TRITON'S SURFACE AGE AND IMPACTOR POPULATION REVISITED (EVIDENCE FOR AN INTERNAL OCEAN).

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Summary: The geology of Triton is fascinating, complex, and largely enigmatic. Its surface is relatively youthful, but the ages of its various terrains have been poorly constrained because the flux of impacting bodies in the Neptune region has been poorly known. Here we combine crater count data for Triton with much improved estimates of impact rates that include the Kuiper Belt as the dominant source of impactors. We find both that the population of impactors creating the smallest observable craters (a few km in diameter) must be sub-km in scale and that the population can be fit by a –3 differential power-law size index. Such results can be used as a significant, if indirect, probe of the unseen small body population of the Kuiper Belt. We also calculate estimated ages for several regions of Triton's surface imaged by Voyager 2, and find that Triton was probably active on a time scale no greater than 0.1–0.3 Gyr ago (some 2% to 6% of the age of the solar system), and perhaps much more recently. After Io and Europa, Triton appears to be the most active outer solar system satellite (Titan being an unknown at the moment), and the time-averaged volumetric resurfacing rate on Triton implied by our results is similar to estimates for Venus and the Earth's intra-plate zones. Given the geological evidence that much of the recent volcanic activity on Triton is deep-seated (as opposed to surficial and insolation-driven), a logical source for the lavas is a perched layer of low melting-point materials such as aqueous ammonia and/or methanol — an internal ocean.

Introduction: Triton is unique in its utility for cratering studies. No terrains observed by Voyager can be classified as ancient, much less primordial, hence no surface has reached saturation-equilibrium. As the largest crater (Mazomba) is only 27 km in diameter, confusion due to secondaries from still larger craters is absent as well. Although crater detection (and counting) is difficult in the geologically complex bright (polar) and cantaloupe terrains, a broad variety of plains units exist on Triton's leading hemisphere where crater discrimination is excellent [1, 2, 3].

Triton is in addition close to what is regarded as the dominant source region for ecliptic comets, the Kuiper Belt and its scattered component [e.g., 4, 5, 6], and far from other potential impactor sources such as the asteroids and the Trojan clouds. The Neptune system is also remarkably empty [7]; Nereid orbits well outside Triton's position and the small satellites and rings discovered by Voyager 2 lie well inside, close to Neptune. This situation is generally taken to be the result of the dynamical violence induced by Triton's post-capture orbital evolution, with any debris from pre-existing satellites accreted or scattered. If the region from Proteus to Nereid is truly empty save for Triton (an important point to which we return below), then a "population II" like ensemble of planetocentric impactors should not exist either. Thus Triton may serve as a template to fundamentally constrain the cometary mass distribution. With recent numerical work on the likely flux of objects from the Kuiper Belt [5], we can in turn offer the first quantitative constraints on Triton's surface age and level of geological activity.

Crater Scaling: Masses of crater-producing impactors are determined by standard Schmidt-Holsapple scaling [e.g., 8, 9]; scaling constants appropriate for ice are used and the gravity regime is assumed. We have estimated the excavated volumes for the craters in several ways. The simplest is to assume that each crater is a geometrically similar figure of revolution. We have also taken the simple-to-complex transition into account. This transition has been estimated variously at 6 and 11 km, based respectively on depth-diameter measurements ([10], see Fig. 16 in [3]) and morphology [2]). Depth or shape information exists for only a handful of complex craters on Triton [3], so a formal relationship between transient and final crater diameters based on a reconstruction of transient crater geometries cannot be made. It is, however, likely that these diameters follow a relationship similar to that derived for complex craters on Ganymede [11]. Despite these potential geometrical complications, the greatest uncertainty in the crater scaling probably remains the absolute calibration of the cratering efficiency, perhaps a factor of 2 in terms of volume.

Impactor Velocities and Sizes: Objects in the Kuiper Belt are perturbed by Neptune's gravity until they become Neptune crossing. At this point they may collide with Neptune or one of its satellites, be scattered into a remnant disk of higher eccentricities and inclinations, or continue to evolve under the control of Neptune until they become Uranus crossing, at which point they may be detached from Neptune's influence [5, 6]. We will refer to this entire ensemble as Kuiper Belt objects. These objects encounter Neptune at its gravitational sphere of influence with velocities ranging from nearly zero to ~3.5 km/s [5]. The average is about ~0.3 of Neptune's mean orbital speed (5.4 km/s). The average impact speed on Triton is the root-sum-square of this encounter speed, the escape speed at Triton's orbital position (6.2 km/s), Triton's circular velocity (4.4 km/s), and the escape speed from Triton (1.45 km/s), or ≈ 8 km/s. Velocities at the apex and antapex of motion, where the impactor and satellite velocities add or subtract, respectively, rather than add in quadrature, may be substantially higher and lower, respectively [12].

For this range of impact velocities, and assuming a range of plausible densities for both Triton's icy surface and cometary impactors, the maximum impactor diameter required to create the largest craters on Triton does not exceed 10 km (for an average impact angle of 45˚). At the small end, impactor diameters of order 1-to-a-few 100 m suffice. While these numbers sound prosaic, they demonstrate that the objects that cratered Triton have sizes that are thought typical of comets and, simply, that smaller Kuiper Belt objects exist.

Impactor Size-Frequency Distribution: We concentrate on "Area 1" of Strom and co-workers, which displays the highest areal density of craters (181 craters with diameters > 3 km on 4.2% of Triton's surface) and therefore the best statistical confidence [1, 2]. For the impactor population we use a two-component (i.e., broken) differential power law such as has been used to represent the Kuiper Belt population [13]; the differential power-law size index is b_1 for impactors under 10 km diameter and b_2 above this size. Given the size distribution of Triton's craters, our simulations are clearly most sensitive to b_1, so we adopt $b_2 = -4.5$ from [13].

We select impact velocities from a uniform distribution between the maximum and minimum possible, and for a range of surface/impactor density ratios. The models simulations show that the Voyager data are best fit by impactor distributions with $b_1 \approx -3$. This result is robust to parameter variations, and is in accord with independent estimates of b_1 for the Kuiper Belt population [13] and for the (cometary) impactor population responsible for young rayed craters on Ganymede [12]. In addition, $b_2 = -4.5$ is consistent with the lack of large craters on Triton as a whole.

Surface Ages: To determine the cratering rate on Triton we adopt the rate of collisions with Neptune of comets > 1 km diameter estimated in the detailed numerical simulations of [5], 1.2 comets/kyr. We correct for Triton's smaller size, mass, and distance from Neptune. Area 1 is near the apex of motion, so we also correct for the flux enhancement there, about a factor of two [1, 12]. An estimate of the Oort cloud comet impact rate (not included in [5]) is scaled from previous results for Pluto [14], and appears to be ~20% of the Kuiper Belt object impact rate.

Combining the flux estimates with a $b_1 = -3$ power law, we find an estimated surface age for Area 1 of order 100 Myr. Area 2, which consists of stratigraphically younger volcanic plains [1], is estimated in terms of crater counts to be younger by ~40%. These ages are an order of magnitude less than the roughly 1 Gyr surface age estimated in [1], and are primarily predicated on vastly improved knowledge of the Kuiper Belt population and consequent impact rates. Shoemaker did, however, suspect in 1989 that if a transneptunian comet belt did exist, then such young surface ages would be obtained [1].

Given the uncertainties in crater scaling, as well as the stated uncertainty in the impact rate of a factor of 2 [5], the plains of Triton could be several 100 Myr old, but even this is a small fraction of the age of the solar system. The uncertainties work the other way as well: Triton could be younger still.

Implications for Triton: A possible implication is that, if Triton's geological activity is tied to the waning stages of post-capture tidal heating, Triton's capture occurred rather late in solar system history, perhaps within the last ~1 Gyr. Possible corroboration can be found in crater counts from the highest resolution Voyager frames [3], in which crater densities increase markedly below ~ 7 km diameter, and appear to follow a –4 or steeper differential slope. Such a slope at small crater sizes is characteristic of an internal, planetocentric impactor population [8], one which presumably would have been swept up not very long after capture.

On the other hand, while possible, a late capture for Triton is statistically unlikely, and it has long been appreciated that Triton's geological activity may be due to radiogenic heating alone (internal potential temperatures easily exceed the eutectic melting points of plausible mantle ice compositions) [e.g., 7]. Furthermore, the sweep-up of a prograde planetocentric debris population by a retrograde satellite may take drastically longer than that by a prograde satellite (the usual situation), because of the fundamental lack of resonant interactions that cause the debris to evolve into satellite-crossing orbits. But regardless of when capture occurred, the geological evidence for deep-seated (i.e., large-scale caldera/rift complexes such as Leviathan Patera/Kraken Catena/etc.) and (with our results) recent volcanism implies that Triton should be thought of geologically active icy satellite, and probably one that shares a fundamental characteristic with several other icy satellites — an internal liquid layer or ocean.

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