bodies are made of a metallic, mostly iron, central core, surrounded by a solid silicate mantle. Examples include Earth, the inner planets of the Solar System, the Moon and some of the large moons of Jupiter (Io, Europa, and Ganymede), large asteroids (e.g., Vesta, as revealed by the recent Dawn mission [1]), and presumably super-Earths in extrasolar systems (see, e.g., [2]). In all cases, the metal compound was liquid when the core formed during planet accretion and the core has remained liquid during some period whose duration depends on the planet size, the core chemical content, etc. For instance, the cores of the Earth and Moon are still partly liquid presently, as proven by seismic studies (e.g., [3]). Understanding the fluid dynamics of planetary cores, from their formation up to their present dynamical state, remains a tremendous challenge in planetary fluid dynamics, despite more than half a century of intense research. Beyond the challenge in fundamental fluid dynamics to understand these extraordinary flows involving turbulence, rotation, and/or buoyancy effects at typical scales well beyond our day-to-day experience, a global knowledge of the involved processes is fundamental to a better global understanding of the dynamics of planets. Indeed, the flow driven by buoyancy and/or rotation in the core significantly influences the planet's thermal and orbital evolution because of heat advection, viscous dissipation, coupling with the overlying mantle, solidification, etc. Also, fluid motions in conducting liquid cores are the main mechanism for generating planetary magnetic fields through dynamo action, one of the essential ingredients for planetary habitability.

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The main obstacle to quantitative modeling and understanding of planetary core flows stands in the extreme value of the involved physical dimensionless parameters. For instance, typical present-day flows at the Earth's core surface have a Reynolds number (measuring the relative importance of flow nonlinearity compared to viscous effects) $\mathrm{Re} = UR/\nu \simeq 10^9$, where ν is the core viscosity, R its radius, and U a typical velocity given by the measured drift of magnetic patterns at the core surface: Core flows are thus highly turbulent. Another relevant dimensionless parameter is the Ekman number, which quantifies the relative importance of viscous and Coriolis forces: $E = \nu/\Omega R^2$, where Ω is the planet rotation rate (spin). Earth is a fast rotator with $E \simeq 10^{-15}$. Schematically, even with the most powerful computational tools, direct numerical simulation becomes barely feasible above $\mathrm{Re} \simeq 10^6$ and/or below $E \simeq 10^{-6}$, and at this level, a single computational run takes months for a few turnover times, which is not long enough to develop a converged statistical description of the flow. Studies relevant to planetary flows rely on the general principle of dynamical similitude and scaling laws, supported by asymptotic theory: Rather than reproducing in a model the exact parameters of a planetary flow, the effort is focused on reaching the same dynamical regime, with the correct balance of forces. A systematic exploration of the parameter space then allows for the derivation of generic scaling laws that are extrapolated towards planetary scales and challenged against available data (e.g., [4]). In this approach, laboratory experiments are especially useful because they reach more extreme values of the relevant parameters and more extreme levels of turbulence than simulations. In addition, experiments allow for the systematic exploration of the parameter space using very long data acquisition. The drawbacks are of course the difficulty in data acquisition and the limitations of accessible geometries and physics compared to simulations. Both approaches, underlined by theoretical analyses, are thus fully complementary.

Since the seminal analytical works of Roberts [5] and Busse [6], most research on the fluid dynamics of planetary cores has focused on convection. Indeed, buoyancy is naturally present in planetary cores because of both radiogenic and primordial heat and thermal convection takes place providing the temperature profile is superadiabatic. In addition, while planetary cores are mostly made of iron, they may also include some amount of light elements: Convection may then be driven by thermal energy and light elements released during the solidification of this alloy. Early analytical works (e.g., [6]), complemented by innovative laboratory experiments (e.g., [7,8]) and numerous direct numerical simulations (e.g. [9]), have provided a clear picture of the convective flow organization in a rapidly rotating spherical shell, at least for moderate values of the Ekman number and of the supercritical Rayleigh number (i.e., the ratio between buoyancy and diffusive forces). One of the most significant outcomes of this research was to demonstrate that those convective flows in an electrically conducting fluid can generate a dynamo [9]. Today the most advanced numerical models, supported by asymptotic theory and by a new generation of large-scale experiments, succeed in addressing the highly nonlinear convective regimes (see, e.g., [10–12]), where the buoyant flows excited at small scale build up large vorticity structures, of importance for sustaining the dynamo effect [13].

The convective dynamo model has proven successful to explain the Earth's magnetic field, its dipolar shape and amplitude, and the existence of polar reversals (see [14] and references therein). The same model has been applied to other planetary cores. However, its results are sometimes difficult to reconcile with available observational data and its validity can be questioned in many planetary configurations. For instance, the evolution of the Earth's thermal state is still controversial and the associated energy budget may appear difficult to reconcile with a convective dynamo, especially before the onset of inner core growth [15]. Also, the small size of the Moon and Ganymede makes it difficult to maintain a sufficient temperature gradient to sustain convection and to explain their past and present magnetic fields, respectively [16–18]. In addition, the unusually low amplitude of the magnetic field on Mercury is difficult to explain with the standard scaling laws derived from convective models [19]. More generally, and even in planets where convection is present, it is of fundamental importance to also explore the role that other instabilities play in the organization of core flows.

A huge amount of energy is stored in the rotational motion of planets (spin and orbit) and one could thus rely on this reservoir to sustain intense core flows. For instance, the rotational energy of the Earth-Moon system is approximately 1.7×10^{29} J, while the power necessary to sustain the present-day magnetic field of Earth is approximately 10^{11} W. Hence, less than 8% of the available rotation energy is necessary to sustain the dynamo over the age of Earth. The question is how the system can extract energy from its rotation to drive intense fluid flows? If planets were perfectly nondeformable systems rotating with a perfectly constant rotation vector, their fluid layers would behave rigidly and rotate as solid bodies. This is never the case. The rotation of a real celestial body is always perturbed by gravitational interactions with its companions, which generate periodic perturbations of its shape (i.e., tides), of the direction of its rotational vector (i.e., precession), and of its rotation rate (i.e., libration and length-of-day variation). Those three types of perturbations are generically called harmonic or mechanical forcings. Malkus [20–22] was the first to highlight the relevance of those harmonic forcings for planetary core flows, but his work was at that time largely rejected, owing to a misunderstanding on the associated energy balances, as later elucidated by [23]: Critiques indeed focused upon establishing the energetic irrelevance of the laminar response to mechanical forcing, rather than considering the fully turbulent case, which is significantly more energetic and thus more relevant for planetary bodies. The key point is that small mechanical forcings do not provide the energy to drive the flows: They play the role of conveyers that extract part of the available rotational energy and convert it into intense fluid motions, generated by rotational fluid instabilities. Since the reestablishment of Malkus's seminal ideas in the late 1990s, the fluid dynamics driven by mechanical forcing have been the subject of a growing interest in the fluid dynamics and planetary sciences communities, combining analytical, experimental, and numerical studies (e.g., [24–27]). In this paper I provide an overview of some recent research and established results in this domain, followed by a personal prospect of needed future works, focusing specifically on the elliptical instabilities driven in planetary cores by tides and libration.

II. TIDE AND LIBRATION DRIVEN ELLIPTICAL INSTABILITIES: WHAT DO WE KNOW?

Planetary cores, like any rotating fluid, support eigenmodes of oscillation called inertial modes, whose restoring force is the Coriolis force and whose frequencies in the rotating frame of reference range between plus and minus twice the spin frequency. Those modes are usually damped by viscosity, but they can be resonantly excited by the small, yet regular, harmonic forcings of libration, precession, and tides (see, e.g., the review [28]). Let us consider, for instance, a planet with an orbiting moon along an elliptical orbit (Fig. 1), both having a solid mantle and liquid core. Gravitational interactions produce tides on the planet and moon, i.e., give an ellipsoidal shape to all layers, including surfaces and core-mantle boundaries. Most large planets are nonsynchronized, i.e., their spin and the moon's orbital rate are different: So the rotation rate of the fluid core and of its tidal distortion are different. As a result, the base flow in the planet core, in the frame of reference where the elliptical deformation is stationary, consists in a rotation along two-dimensional elliptical streamlines. On the contrary, most moons are synchronized, i.e., their spin equals their orbital rate. Hence, they always show the same side to their planet, their tidal distortion is frozen in their mantle, and the rigid ellipsoidal moon rotates as a whole at a constant rate. However, this is only true on average: Due to the eccentricity of its orbit, the moon's orbital rate varies along the orbit following Kepler's third law and a restoring torque affects the moon's spin, which actually undergoes small oscillations around its mean value, called librations. The moon's core base flow in the frame of reference where the elliptical deformation is stationary then consists in oscillations along two-dimensional elliptical streamlines. More information about the astrophysical complexities behind this very schematic view can be found, for instance, in [29]. Here we simply notice that the two configurations described above have the basic ingredients for exciting the generic elliptical instability, described, for instance, in [30]: As is well known for unbounded vortices in various contexts ranging from wakes to turbulence, such elliptical base flows can nonlinearly resonate with two inertial modes of the rotating fluid, giving rise to three-dimensional flows and turbulence.

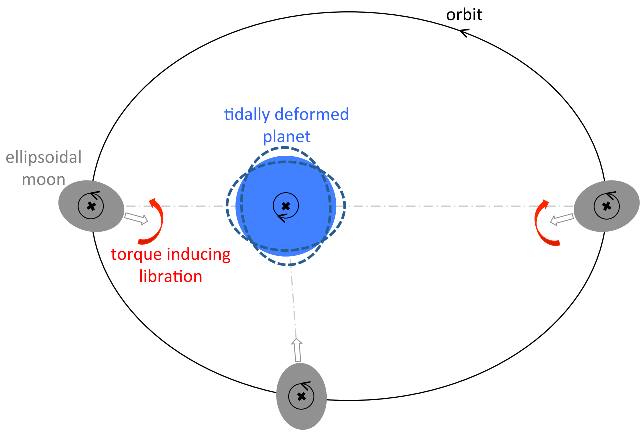

FIG. 1. Schematic representation of a planet-moon system with an elliptic orbit (top view), illustrating the tidal distortion of the planet, the frozen-in ellipsoidal shape of the moon, and the libration induced by the gravitational torque (for more details see, e.g., [31]). All angles and dimensions have been exaggerated for clarity.

From an analytical point of view, the elliptical instability can be tackled by two different approaches. The global approach consists in decomposing the fluid motions as the elliptical base flow plus some inertial modes and then looking for resonances. Instability takes place when the nonlinear interaction between the base flow and some inertial mode A excites an inertial mode B, while the nonlinear interaction between the base flow and mode B reinforces mode A. This is possible only when some resonance conditions are fulfilled: The frequency of the tides or libration forcing must be equal to the difference between modes A and B frequencies and the azimuthal wave number of the forcing (i.e., 2 for the elliptical flows considered) must be equal to the difference between modes A and B azimuthal wave numbers. Note that the former condition imposes a restriction on the possible range of exciting tide or libration frequencies, since inertial mode frequencies range between plus and minus twice the spin frequency in the spin frame of reference. As a complement to the global approach, the local approach quantifies the threshold and growth rate of the elliptical instability. Following the well-known Wentzel-Kramers-Brillouin method, it consists of looking for short-wavelength, plane-wave perturbations on the base flow. Additional complexities of planetary interest, such as the presence of a stable density profile and/or of an ambient magnetic field, can be straightforwardly introduced. Generic analytical formulas are obtained, in the range of frequencies where elliptical instability is possible [29]: The growth rate is proportional to the amplitude of the elliptical forcing (i.e., the product of the streamline ellipticity times the differential rotation of the fluid vs the elliptical distortion) minus the dissipative effects coming from viscous dissipation and possibly from Joule dissipation. The effect of a stable density profile is more complex, depending on the specific shape of gravitational isopotentials and isopycnals: A stratification can then either enhance or inhibit the elliptical instability.

These analytical results have been validated by experimental investigations, including those based on the two setups presented in Fig. 2 [31–34]. Figure 2(a) shows a laboratory model of a rotating planet, tidally deformed by an orbiting moon. It consists of a hollow sphere of radius 10 cm, cast in a silicone gel that is both deformable and transparent. The sphere is filled with water and set in rotation about its vertical axis at a constant angular velocity, up to 180 rpm. In addition, to generate a tidal deformation on the rotating fluid, two vertical cylindrical rollers are applied symmetrically on the sphere and rotate independently at a constant angular velocity, up to ±180 rpm. With this system, Ekman numbers down to 5×10^{-6} can be reached. In order to excite elliptical instability at this (relatively) large Ekman number in comparison with planets, the amplitude of the tidal

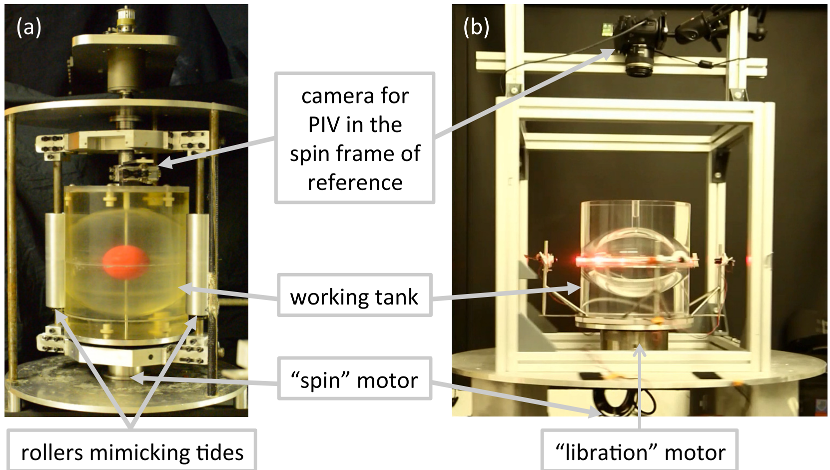

FIG. 2. Pictures of (a) the tide setup at IRPHE, France and (b) the libration setup at UCLA, USA (©A. Grannan). The typical radius of both tanks is 10 cm and the typical spin velocity is 30–180 rpm.

deformation β is exaggerated, up to 10^{-1}, while the corresponding planetary values are on the order of 10^{-7}–10^{-4}. Figure 2(b) shows a laboratory model of a librating planet. The working tank consists of a hollow ellipsoid of typical radius 10 cm, machined cast from acrylic and filled with water. Here also the harmonic forcing is replicated using two motors. The first motor rotates a turntable and superstructure at a constant angular velocity of 30 rpm, while the second superimposes a sinusoidal oscillation of the working tank. As in the tide experiments, the relatively large value of the Ekman number 2×10^{-5} is compensated for by an exaggerated amplitude of harmonic forcing, with an ellipsoidal deformation $\beta = 0.34$ and a libration angle up to 140°. Through a systematic exploration of the accessible parameter range, changing the amplitude and frequencies of the harmonic forcings, those two setups have validated the main conclusions of the analytical global and local approaches, using simple flow visualization, namely, the existence of a limited range of excitation frequency, the existence within this range of various flow resonances, and the validity of the threshold and growth rate formulas [31–35]. Recently, particle image velocimetry (PIV) measurements in the spin frame of reference have quantitatively validated the expected analytical base flow as well as the global mechanism for resonance by explicitly exhibiting the superimposition of two inertial modes [33,34].

The drawbacks in experiments are of course the difficulty in data acquisition (e.g., PIV remains up to now limited to two-dimensional measurements in a single equatorial plane) and the limitations of accessible geometries and physics (e.g., how to make a radial gravity field in a spherical geometry in the laboratory). Hence, laboratory approaches have been fruitfully complemented by numerical simulations. The great difficulty here stands in the specific geometry necessary to excite elliptical instability driven either by tides or libration. Indeed, most existing numerical tools for studying planetary cores dynamics assume an axisymmetry of the system around its rotation axis in order to use a fast and powerful spherical harmonics decomposition. Accounting for the ellipsoidal shape of flow streamlines in planetary cores necessitates tricky boundary conditions [36], virtual body forces to locally deform otherwise circular streamlines [37], or the use of alternative, less efficient, numerical methods. Over the past six years, significant results have been obtained using finite-element and spectral-element methods, addressing the full ellipsoidal geometry of planetary cores with Ekman numbers down to $E = 5 \times 10^{-5}$ [38–40] (see Fig. 3). Beyond further validating analytical results regarding base flow, mode coupling, threshold, and growth rate, those simulations have tackled configurations of planetary interest, but out of reach of laboratory investigations: for instance, the

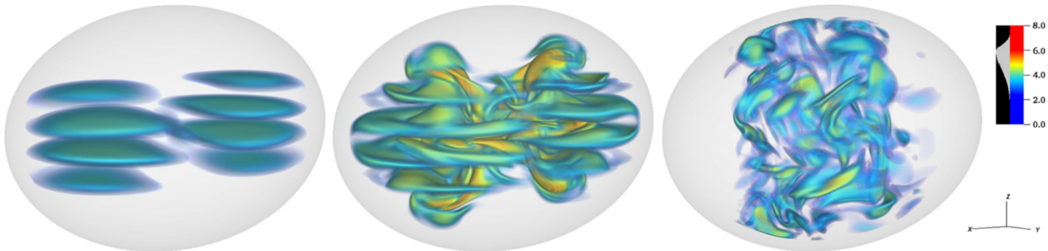

FIG. 3. Volume rendering of the enstrophy in the bulk of a librating ellipsoid, unstable to the libration driven elliptical instability. Shown from left to right are inertial modes excited during the initial exponential growth of the instability, the first saturation of the flow, and the quasisteady saturated turbulent state. For this numerical simulation, the libration frequency is equal to four times the spin frequency and the Ekman number $E_{\text{num,lib}} = 10^{-4}$. (Reprinted from [38] with the permission of AIP Publishing.)

existence in real planets of polar flattening [39], of a radial stratification in subadiabatic cores, or of convection driven by radial gravity in superadiabatic cores [41].

Satisfyingly, none of these additional complexities significantly challenges the existence of the tide and libration driven elliptical instabilities in planetary configurations: On the basis of the validated scaling laws, extrapolated towards real planetary values, their presence has thus been quantitatively envisaged in several planets. To cite a few, elliptical instability is expected in most known super-Earths [29], since planets detected up to now in extrasolar systems are especially close to their stars, hence especially deformed elliptically. The same conclusion applies in our Solar System to Io, significantly deformed by the nearby giant planet Jupiter [42]. The resulting three-dimensional core flow is then expected to induce a magnetic field from the ambient Jovian magnetic field, if not generating its own dynamo, hence contributing to the surprising magnetic signature detected by the Galileo space mission [43,44]. Elliptical instability is also strongly expected in the Moon's core during the Late Heavy Bombardment (4.1–3.8 Ga ago), when the meteorites impacts were large enough to desynchronize the Moon, inducing either differential rotation between the liquid core and the elliptical distortion or at least large-amplitude libration [17]. The resulting three-dimensional flow is then expected to have produced a lunar dynamo, explaining part of the surprising magnetic signature recorded in rock samples, brought back by Apollo space missions and recently reanalyzed (see, e.g., [45]). On Mars, an innovative scenario has been proposed in [46], where a large asteroid captured on a retrograde orbit may have excited a tide driven elliptical instability, hence a dynamo, during hundreds of 10^6 years before colliding with the planet.

The situation for the Earth is more controversial, because present estimates of its core deformation place it at the edge of the instability threshold, in the absence of a magnetic field. Two points, however, are worth mentioning: The early Earth, which rotated faster and was more deformed by the then closer Moon, was clearly unstable to the tide driven elliptical instability and evidence suggesting that Earth's magnetic field already existed 4 Ga ago [47], i.e., largely before the onset time of inner core crystallization, is difficult to explain through a convectively driven dynamo alone [15,48]. A tidal instability in the Earth's core, responsible for the geodynamo, is conceivable, and the global energy budget of the Earth's rotational dynamics provides an additional argument for this. Indeed, models supported by lunar laser ranging measurements indicate that 3.7 TW is continuously injected from the Earth-Moon-Sun orbital system into the Earth, while 0.2 TW is dissipated into the Earth's atmosphere and mantle, 1 TW in the deep ocean, and 1.5–2 TW in shallow seas [49]. Hence, 0.5–1 TW of the dissipated rotational power is still missing in the current energy budget: It may very well be continuously injected into the outer core by the excitation of a tide driven elliptical instability, where it can fulfill or can have fulfilled the energy requirements of the geodynamo estimated to range between 0.1 and 2 TW [50].

III. TIDE AND LIBRATION DRIVEN ELLIPTICAL INSTABILITIES: WHAT DO WE NEED TO KNOW?

Schematically, one can claim today that the mechanisms and thresholds of elliptical instabilities driven by tides and libration are well known (see [28] and references therein). However, at least two very challenging points remain to be tackled to validate those mechanically driven flows for planetary applications.

First, the saturation process of the excited elliptical instability remains unknown, giving rise either to large cycles of growth, saturation, and collapse (as first reported by [22]) or to sustained bulk-filling turbulence (see, e.g., [33]). Explaining these complex behaviors is very challenging and reflects in several aspects the intense research activity in rotating turbulence [51,52]: It is clearly beyond the scope of this paper. However, without claiming exhaustivity or mathematical rigor, one can suggest here, from very simple considerations, two plausible physical mechanisms in connection with the two observed types of saturation. In the first mechanism, excited inertial modes, once reaching a sufficient amplitude, can nonlinearly self-interact and give rise to a quasigeostrophic flow, which perturbs the rotating base flow and detunes the excited modes, inducing the collapse of the whole resonant scaffolding. In the second mechanism, each of the first resonating inertial modes, once reaching a sufficient amplitude, could act as a seed to nonlinearly excite two additional inertial modes, hence priming an energy cascade of triadic resonances. Such a cascade has been described recently around internal-wave attractors [53], in the closely related context of the parametric subharmonic instability of internal gravity waves [54], another vivid research area in geophysical fluid mechanics (see, e.g., [55–57]).

In addition to this question of flow saturation, better knowledge of the statistics of the excited turbulence is necessary to understand the energy repartition between the various time and length scales in planetary applications: Is this mechanically forced turbulence of rotating turbulence type, of Kolmogorov turbulence type, or of wave turbulence type? Only the latest experimental investigations with quantitative flow measurements [33,34] and the latest numerical simulations reaching low enough Ekman number [34,38] have begun to quantitatively investigate the asymptotic time and space spectra of the tide and libration driven turbulence. Strong signatures of triadic resonance cascade have been exhibited, as well as some possible universal behaviors coincident with rotating turbulence, with spatial and temporal energy spectrum scaling approaching k^{-3} and ω^{-3}, respectively (see, e.g., Fig. 4). Nevertheless, current investigations are inherently limited for planetary applications by the relative large values of the accessible elliptical deformations and Ekman numbers. Indeed, for studying the threshold and initial growth of the instability, it is sufficient to reproduce in experiments and simulations the ratio between elliptical forcing and dissipation: The trick then consists in artificially increasing the forcing to compensate for the overestimated dissipation. However, the study of nonlinear effects *a priori* necessitates tackling the planetary relevant limit of small ellipticity, hence of very small Ekman number. Local numerical approaches then offer a nice way to reach these limits, considering only a small rectangular domain within the rotating ellipsoidal body, with periodic boundary conditions [58]. Such models allow high and reasonably fast resolution of the full nonlinear dynamics without solving the complex boundary layers, the ellipsoidal flow being imposed as a background. In their first study, Barker and Lithwick [58] showed that the nonlinear outcome of the resonant flow leads to the formation of long-lived geostrophic vortices, shutting off the elliptical instability. However, questions remain regarding the realistic attenuation of these vortices, ending up being the size of the considered box following an inverse cascade mechanism. For instance, adding Joule dissipation from a weak initial magnetic field prevents those large-scale vortices from forming, promoting a quasisteady state of dissipation [59]. Clearly, the nonlinear fate of the elliptical instability in a planetary context deserves additional investigations in the near future, combining not only experiments and numerical tools, but also theoretical analyses.

The second challenging prospect concerns the magnetohydrodynamics of flows driven by tides and libration, which is still largely unknown. In particular, while dynamo action from elliptical instability has been assumed in several planetary applications [15,17], it has up to now effectively been realized

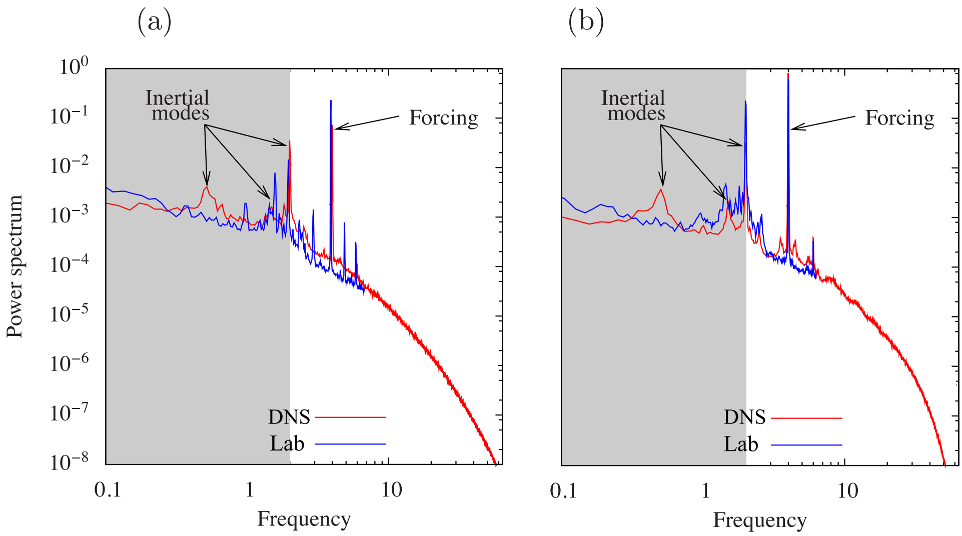

FIG. 4. Power spectrum of the saturated turbulent flow in (a) tidal experimental and numerical studies and (b) libration experimental and numerical studies. In all cases, the forcing frequency is equal to four times the spin frequency. The Ekman numbers are respectively equal to $E_{\mathrm{expt,tide}} = 1.5 \times 10^{-5}$, $E_{\mathrm{num,tide}} = 5 \times 10^{-5}$, $E_{\mathrm{expt,lib}} = 2.7 \times 10^{-5}$, and $E_{\mathrm{num,lib}} = 10^{-4}$. (Reproduced from [34].)

only twice, in numerical simulations of limited dynamical regimes. The reason for this stands in the huge numerical challenge in solving flows in fully three-dimensional geometries with the addition of the induction equations (see, e.g., [60]). The first numerical realization of a libration driven dynamo was in [61], considering the kinematic dynamo of an unstable flow at $E = 3 \times 10^{-3}$ for a simplified geometry, where the planetary core is spheroidal and librating about an axis perpendicular to its symmetry axis. The first tidal dynamo was shown in [37], considering a spherical geometry where a virtual body force locally transforms circular streamlines into ellipsoidal streamlines. A magnetic field with a dominant dipolar component was obtained from a self-consistent dynamo calculation at $E = 5 \times 10^{-3}$, as shown in Fig. 5. In addition to these studies, [59] also exhibited dynamo action

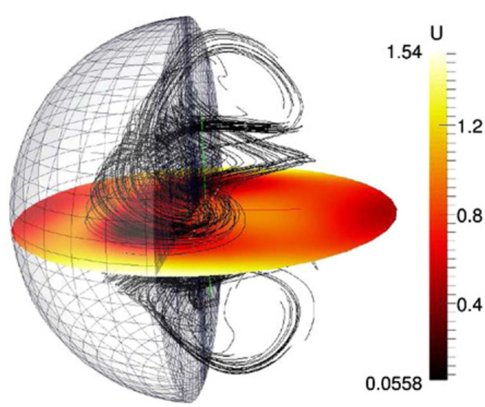

FIG. 5. Magnetic field lines and velocity magnitude in an equatorial slice in the tidal dynamo of Cébron and Hollerbach [37]. Here the Ekman number is $E = 5 \times 10^{-3}$ and the magnetic Prandtl number (i.e., the ratio of viscosity and magnetic diffusivity) is $\mathrm{Pm} = 5$. [Reproduced with permission from [37] (©AAS).]

in their local numerical model, for a much more turbulent tidal flow; however, again, the extension of local computations towards global conclusions still deserves investigations. In short, those three seminal studies have opened the way for a systematic exploration of the parameter space and for a systematic characterization of the obtained magnetic field, similarly to what has been done since the first convective dynamo realization in [62]. Among the exciting questions to be answered for planetary applications, one can mention the typical shape of the generated magnetic field (i.e., dipolar or not, with an amplitude fixed by energy balances [63]), as well as the existence of magnetic field reversals. Here also significant progress is expected in the next few years, through a thoughtful use of the various numerical tools and analytical approaches, and even laboratory experiments.

IV. BEYOND TIDE AND LIBRATION DRIVEN ELLIPTICAL INSTABILITIES

In conclusion, it is a very exciting time for research in core fluid dynamics, in the context of intense activity in planetary exploration, involving past, current, and future space missions: See, for instance, the paleomagnetic reanalyses of Moon's Apollo samples (e.g., [45]); the ongoing Dawn mission around asteroid Vesta and dwarf planet Ceres (e.g., [1]); the forthcoming Juice mission, which will spend at least three years making detailed observations of the giant gaseous planet Jupiter and three of its largest moons, Ganymede, Callisto and Europa; and the ongoing NASA and ESA extrasolar systems explorations. The analysis and interpretation of available and forthcoming data necessitate innovative fundamental models, providing alternative mechanisms to the standard convective models in explaining the variety of behaviors and magnetic fields observed in planets, both in our Solar System and in extrasolar ones. For the specific case of tide and libration driven elliptical instabilities, combined theoretical, numerical, and experimental approaches have led to significant progress. Yet many open questions remain, regarding especially the nonlinear saturation and turbulent state of the flows, as well as the shape and intensity of the corresponding dynamo. Beyond tide and libration driven elliptical instabilities, other routes towards core turbulence and dynamos have also been recently explored. For instance, the nonlinear self-interaction of an excited inertial mode, directly forced by harmonic forcing, drives an intense and localized axisymmetric jet that becomes unstable at low Ekman number because of a shear instability [64]; the characteristics of the excited turbulence and the dynamo capability of this flow remain to be studied. Also, the precession driven flow has recently been reinvestigated, showing the prevalence of a shear driven parametric instability [65]; an inverse cascade then sets in, leading to the formation of large-scale cyclones capable of dynamo action [66]. In addition, other types of mechanical forcing, like nutation and latitudinal libration [67], are present at the planetary scale, but their study is still in its infancy. Finally, it is worth mentioning that while the various mechanical forcings should be first studied separately, several of them are present simultaneously in each real planet; nonlinear interactions are then to be expected, as highlighted in [68,69]. Mechanical forcings may also be superimposed on an existing turbulent convective field and the subsequent nontrivial couplings deserve in-depth investigation, following [70]. There is no doubt that the interdisciplinary research area of rotating core fluid dynamics will remain vibrant in the next few years, benefiting from the simultaneous advances in fluid metrology, nonstandard numerical methods, and planetary exploration.

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