TRITON'S FRACTURES AS EVIDENCE FOR A SUBSURFACE OCEAN.

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Introduction: Triton has been studied with Earth-based telescopes since its discovery in 1846 and, in 1989, was visited by the Voyager 2 spacecraft. Images revealed a surface that is largely free of major impact cratering [1], indicative of a youthful surface age [2]. Triton has a tenuous nitrogen atmosphere in vapor pressure equilibrium with surface ice [3,4]. Particulate plumes rising 8 km above the surface were imaged, along with surficial fans of dark material, presumably deposited as a result of previous plume activity [1]. With a radius of 1353 km, Triton's mean density of 2061 kg m^{-3} implies a high silicate fraction relative to many satellites of the outer solar system, with an ice/water upper layer only a few hundred km thick.

Triton is the only large solar system moon in a retrograde orbit, which alone suggests that the moon did not form in a traditional dusty debris disk with the other prograde Neptunian satellites. This orbit will slowly decay, leading to Triton's demise in a few billion years [5]. A primary mechanism capable of generating a retrograde orbit is the capture of a previously unbound object from a heliocentric orbit [6,7]. After capture Triton orbited with a high eccentricity before evolving to its current orbital state. But with an eccentricity of 0.000016, Triton also has one of the most circular orbits amongst satellites. In order to evolve from the high eccentricity state to the present state (low eccentricity, low obliquity, and tidally locked rotation), it is necessary for the system to pass through an intense period of tidal energy loss. Tidal damping of Triton's eccentricity, spin, and obliquity is likely to have induced large-scale melting in Triton's ice shell, and possibly the heating and melting of parts of a silicate/iron core. The combination of a high orbital eccentricity and a warm interior has likely produced tidal activity on Triton throughout its evolution.

Today we identify Europa, Ganymede, Callisto, Enceladus, and Titan as ocean worlds [8]. Active icy moons (Europa, Enceladus, and Titan) have the following in common: young surfaces, extensive tidal-tectonics, and liquid subsurface global oceans. Should Triton join this list? It certainly has a young surface and tectonic features on its surface [9], indicating that a subsurface global ocean may allow tidal stresses to currently modify the surface.

Tidal Stress on Triton: Triton's circular orbit precludes ongoing tidal stresses driven by orbital eccentricity as experienced by Europa or Enceladus. However, Triton does experience long-term tidal deformation related to its semi-major axis evolution. Triton's retrograde orbit causes its orbit to steadily decay, decreasing the distance between it and Neptune, and thus increasing the height of the tide raised on the icy moon. To calculate tidal stresses due to orbital decay, we use a thin-shell approximation for surface stresses caused by tidal elongation [10,11]. The outer elastic layer is assumed to be decoupled from the deeper interior of the body (e.g., by a fluid layer), implying there is negligible shear between the elastic shell and the interior. This condition is plausible since Triton has experienced large tidal heating in the past and its interior may still be warm enough to have a subsurface ocean, or at the very least, deform as if it had a low shear strength. The horizontal strain of this shell, as required to fit the elongated interior, produces stress on the surface, given by:

$$\sigma_{\theta\theta} = \frac{3M\mu h_2}{8\pi\rho_{av}}\left(\frac{1}{a_f^3}-\frac{1}{a_i^3}\right)\left(\frac{1+\upsilon}{5+\upsilon}\right)(5+3\cos 2\theta) \quad (1)$$

$$\sigma_{\phi\phi} = -\frac{3M\mu h_2}{8\pi\rho_{av}}\left(\frac{1}{a_f^3}-\frac{1}{a_i^3}\right)\left(\frac{1+\upsilon}{5+\upsilon}\right)(1-9\cos 2\theta) \quad (2)$$

where θ is the colatitude measured with respect to the axis through the center of the tidal bulge [12]. The quantity $\sigma_{\theta\theta}$ is the stress along the surface in the direction transverse to the tidal bulge, while $\sigma_{\varphi\varphi}$ is the stress along the surface in a direction orthogonal to $\sigma_{\theta\theta}$. In these expressions, μ is the rigidity of the shell, ν is Poisson's ratio, ρ_{av} is the average density of the body, and M is the mass of the tide-raiser, which changes from a distance a_i to a distance of a_f during orbital migration. The magnitude of the tidal stress on the surface is directly proportional to the Love number h_2. Compressive stresses are defined here to be negative and tensional stresses positive. Note that the strong power terms of a^{-3} allow even small changes in semi-major axis to result in significant stress production.

For a water-ice crust, we use the conventional values of the elastic parameters: $\mu = 3.52 \times 10^9$ Pa and $\nu = 0.33$. We also assume a tidal response given by $h_2 =$

1.29, consistent with the tidal response of other icy satellites that have subsurface oceans.

Our results indicate that even modest amounts of orbital decay should generate tidal stresses on Triton exceeding the eccentricity-driven stresses on Europa that have caused extensive tectonic activity there. If Triton fails under similar conditions, fractures may have formed in response to the orbital decay stresses. Voyager observations of the surface revealed large fractures that can be used to test our prediction of tidal-tectonic activity. All the fractures mapped in this study are near the sub-Neptune point and mostly fall within the zone predicted to experience tension in both principal stress directions (Fig. 1).

Furthermore, tidal stress from orbital decay can be decomposed along the fractures mapped to determine whether observed fractures correlate with tidal tensile stresses from orbital decay. We selected several points along the fractures and calculated principal tidal stresses from orbital decay at those locations. Then, using the measured strike of the fracture, the principal stresses were decomposed into component normal and shear stresses resolved onto the fracture surface. Most of the observed fractures experience tensile stresses normal to their strike (Fig. 1). In a few cases, fractures transition from regions where they experience tension into regions where they experience compressional normal stress. Propagation of the fracture into the compressive stress region may have prevented further propagation and aided in limiting the extent of the fracture on the surface.

Conclusions: There is compelling evidence that Triton should be considered an ocean world. Fractures observed on Triton's surface are consistent in location and orientation with tidal stresses produced by the decay of Triton's orbit as it migrates toward Neptune. Tidal stresses can only reach levels to fracture the surface if a subsurface ocean exists; a solid interior will result in smaller tidal stress and likely no tectonic activity. Tidal stresses therefore provide a mechanism for fracturing and volcanism analogous to activity observed on Enceladus and, possibly, Europa. Given that Triton's interior has dissipated a tremendous amount of energy as heat, which likely drove differentiation, and that this heat may remain until the present day, an energy source likely exists to drive geologically recent activity. Moreover, it is possible that tidal volcanism has facilitated, if not dictated, the expression of this activity on Triton's surface.

References:

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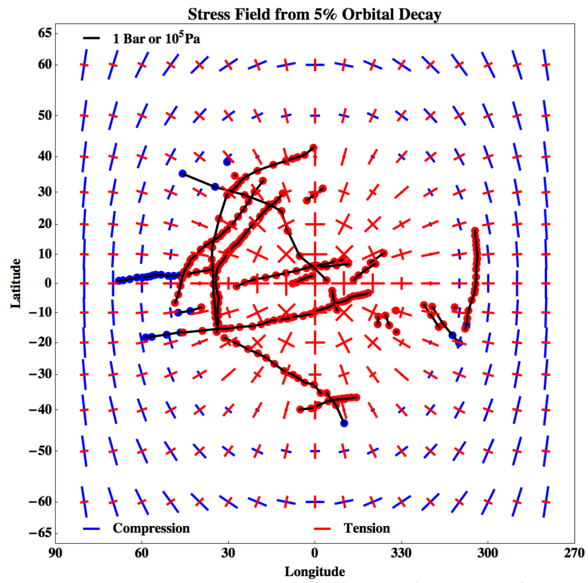

Figure 1. Fractures mapped on Triton's surface are shown in black, superimposed on the stress field calculated from $0.7R_{Neptune}$ of orbital decay. Tensile principal stresses are shown by red ticks and compressive stresses by blue ticks. Mapped fractures are located predominantly within tensile regions. At various locations along each fracture, stress components were resolved along the fracture strike, with tensile normal stress represented as red points and compressional normal stress as blue points. Due to limitations in imagery, mapping of fractures over the whole surface is not possible.