EPSC Abstracts
Vol. 7 EPSC2012-648 2012
European Planetary Science Congress 2012

Tidal dissipation in giant planets and the orbital evolution of their satellite systems

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Almost all the regular satellites of the giant planets in the solar system exert tidal forcing at frequencies within the range for which inertial waves can be excited inside the planet. The damping of inertial waves through their interaction with turbulent convection or magnetic fields, or through nonlinear processes, provides a mechanism of tidal dissipation and leads to the orbital migration of the satellites, allowing them in some cases to enter orbital resonances.

Lainey et al. [1,2] have recently estimated the tidal dissipation in Jupiter and Saturn by fitting a dynamical model to observations of satellites over the last century or so.

Using spectral numerical methods, we compute the linearized response of a uniformly rotating compressible fluid body to tidal forcing by the Y_2^2 spherical harmonic over the relevant range of tidal frequencies. Self-gravity and viscosity are included, while magnetic fields and non-adiabatic effects are neglected. The presence of convection is considered only to the extent that it establishes a (nearly) adiabatic stratification and provides an enhanced effective viscosity. Since the interior structure of giant planets is not fully understood, we use a variety of simplified and parametrized models to investigate the dependence of the dissipation rate on the interior structure.

The efficiency of tidal dissipation is quantified by computing the frequency-dependent complex potential Love number $k_2^2(\omega)$ of the body. The negative imaginary part of this dimensionless quantity is inversely related to the tidal quality factor and bears a simple relation to the total viscous dissipation rate, which is verified numerically.

The tidal response is complicated by the fact that, in the absence of viscosity, inertial waves do not form smooth eigenfunctions with a discrete spectrum, except in special cases where the density profile is smooth and the waves propagate in a full sphere. If the inertial waves are excluded from a solid or stably stratified core, or if they are internally reflected from interfaces between fluid layers of different phases or compositions, then the response depends in a complicated way on the tidal frequency and the viscosity, resulting in a non-steady orbital migration of satellites.

The frequency-averaged dissipation rate increases strongly with the size of the region from which the waves are excluded. For this reason, models of Saturn generally result in more efficient tidal dissipation than models of Jupiter, which is broadly consistent with the observational results of Lainey et al. The presence or absence of density discontinuities in the hydrogen and helium envelope can have an important bearing on the results.

Tidal forcing of Saturn by Mimas occurs at a frequency that is close to a resonance with a large-scale normal mode that exists in a full sphere. Even when a core is present, this mode retains an important influence and can result in greatly enhanced dissipation.

We also investigate the amplitude and spatial structure of the tidal response and discuss whether the linear solutions may be susceptible to secondary instabilities for the parameters relevant to solar-system applications.

References

[1] Lainey, V., et al. (2009), Nature, 459, 957

[2] Lainey, V., et al. (2012) arXiv:1204.0895