

ELASTIC FLEXURE AROUND SPUTNIK PLANITIA, PLUTO, AND EVIDENCE FOR A VERY HIGH HEAT FLUX. A. C. Mills^{1,2} and L. G. J. Montési¹, ¹Department of Geology, University of Maryland, College Park, MD 20742, amills12@umd.edu. ²Smithsonian Institution National Air and Space Center for Earth and Planetary Studies, Washington, DC 20560.

Overview: One of the most remarkable geological features of Pluto is the $1,300 \times 500 \text{ km}^2$ elliptical basin called Sputnik Planitia. Currently, the basin is filled by about 10 km of convecting nitrogen ice [1, 2, 3]. Sputnik Planitia has been interpreted as an impact basin hosting a nitrogen ice deposit [4, 5] or a flexural basin resulting from the deposition of a large ice cap [6]. Here, we test if the current topography of Sputnik Planitia and its surroundings contain evidence for the flexural bulge that would have formed in a thin elastic plate loaded by a large deposit of nitrogen ice inside Sputnik Planitia.

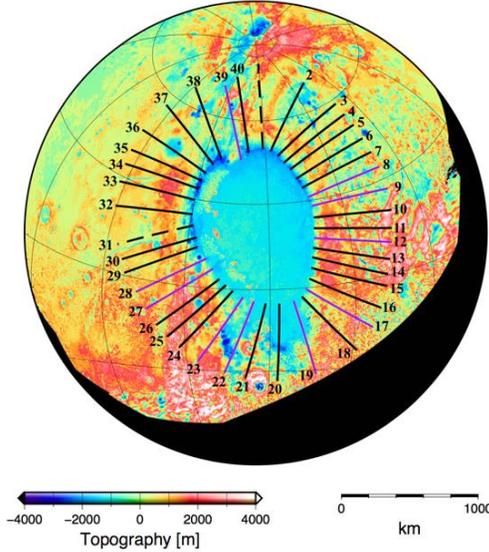


Figure 1. Topographic map of Pluto [1], reported in a Lambert Equal Area projection centered at 175°E , 20°N . The map also shows the 40 tracks considered in this study. The black region is an area of no data. Black tracks represent profiles with evidence of flexure, and purple tracks are profiles without evidence of flexure.

Methods: Forty 600 km-long tracks perpendicular to the edge of Sputnik Planitia (Figure 1) were extracted from a stereo-derived topography digital elevation models (DEM) of Pluto [1] and imported into Matlab as vectors of distance \mathbf{x} vs. elevation \mathbf{t} . Data points in regions clearly modified by craters were removed from the profile to focus on possible flexural signals.

The topography was compared to the deflection of a thin elastic plate subjected to a series of vertical loads $\{V_i\}$ at position $\{x_i\}$. According to [7] the deflection, w , produced by a single load obeys Eq. 1:

$$D \frac{d^4 w}{dx^4} + \rho_m g w = V_i \delta(x - x_i) \quad (1)$$

where ρ_m is the density of water underneath the ice (1030 kg/m^3), g is the acceleration of gravity (0.62

m/s^2), δ the Dirac distribution, and $D \equiv \frac{Eh^3}{12(1-\nu^2)}$ is the flexural rigidity, with E the Young's modulus (9 GPa), ν Poisson's ratio (0.3), and h the elastic thickness of the plate, which is not specified *a priori*. Each load induces a deflection of the plate given by

$$w_i(x) = w_i^0 M_i(x), \quad \text{with} \quad (2)$$

$$M_i(x) \equiv \left[\sin \frac{x-x_i}{\alpha} + \cos \frac{x-x_i}{\alpha} \right] \exp \frac{x-x_i}{\alpha} \quad (3)$$

where $\alpha = \left[\frac{4D}{\rho_m g} \right]^{1/4}$ is the flexural parameter and $w_i^0 \equiv \frac{V_i \alpha^3}{8D}$ is the deflection amplitude. In addition, the reference elevation of the region surrounding Sputnik Planitia is w_0^0 . Therefore the expected topography is given by

$$w = \sum_{i=0}^n w_i^0 M_i(x) \quad (4)$$

with $M_0(x) = 1$.

For each profile, we invert for α and $\{w_i^0\}$. To do this, we specify possible load location $\{x_i\}$ every 50 km from -2000 km to 0 km , where 0 km is the start of the profile outside Sputnik Planitia. Then, for each candidate value of α , we assemble the functional forms in Eq. 4 into an operator matrix \mathbf{M} with elements $M_{ij} = M_i(x_j)$. The load vector that produces the best fitting profile for this value of α is given by

$$\mathbf{w}^0 = (\mathbf{M}'\mathbf{M} + \mathbf{C})^{-1}(\mathbf{M}'\mathbf{t}) \quad (5)$$

Where \mathbf{C} is a mass matrix helping to regularize the solution. Misfit is quantified using

$$\chi^2 = \sum_j \frac{(t_j - w_j)^2}{\sigma_t^2} \quad (6)$$

where σ_t^2 is an estimate of the noise level in the profile, taken as the variance of \mathbf{t} over the last 200 km of the profile.

The procedure is repeated for all candidate values of α and the value providing the minimum χ^2 is recorded as the optimum α . Uncertainty on α is given by the range of values for which χ^2 exceeds the minimum χ^2 by less than a threshold value $\Delta\chi^2$ such that

$$1 - p = P\left(\frac{n}{2}, \frac{\Delta\chi^2}{2}\right) \quad (7)$$

Where $P \equiv \frac{\int_0^x e^{-t} t^{n-1} dt}{\int_0^\infty e^{-t} t^{n-1} dt}$ is the incomplete gamma function, n is the number of degrees of freedom, and $p = 68\%$, is the confidence limit (1σ) [8].

Results: Fourteen profiles (1-3, 6-7, 20, and 29-36) provide well-constrained elastic flexure estimates. Figure 2 shows the example of profile #31, one of the best constrained profiles, with $\alpha = 128_{-36}^{+52} \text{ km}$, and profile #1, with $\alpha = 90_{-68}^{+36} \text{ km}$. Sixteen profiles (4-5, 10-11,

13-16, 18, 21, 24-26, 37-38, and 40) are consistent with flexure. Only ten profiles (8-9, 12, 17, 19, 22-23, 27-28, and 39) showed no evidence of flexure. A rigid plate cannot be ruled out for these profiles, due to high topographic variance (degraded terrains). Profiles that do not show evidence for elastic flexure are typically in the northwest tip of Sputnik Planitia or at its southwest end, where the Planitia opens to pitted plains [1].

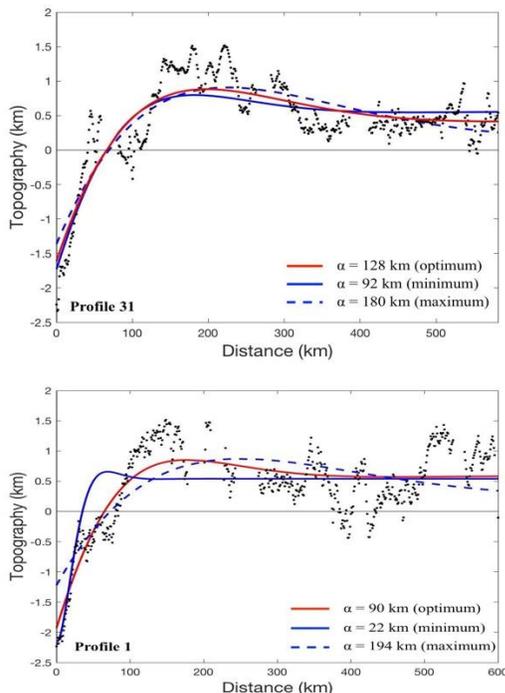


Figure 2. Topographic profiles #31 and #1 (black dots) with optimal flexural model (red) and profiles for the smallest (dashed blue line) and maximum (solid blue line) acceptable values of α .

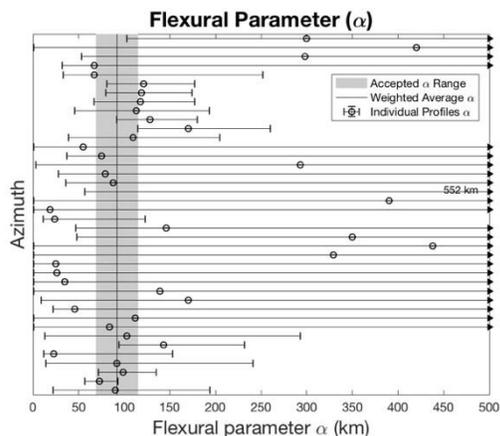


Figure 3. Flexural parameter with 1σ uncertainty for all 40 profiles analyses. Arrows indicate that the largest permissible value exceeds plot limits and is often unbounded. The vertical line and grey band report the weighted average of the flexural parameters.

The flexural parameter obtained for each profile, weighted by the range of acceptable value as described

above, provides an ensemble view of the structure of the terrains surrounding Sputnik Planitia (Figure 3). The overall flexural parameter is 92 ± 23 km, which corresponds to an elastic thickness of $h_e = 23 \pm 8$ km. The minimum nitrogen ice load thickness required for this elastic thickness is 4.6 ± 0.4 km (Figure 4). Thus, the flexure does not require a nitrogen ice load thickness that exceeds the current amount inside Sputnik Planitia.

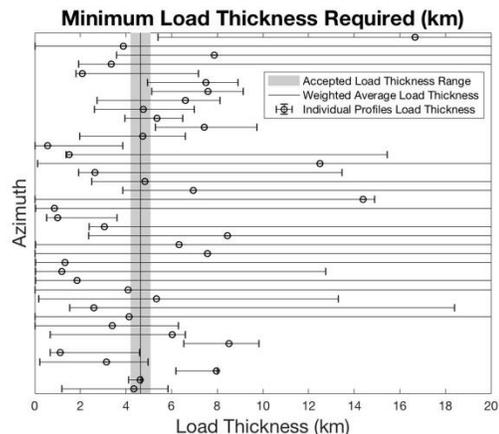


Figure 4. Minimum load thickness required for flexure with 1σ uncertainty for all 40 profiles analyses. Arrows indicate that the largest permissible value exceeds plot limits and is often unbounded. The vertical line and grey band report the weighted average load thickness.

To better understand the implications of this elastic thickness value for Pluto, we estimate the heat flux associated with these estimates according to

$$Q = 567 \frac{\ln(T_e/T_s)}{h_e} \quad (8)$$

where T_s is the surface temperature, T_e the maximum temperature for which elastic behavior dominates (estimated as 100 to 150 K), and we assume a thermal conductivity $k = \frac{567}{T} \text{ Wm}^{-1}\text{K}^{-1}$ [9]. A heat flux of at least 15 mW/m^2 is necessary to explain the elastic thickness. This value is twice as high as the maximum heat flux estimated from thermal evolution models [10, 11]. The origin of the heat flux anomaly is unclear, as neither tidal heating nor radiogenic heat production are likely to exceed the estimates used in previous studies. The high interior temperature might be related to heat deposited by the proposed Sputnik Planitia impact [4,5].

References: [1] Moore J.M. et al. (2016) *Science* 351, 1284-1293. [2] Trowbridge W.B. et al. (2016) *Nature* 534, 79-81 [3] McKinnon W.B. et al. (2016) *Nature*, 534, 82-85. [4] Nimmo F. et al. (2016) *Nature*, 540, 94-96. [5] Keane J. T. et al. (2016) *Nature*, 540, 90-93. [6] Hamilton D. et al. (2016) *Nature*, 540, 97-99. [7] Turcotte D.L. and Schubert G. (2014) *Geodynamics* [8] Press W.H. et al. (2007) *Numerical Recipes*. [9] Klinger J. (1980) *Science*, 209, 271-272. [10] Robuchon G. and Nimmo F. (2011) *Icarus* 426-439. [11] Hammond N.P. et al. (2016) *GRL* 43, 6775-6782.