**ELASTIC FLEXURE AROUND SPUTNIK PLANITIA, PLUTO, AND EVIDENCE FOR A VERY HIGH HEAT FLUX.**

A. C. Mills[1,2] and L. G. J. Montési[1], [1]Department of Geology, University of Maryland, 8000 Regents Dr, College Park, MD 20742, amills12@umd.edu. [2]Smithsonian Institute 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 km by 500 km elliptical basin called Sputnik Planitia. Currently 3 km deep, the basin is filled by about 10 km of convecting nitrogen ice [1, 2, 3]. Sputnik Planitia may be an impact basin hosting a nitrogen ice deposit [4, 5] or a flexural basin resulting from the deposition of a large ice cap [6]. 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.
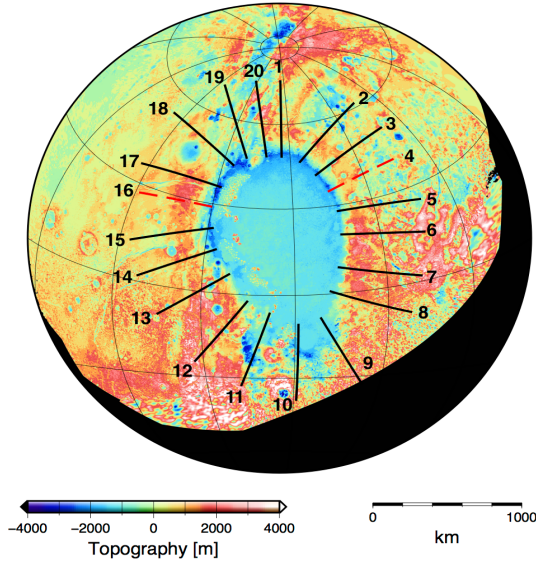


**Figure 1.** Topography of Pluto, reported in a Lambert Equal Area projection centered at 175°/20° [1]. The map also shows the 20 tracks considered in this study. The black region is an area of no data.

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

The topography is compared with the deflection of a thin elastic plate subjected to a series of vertical loads $\{V_i\}$ at position $\{x_i\}$. For a single load, elastic flexure is governed by [7]

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

Where, $w$ is the predicted deflection, $\rho_m$ is the density of water underneath the ice (1030 kg/m³), $g$ is the acceleration of gravity (0.62 m/s²), $\delta$ the Dirac distribution, and $D \equiv \frac{Eh^3}{12(1-v^2)}$ is the flexural rigidity, with $E$ the Young's modulus (9 GPa), $v$ Poisson's ratio (0.3), and $h$ the elastic thickness of the plate. Each load induces a deflection of the plate given by

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

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

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 $\alpha$ 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 $\alpha$, we assemble the functional forms on Eq. 4 into an operator matrix $\mathbf{M}$ such that $M_{ij} = M_i(x_j)$. The load vector that produces the best fitting profile for this value of $\alpha$ is given by

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

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

The procedure is repeated for all candidate values of $\alpha$ and the value providing the minimum $\chi^2$ is recorded as the optimum $\alpha$. Uncertainty on $\alpha$ is given by the range of values for which $\chi^2$ exceeds the minimum $\chi^2$ 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 $P \equiv \frac{\int_0^x e^{-t} t^{a-1} dt}{\int_0^\infty e^{-t} t^{a-1} dt}$ is the incomplete gamma function, $n$ is the number of degrees of freedom, and $p = 68\%$, is the confidence limit (1$\sigma$) [8].

**Results:** Eight profiles (1-4, 14-17) provide well-constrained elastic flexure estimates. Figure 2 shows the example of Profile 16, one of the best constrained profiles, with $\alpha = 109^{+33}_{-26}$ km. Profiles 7 and 13 are also well fit by the elastic model, and three more profiles (8,

12, 18, 20) are consistent with flexure. However, 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].
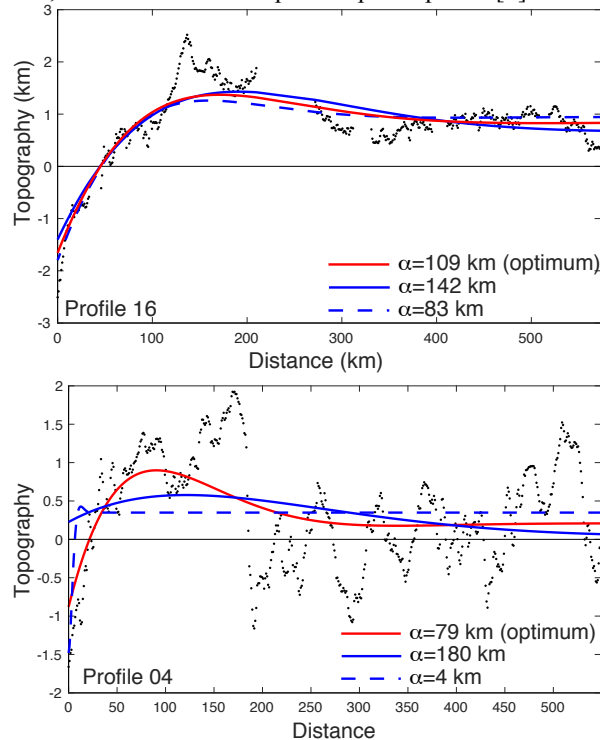


**Figure 2.** Topographic profile #16 and #4 (black dots) with optimal flexural model (red) and profiles for the smallest (dashed blue line) and maximum (solid blue line) acceptable values of $\alpha$. The corresponding tracks are shown in red in Figure 1.
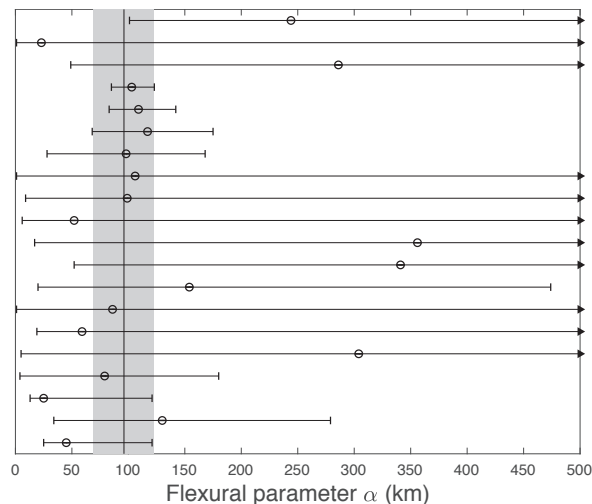


**Figure 3.** Flexural parameter with $1\sigma$ uncertainty for all 20 profiles analyses. Arrows indicate that the largest permissible value exceeds plot limits and is often unbounded. The vertical line and grey band report the weighted average of the flexural parameters.

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 96±27 km, which corresponds to an elastic thickness of $h_e = 25^{+10}_{-9}$ km.

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

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

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 $k = \frac{567}{T}$ $Wm^{-1}K^{-1}$ [9]. A heat flux of at least 15 mW/m$^2$ and more likely exceeding 20 mW/m$^2$ is necessary to explain the elastic thickness (Figure 4). These values far exceed the maximum heat flux estimated from thermal evolution models [10, 11]. The origin of the heat flux anomaly is unclear at this point, as neither tidal heating nor radiogenic heat production are likely to exceed the estimates used in previous studies.
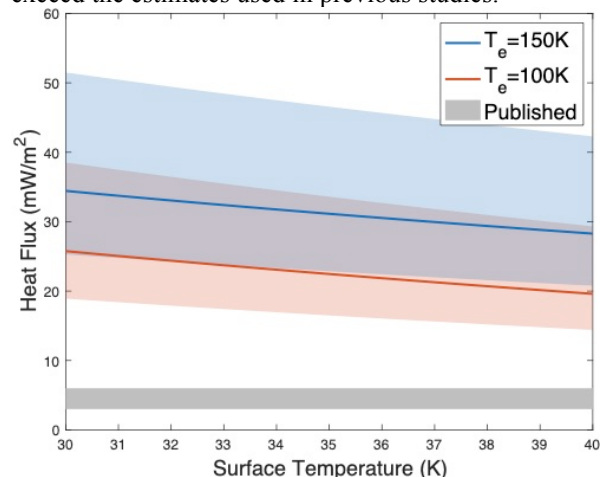


**Figure 4.** Heat flux estimate as a function of surface temperature for two values of the elastic temperature and an elastic thickness of $25^{+10}_{-9}$ km (preferred value: solid line; uncertainty: colored fields). The grey band shows previous estimates of the highest possible heat flow [10,11]

**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.