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Modeling stresses on satellites due to nonsynchronous rotation and orbital eccentricity using gravitational potential theory

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ABSTRACT

The tidal stress at the surface of a satellite is derived from the gravitational potential of the satellite's parent planet, assuming that the satellite is fully differentiated into a silicate core, a global subsurface ocean, and a decoupled, viscoelastic lithospheric shell. We consider two types of time variability for the tidal force acting on the shell: one caused by the satellite's eccentric orbit within the planet's gravitational field (diurnal tides), and one due to nonsynchronous rotation (NSR) of the shell relative to the satellite's core, which is presumed to be tidally locked. In calculating surface stresses, this method allows the Love numbers h and ℓ, describing the satellite's tidal response, to be specified independently; it allows the use of frequency-dependent viscoelastic rheologies (e.g. a Maxwell solid); and its mathematical form is amenable to the inclusion of stresses due to individual tides. The lithosphere can respond to NSR forcing either viscously or elastically depending on the value of the parameter $\Delta \equiv \frac{\mu}{\eta\omega}$, where μ and η are the shear modulus and viscosity of the shell respectively, and ω is the NSR forcing frequency. Δ is proportional to the ratio of the forcing period to the viscous relaxation time. When $\Delta \gg 1$ the response is nearly fluid; when $\Delta \ll 1$ it is nearly elastic. In the elastic case, tensile stresses due to NSR on Europa can be as large as $\sim$3.3 MPa, which dominate the $\sim$50 kPa stresses predicted to result from Europa's diurnal tides. The faster the viscous relaxation the smaller the NSR stresses, such that diurnal stresses dominate when $\Delta \gtrsim 100$. Given the uncertainty in current estimates of the NSR period and of the viscosity of Europa's ice shell, it is unclear which tide should be dominant. For Europa, tidal stresses are relatively insensitive both to the rheological structure beneath the ice layer and to the thickness of the icy shell. The phase shift between the tidal potential and the resulting stresses increases with Δ. This shift can displace the NSR stresses longitudinally by as much as 45° in the direction opposite of the satellite's rotation.

1. Introduction

A body subject to a varying gravitational potential will experience tidal deformation as different portions of the body are subjected to different gravitational forcing. The stresses arising from tidal deformations will be either stored elastically, relieved through material failure, or relaxed away viscously. Both failure and relaxation are dissipative processes capable of doing significant work; elastic storage of stress is reversible. In a viscoelastic body, the partitioning of stress among elastic storage, failure, and relaxation will depend on the strength and rheological properties of the body, and on the period of the forcing potential. If the forcing period is roughly equal to or greater than the natural viscous relaxation time of the material being forced, significant viscous relaxation could result, preventing or reducing the extent of material failure and reducing the amount of stress stored elastically.

In the case of natural satellites there are many possible sources of time-variable tidal deformation, for example tidal despinning (Melosh, 1977, 1980b), reorientation relative to the spin axis (Melosh, 1975, 1980a), orbital recession or procession (Squyres and Croft, 1986; Helfenstein and Parmentier, 1983), nonsynchronous rotation (Helfenstein and Parmentier, 1985), polar wander (Leith and McKinnon, 1996), and radial and libra-

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tional tides due to an eccentric orbit (Yoder, 1979; Hoppa, 1998; Greenberg et al., 1998). Many satellites exhibit large-scale systems of linear surface features that have been interpreted as faults, fractures, and other tectonic structures, and which have been linked to the above mechanisms. Examples include the three resonant Galilean satellites (McEwen et al., 2004; Greeley et al., 2004; Pappalardo et al., 2004), several of the middle-sized uranian and saturnian satellites (Squyres and Croft, 1986; Croft and Soderblom, 1991; Nimmo and Pappalardo, 2006; Nimmo et al., 2007), Triton (Croft et al., 1995), and even Mars' small irregular satellite Phobos (Dobrovolskis, 1982). In these cases, observations of a satellite's global tectonic features, combined with a model of its tidal deformation, can be used to gain understanding of the satellite's dynamical and structural evolution.

In the case of icy satellites, viscous effects are likely to play an important role in the stress environment. This is because viscosity generally drops significantly as a material approaches its melting point, and the melting point of ice is much lower than that of silicates. Additionally, tidal heating appears to be an important factor in the histories of many icy bodies (Ojakangas and Stevenson, 1989; Meyer and Wisdom, 2007; Showman et al., 1997), meaning portions of the icy moons may have spent significant periods of time at relatively high temperatures.

In this work, we develop a model of tidal deformation and stress for an arbitrary satellite that is based on long-standing methods of computing global tides and stresses on the Earth. We treat the lithosphere as a layered Maxwell viscoelastic solid to understand how the relaxation of tidal stresses could affect the interpretation of global tectonic features. We focus on nonsynchronous rotation (NSR) and eccentricity (diurnal) tides, which offer the most plausible explanation for the pattern of lineaments observed on the surface of Europa (Helfenstein and Parmentier, 1985; McEwen, 1986; Leith and McKinnon, 1996; Geissler et al., 1998; Greenberg et al., 1998; Hoppa, 1998; Hoppa et al., 1999a, 1999b; Figueredo and Greeley, 2000; Kattenhorn, 2002; Spaun et al., 2003). We assume the satellite has radially dependent material properties, and include a rocky core, a hydrostatic ocean, and a lithospheric shell of arbitrary thickness having multiple viscosity layers. The frequency-dependent response is incorporated into the model through the use of complex-valued Lamé parameters and Love numbers. For demonstration purposes we apply the model to Jupiter's satellite Europa. We assume Europa's lithosphere consists of a high-viscosity outer layer surrounding a low viscosity inner layer, which approximates an ice shell undergoing stagnant lid convection. A parallel approach has been undertaken by Harada and Kurita (2007), who also consider a tidal potential method and viscoelastic relaxation of NSR stresses, but who do not provide the details of their calculations.

Our approach of deriving stresses directly from the gravitational potential has several advantages over previously published approaches, which derive stresses based on an instantaneous change in the triaxial ellipsoid describing a satellite's shape (Melosh, 1977; Helfenstein and Parmentier, 1985; Leith and McKinnon, 1996; Hoppa, 1998):

1. It allows the Love numbers h and ℓ to be specified independently, decoupling the radial and lateral tidal deformations.
2. It allows the use of realistic rheological properties for the body (e.g. treatment of the ice shell as a Maxwell solid; radially dependent structural properties, including the presence of a solid core; compressibility), and does not require that the outer shell be thin.
3. Because viscoelastic effects are included directly into the equations of motion, the results can be applied to all possible combinations of NSR rates and viscosity values.
4. Its mathematical form is amenable to the inclusion of individual potential terms (NSR or diurnal) and the future inclusion of other terms in the description of the potential (e.g., obliquity or polar wander).

In this paper we describe the NSR and diurnal tidal forcing mechanisms (Sections 2 and 3), and develop a mathematical framework for computing the resulting outer surface stresses both for elastic (Section 4) and viscoelastic (Section 5) satellites. The effects of viscoelasticity on the NSR stresses are discussed qualitatively in Section 6. We use the viscoelastic model developed in Section 5 to compute diurnal and NSR stresses for Europa (Sections 7 and 8), and compare with results computed using previously published methods (Section 9). More mathematical detail is provided in Appendices A and B.

2. Stressing mechanisms

2.1. Nonsynchronous rotation

The tidal despinning timescales for large natural satellites are short compared to the age of the Solar System, meaning that today nearly all satellites are synchronously locked, always showing their parent planet the same hemisphere (Peale, 1999). However, many large icy satellites are believed to have global oceans which decouple the motions of their floating shells from their interiors (Schubert et al., 2004). Such a decoupled shell could experience a net tidal torque, and could rotate slightly faster than synchronously (cf. Greenberg and Weidenschilling, 1984; Ojakangas and Stevenson, 1989). From the rotating shell's point of view, the apparent location of the parent planet moves slowly across the sky. The tidal bulge, which remains fixed relative to the parent planet, appears to migrate in the direction opposing the rotation. As the bulge passes over a region of the shell, that region deforms and experiences a stress. If NSR exists, it should occur with a period similar to the thermal diffusion or viscous relaxation timescales of the shell (Greenberg and Weidenschilling, 1984; Ojakangas and Stevenson, 1989), and thus viscous relaxation is likely to influence NSR stresses. Observations constrain the present period of NSR of Europa's ice shell to be $>10^4$ yr (Hoppa et al., 1999c). NSR could also affect Ganymede (Collins et al., 1998; Zahnle et al., 2003; Nimmo and Pappalardo, 2004) and Io (Greenberg and Weidenschilling, 1984; Schenk et al., 2001), and could apply to other satellites with fluid or low-viscosity interiors.

2.2. Diurnal tides

Diurnal stresses for a synchronously rotating satellite have the same period as a satellite's orbit. They arise on a satellite in an eccentric orbit for two reasons. First, for an eccentric orbit the distance between the satellite and the planet changes with time, thus changing the amplitude of the planet's gravitational force on the satellite, creating the "radial tide." At periapse the tidal bulge is larger than at apoapse, and this daily deformation results in diurnally varying stresses.

Second, a synchronously orbiting satellite in an eccentric orbit does not always keep the same face toward the planet. A satellite at periapse is orbiting slightly faster than its (constant) rotation rate, and at apoapse is orbiting slightly slower. This causes the tidal potential to rock back and forth relative to fixed points in the satellite, inducing a "librational tide" (Yoder, 1979; Greenberg et al., 1998).

As will be seen below, the magnitudes of these tides are proportional to the orbital eccentricity ϵ (for small values of ϵ). Diurnal tides have been suggested to explain the formation of the