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Layered semi-convection and Tides in giant planet interiors

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Abstract

Layered semi-convection could operate in giant planets, potentially explaining Saturn's luminosity excess and playing a role in causing the abnormally large radii of some hot Jupiters. In giant planet interiors, it could take the form of density staircases, which are convective layers separated by thin stably stratified interfaces. In addition, the efficiency of tidal dissipation is known to depend strongly on the planetary internal structure. It is crucial to improve our understanding of the mechanisms driving this dissipation, since it has important consequences to predict the long-term evolution of any planetary system. In this work, our goal is to study the resulting tidal dissipation when internal waves are excited by other bodies (such as the moons of giant planets) in a region of layered semi-convection. We find that the rates of tidal dissipation can be enhanced in a region of layered semi-convection compared to a uniformly convective medium, where the latter corresponds with the usual assumption adopted in giant planet interior models. In particular, a region of layered semi-convection possesses a richer set of resonances, allowing enhanced dissipation for a wider range of tidal frequencies. Thus, layered semi-convection could contribute towards explaining the high tidal dissipation rates observed in Jupiter and Saturn, which have not yet been explained by theory. Further work is required to explore the efficiency of this mechanism in global models.

1 A first study of tidal dissipation in layered semi-convection

1.1 Context

It has been found that the rates of tidal dissipation in Jupiter and Saturn are higher than previously thought (1; 2; 3). This has important astrophysical consequences since tidal interactions are a key mechanism for driving the rotational, orbital and thermal evolution of moons, planets and stars over very long timescales. Moreover, we know that this evolution, linked to the efficiency of tidal dissipation in celestial bodies, strongly depends on their internal structures. Recent observations by the JUNO spacecraft seem to be consistent with interior models of Jupiter in which the heavy elements of the core are diluted in the envelope (4). This could lead to the development of layered semi-convection , in which a large number of convective layers are separated by thin stably stratified interfaces. In this work, we study the impact of layered semi-convection upon the efficiency of the so-called dynamical tide, that is the viscous and thermal dissipation of tidal waves.

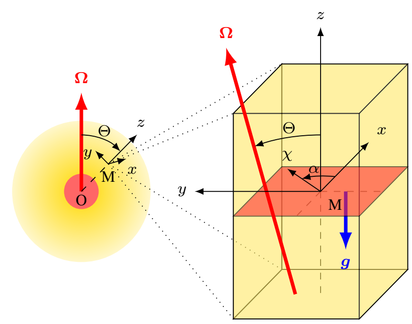

Figure 1: Our local Cartesian model.

1.2 Dissipation rates in a layered profile

To simplify our initial study, and because tidal waves typically have very short wavelengths, we carry out our analysis in a local Cartesian box centred on a given point M of the fluid envelope (see Fig. 1). This al-

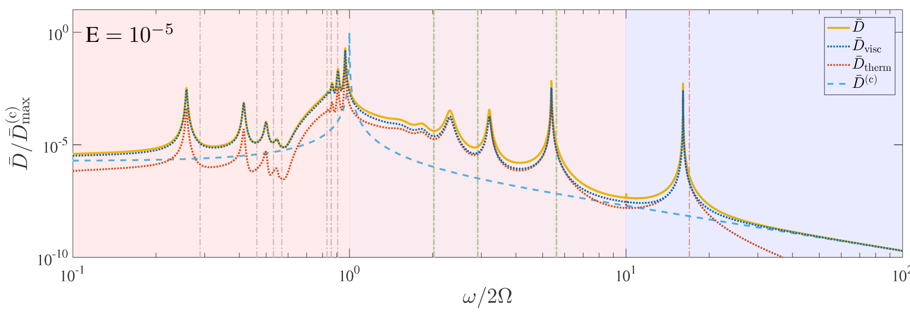

Figure 2: Example of a normalised dissipation as a function of tidal frequency for an Ekman number $\mathrm{E} = 10^{-5}$.

lows us to study the local properties of the propagation and dissipation of internal waves in a region of layered semi-convection. We take into account rotation through the Coriolis acceleration (the rotation vector is $\mathbf{\Omega}$ on Fig. 1), and the region of layered semi-convection is modelled by a buoyancy frequency profile, $N(z)$, that is zero in the convective regions and positive in stably stratified interfaces. The mean stratification in the vertical direction is then $\bar{N}$. Finally, viscous and thermal are included through constant kinematic viscosity ν and thermal diffusivity κ.

We give an example of our results focusing on the case with one stably stratified interface in the middle of our box, with the dissipation being characterised by choosing $\nu/2\Omega = \kappa/2\Omega = 10^{-5}$. The dissipation rates calculated numerically are plotted as a function of tidal forcing frequency on Fig. 2. The total dissipation rate, $\bar{D}$, is represented by the solid orange line (its viscous and thermal contributions are represented by the dotted blue and red lines, respectively). For comparison, we plot the corresponding quantity in a fully convective medium, $\bar{D}^{(\mathrm{c})}$ by the dashed light blue line.

We clearly see here that the layered structure introduces new resonances. Those additional resonances are broadly distributed over the frequency spectrum. Some correspond to resonances with inertial modes, corresponding to frequencies $\omega \lesssim 2\Omega$ (pink region on Fig. 2); some with super-inertial gravito-inertial modes, corresponding to frequencies $2\Omega \lesssim \omega \lesssim \bar{N}$ (purple region on Fig. 2); and finally some with gravity modes, corresponding to frequencies $\bar{N} \lesssim \omega \lesssim \max N$ (blue region on Fig. 2). As a result, the total dissipation rate is higher in the layered case (orange line) than in the fully convective case (dashed light blue line) – in particular in the sub-inertial range ($\omega < 2\Omega$) relevant to tidal forcing – except near the Coriolis frequency ($\omega \sim 2\Omega$).

1.3 Conclusions

We computed the dissipation rates in a region of layered semi-convection as a function of tidal frequency using a local Cartesian model. We found that a region of layered semi-convection possesses a richer set of free modes than a fully convective medium – which is the model that is usually adopted for giant planet interiors. As a result, there are more resonances that can potentially be excited compared to a convective medium. This makes it more likely for a satellite to enter a resonance with enhanced tidal dissipation (potentially by several orders of magnitude). Further work is required to explore and confirm the influence of layered semi-convection on tidal dissipation in global models.

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