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Application of normal-modes formalism to the determination of tidal deformations and stresses at the surface of Europa

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Abstract

Europa, the smallest of the Galilean satellites, is characterized by a young water-ice surface showing a rich structure of cracks, ridges and chaotic terrain. The formation of the complex structure of ridges and cracks observed on the Europan surface has been related to stress fields on the surface, which have been induced by eccentricity-driven tides - also known as diurnal tides - and probably nonsynchronous rotation of the icy shell [1] [2] [3]. Other suggested sources of stresses at the surface are the obliquity of Europa's rotation axis [4], true polar wander [5] and the cooling of the viscoelastic ice shell [6].

In this study, we focus on the determination of the stress patterns at the surface of Europa caused by eccentricity-driven tides and nonsynchronous rotation. In order to achieve this goal, we consider interior models composed of five homogeneous incompressible spherical layers: a metallic core, a silicate mantle, a fluid ocean, a low-viscous ice layer or asthenosphere and a high-viscous brittle outer layer or lithosphere. The mantle and ice layers are modeled as Maxwell viscoelastic layers. The ocean and the metallic core are treated as fluid layers. The division of the icy shell in two sublayers with different viscosities is consistent with thermal models dealing with stagnant lid convection in the icy shell [7] and with the morphology of impact craters on the surface of Europa [8] [9]. The outer radius and density of each of the layers from the proposed interior models satisfy the constraints on average density, $\rho_{av} = 2989\ \mathrm{kg\,m^{-3}}$, and axial moment of inertia factor, $\frac{C}{MR^2} = 0.346$, of Europa [10] [11].

The response of Europa's interior to the eccentricity-driven and the non-synchronous tidal potential can be determined by applying the normal mode formalism to compute the Love numbers h_2, k_2 and l_2 at the surface. In difference with other methods to compute the Love numbers, like numerical integration techniques [2] [3], the normal modes method allows to determine the Love numbers in an almost complete analytical way by making use of the propagator matrix technique [12]. In the case of the five layers model introduced before, six relaxation modes will be obtained: the surface mode M_0, the core mode C_0, the buoyancy modes M_2 and M_3 at, respectively, the ocean-asthenosphere boundary and the ocean-mantle boundary, and the transient modes T_1 and T_2 triggered at the asthenosphere-lithosphere boundary due to the difference in Maxwell relaxation time between these two ice layers. The obtained Love numbers are purely real and composed of an elastic contribution and a mode-dependent contribution.

Once the Love numbers are known, we can determine the viscoelastic deformation and stresses at the surface of Europa by applying the forcing function to the body of interest. From the performed computations, it is clear that the radial deformation u_r is substantially larger for models with a subsurface ocean ($u_r \approx 15$ m to ≈ 30 m) than for models in which the mantle is in direct contact with the asthenosphere ($u_r \approx 0.6$ m). If a subsurface ocean is present, the amplitude and phase-lag of the radial deformation primarily depends on the thickness of the icy shell, the rigidity of ice and the viscosity of the asthenosphere. The magnitude of the deformation decreases as the ice shell becomes thicker, where the effect is more pronounced for high rigidities ($\mu_{ice} = 1.0{\cdot}10^{10}$ Pa). The phase-lag is primarily determined by the contribution of the transient mode T_2, which is the relaxation mode with the shortest relaxation time. In general, viscoelastic contributions to the radial deformation are only important if the relaxation time of the mode is smaller than 52.5 days in Europa's case. In addition, in the case of stresses at the surface, the ratio between the period of the forcing function and the Maxwell relaxation time of the lithosphere determines whether viscous relaxation effects are important for the magnitude and direction of the stress patterns at the surface. We found that only the transient modes T_1 and T_2 have a sufficiently short relaxation time in order to contribute to the stresses induced by the diurnal tides. In the case of stresses induced by nonsynchronous rotation, also the surface mode M_0 will generate a contribution. These results are consistent with the ones recently published in [3].

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