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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 ~3.3 MPa, which dominate the ~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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