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Surface stress patterns and the possibility of a subsurface ocean on Europa

H.M. Jara-Orué and L.L.A. Vermeersen
Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands (e-mail: h.m.jaraorue@tudelft.nl)

1. Introduction

The geologically young icy surface of Jupiter's moon Europa is characterized by the presence of a rich network of cracks and ridges, whose formation has been related to stresses acting on the icy shell [3]. Tidal stresses in Europa's surface are induced by sources of time-variable tidal deformation, which either act at diurnal timescales or at much longer timescales. At diurnal timescales ($\sim$3.55 days), tidal stresses are the result of the non-zero eccentricity of Europa's orbit, the non-zero obliquity of Europa's spin axis [1] and forced longitudinal librations of the ice shell [7]. At longer timescales (>12,000 years), significant tidal stresses might be caused by non-synchronous rotation (NSR) of the ice shell [2] and true polar wander [5].

2. Modeling

The interior of Europa will be assumed to consist of five homogeneous incompressible layers: a metallic core, a silicate mantle, a liquid ocean, a low-viscous ice layer (asthenosphere) and a high-viscous outer layer of ice (lithosphere). The mantle and both ice layers are modeled as Maxwell viscoelastic layers, whereas the core and the ocean are modeled as inviscid fluid layers. In our models both ice layers are characterized by a rigidity μ equal to 3.487 GPa [9]. The viscosity η_a of the asthenosphere is assumed to range between 10^{13} and 10^{17} Pa·s, while the viscosity η_l of the lithosphere is assumed to be larger than 10^{19} Pa·s.
The tidal response of a viscoelastic planet is usually expressed in terms of the Love numbers h_2, l_2 and k_2. In contrary to previous research (see e.g. [9]), the tidal Love numbers are calculated by means of the propagator matrix technique [8] rather than by numerical integration. Consequently, the obtained Love numbers are purely real and consist of an elastic component and a delayed component. In the case of the five layers interior models introduced here, the delayed component is generated by the contribution of six relaxation modes: the surface mode M_0, the core mode C_0, the buoyancy modes M_2 and M_3 at the ocean-ice boundary and the ocean-mantle boundary, and the transient modes T_1 and T_2 at the interface between the two ice layers. The subdivision of the delayed response in multiple relaxation envelopes is aimed to provide a better insight into the geophysical mechanisms governing the relaxation process [8].

3. Tidal stresses

The elements of the stress tensor at Europa's surface can be retrieved from analytical expressions that have been derived from the obtained normal mode response and the description of the tidal force as a potential. These expressions, which in the incompressible limit are similar to the ones published in [9], show that the state of relaxation of tidal stresses is governed by a dimensionless parameter proportional to the ratio between the period T of the acting force and the Maxwell relaxation time $\tau_l = \eta_l/\mu$ of the lithosphere. In case of diurnal tidal stresses, the period of the acting force ($T \sim 3.55$ days) is several orders of magnitude smaller than the characteristic relaxation time of the lithosphere ($\tau_l > 90$ years). Hence, diurnal stresses will be elastically stored in this upper ice layer. This is not the case for stresses which have been induced by long-term periodic mechanisms such as non-synchronous rotation (NSR) of the ice shell, because the period of the acting force ($T > 12,000$ years) might largely exceed the value of τ_l. As a consequence, NSR stresses at Europa's surface might experience severe viscoelastic relaxation.
The response of Europa to the acting tidal forces also includes a delayed component, which will introduce a phase-lag to the spatial distribution of the stress patterns at the surface. The phase-lag of the diurnal stress field is completely defined by the contribution of the transient modes T_1 and T_2 and is largest for viscosities ranging between 10^{14} and 10^{15} Pa·s. On the other hand, the phase-lag of the NSR stress field is primarily dominated by the relaxation of the elastic component. However, the influence of the buoyancy mode M_2 becomes important in cases that the viscosity contrast between the two ice layers is less than 10^5 Pa·s.

Since ice-I is more prone to fail in tension, a crack in Europa's ice shell will be initiated when the magnitude of the local tensile stress exceeds the tensile strength of ice [3]. The tensile strength of Europa's ice at the surface is one of the poorest constrained mechanical parameters, with values ranging from $\sim$40 kPa for porous and fractured ice to $\sim$3 MPa for fracture-free and non-porous ice (see e.g. [6]).

3.1. Diurnal tidal stresses: eccentricity

The diurnal stress field can be regarded as being highly variable as it completes a full rotation about the surface after every orbital revolution. Tensile faults propagating through the icy surface will then encounter an ever-changing stress field in both magnitude and direction. The final shape of the generated cracks will be most probably cycloidal, as suggested by e.g. [4].

For interior models that include a subsurface ocean the magnitude of the largest tensile stresses ranges between $\sim$80 kPa and $\sim$110 kPa, depending on the structural and rheological properties of the ice layers. In these cases, diurnal tensile stresses would only exceed the tensile strength of ice if the upper lithosphere is considered to be porous and fractured. If a subsurface ocean is absent, the magnitude of the largest tensile stresses would be smaller than 5 kPa as long as the viscosity of the asthenosphere remains larger than the viscosity of ice at melting temperatures. Therefore, it seems that the existence of cycloidal features on Europa's surface requires the presence of a subsurface ocean underneath the ice shell.

3.2. NSR stresses

The relaxation state of NSR stresses at the surface of Europa depends on the ratio $\Delta = T_{nsr}/(4\pi\tau_l)$, in which T_{nsr} (>12,000 years) is the period of one complete rotation of the ice shell with respect to the locked interior. In cases that viscoelastic relaxation of stresses does not take place (i.e. for $\Delta < 0.1$), NSR stresses at the surface might become as large as $\sim$4 MPa. However, the assumed rheological properties of Europa's lithosphere constrain Δ to be at least equal to 1. Due to the effect of viscoelastic relaxation, the magnitude of the largest NSR stresses at the surface decreases from $\sim$3 MPa for $\Delta = 1$ to $\sim$40 kPa for $\Delta = 100$.

As diurnal stresses always act on Europa, the magnitude and direction of the stress patterns at the surface will depend on the relative strength of NSR stresses with respect to diurnal stresses and hence on the value of Δ. Based on the temporal variability of the stress patterns at the surface, we identify the existence of three main regimes: nearly static for $\Delta \leq 5$, transitional for $5 < \Delta < 30$ and highly-variable for $\Delta \leq 30$. In the nearly static regime, the resulting stress patterns can explain the formation of global lineaments. On the other hand, the formation of cycloids is best explained by highly-variable stress fields.

An interesting characteristic of Europa's surface is that cycloids coexist with global lineaments, implying variations of the ratio Δ throughout the geological history of Europa. The change of Δ as a function of time requires either secular variations in the rotation rate and/or variations of the rheological properties of the lithosphere. In both cases, we expect that such variations require the existence of a dynamic ice shell covering a subsurface ocean that decouples the rotational motion of the ice shell from the motion of the innermost layers.

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