SPUTNIK PLANITIA BASIN AS A TRIGGER FOR MELTING AND REORIENTATION OF PLUTO'S ICE SHELL.

M. Kihoulou[1] and V. Patočka[1]. [1] Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, 18000 Prague, Czech Republic

Introduction: The topography of the dwarf planet Pluto is dominated by an elliptic basin, informally called Sputnik Planitia. Several observations indicate that the basin is of impact origin, such as its elliptic shape and multiring structure [1]. Sputnik Planitia lies close to the Pluto-Charon tidal axis, which suggests that the basin produces a positive gravity anomaly despite its negative topography. The mass excess is being credited to a combination of the solid nitrogen layer and an ocean uplift that might have been generated by the basin-creating event [2]. However, impact simulations suggest that impact-induced ocean uplift is not sufficiently large to compensate the basin's negative topography, unless the ocean is anomalously dense ($\gtrsim 1100$ kg/m^3) [3]. Moreover, due to low viscosity of ice near the ice/ocean boundary (IOB), the uplift would soon disappear, because the pressure gradient along the IOB would drive lateral flow within the shell, filling the region with ice. In order to maintain the uplift for billions of years, the presence of an insulating and highly viscous clathrate layer at the IOB was proposed [4]. Finally, numerous extensional faults on Pluto's surface suggest that the initially liquid subsurface ocean is at least partially frozen at present [5]. With increasing shell thickness, the ocean uplift becomes less significant. Altogether, it is problematic to maintain the positive gravity anomaly and thus explain the basin's observed location.

Here we present an alternative mechanism for generating an uplift of the subsurface ocean of Pluto. Due to an insulating effect of the nitrogen layer, the temperature at the surface of Pluto's ice shell is likely to vary laterally. As explained in the following paragraphs, this results in variations of heat flux and build-up of topography at the IOB. Depending on the assumed ice shell thickness and viscosity, the obtained uplift may be sufficient to generate an overall positive gravity anomaly. In a next step, we compute the characteristic timescale of ice shell reorientation for selected cases, showing that while a thin shell responds quickly and reorients completely, a thick and colder shell is much more stable. This opens the possibility that Sputnik Planitia may have obtained its position in the past and the subsurface ocean can be completely frozen at present. Later freezing of the ocean and the corresponding change in sign of the overall geoid triggers only a sluggish response, and can be outweighed by fossil constituents of the tidal and rotational bulge.

Shell melting: Since solid nitrogen has significantly lower thermal conductivity than the water ice, Sputnik Planitia can act as a thermal insulator and introduce a spatial variation of temperature at the ice shell's outer surface. From various estimates of the basin floor temperature [6,7] we adopt 63 K, the melting temperature of nitrogen. This value is 23 K warmer than the exposed ice surface outside of the Sputnik Planitia basin [8].

We perform 2D axisymmetric spherical numerical simulations of viscous flow within the ice shell. The temperature profile is assumed to be conductive, and the variations of temperature at the outer boundary thus result in heat flux variations at the IOB. Viewing the cooling history of the shell as a series of stationary states (i.e. the quasi-steady approach), we assume the heat flow from the ocean to balance the heat withdrawn by the ice shell. This allows us to study shells with different thicknesses independently. While the heat flux from the ocean is considered to be spatially uniform, the heat flux at the base of ice is spatially variable. This triggers undulations of the IOB - the ice melts in regions where the heat flux discontinuity is negative [9]. A stationary flow develops and the initially spherical IOB builds up a stable non-zero topography (Figure 1). This mechanism thus explains an uplift below Sputnik Planitia as a natural consequence of the temperature variations at the ice shell's outer surface.

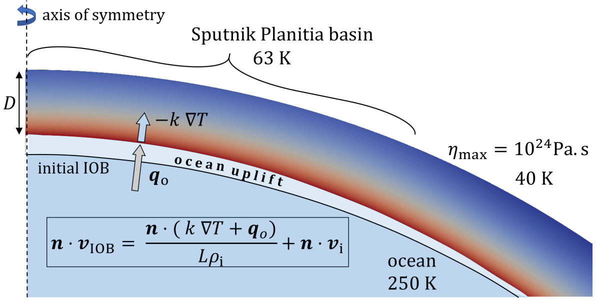

Figure 1: Problem description. Melting is triggered by a heat flux discontinuity between the ocean (gray arrow) and the base of the ice shell (blue arrow). The boundary condition relates it together with the IOB velocity and the ice flow velocity [9]. Color in the shell represents the temperature (40 - 250 K).

Amplitude of the uplift depends on the magnitude of the heat flux discontinuity and on the viscosity of ice. The heat flux discontinuity is determined by the shell thickness and the temperature difference between the basin floor and its surroundings, while the viscosity of ice depends on its grain size and on the ocean temperature (see Figure 1). We consider nonlinear ice rheology and our simulations are limited to only those combinations of parameters that do not trigger thermal convection.

Pluto's reorientation in space depends on its moment of inertia, which can be computed from the gravity signal at the spherical harmonic degree *2* [10]. In order to explain the present day position of Sputnik Planitia, the combined gravity anomaly of the uplift, the surface crater, and of the nitrogen layer need to add up to a positive value. Figure 2 shows the obtained degree 2 gravity anomaly (Δ*g*) for various ice shell thicknesses (*D)* and grain sizes.

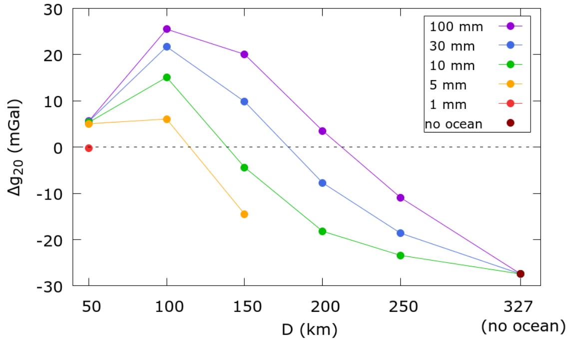

Figure 2: Overall gravity anomaly at the spherical harmonic degree *2*. Thin shell can generate only a small uplift - already a slight change in the IOB topography balances the heat fluxes and thus stops the melting. Thicker shell can generate larger uplift, but its gravity signal rapidly decreases with the IOB depth.

Reorientation timescales: The gravity anomalies reported in Figure 2 would drive true polar wander on Pluto, i.e. Pluto's ice shell would reorient in space. We use the code LIOUSHELL [11] to compute the dynamics of such a process. We assume only the case in which Sputnik Planitia lies in the plane spanned by the rotation and tidal axes, and thus both the tidal and rotational torques act in the same direction.

In Figure 3, we focus on two situations. First, we investigate the full reorientation of Sputnik Planitia towards the tidal axis. For a 100 km thick ice shell with grain sizes larger than 10 mm, i.e. for the cases with the largest positive gravity anomalies, polar motion is rapid and the basin would get close to the tidal axis within less than 100 Myr, regardless of its initial location. Second, we investigate the poleward reorientation for a completely frozen hydrosphere. Driven by the gravity signal of the crater and nitrogen alone, the reorientation takes nearly a billion years.

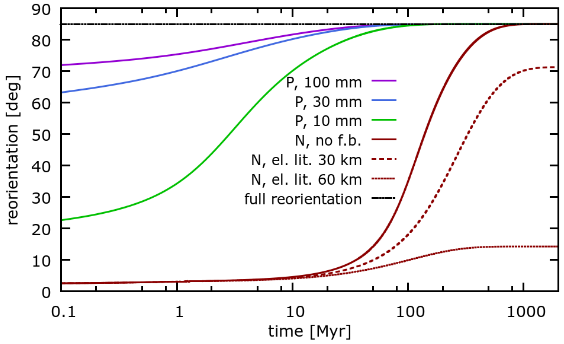

Figure 3: Reorientation timescales for positive (P) and negative (N) gravity anomalies. The positive gravity anomalies obtained for a 100 km thick ice shell completely reorient Sputnik Planitia toward the Pluto-Charon axis within less than 100 Myr (green, blue, violet). The subsequent poleward reorientation, driven by the negative anomaly corresponding to a completely frozen hydrosphere, takes several hundreds of Myr. Its final amplitude is significantly reduced if the outer part of the shell is assumed to be elastic, with a fossil constituent of the tidal and rotational bulge (dark red).

More importantly, the poleward reorientation of a fully frozen hydrosphere may be only partial. Assuming that some outer part of Pluto's ice shell is elastic [12], it would contain the so-called fossil bulge [10], i.e. part of the rotational and tidal bulge would not respond to the changing position of the pole. For an effective elastic thickness of 60 km, the fossil bulge outweighs the loading caused by the basin, and the poleward reorientation of the shell stops at 15 degrees, i.e. close to the present day location.

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