DOES TRITON'S ICE CAP REVEAL ITS INTERNAL HEAT AND OCEAN?

Michael M. Sori[1], [1]Purdue University (msori@purdue.edu)

Introduction: Neptune's moon Triton was shown to be an active world by the Voyager 2 mission [1], arguably with the youngest surface of any icy body in the Solar System [2]. Triton is a possible "Ocean World" with subsurface liquid water, and as such, knowing its internal heat is of great interest to the scientific community. However, direct measurements of heat flow at other worlds are challenging to make.

Surface features can be used to constrain internal heat. On Triton, there exists a large, bright feature that is likely a thick, perennial deposit of nitrogen ice [3]. This ice sheet covers nearly the entire southern hemisphere, reaching equatorial latitudes at some longitudes, and is far larger than the other known extraterrestrial ice sheets on Mars and Pluto. I hypothesize that Triton's nitrogen ice is limited in vertical extent by the moon's internal heat, which causes unusually extensive lateral growth.

Two processes that could limit vertical growth of ice are considered. First, nitrogen ice may melt at its base once a certain thickness is attained, which could hinder further vertical growth. Second, nitrogen ice may viscously deform, spreading outward from the pole. The efficacy of both processes is sensitive to geothermal heat. These possibilities have been considered previously [4], but before important properties of nitrogen ice were measured [5]. Here, I use Voyager 2 observations and numerical models to test if these processes are viable ways to explain the nitrogen ice sheet's great extent, and if so, what constraints on Triton's internal heat can be inferred.

Basal Melting: I consider the possibility that nitrogen ice melts at its base, hindering further thickening and causing outward growth. A key parameter needed to test this idea is the current ice thickness. This measurement is difficult to infer from Voyager 2 data, but some constraints on it can be indirectly obtained. Based on the way that the ice superposes topography (Figure 1), I conclude the maximum ice thickness is between 300–1000 m thick. This estimate is similar to those made by others [6, 7].

Fourier's law is used with the temperature-dependent thermal properties of nitrogen ice to determine what geothermal heat Q is needed to attain melting at the base, which occurs at ~63 K. Results are shown in Figure 2. For a nominal case of pure nitrogen ice, melting occurs at $Q = 5.2$ mW/m^2 for a 1000-m-thick ice sheet and at 17.1 mW/m^2 for a 300-m-thick sheet. The required Q can plausibly be as low as 4.0 mW/m^2 or as high as 30.3 mW/m^2 when impurities or porosity is considered, but in the absence of observations of such structure I consider a range of 5–18 mW/m^2 to be the nominal heat flow required.

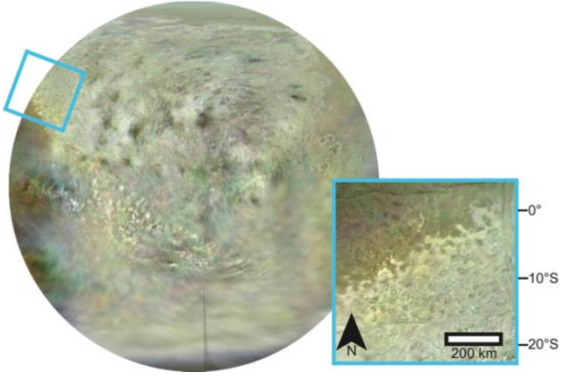

Figure 1. South polar projection of Triton's surface showing bright nitrogen ice, with inset showing how the ice superposes and infills underlying topography.

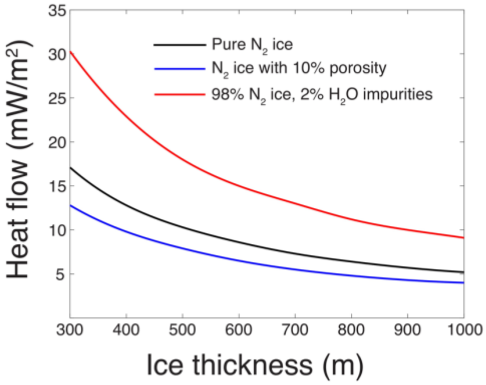

Figure 2. Geothermal heat flow required for basal melting of nitrogen ice for various cases.

Ice Flow: I consider the possibility that viscous spreading and accumulation/sublimation of nitrogen can result in the observed great extent of Triton's nitrogen ice without basal melting. The goal is to test if nitrogen ice on Triton can realistically flow to equatorial latitudes before sublimating away entirely.

First, I use an ice accumulation model to quantify accumulation and sublimation. The model assumes vapor pressure equilibrium of nitrogen ice with Triton's atmosphere. Uncertainties in various quantities exist, but typical models predict sublimation at latitudes <20°, with fast sublimation rates on the order of centimeters per Neptune year. Results are generally consistent with past work, especially the idea that ice accumulation alone would not result in perennial equatorial ice [8].

I use finite element method models to test if ice flow can plausibly "replenish" centimeters of lost ice at low latitudes in a Neptune year, thereby allowing low latitude ice to exist perennially. The model is 2D axisymmetric and assumes a nominal geometry of ice with maximum thickness 1000 m and tapering to zero at the equator. Multiple possible rheologies are considered [5, 9], with emphasis placed on the laboratory experiments of [5]. Geothermal heat Q is a critical parameter (warmer temperatures lead to more deformable ice), and is varied.

I find that viscous spreading can explain the ice cap's great extent. Conservatively, the ice flow model needs to result in a flux of at least 1×10^{10} m^3 of nitrogen ice delivered to latitudes <20°S to counteract sublimation. This ice flux does not occur in the end-member case of no geothermal heat, but can be attained if a modest heat flow exists and softens basal nitrogen ice. $Q > 2$ mW/m^2 permits the perennial existence of low-latitude nitrogen ice for some realistic combination of free parameters. See Figure 3.

Implications: $Q > 2$ mW/m^2 can realistically result in Triton's large ice sheet through viscous spreading of nitrogen ice without basal melting. Basal melting may additionally occur; if so, Q is between 5–18 mW/m^2.

The near-surface heat flow currently expected on Triton from radiogenic heating alone is 2.4 mW/m^2 [10]. Thus, if basal melting does occur, another source of internal heat is required. This heat could come from obliquity tides, which would yield heat flow between 7–18 mW/m^2 [10], consistent with our estimates. This heat flow would be sufficient to drive endogenic activity today, and could sustain a subsurface ocean of liquid water depending on the structure and state of Triton's ice shell. Therefore, independent evidence of basal liquid nitrogen on Triton would strengthen the case for the moon as an "Ocean World".

Comparisons with other ice sheets are enlightening. On Mars, most authors do not think that the broad structure of the polar layered deposits (PLDs) is controlled by ice flow and basal melting [e.g., 11]. This contrast with what is proposed here on Triton is explained by the different surface temperature, thermal conductivity, and rheology of the water-ice PLDs compared to Triton's nitrogen ice. On Pluto, the large nitrogen ice sheet in Sputnik Planitia is vigorously convecting [12, 13]. Nitrogen ice convection was not detected on Triton. I calculate the expected Rayleigh number and conclude that convection is not expected for Triton's nitrogen ice sheet because of its likely lesser thickness compared to Sputnik Planitia. The key difference is that Pluto's nitrogen ice is topographically confined in an impact basin, allowing great vertical growth. Therefore, the same ice physics leads to different outcomes on Triton, Mars, and Pluto.

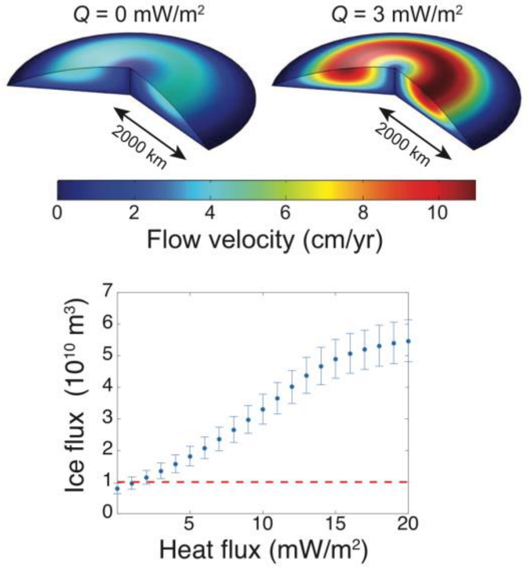

Figure 3. Model results showing flow velocities in a nitrogen ice cap on Triton (top), and the total volume of ice that enters latitudes of net sublimation (bottom). The red dashed line represents the minimum flux required for a successful model run. Error bars represent uncertainties in ice rheology.

Conclusions: Triton's extensive polar cap may plausibly be controlled by viscous spreading and/or basal melting of nitrogen ice. In the absence of basal melting, a loose constraint on heat flow of $Q > 2$ mW/m^2 would be implied. If basal melting does occur and could be independently inferred, a $Q > 5$ mW/m^2 would instead be required. This heat flux would require a source beyond radiogenic heating and be sufficient to power geological activity. These ideas can be explicitly tested with future data. Topographic data of Triton's icy terrains would be especially valuable, as would high-resolution images that could be used to search for evidence of liquid nitrogen. These data can be realistically collected by a flyby mission to the Neptune system [e.g., 14].

Acknowledgments: The image mosaic used is at https://www.lpi.usra.edu/icy_moons/neptune/triton.

References: [1] Smith et al. (1989), *Science* 246. [2] Schenk and Zahnle (2007), *Icarus* 192. [3] Moore and Spencer (1990), *GRL* 17. [4] Brown and Kirk (1994), *JGR* 99. [5] Yamashita et al. (2010), *Icarus* 207. [6] Spencer and Moore (1992), *Icarus* 99. [7] McKinnon and Kirk (2014), *Enc. Of the Solar System* 3rd ed. [8] Hansen and Paige (1992), *Icarus* 99. [9] Umurhan et al. (2017), *Icarus* 287. [10] Nimmo and Spencer (2015), *Icarus* 246. [11] Karlsson et al. (2011), *GRL* 38. [12] McKinnon et al. (2016), *Nature* 534. [13] Trowbridge et al. (2016), *Nature* 534. [14] Prockter et al. (2019), *LPSC* 50th, 3188.