Elastic Flexure Around Sputnik Planitia, Pluto, and Evidence for a Very High Heat Flux

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Introduction

Sputnik Planitia

- Large teardrop-shaped basin located on Pluto at 20°N 180°E
- Size: 1300 km by 900 km
- Depth: 3-4 km (basin)
- 10 km deposit of nitrogen ice
- Water ice basement

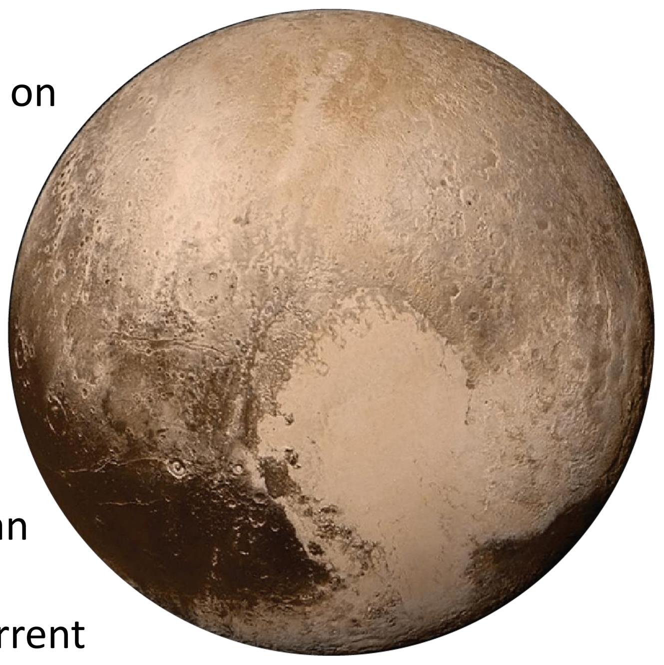

Fig.1. Global view of Pluto from the Long Range Reconnaissance Imager (LORRI) with color information from the Ralph instrument aboard NASA's New Horizons spacecraft. Sputnik Planitia appears as the light-colored region at the center (NASA/APL/SwRI)

Formation Hypotheses

- An ancient impact basin created by an impactor later filled with N_2 ice. The feature would have moved to the current location through polar wander. [Keane et al., 2016; Nimmo et al., 2016].
- Runaway deposition of N_2 ice due to albedo feedback at the ±30° [Hamilton et al., 2016]. The depression is due to elastic flexure under the load of a thick N_2 ice cap. Most of the cap has since sublimated away

Hypothesis

The topography of Pluto around Sputnik Planitia matches the prediction of an elastic plate flexed by a large nitrogen ice load

Flexure Modeling

Flexure Model

- The deflection w of an elastic plate in two dimensions obeys:

$$D\frac{d^4w}{dx^4} + \rho_m g w = V_0$$

where $\alpha = \left[\frac{4D}{\rho_m g}\right]^{1/4}$ is the flexural parameter, $D = \frac{E*h^3}{12(1-\nu^2)}$ is the flexural rigidity, ρ_m is the density of the layer underlying the ice shell, g is the gravity on Pluto, E is the Young's modulus of water ice, h is the elastic thickness, and ν is Poisson's ratio.

For a single vertical load at $x = 0$, the boundary conditions are $D\frac{d^3w}{dx^3} = \frac{1}{2}V_0$ and $\frac{dw}{dx} = 0$

- The deflection due to several line loads is found by superposition:

$$w = \sum_i \frac{V_i\,\alpha^3}{8D}\left(\sin\frac{x - x_i}{\alpha} + \cos\frac{x - x_i}{\alpha}\right)\exp\left(-\frac{x - x_i}{\alpha}\right)$$

where $\{V_i\}$ is the magnitude of the loads at position $\{x_i\}$

Inversion

- The load vector **V** that produces the topography **w** is found by least squares optimization:

$$\mathbf{V} = (\mathbf{M}'\mathbf{M} + \mathbf{C})^{-1}(\mathbf{M}'\mathbf{w})$$

where **M** is the operator matrix that links a load at position x_j to deflection at a point x_i

$$M_{ij} = \frac{\alpha^3}{8D}\left(\sin\frac{x_i - x_j}{\alpha} + \cos\frac{x_i - x_j}{\alpha}\right)\exp\left(-\frac{x_i - x_j}{\alpha}\right)$$

And $\mathbf{C} = \sigma_m^{-2}\,\delta_{ij}$ is the covariance matrix and σ_m is the mass variance

Best Fit

- Test multiple flexural parameters to find the best fit flexure with the data through χ^2 optimization:

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

where t_i is topography data, w_i is the predicted deflection, and σ_t is the noise of the topographic data

- Uncertainty of the flexural parameter is determined by the range of α values for which χ^2 exceeds the minimum χ^2 by less than a threshold value $\Delta\chi^2$ associated with the confidence limit p =68% (1-sigma uncertainty). $\Delta\chi^2$ is given by the inverse incomplete gamma function, i.e., by solving:

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

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 and n is the number of fitted parameters.

Elastic Thickness

- Elastic thickness is evaluated by rearrangement the formula for flexural rigidity:

$$D = \frac{\rho_m\, g\, \alpha^4}{4}$$

$$h = \frac{12D(1-\nu^2)}{E^{1/3}}$$

Results

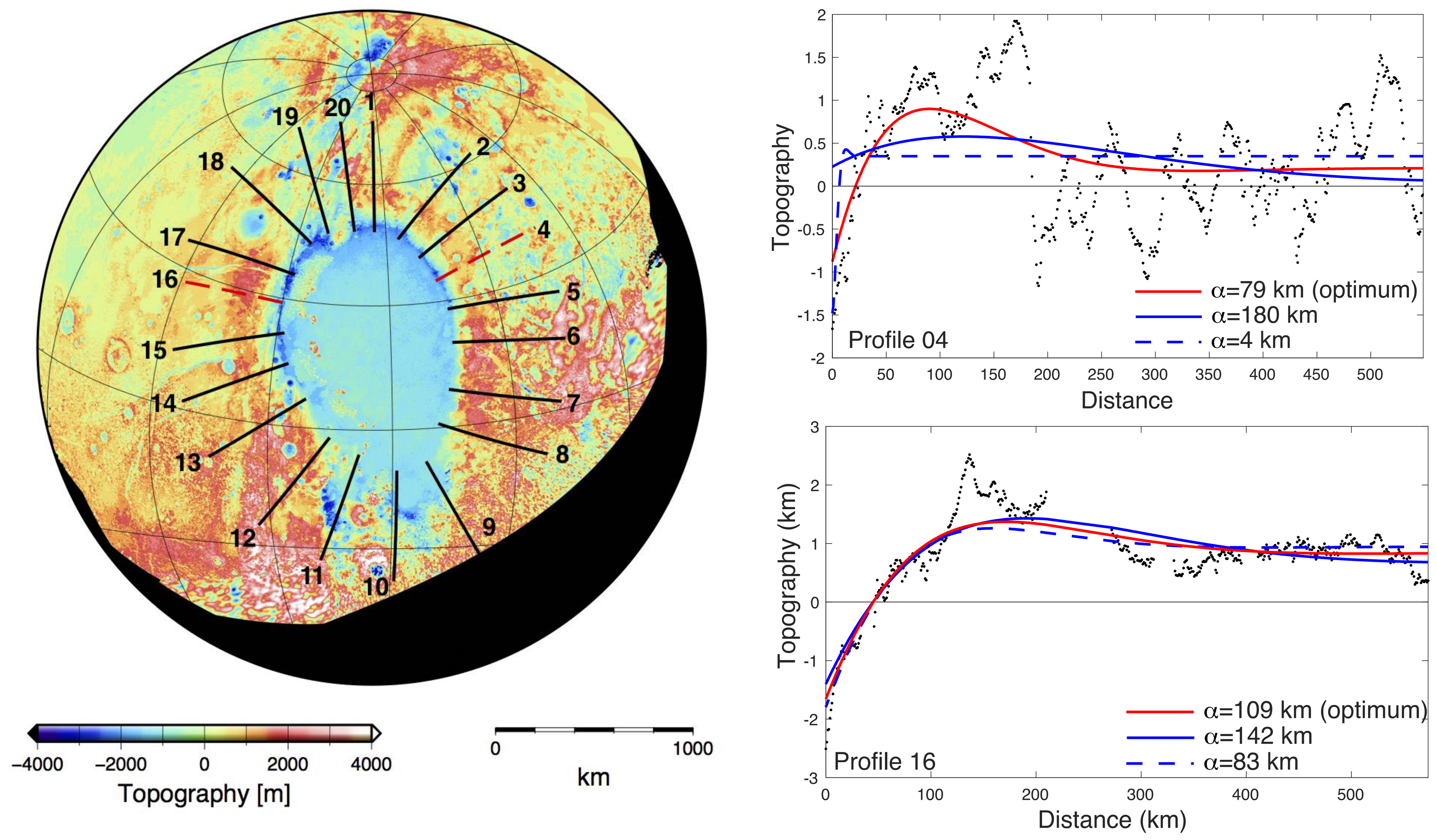

Figure 2. Right: Topographic profile 16 and 4 (black dots) with optimal flexural model (red) and profiles for the smallest (dashed blue line) and maximum (solid blue line) acceptable values of α. **Left:** The corresponding tracks are shown in red.

- 14 profiles (1-4, 7, 12-18, and 20) are consistent with flexure and dominantly located on the Western and Eastern edges of Sputnik Planitia as shown in **Figure 2** left panel
- 6 profiles do not show evidence of elastic flexure and typically in the northwest tip of Sputnik Planitia or the southwest end where degradation occurs
- Profile 16 was one of the best constrained profiles with $\alpha = 109^{+33}_{-26}$ km as shown in **Figure 2** right bottom panel
    - Note: Craters were removed from profiles as they are not representative of the topography when the flexure took place, better constraining the acceptable α

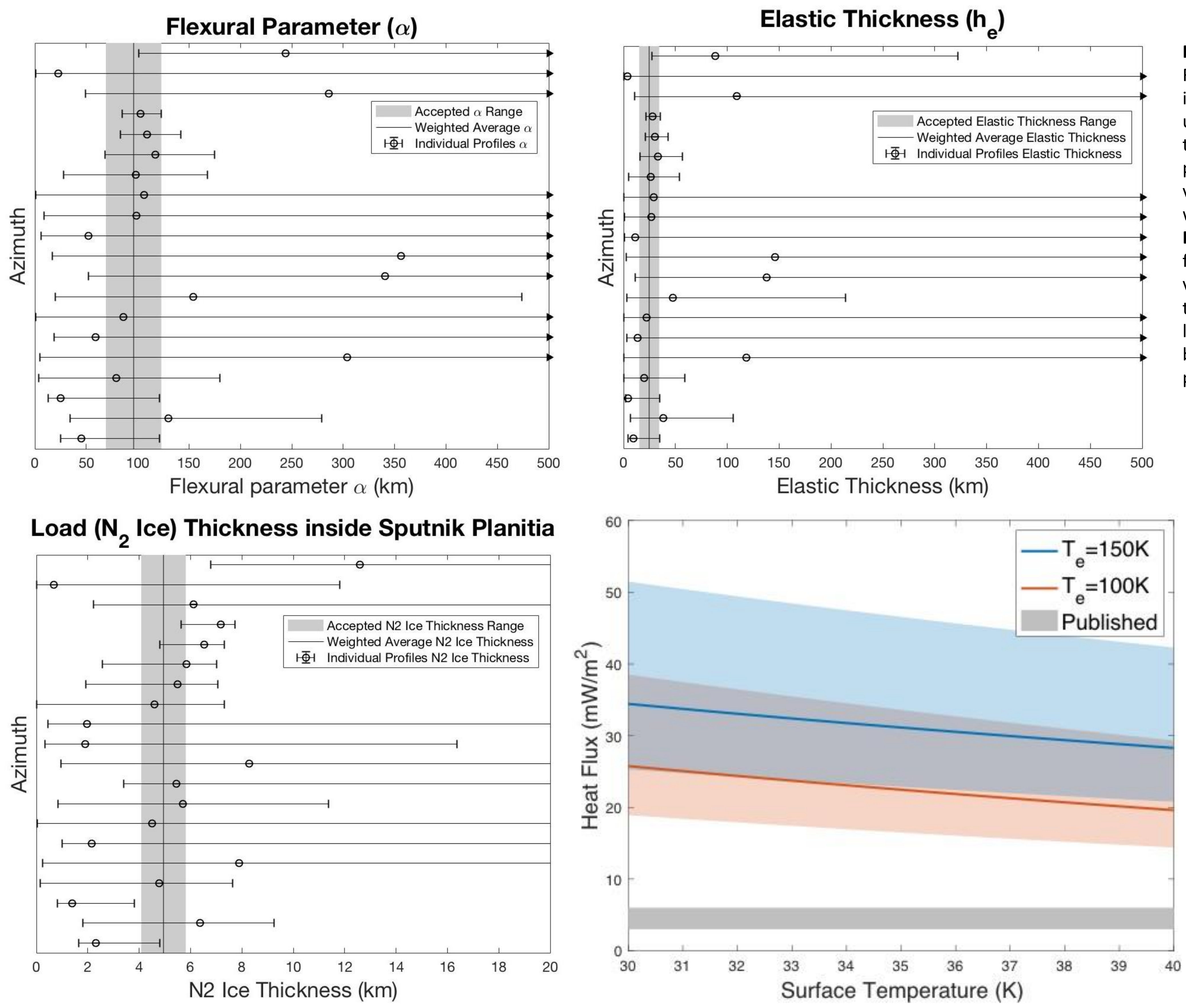

Figure 3. Top left, top right, and bottom left: Flexural parameter, elastic thickness, and N_2 ice thickness, respectively, with 1σ uncertainty for all 20 profiles. Arrows indicate that the largest permissible value exceeds plot limits and Is often unbounded. The vertical line and grey band report the weighted average of the flexural parameters. **Bottom right:** Heat flux estimate as a function of surface temperature for two values of 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.

- Overall flexural parameter: 96 ± 27 km
- Corresponding elastic thickness: 25^{+10}_{-9} km
- N_2 ice thickness: 5 ± 1 km
- Based on the elastic thickness range, the heat flux is at least 15 $\frac{\text{mW}}{\text{m}^2}$, but more likely exceeds 20 $\frac{\text{mW}}{\text{m}^2}$ to explain the elastic thickness, far exceeding the maximum heat flux estimated by previous thermal evolution models
- The high heat flux is also consistent with an ancient age development of the flexural signal

Conclusions

Out of the 20 topographic profiles examined here, 14 are well matched by an elastic flexure model based on the superposition of line loads located inside Sputnik Planitia. These profiles were located on the Western and Eastern edges of Sputnik Planitia. The average elastic thickness is 25^{+10}_{-9} km, corresponding to a heat flux of at least 15 $\frac{\text{mW}}{\text{m}^2}$. This heat flux is a factor of 2 smaller than that of Europa's but exceeds predictions of thermal evolution models by a factor of 5. The large heat flux is yet unexplained but could be linked to the heat deposited regionally by a large impact such as the one that may have formed Sputnik Planitia. A high heat flux is generally easier to explain if flexure took place early in the history of Pluto. The nitrogen ice load that would be required to produce the elastic thickness is 5 ± 1 km which is in the range of the current thickness of Sputnik Planitia's nitrogen ice component. It is not necessary to invoke a ice cap significantly thicker than the N_2 ice deposit currently in Sputnik Planitia.

The next step for research will be to compare the topographic profiles to that of an impact and find if the topography around Sputnik Planitia might be explained as the remnant of a impact ejecta blanket. Also, we plan to calculate the amount of energy needed to be deposited by the proposed impact for comparison with the heat flux implied by our analysis around Sputnik Planitia