# INVESTIGATIONS OF THE SURFACES AND INTERIORS OF OUTER PLANET SATELLITES

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Studies under NSG 7315 during 1985/86 include: 1) Tidal heating and the structure and evolution of Io and Europa, 2) Crater relaxation on icy satellites using realistic non-Newtonian ice rheology, 3) Convection through phase transitions in the interiors of icy satellites. The abstracts of published papers on these subjects are reproduced below.

## Tidal Heating in an Internal Ocean Model of Europa

M.N. Ross and G. Schubert, ***Nature***, in press, 1986

The tidal response of a three-layer Europa model is calculated. The model consists of an elastic lithosphere (ice shell) above an inviscid water layer (internal ocean) and an elastic core (silicate). The tidal distortion of a decoupled ice lithosphere is a factor of 2 less than previously thought. For a given dissipation factor Q (equal in the ice and silicate) tidal heating in the lithosphere is a factor of 4 less than previous estimates while tidal heating in the core is 30% less. At the current value of orbital eccentricity tidal heating is only marginally able to prevent the internal ocean from freezing; $Q<25$ is required. If Q in the silicate core equals 100 then Q in the ice lithosphere must be less than 17 for an internal ocean to be stable against freezing. If silicate $Q\approx25$ then lithosphere $Q<37$ is required for internal ocean stability. The persistence of an internal ocean is made somewhat more probable if a low conductivity surface layer insulates the ice lithosphere and raises near surface temperatures above the solar equilibrium value. Cyclical tidal stresses in the lithosphere are currently about 1/10 of the yield strength of ice, making it unlikely that these stresses cause the curvilinear features on Europa.

## Finite Element Models of Non-Newtonian Crater Relaxation

P. Thomas and G. Schubert, ***Proc. Lunar Sci. Conf. 17th, J. Geophys. Res.***, in press, 1986.

Models of viscous crater relaxation proposed to date for the icy satellites of the outer solar system assume the behavior of a Newtonian medium, with viscosity $\eta$ independent of effective stress $\tau$. While this is reasonable if both effective stresses and temperatures are very low, laboratory data on ice indicate that, at effective shear stresses ($\tau \sim 0.1$ *MPa*) and temperatures ($\sim$ 173K) likely to occur in regions underlying craters, non-Newtonian behavior is probable. Such material would have a viscosity-effective stress relation given by $\eta(\tau)\propto \tau^{1-n}$, where $n \approx 4$. It is likely, due to the low activation energy of ice at these temperatures,

that stress differences may affect the profile of relaxing craters to a greater extent than temperature differences. To investigate the effects of a non-Newtonian rheology on the profiles of relaxing craters, two-dimensional finite element simulations have been performed. Initially, effective stresses are highest in the region below the crater center, producing a zone of relatively low viscosity. Relaxation flow forces this region into a convex bulge as the crater relaxes. At later stages, the low viscosity region moves to beneath the crater rim, leading to enhanced relaxation of crater rims, compared to a Newtonian rheology. The reduction of effective stress as the crater relaxes increases viscosity in the region beneath the crater. As a result, relaxation rates are quite rapid compared to those in later stages. This is in marked contrast to the exponential behavior of depth with time associated with Newtonian relaxation. The short relaxation times observed for the craters modelled indicate that a silicate component may be required in the crusts of icy satellites to account for the observed crater populations.

Tidally Forced Viscous Heating in a Partially Molten Io
M.N. Ross and G. Schubert, *Icarus, 64*, 391-400, 1985.

We investigate tidal dissipative heating in two different models of Io. The partially molten asthenosphere model consists of a rigid core and a thin (less than 400km thick) partially molten "decoupling" layer (asthenosphere) surrounded by an elastic lithosphere. In the partially molten interior model the interior beneath the lithosphere is partially molten throughout. The partially molten region in each model is assumed to possess negligible shear strength and to be characterized by a Newtonian viscosity. Tidal deformation and dissipation in the core of the thin asthenosphere model are assumed negligible. Fluid in the viscous layers is forced to circulate by the tidal distortion of the outer shell, modeled here as a sinusoidal variation with time of the distortion amplitude. As a result, heat is generated in the fluid by viscous dissipation. There are two heating mechanisms in our models: "elastic" dissipation in the lithosphere $\propto 1/Q$ and viscous dissipation in the partially molten region. Numerical calculations are carried out for a 90-km-thick lithosphere with Q=100. This thickness maximizes dissipation in a decoupled lithosphere; other reasonable values of lithosphere thickness do not alter our calculations. Under the constraint that total dissipation equals the observed radiated heat loss we derive the viscosity of the partially molten region in each model. We a posteriori evaluate the assumption that the lithosphere is decoupled from the interior by calculating the distortion of an elastic shell due to the viscous stresses on the lower surface of the outer shell. If the interior viscosity is such that the total dissipation is equal to the observed heat flux from Io, viscous stresses produce negligible distortion of a 90-km-thick shell. This validates the assumption of a decoupled shell. The derived viscosity for both models is characteristic of a partially molten rock. In the thin asthenosphere model the derived viscosity is so low that a very high degree of partial melt is necessary, about 40% crystal fraction in a 400-km-thick asthenosphere and about 0% in a 1-km-thick asthenosphere. In the partially molten interior model the derived viscosity corresponds to a magma with about 60% crystals. Consideration of convective efficiencies demonstrates the plausibility of a stable thermal steady state for both models. A significant portion (75% for Q = 100) of Io's tidal heating can be the result of viscous dissipation in a partially molten region that decouples the outer shell from the interior. The partially molten layer can be considered a "global magma ocean."

Phase Transistions and Convection in Icy Satellites
D. Bercovici, G. Schubert, and R.T. Reynolds,
*Geophys. Res. Lett.*, *13*, 448-451, 1986.

The effects of solid-solid phase changes on subsolidus convection in the large icy moons of the outer solar system are considered. Phase transitions affect convection via processes that distort the phase change boundary and/or influence buoyancy through thermal expansion. Linear stability analyses are carried out for ice layers with a phase change at the midplane. Two exothermic phase transitions (ice I - ice II, ice VI - ice VIII) and two endothermic transitions (ice I - ice III, ice II - ice V) are considered. For the exothermic cases, the phase change can either impede or enhance whole-layer convection. For the endothermic cases, the phase change always inhibits whole-layer convection overturn and tends to enforce two-layer convection. These results place some constraints on possible models of icy satellite evolution and substructure.

Crater Relaxation as a Probe of Europa's Interior
P.J. Thomas and G. Schubert, ***Proc. Lunar and Planet. Sci. Conf. 16th Planet. Sci. Conf. 16th, J. Geophys. Res.***, ***91***, D453-D459, 1986

Viscous relaxation rates of craters are examined to discriminate among models of Europa's interior. It is shown that the presence of an insulating surface regolith is required for ice lithospheres that do not contain a liquid $H_2O$ layer. Without the presence of such an insulating regolith, relaxation times for craters $\cong$ 100 km in diameter are excessively long ( > 1 b.y.) and thus inconsistent with the absence of such features in Voyager images. Finite element calculations indicate that a thick insulating surface frost layer (raising surface temperatures $\gtrsim$ 40 K above the solar radiation ambient temperature of 92 K) allows a 25-km-thick surface viscous layer to relax $\gtrsim$ 100-km-diameter craters on the short timescales ($\cong$ 100 m.y.) required. If the icy lithosphere is 100 km thick (and without a liquid $H_2O$ layer, but containing a subsolidus convecting region), surface temperatures need to be raised 20 K by insulation to allow relaxation of craters in this size range to occur within the required time.