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New constraints on Saturn's interior from Cassini astrometric data

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ABSTRACT

Using astrometric observations spanning more than a century and including a large set of Cassini data, we determine Saturn's tidal parameters through their current effects on the orbits of the eight main and four coorbital Moons. We have used the latter to make the first determination of Saturn's Love number from observations, k_2=0.390 ± 0.024, a value larger than the commonly used theoretical value of 0.341 (Gavrilov & Zharkov, 1977), but compatible with more recent models (Helled & Guillot, 2013) for which the static k_2 ranges from 0.355 to 0.382. Depending on the assumed spin for Saturn's interior, the new constraint can lead to a significant reduction in the number of potential models, offering great opportunities to probe the planet's interior. In addition, significant tidal dissipation within Saturn is confirmed (Lainey et al., 2012) corresponding to a high present-day tidal ratio $k_2/Q=(1.59 \pm 0.74) \times 10^{-4}$ and implying fast orbital expansions of the Moons. This high dissipation, with no obvious variations for tidal frequencies corresponding to those of Enceladus and Dione, may be explained by viscous friction in a solid core, implying a core viscosity typically ranging between 10^{14} and 10^{16} Pa.s (Remus et al., 2012). However, a dissipation increase by one order of magnitude at Rhea's frequency could suggest the existence of an additional, frequency-dependent, dissipation process, possibly from turbulent friction acting on tidal waves in the fluid envelope of Saturn (Ogilvie & Lin, 2004; Fuller et al. 2016).

1. Introduction

Tidal effects among planetary systems are the main driver in the orbital migration of natural satellites. They result from physical processes arising in the interior of celestial bodies, not observable necessarily from surface imaging. Hence, monitoring the Moons' motions offers a unique opportunity to probe the interior properties of a planet and its satellites. In common with the martian and jovian systems (Lainey et al., 2007, 2009), the orbital evolution of the saturnian system due to tidal dissipation can be derived from astrometric observations of the satellites over an extended time period. In that respect, the presence of the Cassini spacecraft in orbit around Saturn since 2004 has provided unprecedented astrometric and radio-science data for this system with exquisite precision. These data open the door for estimating a potentially large

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number of physical parameters simultaneously, such as the gravity field of the whole system and even separating the usually strongly correlated tidal parameters k_2 and Q.

The present work is based on two fully independent analyses (modeling, data, fitting procedure) performed at IMCCE and JPL, respectively. Methods are briefly described in Section 2. Section 3 provides a comparison between both analyses as well as a global solution for the tidal parameters k_2 and Q of Saturn. Section 4 describes possible interior models of Saturn compatible with our observations. Section 5 discusses possible implications associated with the strong tidal dissipation we determined.

2. Material and methods

Both analyses stand on numerical computation of the Moons' orbital states at any time, as well as computation of the derivatives of these state vectors (see Section 2.1) with respect to: (i) their initial state for some reference epoch; (ii) many physical parameters. Tidal effects between both the Moons and the planet are introduced by means of the amplitude of the tidal bulge and its time lag associated to dissipation processes. The gravitational effect of the tidal bulge is classically described by the tidal Love number k_2 and the tidal ratio k_2/Q. The Love number k_2 is defined as the ratio between the gravitational potential induced by the tidally-induced mass redistribution and the tide-generating potential. As the interior does not respond perfectly to the tidal perturbations, because of internal friction applied on tides, there is a time lag between the tide-raising potential and the tidally-induced potential. The torque created by this lag is proportional to the so-called tidal ratio k_2/Q. The amplitude and lag of the tide potential can also be described using a complex representation of the Love number, where the real part correspond to the part of the potential aligned with the tide-raising potential, while the imaginary part describes the dissipative part (see also Section 4). The factor Q, often called the quality factor (Kaula 1964), or the specific dissipation function, Q^{-1}, in its inverse form, is inversely proportional to the amount of energy dissipated by tidal friction in the deformed object. Coupled tidal effects such as tidal bulges raised on Saturn by one Moon and acting on another are considered. Besides the eight main Moons of Saturn, the coorbital Moons Calypso, Telesto, Polydeuces, and Helene are integrated in both studies.

Although the two tidal parameters k_2 and Q often appear independently in the equations of motion, the major dynamical effect by far is obtained when the tide raised by a Moon on its primary acts back on this same Moon. In this case, only the ratio k_2/Q is present as a factor for the major term, therefore preventing an independent fit of k_2 and Q. However, the small co-orbital satellites raise negligible tides on Saturn and yet react to the tides raised on the planet by their parent satellites (see Figure in Appendix A.1). This unique property allows us to make a fit for k_2 that is almost independent of Q (see Appendix A.1). In particular, we find that the modeling of such cross effects between the coorbital moons allows us to obtain a linear correlation between k_2 and Q of only 0.03 (Section 3 and Appendix A.4). Thanks to the inclusion of Telesto, Calypso, Helene and Polydeuces, we can estimate k_2 essentially around the tidal frequencies of Tethys and Dione.

2.1. IMCCE's approach

The IMCCE approach benefits from the NOE numerical code that was successfully applied to the Mars, Jupiter, and Uranus systems (Lainey et al., 2007, 2008, 2009). It is a gravitational N-body code that incorporates highly sensitive modeling and can generate partial derivatives needed to fit initial positions, velocities, and other parameters (like the ratio k_2/Q) to the observational data. The code includes (i) gravitational interaction up to degree two in the spherical harmonics expansion of the gravitational potential for the satellites and up to degree 6 for Saturn (Jacobson et al. 2006); (ii) the perturbations of the Sun (including inner planets and the Moon by introducing their mass in the Solar one) and Jupiter using DE430 ephemerides; (iii) the Saturnian precession; (iv) the tidal effects introduced by means of the Love number k_2 and the quality factor Q.

The dynamical equations are numerically integrated in a Saturncentric frame with inertial axes (conveniently the Earth mean equator J2000). The equation of motion for a satellite P_i can be expressed as (Lainey et al. 2007)

$$\ddot{\vec{r}}_i = -\frac{G(m_0+m_i)\vec{r}_i}{{r_i}^3} + \sum_{j=1,j\neq i}^{N} Gm_j\left(\frac{\vec{r}_j-\vec{r}_i}{{r_{ij}}^3} - \frac{\vec{r}_j}{{r_j}^3}\right) + G(m_0+m_i)\nabla_i U_{\hat{i}\hat{0}} + \sum_{j=1,j\neq i}^{N} Gm_j \nabla_j U_{\hat{j}\hat{0}} + \frac{(m_0+m_i)}{m_i m_0}\left(\vec{F}^T_{\hat{i}\hat{0}} - \vec{F}^T_{\hat{0}\hat{i}}\right) - \frac{1}{m_0}\sum_{j=1,j\neq i}^{N}\left(\vec{F}^T_{\hat{j}\hat{0}} - \vec{F}^T_{\hat{0}\hat{j}}\right) + GR \tag{1}$$

Here, $\vec{r}_i$ and $\vec{r}_j$ are the position vectors of the satellite P_i and a body P_j (another satellite, the Sun, or Jupiter) with mass m_j, subscript 0 denotes Saturn, $U_{\hat{k}\hat{l}}$ is the oblateness gravity field of body P_l at the position of body P_k, GR are corrections due to General Relativity (Newhall et al. 1983) and $\vec{F}^T_{\hat{l}\hat{k}}$ the force received by P_l from the tides it raises on P_k . This force is equal to (Lainey et al. 2007)

$$\vec{F}^T_{\hat{l}\hat{k}} = -\frac{3k_2 G{m_l}^2 R^5 \Delta t}{{r_{kl}}^8}\left(\frac{2\vec{r}_{kl}(\vec{r}_{kl}\cdot\vec{v}_{kl})}{{r_{kl}}^2} + (\vec{r}_{kl}\times\vec{\Omega} + \vec{v}_{kl})\right) \tag{2}$$

where $\vec{r}_{kl} = \vec{r}_k - \vec{r}_l$, $\vec{v}_{kl} = d\vec{r}_{kl}/dt$, $\vec{\Omega}$, R, and Δt being the instantaneous rotation vector, equatorial radius and time potential lag of P_k, respectively. The time lag Δt is defined by

$$\Delta t = T\arctan(1/Q)/2\pi \tag{3}$$

where T is the period of the main tidal excitation. For the tides raised on Enceladus, T is equal to $2\pi/n$ (n being Enceladus' mean motion) as we only considered the tide raised by Saturn. For Saturn's tidal dissipation, T is equal to $2\pi/2(\Omega\text{-}n_i)$ where Ω is the spin frequency of Saturn and n_i is the mean motion of the tide raising saturnian Moon P_i. Δt depends on the tidal frequency and on Q, therefore it is not a constant parameter.

It is clear from the second term in the right hand side of Eqs. (2) and (3) that k_2 and Q are completely correlated. To separate both parameters, we consider the action on any Moon of the tides raised on Saturn by all other Moons (see also Appendix A.1). Neglecting tidal dissipation in that case provides the extra terms

$$\sum_{j=1,j\neq i}^{N}\frac{\vec{F}^T_{ij}}{m_i} = \frac{3k_2 Gm_j R^5}{2r_i^5 r_j^5}\left[-\frac{5\left(\vec{r}_i\cdot\vec{r}_j\right)^2\vec{r}_i}{r_i^2} + r_j^2\vec{r}_i + 2\left(\vec{r}_i\cdot\vec{r}_j\right)\vec{r}_j\right]. \tag{4}$$

For an unspecified parameter c_l of the model that shall be fitted (e.g. $\vec{r}(t_0)$, $d\vec{r}/dt(t_0)$, Q...), a useful relation is (Lainey et al. 2012 and references therein)

$$\frac{\partial}{\partial c_l}\left(\frac{d^2\vec{r}_i}{dt^2}\right) = \frac{1}{m_i}\left[\sum_j\left(\frac{\partial\vec{F}_i}{\partial\vec{r}_j}\frac{\partial\vec{r}_j}{\partial c_l} + \frac{\partial\vec{F}_i}{\partial\dot{\vec{r}}_j}\frac{\partial\dot{\vec{r}}_j}{\partial c_l}\right) + \frac{\partial\vec{F}_i}{\partial c_l}\right], \tag{5}$$

where $\vec{F}_i$ is the right hand side of Eq. (1) multiplied by m_i. Partial derivatives of the solutions with respect to initial positions and velocities of the satellites and dynamical parameters are computed from simultaneous integration of Eqs. (5) and (1).