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Tidal stress and jets activity on Enceladus

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Abstract

The eruptions of water vapor and ice particles on Enceladus' south pole together with huge heat production suggest the presence of a strong source of energy within Enceladus' interior. The abnormal endogenic power is probably the consequence of strong tidal dissipation along the ridges and within the ice shell during a recent history [1]. The jets activity was shown to be controlled by diurnal changes in the tidal stresses from Saturn [2, **?**]. This activity, however, seems to be delayed by $3-4$ hours than expected for a purely elastic response and a global ocean. Here, we study under which conditions the delay can be explained using a parameterized viscoelastic model. Especially, we concentrate on the influence of width of the internal ocean and 3D viscosity structure of the ice shell on the stress distribution.

1. Method and model

The response of the Enceladus' ice shell to the tidal loading is computed numerically in the time domain and allows to use a 3D viscosity structure and a localized internal ocean [3, 1]. The mass and momentum conservation equations are solved in a spherical shell using the Andrade rheology [4]. A deep internal ocean of limited lateral extend can be prescribed via boundary conditions on the bottom boundary (pseudo free-surface for areas with a supposed ocean and no-slip for areas with no ocean).

A varying ice shell thickness H is considered in the range $50-80\,\mathrm{km}$. At the base of the ice shell, a localized deep ocean symmetric with respect to the south pole is supposed with angular width Δ varying between $0°$ (no ocean) and $360°$ (global ocean). Above the ocean, a low viscosity zone with a minimum viscosity $\eta = 10^{13-15}\,\mathrm{Pa\,s}$ is assumed. Outside this region, a uniform viscosity of $10^{20}\,\mathrm{Pa\,s}$ is considered. Additionally, A high-viscosity lithosphere of thickness L is supposed.

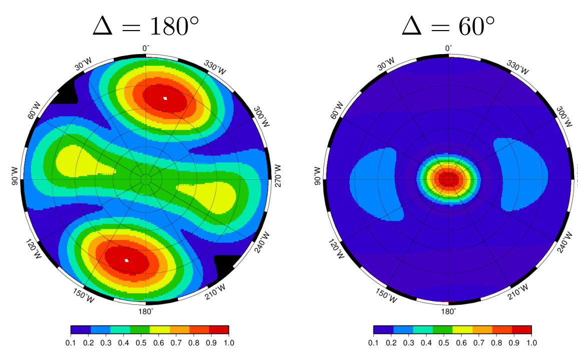

Figure 1: An example of the stress patterns dependence on the ocean width. Normalized stress invariant is shown on the surface of the south hemisphere and near apogee for models with $H = 60\,\mathrm{km}$, $\eta = 10^{14}\,\mathrm{Pa\,s}$, $L = 5\,\mathrm{km}$.

2. Stress patterns

The numerical simulations show that both amplitude and the stress patterns depend on the internal structure. In the range of studied parameters, the maximum stress increases with decreasing ice shell thickness, lithosphere thickness and minimum viscosity. Varying ocean width Δ from $180°$ to $360°$ changes the magnitude of maximum stress by about 15%. For smaller oceans ($\Delta \leq 120°$), the maximum stress is reduced by at least 50% in comparison with the global ocean. The stress patterns along the orbit depends strongly on internal parameters. Whereas the weak interior tends to delay the shell response, the presence of a localized internal ocean changes also the patterns itself (see Fig 1).

3 Plume activity delay

The recently shown orbital dependence of eruption activity and plume brightness [2] is consistent with time varying tensile stresses along the tiger stripes [5]. The observed activity is nevertheless somewhat delayed

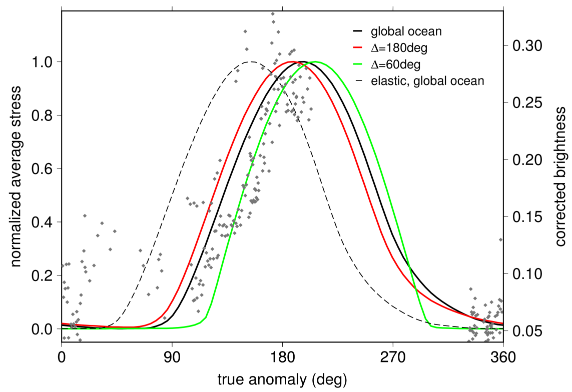

Figure 2: Comparison of the time evolution of the observed corrected brightness [2] (black diamonds) and the normalized tensile stress. Dashed line: elastic model with global ocean. Solid lines: viscoelastic models computed for $H = 60\,\mathrm{km}$, $\eta = 10^{14}\,\mathrm{Pa\,s}$, $L = 5\,\mathrm{km}$ and Δ $60°$, $180°$ and $360°$ (green, red and black line, respectively).

compared to the case with a purely elastic shell and a global ocean. As shown above, the stress pattern is sensitive to the size of internal ocean and viscosity distribution in the ice shell. The observed delay may thus provide a constraint on the internal structure.

We compare the time variations of plume brightness reported by VIMS observations [2] and the computed variations of average tensile stress along the tiger stripes. As shown in Fig. 2, the increase in brightness is delayed by 3–4 hours in comparison with the tensile stress increase (averaged along the tiger stripes) predicted for a purely elastic model with a global ocean. This time discrepancy can be reduced for viscoelastic models with a localized ocean, a weak interior and a thin lithosphere. The delay decreases with decreasing minimum viscosity and lithosphere thickness. In contrast, dependence of the delay on the ocean width is rather complex due to changes in stress patterns. The stress predictions consistent with the observed brightness are obtained for an ocean width varying between $60°$ and $90°$.

4. Tidal dissipation

Tidal heating strongly varies with all studied parameters. The global tidal heating does not exceed $5\,\mathrm{GW}$ for most models. Nevertheless, the maximum heating for our models can be as high as several tens of gigawatt but only for cases with the minimum viscosity $\eta = 10^{13}\,\mathrm{Pa\,s}$ and ocean width larger than $180°$. For the models explaining the observed brightness curve

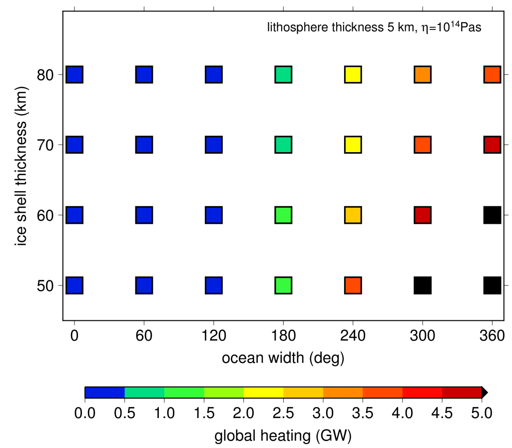

Figure 3: Global tidal heating as a function of the ocean width and the ice shell thickness and for lithosphere thickness $5\,\mathrm{km}$ and $\eta = 10^{14}\,\mathrm{Pa\,s}$.

the predicted tidal heating is low ($< 0.5\,\mathrm{GW}$, Fig. 3).

5. Summary and Conclusions

The observed delay in eruption activity hints at the presence of only a small localized internal ocean ($\Delta = 60 - 90°$). We further show that the observed activity is consistent with a thin lithosphere over a warm ice mantle in the south polar region. However, tidal heating for such models is low ($< 0.5\,\mathrm{GW}$) and cannot explain the present day heat loss in Enceladus' southern polar region. The low tidal heating for models explaining the delayed jets activity may thus be used as an argument supporting the hypothesis of episodic activity on Enceladus.

Acknowledgements

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