EPSC Abstracts
Vol. 7 EPSC2012-257 2012
European Planetary Science Congress 2012

Libration driven elliptical instability in synchronized moons and Super-Earths

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Abstract

The elliptical instability is a generic instability which takes place in any rotating flow whose streamlines are elliptically deformed. Up to now, it has been widely studied in the case of a constant, non-zero differential rotation between the fluid and the elliptical distortion with applications in turbulence, aeronautics, planetology and astrophysics. Having extended previous analytical studies, we report the first numerical evidence that elliptical instability can also be driven by libration, i.e. periodic oscillations of the differential rotation between the fluid and the elliptical distortion, with a zero mean value. Our results suggest that intermittent, space-filling turbulence due to this instability can exist in the cores and sub-surface oceans of so-called synchronized planets and moons. Our results are thus finally applied to the synchronized moons of the solar system as well as to three Super-Earths

1. Introduction

The flow in fluid layers of planets and moons is of primary interest for their dynamics and evolution. Indeed, internal flows create energy dissipation, which remain negligible for stable laminar flows, but become significant for turbulent ones. Moreover, internal flows are directly responsible for magnetic field generation, either by induction of an existing background magnetic field or by excitation of a self-sustained dynamo. Finally, heat fluxes are also directly linked to flows in fluid layers, which can act as thermal blankets for stably stratified configurations, or as efficient heat flux conveyers in the case of convective flows.

Planetary fluid layers are subject to body rotation, which implies that inertial waves can travel through them. Usually damped by viscosity, these waves can be excited by libration, precession and tides, seen by the rotating fluid as harmonic mechanical forcings of azimuthal periodicity $m = 0$, 1 and 2 respectively. The fluid response to such forcings in ellipsoids is a long standing issue (see e.g. [1] for tides). In particular, it has been shown that the dynamics of a fluid layer are completely modified when the forcing directly resonates with an inertial wave. In addition, inertial waves can also form triadic resonances, leading to parametric inertial instabilities. For instance, the so-called shear instability can be excited by precession [2] and the elliptical instability can be excited by tides [3, 4] and librations [5].

2. Elliptical instability

The elliptical instability is a generic instability that affects any rotating fluid whose streamlines are elliptically deformed. A fully three-dimensional turbulent flow is excited in the bulk as soon as (i) the ratio between the ellipticity of the streamlines β and the square root of the Ekman number E (which represents the ratio between the viscous and Coriolis forces) 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 gravitational deformation of the rigid boundaries of the considered fluid layer, corresponding either to dynamic tides or static bulges. The differential rotation between the fluid and the elliptical distortion can be oscillatory when due to libration in synchronized systems, or stationary, as for instance in non-synchronized ones: the elliptical instability is then refereed to as libration driven elliptical instability (LDEI) and tide driven elliptical instability (TDEI) respectively. TDEI and LDEI have already been suggested to take place respectively in Earth [6] and in Io [5]. In this work, we have validated the existence of the LDEI. To do so, we first extend previous analytical studies using a local WKB approach that allows us to determine a generic formula for the growth rate of LDEI. We then present the numerical validation of the existence of the LDEI, in good agreement with the theoretical results. Finally, implications for synchronized moons and Super-Earths are discussed, taking into account the presence of imposed thermal and magnetic fields.

3. Applications

Our theoretical results are applied to moons of the solar system as well as to two Super-Earths, CoRoT-7b and GJ-1214b. Regarding LDEI, the core of Io is shown to be stable, contrary to previously thought [5], whereas Europa (Fig. 1), CoRoT-7b and GJ-1214b cores are clearly unstable over a large range of libration amplitude. The subsurface ocean of Europa and the core of Titan are also unstable, but in the vicinity of threshold. This present state-of-the-art does not preclude more unstable situations in the past.

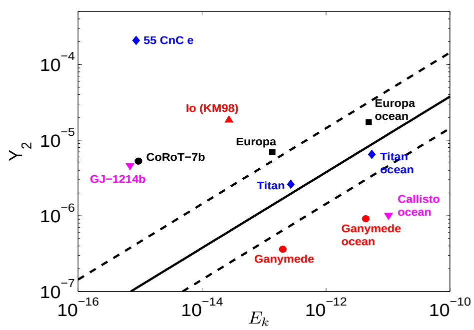

Figure 1: LDEI stability diagram for synchronized celestial bodies in the optimal case for the instability, i.e. an optical libration for a quasi-equilibrium tide. The horizontal axis represents the Ekman number E_k based on the thickness of the fluid layer. The label KM98 for Io reminds that the point is placed with the values used by [5]. The zone below the black line is the stable zone, whereas the black dashed lines represent respectively the uncertainties on the threshold.

4. Consequences

One can wonder what are the signatures and consequences of such an instability on the planetary dynamics. A first consequence would be on the orbital evolution and synchronization process: indeed, the elliptical instability generates three-dimensional turbulent flows with cycles of growth, saturation, fluctuations and relaminarization [4]. Timescales involved range typically between the spin period and the typical growth time of the instability. Dissipation rates at the planetary scale, hence its celestial dynamics, would then follow the same variations, with periods of rapid evolution when an elliptical instability is present, followed by more quiescent periods. The second consequence would be on heat flux variations at the planetary surface: indeed, as shown in [7], flows driven by elliptical instability are very efficient in transporting heat by advection. Hence, sub-adiabatic cores should not be regarded as thermal blankets when tidally unstable. Besides, in the presence of natural thermal convection, the superimposition of chaotic elliptically driven flows would induce large scale variations of the same amplitude as the background heat flux. Internal flows driven by elliptical instability are also directly responsible for magnetic field generation. The question of whether or not LDEI and TDEI are dynamo capable is still open and remains out of reach of the currently available numerical capacity. But in any case, elliptically driven flows induce a magnetic field from an existing background one, with a significant amplitude. For instance, starting from the jovian magnetic field component along the rotation axis, the LDEI in Europa subsurface ocean is capable of explaining the perturbation of the background z-component of the magnetic field from 410 nT to 380 nT at a distance of Europa about 1.5 Europa radius, as measured by the Galileo's E4 flyby (see [8]).

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