Flows Driven by Harmonic Forcing in Planetary Atmospheres and Cores

Michael Le Bars

Abstract It is a commonly accepted hypothesis that convective motions are responsible for most flows in planetary and stellar fluid layers, and in particular that convective motions are responsible for planetary dynamos, as it is the case on Earth today. However, the validity of the convective dynamo model can be questioned in certain planets. Besides, even in planets where the dynamo is of convective origin, additional driving mechanisms may significantly modify the organization of fluid motions in their core. The same question holds for all large-scale flows in any fluid layer of astrophysical bodies, such as atmospheres of gas giants, subsurface oceans of icy satellites, and convective/radiative zones of stars. In particular, three mechanical forcings present at the planetary scale remain largely unknown regarding their fluid mechanics and planetary consequences: libration, precession, and tidal distortions. Combining analytical studies with numerical simulations and laboratory experiments, we show here that libration and tides can drive highly energetic turbulent flows, which could for instance participate in the generation of Jupiter bands and in the generation of the past Moon magnetic field. The key point is that flows are excited by resonance mechanisms such as the elliptical instability, where the harmonic forcing only acts as a conveyor to extract energy from the huge reservoir related to the rotational dynamics of planetary systems. Even small forcing can thus have important consequences.

1 Introduction

Since the seminal works of the 1960s and 1970s (see for instance Busse 1970; Spiegel 1971, …), most research on the domain of planetary and stellar flows has focused on convection. In planetary sciences, one of the most significant outcomes of this

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M. Le Bars (✉)
Rotating & Geophysical Flows, Institut de Recherche sur les Phénomènes Hors Equilibre
(IRPHE), UMR 7342, CNRS - Aix-Marseille University, 49 rue F. Joliot Curie,
Marseille Cédex 13 13384 , France
e-mail: lebars@irphe.univ-mrs.fr

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research (see Glatzmaier and Roberts 1995) was to demonstrate that convective flows in a spherical shell indeed generate a dynamo, and that the present magnetic field of the Earth is most probably due to such motions driven by the solidification of its iron core. Since its formulation, this same model has been applied, with only marginal modifications, to other planetary systems. However, the validity of the convective dynamo model can be questioned in certain planets and moons, for instance in Mercury and Ganymede. More generally, it is often tacitly assumed that all motions in fluid layers of astrophysical bodies (e.g. atmospheres of gas giants, subsurface oceans of icy satellites, convective zones of stars, …) are controlled and driven by convective effects only. For instance Jupiter's bands may be explained by the surface trace of deep convective flows (Heimpel et al. 2005). But in the view of the latest data coming from moons and planets in our solar system as well as from more exotic extrasolar ones (see for instance the fast magnetic inversions in Tau-Boo studied by Donati et al. 2008), it is now high time to re-evaluate these standard models and to explore the role of other instabilities in the organization of fluid motions at the planetary and stellar scales. In particular, three processes are generically present at the planetary or stellar scales, but remain mostly neglected when looking at their driving influence in fluid layers: precession, tidal distortion and libration.

Precession corresponds to the periodic change in the orientation of the rotational axis of a planet. The flow of a rotating viscous incompressible homogeneous fluid in a precessing container has been studied for over one century for both planetary and engineering applications. In the spheroidal geometry, the early work of Poincaré (1910) demonstrated that the flow of an inviscid fluid has a uniform vorticity and takes the form of an inclined solid body rotation called tiltover. But precession can also drive turbulence (e.g. Noir et al. 2003), whose origin remains a matter of debate and the subject of current research.

Tidal distortions come from the gravitational interactions of any planet with its neighbours. They affect all the layers of a given body, which all take an ellipsoidal shape with the long axis oriented towards the deforming body. Tidal distortions are generally time-periodic (i.e. dynamic tides), but they also have a static component in synchronized systems (i.e. static bulges). The most obvious consequences of dynamic tides are of course the oceanic flows on Earth, but they are also responsible for the intense volcanism on Io for instance, and for various flows that we will detail in Sect. 3.

The term longitudinal libration (hereafter called libration) refers to periodic variations in the rotation rate of a planet around its axis. Such oscillations are present in many bodies stacked in a spin–orbit resonance. The determination of the librational motions of a planet allows to better constrain its internal organization (see for example, Margot et al. 2007). Libration may play a fundamental role in the dynamics of planetary fluid layers, for example in the liquid core of Ganymede, in the subsurface ocean of Europa and Titan, or in the atmosphere of hot-Jupiters and in the core of super-Earths in extrasolar systems. This will be shown in Sect. 4.

From a fluid dynamics point of view, libration, precession and tides correspond to closely related mechanisms, which we generically call "harmonic forcing": they correspond to periodic perturbations of an otherwise simple solid-body rotation,

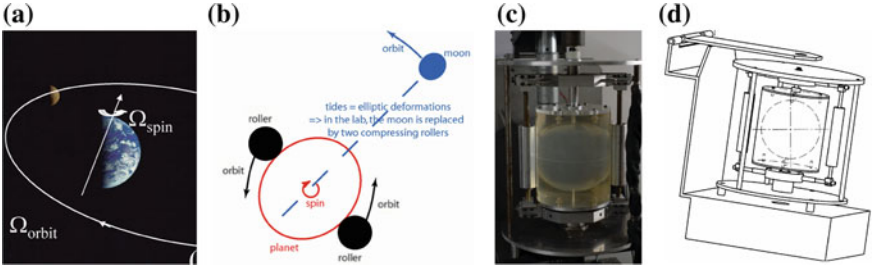

Fig. 1 Experimental set-up. The picture in (**a**) highlights the existence of two different rotation rates: the spin rate of the studied planet, and the orbital rate of the body responsible for the tidal deformation. As shown in the equatorial cross-section (**b**), this companion body is replaced in our set-up by two symmetric rollers. **c** and **d** show the experimental set-up

with an azimuthal wave number m respectively equal to 0, 1 and 2. For planetary systems, it is well known that a huge amount of energy is stored in their rotational dynamics (spin and orbit): those mechanical forcings could play the role of efficient conveyers that extract this energy and drive large scale and intense fluid motions, as initially suggested by Malkus for the Earth (1963, 1968, 1989). Note that the studies of Malkus have long been neglected by the scientific community, mainly because of a misunderstanding (e.g. Rochester et al. 1975): as later mentioned by Kerswell (1996), 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 energetics, thus more relevant for astrophysical bodies. Malkus' studies are now being rehabilitated, in the view of the latest results from space missions and extrasolar systems observations that highlight the need to go beyond the standard models in order to understand the variety of planetary and stellar configurations. My team "Rotating and Geophysical Flows" at IRPHE has largely contributed to this rehabilitation over the past 10 years, and I will shortly present below our main contributions in the field of tides and libration driven flows.

2 Methods

Our studies are based on combined theoretical, experimental and numerical approaches. Our purpose is to describe generic physical mechanisms and to derive and validate generic scaling laws, which are then extended towards planetary applications.

Following the first study by Malkus (1989), we have developed an original experimental set-up to study the tides driven flows in spherical geometry (Fig. 1). In this device, the container consists in a hollow sphere molded into a deformable silicone matrix and filled with water, that is set in rotation. The container is elliptically deformed by a pair of opposed rollers that mimics a tidal deformation rotating at an independent "orbital" velocity. Typical parameters are: radius R = 10 cm, rotation rates up to ±160 rpm, and tidal distorsion up to 5 mm. Our device is equipped with two measuring systems: a simple visualization by Kalliroscope (reflective flake particles) in a vertical laser sheet from the laboratory frame, and a camera system with a wireless transmission, embarked in rotation with either the container or the rollers. This visualization is especially interesting since it allows us to perform PIV measurements in an equatorial cross-section and to determine the velocity field that takes place above the imposed rotation. Two types of experiments have been performed so far with this device, as developed in the next sections:

- studies on the effects of tides for both elliptical instability (Le Bars et al. 2010) and zonal wind generation (Morize et al. 2010) in a tidally deformed sphere;
- studies of libration in a perfect sphere, in which case the rollers are removed but the spin rate is modulated sinusoidally (Sauret et al. 2010).

Numerical simulations have been performed using the commercial code COMSOL Multiphysics (e.g. Cébron et al. 2010a,b,c, 2012a). This software is capable of solving Navier–Stokes equations (and additional physics such as a thermal field or the induction equations) using a finite element method: this allows to deal with complex geometries, such as the triaxial ellipsoidal shape representative of tidally deformed and polarly flattened planets and stars. This constitutes a significant added value compared to previous numerical simulations of planetary cores and stars. Indeed, most other numerical resources use spectral methods and hence suppose an exact axisymmetry of the boundaries of the studied body around its rotation axis, which eliminates most of the interesting dynamics that we want to tackle here. All hydrodynamical and MHD aspects of the numerical simulations have been validated by direct comparison with our previous analytical and experimental results.

3 Tides Generated Flows

As for any rotating flow, fluid layers of planets and stars support oscillatory motions called "inertial waves", whose frequencies range between ± twice the spin frequency. Usually damped by viscosity, these waves can nevertheless be excited by harmonic forcings, and in particular by tides. For instance, Ogilvie and Lin (2004, 2007) showed that in stars and atmospheres of gas giants, tidal forcing might excite inertial waves that significantly alter the energy dissipation of the system. The nonlinear interaction of such forced inertial modes can then generate intense axisymmetric geostrophic jets in the bulk of the fluid, which could for instance participate in the generation of Jupiter's stripes (see e.g. our experimental study Morize et al. (2010) and Fig. 2).

Additionally, tidal forcing induces an elliptical deformation of the rotating streamlines in fluid layers that may excite a parametric resonance of inertial waves called the elliptical instability (see e.g. the review by Kerswell (2002)). Initially motivated by the aeronautical applications of the elliptic instability, our research group at IRPHE has significantly participated in its theoretical, numerical and experimental investi-

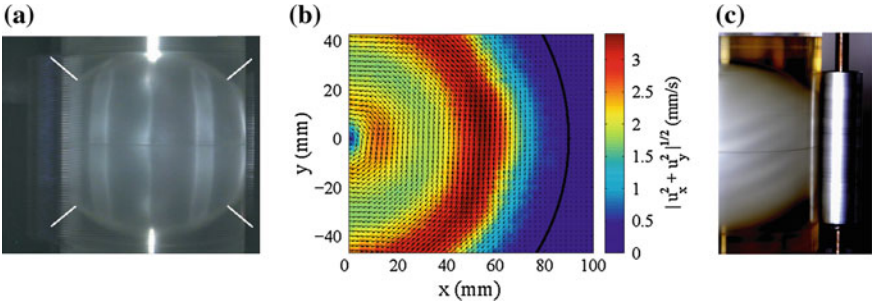

Fig. 2 **a** Axisymmetric geostrophic jet as visualized in our laboratory experiment by Kalliroscope in a meridional plane. **b** Corresponding norm of the horizontal velocity in the equatorial plane, as measured by particle imaging velocimetry (PIV) in the rotating frame. **c** Surface flow visualized by Kalliroscope in the combined presence of tides and precession: the geostrophic flows generate stripes similar to the ones observed for instance on Jupiter. See details in Morize et al. (2010)

gation in spherical containers for planetary and stellar applications (see e.g. Le Bars et al. 2007, 2010; Cébron et al. 2010a). We have also investigated the interaction between elliptic and convective instabilities (Le Bars and Le Dizès 2006; Lavorel and Le Bars 2010; Cébron et al. 2010b). Then, we have studied the response of the flow in a liquid metal when a magnetic field is imposed along the rotation axis. Experimental measurements and numerical simulations have shown the induction of a horizontal magnetic field by the instability as well as its progressive attenuation by Joule dissipation, in perfect agreement with the complete analytical resolution (Lacaze et al. 2006; Herreman et al. 2009; Cébron et al. 2012a). Besides, various chaotic behaviours with excursions and inversions of the induced magnetic field may take place depending on the relative strength of the elliptical forcing and imposed magnetic field (Herreman et al. 2010). Results from these ideal models have been applied to natural systems, showing for example that the early Earth's core was clearly unstable (Cébron et al. 2012b). We have also proposed a complex temporal evolution of binary systems, passing successively through resonance bands of the elliptical instability, separated by stability regions (Le Bars et al. 2010). Lately, we have suggested that the elliptical instability in the Moon's core, temporarily desynchronized by large meteoritic impacts, may be responsible for its early dynamo (Le Bars et al. 2011).

4 Libration Driven Flows

The determination of the librational motions of a planet allows to better constrain its internal organization (see for example, Margot et al. 2007). The main problem of these models is that they tacitly assume the complete absence of specific motions in detected fluid layers outside the viscous Ekman boundary layer. One result of our work was to demonstrate that on the contrary, libration forcing generates complex and intense flows, which participate in the energy balance and orbital dynamics of the planet, and possibly even in the generation of a magnetic field.

Since the solid boundaries surrounding a liquid layer of a planet generically have a triaxial ellipsoid shape, couplings of viscous and topographical origins have to be envisaged. Librational flows generated by viscous coupling have first been studied by Aldridge and Toomre (1969), who observed experimentally that inertial waves can be excited in a sphere at resonant libration frequencies, as latter confirmed numerically (see e.g. Rieutord 1991). More recently, Busse (2010) demonstrated by a weakly nonlinear study in the limit of small libration frequency, that the libration of a sphere generates via the nonlinearities in the Ekman layer, an axisymmetric zonal flow whose amplitude varies as the square of the libration amplitude, regardless of the Ekman number. These predictions were confirmed experimentally and numerically by our group (Sauret et al. 2010), then extended to a more generic configuration (Sauret and Le Dizès 2013). Finally, Noir et al. (2009) have demonstrated experimentally the presence of a centrifugal instability in a librating sphere under the form of Taylor-Görtler type vortices appearing in the viscous layer near the boundary. However, Calkins et al. (2010) emphasised that in the limit of small Ekman numbers relevant to planetary applications, these structures remain localised in the boundary layer and near the equator, and therefore have a very marginal role in the dynamics of the fluid layer. In the view of new numerical results in a cylindrical geometry, we have recently re-evaluated this conclusion by showing a new mechanism of inertial waves generation by the boundary layer turbulence, which could significantly alter the bulk dynamics, no matter what the libration frequency is (Sauret et al. 2012): this mechanism has also been described systematically in the spherical geometry (Sauret et al. 2013).

The libration flows generated by topographic coupling appear to have been even less studied than those with viscous coupling. Recently, Zhang et al. (2011) combined theoretical and numerical approaches, to show the persistence of a zonal wind generation in a triaxial ellipsoidal geometry. They have also suggested that no inertial wave could be forced in this case. However, 4 publications have shown that a hydrodynamic instability of elliptical type driven by librational forcing could develop in triaxial containers (see Fig. 3): the original paper by Kerswell and Malkus (1998) and subsequent contributions of our group (Herreman et al. 2009; Cébron et al. 2012c; Noir et al. 2012). Such a mechanism would be of fundamental importance at the planetary scale because it would generate space-filling turbulence in fluid layers, possibly explaining for instance the magnetic signatures of Io and Europa. This however has to be confirmed by a more systematic experimental and numerical study.

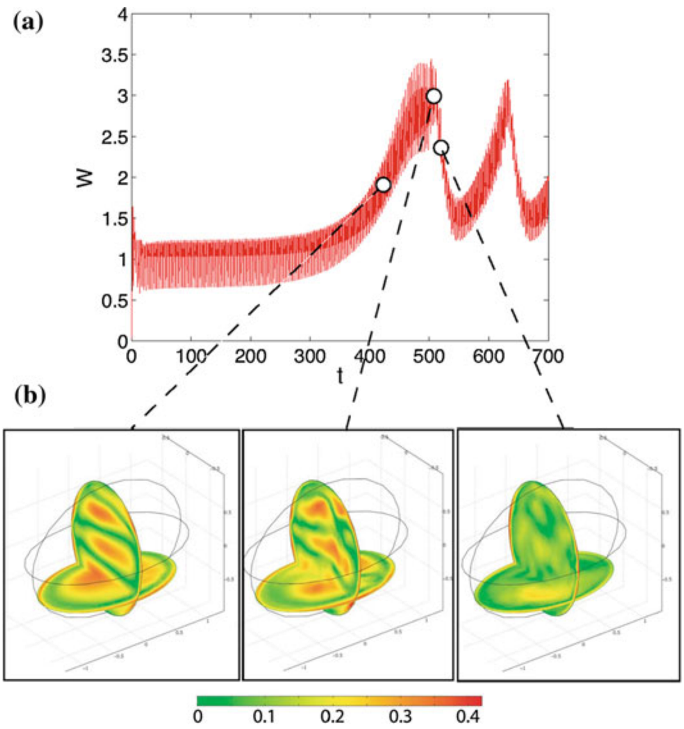

Fig. 3 **a** Time evolution of the absolute value of the axial velocity integrated over the whole container, showing the cycles related to the growth and collapse of the libration driven elliptical instability. Numerical simulations are performed at an Ekman number $E = 5 \times 10^{-4}$. **b** Norm of the velocity field in a meridional cross section and in the plane $z = -0.5$. The sequence shows, from left to right, the typical field during the exponential growth, at saturation and during the collapse. From Cébron et al. (2012c)

5 Conclusions

By combining analytical, experimental and numerical studies, we have shown that "alternative" mechanisms driven by libration, precession and tides, may participate in core and other layers fluid dynamics, where they can replace or significantly perturb usually considered convective motions. For these motions, the source of energy comes from the rotational dynamics of planetary systems (spin and orbit), and the harmonic forcing only acts as a conveyor. Hence, even very small forcing can give rise to intense flows, explaining for instance the existence of strong localized jets when a given inertial wave is resonantly excited (e.g. Jupiter's bands), or the presence of a planetary dynamo when 3D turbulence is excited by elliptical instability (e.g. Moon's dynamo). One should thus remember that on no account, planetary or stellar fluid motions systematically mean convection.

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