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Diurnal, Nonsynchronous Rotation and Obliquity Tidal Effects on Triton using a Viscoelastic Model: SatStressGUI. Implications for Ridge and Cycloid Formation. D. Dubois^{1,2}, D. A Patthoff^{1,3}, R. T. Pappalardo¹,
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Introduction: Neptune's biggest moon Triton orbits at an almost constant distance of about 355,000 km from its parent body. The satellite has a very low eccentricity ($e = 10^{-5}$), and rotates synchronously about Neptune. It is thought to have been differentiated enough for the formation of interior solid and even liquid layers [1]. Generally, diurnal tidal forcing is the main stressing mechanism a satellite with a sufficient eccentricity can experience. Other possibly combined sources participating in the tidal evolution of a satellite can be nonsynchronous rotation (NSR), axis tilt (obliquity), polar wander, and ice shell thickening. Given Triton's current very low eccentricity, the induced diurnal tidal forcing must be relatively non-existent. Triton's eccentricity has most likely changed since its capture [2] and this change in eccentricity may account for the formation of surface features and maintaining a subsurface liquid ocean [2, 3]. Furthermore, obliquity-induced tides have been shown to play a role in Triton's recent geological activity [1] with its high inclination. Thus, modeling Triton's tidal behavior is essential in order to constrain its interior structure, tidal stress magnitudes, and surface feature formation. The latter stems from the surface expression of compressive and extensive mechanisms in the icy shell [4]. Triton has a very rich and complex surface geology, with wavy and cycloidal-like features; a testament to tidal deformation. Single troughs and double ridge formation are also observed on Triton associated with the cantaloupe terrain [2, 5].

Model: We use an enhanced viscoelastic model, SatStressGUI V4.0 [6, 7, 8], to simulate obliquity-driven tides on Triton, a body in hydrostatic equilibrium [9]. The (retrograde) satellite rotates with a period of about -5.8 days, and an eccentricity of 10^{-5} , whereby the diurnal effect is considered to be almost negligible. In this context, we propose a 4-layer interior model (Table 1) and offer a preliminary Love number calculation. The innermost layer is composed of a relatively thick silicate mantle and lies below a putative liquid water ocean. The outermost layers are divided into an inner low viscosity and prone to convection (mainly controlling the tidal dissipation throughout the satellite's evolution) layer, and an outer more viscous and rigid layer. Here we explore the contribution of obliquity-driven tides on cycloid formation and provide constraints on Triton's interior structure.

Layers	Density [kg/m ³]	Young's modulus [Pa]	Poisson's Ratio	Thickness [m]	Viscosity [Pa s]
Upper Ice	920	9.31×10^9	3.30×10^{-1}	4×10^5	1×10^{21}
Lower Ice	920	9.31×10^9	3.30×10^{-1}	5×10^5	1×10^{14}
Ocean	1000	0	0	5×10^4	0
Core	3500	1.00×10^{11}	2.5×10^{01}	1.249×10^6	1.0×10^{25}

Table 1. Input rheological parameters for our 4-layer model.

Obliquity-driven tidal estimates without nonsynchronous rotation: The following figures show the tidal evolution at Triton over the course of 1 orbit around Neptune, with an obliquity of 0.1° and argument of periapsis of 0° . The maps are plotted East positive, with tension marked as positive and compression as negative. The red and blue vectors represent the σ_1 and σ_2 principal components respectively. A tentative cycloidal ridge is modeled with the starting point at 0° longitude and mid-southern hemisphere 30°S latitude, a region known for its unique surface geology [5].

Yield (kPa)	0.9
Propagation strength (kPa)	0.4
Propagation speed (m/s)	3
Propagation direction	East

Table 2. Cycloid generation parameters. The yield strength is the threshold that initiates fracture in the ice. This fracture will propagate as long as the strength is below this threshold and greater than the propagation strength. The propagation speed is usually taken to be <10 m/s.

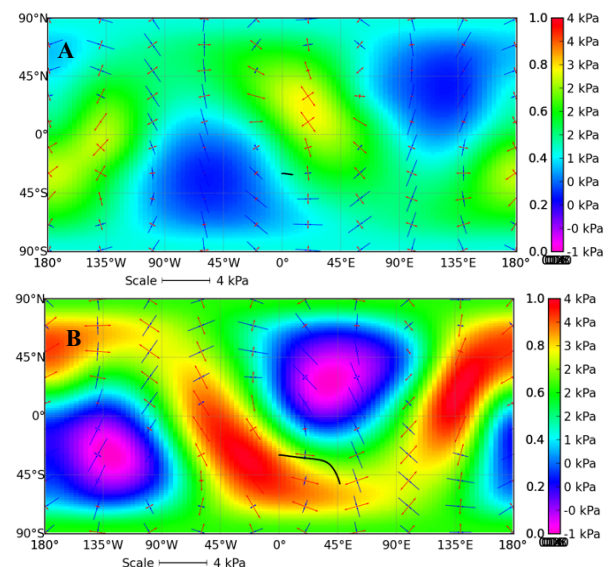


Figure 1. Here we show stresses for obliquity-induced (0.1° obliquity) tidal stress maps at 40° past perijove

(A) and 280° past perijove (B). The latter shows a full cycloid modeled over one orbit, which has already started propagating by the end of (A). Note that the stress magnitudes are relatively low (2-3 kPa), and generating wavy features remains difficult. The parameters used here are given in Table 2. Positive values represent tension while negative represent compression.

Obliquity-driven tidal estimates with nonsynchronous rotation:

In this case, we used the same conditions as in the previous case, while adding NSR effects with a 10 Myr NSR period.

Yield (kPa)	6
Propagation strength (kPa)	4
Propagation speed (m/s)	2
Propagation direction	East

Table 3. Cycloid parameters used in the NSR case, where the ice is more likely to fail with the inclusion of NSR due to the larger stresses.

References: [1] Nimmo F. and Spencer J. (2014) *Icarus*, 1–9. [2] Prockter L. M. et al. (2005) *GRL*, 32, L14202. [3] McKinnon et al. (1995) *Neptune and Triton*, pp. 807–877, Univ. of Ariz, Press, Tucson. [4] Hoppa et al. (1999) *Science*, 285, 1899–1902. [5] Smith B. A. et al. (1989), *Science*, 246, 1422–1449. [6] Wahr J. et al. (2009) *Icarus*, 200, 188–206. [7] Patthoff D. A. et al. (2016) *LPSC XXVII*, 1375. [8] Pappalardo et al. (2016) *LPSC XXVII*, 2712. [9] Schubert et al. (2004) *Jupiter: The Planet, Satellites and Magnetosphere*. Cambridge Univ. Press, pp. 281–306.

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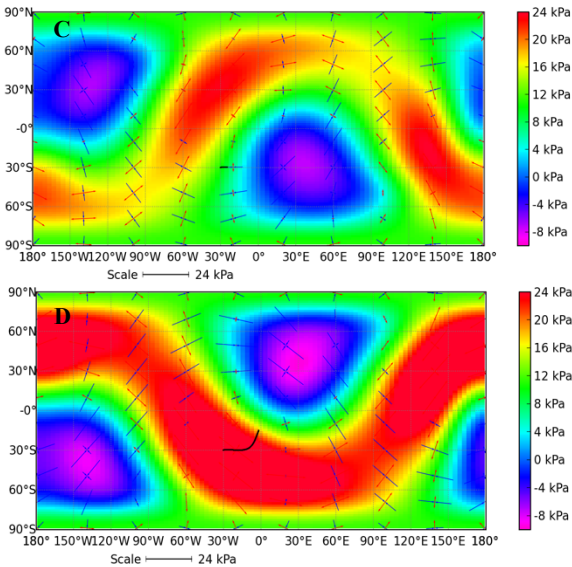


Figure 2. Obliquity-induced (0.1°) with added NSR (10 Myr period) effects at 40° (C) and 280° (D) past-perijove. The magnitudes are larger than with no NSR, and the induced arcuate feature different from the previous case.

We calculate the 0.1° obliquity-related Love numbers where the diurnal effect is minimized to be $h_2 = 1.2$ and $k_2 = 0.2$, which present the same order of magnitude as [8] and h_2 slightly greater than [1]. With added NSR effects, $h_2 = 1.99$ and $k_2 = 0.99$.