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TRITON'S SURFACE AGE AND IMPACTOR POPULATION REVISITED IN LIGHT OF KUIPER BELT FLUXES: EVIDENCE FOR SMALL KUIPER BELT OBJECTS AND RECENT GEOLOGICAL ACTIVITY

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ABSTRACT

Neptune's largest satellite, Triton, is one of the most fascinating and enigmatic bodies in the solar system. Among its numerous interesting traits, Triton appears to have far fewer craters than would be expected if its surface were primordial. Here we combine the best available crater count data for Triton with improved estimates of impact rates by including the Kuiper belt as a source of impactors. We find that the population of impactors creating the smallest observed craters on Triton must be subkilometer in scale and that this small-impactor population can be best fitted by a differential power-law size index near -3. Such results provide interesting, indirect probes of the unseen small body population of the Kuiper belt. Based on the modern, Kuiper belt and Oort cloud impactor flux estimates, we also recalculate estimated ages for several regions of Triton's surface imaged by *Voyager 2*, and find that Triton was probably quite geologically active on a timescale no greater than 0.1–0.3 Gyr ago (indicating Triton was still active after some 90% to 98% of the age of the solar system), and perhaps even more recently. This activity must surpass that explainable by the surface geysers seen by *Voyager* 2 by many orders of magnitude. The time-averaged volumetric resurfacing rate on Triton implied by these results, 0.01 km^3 yr^{-1} or more, is likely second only to Io and Europa in the outer solar system, and is within an order of magnitude of estimates for Venus and for the Earth's intraplate zones. This finding indicates that Triton likely remains a highly geologically active world at present, some 4.5 Gyr after its formation. We briefly speculate on how such a situation might obtain.

Key words: comets: general — Kuiper belt, Oort cloud — planets and satellites: individual (Neptune, Triton)

1. INTRODUCTION

The 1989 *Voyager 2* encounter with the largest satellite of Neptune, Triton, revolutionized our knowledge of this world, revealing it to be a scientifically inspiring satellite, 2700 km in diameter, with an N_2/CH_4 cryoatmosphere, and a morphologically complex surface (e.g., Smith et al. 1989). *Voyager* also discovered detached hazes, atmospheric emissions excited by the precipitation of charged particles from Neptune's magnetosphere, and small vents generating plumes that rise almost 10 kilometers through Triton's atmosphere.

Among the most intriguing questions concerning this distant world is the issue of its surface age and therefore, by extension, the degree of recent or ongoing internal activity within this body. *Voyager* era investigators obtained a crude global surface age estimate of 1 Gyr (Smith et al. 1989; Strom et al. 1990; cf. Croft et al. 1995), but their calculations did not take into account the cratering flux from the (then undiscovered) Kuiper belt.

In what follows we will combine existing crater counts with modern impact flux estimates that include the Kuiper belt, in order to derive new estimates of the surface age on Triton.

This paper extends considerably some preliminary results reported in an LPSC abstract (Stern & McKinnon 1999). A key assumption we make is that the primary process that removes craters from Triton's surface is conventional geological activity (e.g., volcanism), as opposed to a more exotic possibilities such as viscous relaxation, escape erosion, or charged particle degradation. This assumption is strongly supported by Triton's apparently conventional crater size-frequency distribution, and the uniformly fresh appearance of craters on Triton.

2. ATTRIBUTES OF TRITON'S CRATER AND IMPACTOR POPULATIONS

We begin by estimating the typical size scale for craters produced by impacting bodies. Following standard Schmidt-Holsapple crater scaling (e.g., Chapman & McKinnon 1986; Holsapple 1993), the crater diameter D for a specified set of impact parameters and surface properties on a body with gravity g can be estimated from

$$D_{tr} = 1.56d(A\delta/\rho)^{1/3}(1.61gd/v^2)^{-\alpha/3}(\cos\bar{\theta})^{2\alpha/3}\ , \qquad (1)$$

where D_{tr} is the so-called transient diameter, which we assume to be a paraboloid of revolution with a depth/diameter ratio of $1/2\sqrt{2}$ (McKinnon & Schenk 1995). Here d is the equivalent spherical impactor diameter, δ and ρ are the impactor and surface densities, respectively, v is the impact velocity, A and α are scaling constants that depend on the thermomechanical properties of the surface, and $\cos\bar{\theta} = 0.71$ is an adjustment factor to account for the average impact angle ($\theta = 45°$). We adopt a maximum impactor velocity $v_{max} = 11.6$ km s^{-1}, as set by the root-sum-square (rss) of Triton's escape speed and the sum of Triton's orbital speed and the maximum impactor velocity at Triton's orbit. We adopt a minimum impactor velocity

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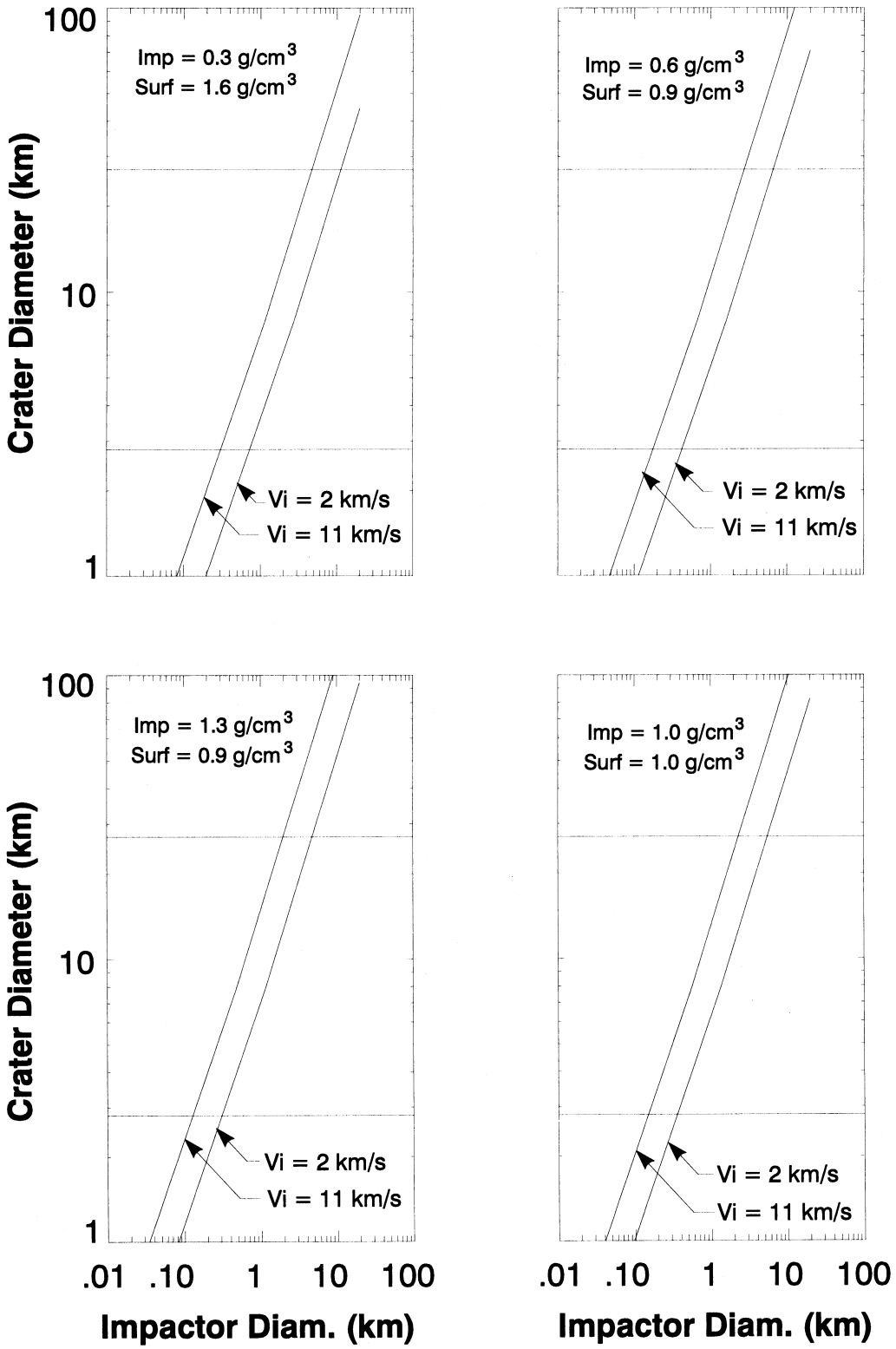


FIG. 1.—Crater diameter estimates for Triton from eqs. (1), (2), and (3) as a function of both impactor diameter and velocity. We take $g = 78$ cm s^{-2} for Triton. We take a minimum impactor velocity $v_{min} = 2.3$ km s^{-1}, as set by the rss of Triton's escape speed and the difference between Triton's orbital speed and the escape speed from Triton's orbit. We take a maximum impactor velocity $v_{max} = 11.6$ km s^{-1}, as set by the rss of Triton's escape speed and the sum of Triton's orbital speed and the maximum impactor velocity at Triton's orbit (which is the rss of the escape speed from Triton's orbit and, from LD97, the maximum encounter speed at Neptune's sphere of influence). Because Triton's surface is icy (e.g., Croft et al. 1995; McKinnon & Kirk 1999), we assume values of A and α appropriate for water ice, i.e., 0.20 and 0.65, respectively (McKinnon & Schenk 1995). Model results were computed from eqs. (1), (2), and (3) assuming a uniform distribution of impact velocities between v_{min} and v_{max}. The subtle upward curvature in the impactor size vs. crater size is due to the diameter correction for complex craters given in eq. (3). The four panels show various cases of (δ, ρ) that bound the probable range of uncertainty with respect to Triton and cometary impactors. The two bold, horizontal lines represent the smallest crater size counted and the largest crater seen on Triton, respectively (Strom et al. 1990).

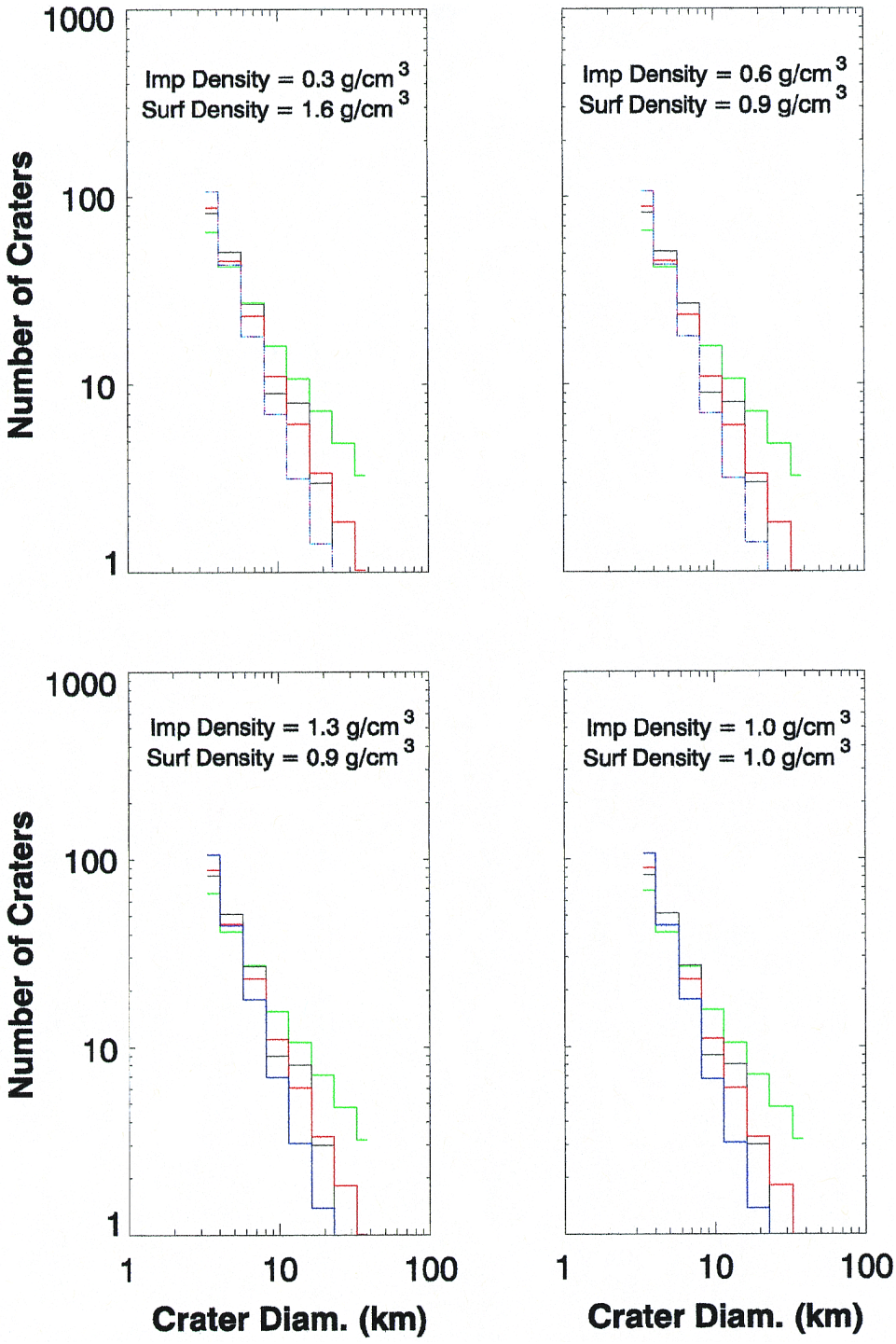


FIG. 2.—Comparison of the differential size-frequency crater distribution in area 1 on Triton (*solid black line*) to model cases with varying impactor size differential distribution power law slopes b (green = −2.0, red = −2.5, and blue = −3.0). In all these model cases the minimum crater diameters shown are for $D = 2.8$ km, which matches the smallest crater sizes counted in area 1 (Strom et al. 1990). We normalized each model case to the integral number of craters in the area 1 data set (181). The four panels display the same suite of four (δ, ρ) cases as in Fig. 1.

$v_{\min} = 2.3$ km s^{-1}, as set by the rss of Triton's escape speed and the difference between Triton's orbital speed and the escape speed from Triton's orbit.

Now, $D_{\rm tr}$ is proportional to the final crater diameter D for $D < D_c$, where D_c is the simple-to-complex crater transition diameter, which is between 6 and 11 km on Triton (Strom et al. 1990; Schenk 1992). We take $D_c = 8$ km. When $D > D_c$, i.e., in the case of complex (flattened) craters, the scaling relationship is also relatively straightforward. Based on both morphological measurements of craters on Triton (Croft et al. 1995) and geometrical models of craters on Ganymede (Schenk 1991; McKinnon & Schenk 1995), the closest analogues to Triton's craters for which extensive data exist, we therefore write

$$D(D < D_c) = 1.3 D_{\rm tr}\,, \quad \text{and} \tag{2}$$

$$D(D > D_c) = (1.3 D_{\rm tr})^{1.11} D_c^{-0.11}\,. \tag{3}$$

The scaling presented in equations (1) and (2) are probably accurate to 30% in D.

To fully explore the range of impactor diameter d that generates the observed craters on Triton, we show Figure 1. This figure evaluates equations (1), (2), and (3) as a function of impactor diameter over both the range of probable impact velocities, and a suite of (δ, ρ) cases spanning the reasonably expected parameter space. The baseline case against which other density pairs may be compared is simply the one of equal densities for impactor and surface (Fig. 1, *lower right*).

Inspecting Figure 1, one concludes that the 2.8–27 km diameter craters identified in *Voyager* images of Triton (Smith et al. 1989; Strom et al. 1990) imply impactors with diameters between 0.1 and 0.7 km (to create the 2.8 km minimum crater diameters counted), and 2–11 km in diameter (to create the largest craters detected, like Mazomba with $D = 27$ km). Such sizes naturally imply comet-sized bodies as the dominant observed Triton impactor population, and as such provide a valuable constraint on the small body population in Neptune's region of the solar system. This is our first result.

We now consider the crater size and number statistics derived from imaging by the *Voyager* 2 spacecraft during its 1989 flyby of Triton, in order to constrain the size-frequency power law index of the impactor population. The best available assessment of Triton's crater statistics (Smith et al. 1989; Strom et al. 1990) discussed four regions on Triton ("areas 1–4") on which careful crater counts were attempted. These areas add up to 16% of Triton's total surface area, out of a total of $\approx$40% of the satellite that was imaged by *Voyager* at resolutions useful for geological analysis. The interested reader can find images of areas 1–4 and a sketch map showing their location on Triton in Smith et al. (1989).[2] Because the observed crater population on Triton in general, and area 1 in particular, is far from saturation equilibrium, and is not manifestly geologically degraded, the Triton crater counts probably represent a production population.

We concentrate initially on area 1, which exhibits the highest density of craters and therefore has the best statistical confidence. Area 1 is located near the apex of Triton's orbital motion and contains 9.79×10^5 km^2 (some 4.2% of Triton's surface area); it displays a total of 181 craters with $d > 2.8$ km. We concur with Strom et al. (1990) that of the four distinct terrains counted on Triton, area 1 has the crater count statistics to best support a size-frequency analysis.

For the small-body impactor population we take a differential power law, as is typically used to represent the Kuiper belt population (Weissman & Levison 1997), of the form $n(d) \propto d^b$. We again select impact velocities to evaluate equation (1) from a uniform velocity distribution between the probable $v_{\min}$ to $v_{\max}$ range for Triton, and use equations (1)–(3) to scale from impactor diameters to crater diameters.

Figure 2 shows the results of model simulations designed to fit b, the power-law exponent on the size-frequency distribution of impactors in area 1. Figure 2 shows that the *Voyager* data are fitted well by relatively shallow power-law slopes of the impactor population, with the nominal value of b being near -2.5. This result is robust to the choice of plausible (δ, ρ) combinations in equation because this ratio appears as a multiplier in the scaling equation and the change in slope at $D = D_c$ is not severe. We note, however, that the resolution in some of the images used in the area 1 count are as poor as 2.2 km per line pair; therefore the bottommost bin or two likely suffered undercounting. Neglecting these bottommost bin or two allows steeper fits, up to $b \approx -3$, within the Poisson statistics of the crater counts. In what follows we adopt $b = -3$ as our preferred solution.

The slope parameter just derived is in accord with both Weissman & Levison's (1997) Kuiper belt model, and is also consistent with Shoemaker & Wolfe's (1982) preferred -3.0 power-law index for ray-crater impactors on Ganymede (presumably comets). This second result provides a new (if indirect) source of information on the population of small bodies that cannot as yet be optically detected in the Kuiper belt, and indicates they are plentiful, as collisional evolution models have predicted (e.g., Stern 1995; Davis & Farinella 1997).

3. IMPACTOR FLUXES

In preparation for estimating surface unit ages, we now estimate the current cratering rate on Triton, $\dot{N}$. The heliocentric flux contributing to $\dot{N}$ consists of terms due to objects on Neptune-crossing orbits from both the Edgeworth Kuiper belt (EKB) (Levison & Duncan 1997, hereafter LD97) and the Scattered Kuiper belt (SKB) (Duncan & Levison 1997) and due to objects in the Oort cloud (Weissman & Stern 1994). For a recent Kuiper belt review, see Farinella, Davis, & Stern (2000).

We neglect the possibility of a significant Neptuneocentric population of impactors (Croft et al. 1995) on two grounds. The first is the great observed emptiness of the Neptunian system with regard to debris and small satellites outside five Neptune radii (Smith et al. 1989). The second is the fact, easily shown, that any small-body impactor population large enough to populate Triton's surface with the *Voyager*-observed craters would, if their orbits are Triton crossing, be swept up on timescales of 1 to 10^3 yr in most cases. Therefore, unless a discrete Neptuneocentric flux event very recently populated Triton with its observed craters, this short sweep up time for Neptuneocentric debris implies a large unseen population of such impactors on Triton-crossing orbits. Indeed, to sustain this population against Triton sweep up over 100 Myr would imply both an accreted veneer of mass up to 10^{24} gm (roughly the mass of a typical Uranian satellite), *and* a surface that is constantly renewed on timescales of 10^3 yr or less.

We will refer to the combined EKB + SKB flux term as the KB contribution. To obtain the total Kuiper belt cratering rate on Triton, we adopt the state-of-the-art comet impact rate estimate by LD97, as revised by Levison et al. (2000, hereafter LDZD00), i.e., $\dot{N}_{\rm Neptune} = 3.5 \times 10^{-4}$ comets yr^{-1} with $d > 2^{+2}_{-1}$ km on Neptune. We then scale that result to Triton, accounting for its smaller diameter and the gravitational focusing at its distance from Neptune. For an average encounter velocity at Neptune's sphere of

[2] We do not consider the results of the six highest resolution *Voyager* frames, reported in summary form by Croft et al. (1995), because the area covered is small and the images used are smeared to varying degrees owing to spacecraft motion.

influence of ≈ 0.3 Neptune's orbital speed (LD97), these factors together conspire to reduce Triton's collision cross section, and therefore its globally averaged collision rate, by a factor near 2.7×10^{-4}, relative to Neptune. Combined with the fact that the time-averaged Kuiper belt source rate into the planetary region has probably declined only by $\sim 5\%$ over the past 0.5 Gyr (Holman & Wisdom 1993; Levison & Duncan 1993), we predict a present-epoch, *globally averaged* KB-impactor source rate of $\dot{N}_{\rm KB} = 1.0 \times 10^{-7}$ comets yr^{-1} with $d > 2$ km, or, in a more useful, surface area–normalized form for our purposes, $\hat{N} = 4 \times 10^{-15}$ craters km^{-2} yr^{-1} due to comets with $d > 2$ km. LD97's estimated uncertainty in deriving the KB term for $\dot{N}_{\rm Neptune}$ is of order a factor of 2.8–4, depending on whether the diameter uncertainty above is convolved with a $b = -2.5$ or $b = -3$ differential power-law size index, respectively.

Neither LD97 nor LDZD00 included an estimate of the Oort cloud (OC) impactor rate on Neptune. Weissman & Stern (1994), however, made a calculation for the Oort cloud impact rates on Pluto, an outer solar system object of similar physical cross section to Triton in a region with relatively similar OC flux. They estimated that the total number of Oort cloud impacts by comets with $d > 2.4$ km on Pluto is ~ 50 over the past 4 Gyr. Scaling this result to Triton's larger physical cross section and enhanced gravitational focusing environment around Neptune, and then adopting a (limiting case) -3 differential power-law size index, we expect ~ 150 impacts with $d > 2$ km on Triton over the past 4 Gyr. This corresponds to an average impact rate of $\dot{N}_{\rm OC} = 3.7 \times 10^{-8}$ yr^{-1} for $d > 2$ km, or $\hat{N} = 1.6 \times 10^{-15}$ craters km^{-2} yr^{-1} due to comets with $d > 2$ km, some $\approx 40\%$ of the $d > 2$ km KB impactor rate. This value, 40%, is likely to be an upper limit, however, because it assumes the perihelion distribution of inner Oort cloud comets extends smoothly across Neptune's dynamical barrier, which is unlikely (Weissman & Stern 1994). This leads us to conclude that the EKB+SKB flux is clearly the dominant contributor to recent cratering on Triton, our third result.

Because the OC cratering rate appears to be only $\sim 40\%$ or less of the EKB+SKB cratering rate, we neglect it in what follows.

Continuing, for a satellite in synchronous rotation like Triton, it is well known that the area around the apex of motion is where impact fluxes should be highest (Shoemaker & Wolfe 1982). And indeed as noted above, area 1, which is near the apex of motion, was the most heavily cratered terrain seen on Triton. Therefore, we must account for this position-dependent flux in interpreting unit ages where craters have been counted on Triton.

Shoemaker & Wolfe (1982) showed that the enhancement factor, η_1, for any given surface unit i, is close to a factor of 2 near the apex and varies approximately as the cosine of the angular distance from the apex of motion, reaching unity 90° from the apex (see their eq. 17). Area 1 stretches from about 20° to 60° from the apex of motion, which yields an area-averaged factor of $\eta_1 = 1.8$ increase for area 1 in its nominal cratering rate over that predicted for the global-average Triton.

4. CRATER RETENTION AGES

The average crater retention age of area i's surface can be estimated from the general relation:

$$T_i = \left(\frac{N_{{\rm crat},i}}{\hat{N}}\right)\left(\frac{1}{\eta_i A_i}\right). \quad (4)$$

Here η_i is from above, A_i is the area of the unit and $N_{{\rm crat},i}$ is the number of craters formed on that unit by impactors of $d > 2$ km; recall $\hat{N}$ is a global average for Triton.

We now evaluate equation (3) for area 1, where $\eta_1 = 1.8$. If we presume that comets are relatively dense and Triton's surface is no denser than pure water ice (Fig. 2, *lower left*), then the age computed from equation (3) assuming $b = -3$, is 240 Myr (600 Myr for $b = -2.5$). More plausibly, for the baseline case of equal densities for impactor and surface, we find $T_1 = 320$ Myr (750 Myr for $b = -2.5$)[3]. The key implication, which is robust for most plausible combinations of δ and ρ, is that area 1 is geologically very young, almost certainly less than 10% of the age of the solar system, and perhaps a good deal younger.

These estimates for T_1 likely represent an upper limit on the timescale for the most recent significant geologic activity on Triton. Why? Even for the limited fraction of Triton imaged at decent resolution by *Voyager*, stratigraphic relationships show that area 1 is older than adjacent units on Triton (Croft et al. 1995), particularly Smith et al.'s (1989) areas 2 and 4. Area 2 is an assemblage of volcanic plains, and is about half as densely cratered at area 1 (Strom et al. 1990). Because area 2 stretches from 60° to 90° from the apex of motion, $\eta_2 = 1.25$, which yields a baseline (i.e., $\rho = \delta$) T_2 of ≈ 230 Myr (550 Myr for $b = -2.5$); as above, these estimates assume all of these craters are due to sources outside the Neptune system. Areas 2 and 4 have similar crater densities and lie at similar distances from the apex of motion, so T_4 is similar to T_2. We note, however, that area 4 comprises part of the northern portion of Triton's southern frost cap, and is thus subject to a variety of surfacial modification processes, so the formation age of this unit may in fact be somewhat older. The craters initially identified on area 3, Triton's cantaloupe terrain, were later shown unlikely to be due to impact (Strom et al. 1990).

Taken together, it is clear that three of the four crater-mapped units on Triton yield crater retention ages that are not only substantially less than 1 Gyr, but may well be of order 0.2–0.3 Gyr. This is our fourth result.[4] The primary reason for the younger ages we have just derived is the inclusion of the Kuiper belt population and its consequent effect on impact rates.

What factors could conspire to substantially increase our estimates of these ages? They could be increased if either $N_{{\rm crat},i}$ were larger, or $\dot{N}$ were smaller. However, because the crater counts are complete at large sizes, it is unlikely that $N_{{\rm crat},i}$ can be substantially increased, particularly for area 1, the oldest of the four units (with the most statistically robust crater counts). Of course, an undercount could have occurred if viscous relaxation or escape erosion has removed significant numbers of craters over time. But

[3] We base the area 1 age determination for $b = -3$ on the 99 craters with $D > 4$ km counted by Strom and coworkers.

[4] And why are there no very large impact craters or basins on Triton? Because Triton's surface is too young to preserve the rare impact scars from 100 km impactors. A simple calculation of KB flux indicates that such objects should impact Triton on timescales of greater than 10^{10} yr. (Regarding ancient impacts, the thermal pulse associated with tidal braking should have erased any primordial surface.)

because the Strom et al. (1990) crater counts rely only on fresh craters, and neglect degraded ones (of which there are few if any known, a fact which itself argues for a recent resurfacing), we believe that it is unlikely this is an important factor. As for reducing $\dot{N}$, there is the caveat noted above that LD97's impact flux (and that of LDZD00) carries an estimated factor of ~ 4 uncertainty, which could allow T to exceed a Gyr; however, this uncertainty is equally likely to decrease $\dot{N}$. Another alternative would be if Triton has until recently had a massive, impact shielding atmosphere (Lunine & Nolan 1992); however, there is no evidence for this in Triton crater morphologies or size-frequency statistics.[5] We thus conclude that our estimated ages are unlikely to be underestimated.

In contrast to the difficulty of raising T, it is easy to imagine lowering Triton's crater retention age below our nominal estimates. For example, as noted above, there must have been some contribution to $\dot{N}$ from the Oort Cloud. T could also be lowered if some fraction of the crater counts were due to other sources, such as (1) if impacting populations other than the Kuiper belt and Oort cloud (e.g., Neptuneocentric) dominate, (2) if many of the craters counted are secondaries from larger craters on the unimaged parts of Triton, or (3) if endogenic (i.e., geological) processes, rather than impacts, created many of the observed craters. Concerning the first possibility, we have already argued above against a dominant Neptuneocentric impactor population being very likely, but it is possible that, for example, a fortuitous, recent Oort cloud shower of significant magnitude could have produced a cratering spike. The latter two possibilities are also unlikely, as the identification of impact crater morphologies on Triton's plains units (which includes area 1) is generally clear, and secondary crater populations characteristically follow steeper size-frequency distributions (e.g., Melosh 1989).

A more serious matter concerns the overall KB cratering rate. LDZD00's revision of LD97 included both longer integration times (for better averages) and a comparison of computed impact rates (direct counts) with those estimated by means of Öpik's equations from the modeled ensemble of ecliptic comets (for comet terminology, see Levison 1997). This resulted in a factor of ≈ 3.5 reduction in impact rates relative to LD97. LDZD00's new impact rate estimates can be turned into cratering rates by calibrating the modeled comet population against active, visible ecliptic comets and estimating the lifetime of the activity (which yields the ratio of active to extinct comets), and estimating a minimum diameter (and mass) for visible comets. Such a procedure was in fact exploited by Zahnle, Dones, & Levison (1998) in their systematic study of cratering rates on the Galilean satellites. In this work Zahnle et al. (1998) estimated that bombardment in the Jovian system is dominated by Jupiter-family, ecliptic comets (JFCs), both active and extinct, and at a rate lower than but within a factor of 2 of that estimated by Shoemaker (1996). Shoemaker's estimate, obtained using Öpik's equations, was dominated by extinct JFCs, and was based on an observed population of asteroidal bodies in JFC-like orbits.

The problem is this: if the Zahnle et al. (1998) estimate is recalibrated to LDZD00, then their cratering rates on the Galilean satellites fall by 3.5 and become ≈ 6 times less than Shoemaker's (1996) estimate for extinct JFCs alone. We are skeptical that Shoemaker's cratering rates are overestimated to such a degree, especially as the logical chain from observed asteroid orbits and magnitudes to crater production rates on the Galilean satellites is a short one. There are cratering rate estimates that are, conversely, much lower than even LDZD00 (i.e., Neukum et al. 1998), but these are based on the assumption that the Gilgamesh basin on Ganymede is the same age as the Orientale basin on the Moon, and otherwise ignore observations of present-day comets and asteroids. We discount these latter estimates. Our view is that Shoemaker's estimates indicate that the calibration in LDZD00 is probably low and that the true cratering rate may be higher than we obtained above by a factor of up to ≈ 6. If so, then all of the terrain ages derived above may also be overestimates by a factor of several. In particular, the age of Triton's leading hemisphere plains (area 1) may be of order 50 Myr, and the age of the young volcanic plains on Triton (area 2) may of order 40 Myr.

5. DISCUSSION

What are the implications of our results vis-à-vis Triton's activity? To begin, let us consider the time-averaged volumetric resurfacing rate on Triton, $\dot{V}_{\rm TR}$. A characteristic depth of several 100 m is required to overtop the rims of the largest craters seen on Triton, and indeed, to bury most of the topographic structures observed (Croft et al. 1995). We assume a global resurfacing depth of 100 m over a (conservative) timescale of 300 Myr, which gives a characteristic volumetric resurfacing rate on Triton of $\dot{V}_{\rm TR} = 0.01$ km^3 yr^{-1} (3×10^8 yr$/T$). Based on uncertainties in the required resurfacing depth and T, it is not implausible that the actual value of $\dot{V}_{\rm TR}$ has been or is a factor of several times higher. Regardless, this resurfacing rate is far higher than what can be supported by the small-scale plume vents seen by *Voyager*, and indicates a far more active world in the geologically recent past than has been formerly appreciated.

This conservative, 0.01 km^3 yr^{-1} resurfacing rate also exceeds the escape-loss erosion (Strobel & Summers 1995) and aeolian transport (Yelle et al. 1995) rates on Triton by 2 orders of magnitude. We therefore conclude that geologic processes are indeed the dominant surface modification process operating on a global scale on Triton (Croft et al. 1995).

Now consider Triton's volumetric resurfacing rate, $\dot{V}_{\rm TR}$, in comparison to other bodies. The lunar resurfacing rate during the active, mare-filling epoch was also ~ 0.01 km^3 yr^{-1} (Crumpler et al. 1992). The current-epoch volcanic resurfacing rates on the Earth (Crumpler et al. 1992), Venus (Bullock et al. 1993; Basilevsky et al. 1997) and Io (Spencer & Schneider 1996) are estimated to be ≈ 4 km^3 yr^{-1}, ≈ 0.1–0.4 km^3 yr^{-1}, and ≈ 40 km^3 yr^{-1}, respectively; the terrestrial rate excluding plate boundaries is ≈ 0.3–0.5 km^3 yr^{-1} (Crumpler et al. 1992). These various comparisons show that Triton clearly appears to be more geologically active than any other solid body in the outer solar system, except the tidally heated satellites Io and Europa.[6]

If Triton has been substantially internally active in the

[5] Reported underabundances of small craters on the Galilean satellites (Chapman et al. 1998) occur only at crater sizes ($D < 1$ km) and for processes well below *Voyager* resolution at Triton.

[6] We note that Titan's volumetric resurfacing rate is unknown at present due to its opaque atmosphere.

geologically recent past, it is natural to imagine that Triton is still active today (or else the geologic engine would have just run out, causing the *Voyager* observations to have occurred at a "special time"). We therefore now consider the question of how Triton, which lacks any significant present-day tidal forcing and has a radius of just 1350 km, could maintain geologic activity 4.5 Gyr after its formation. We discuss two ways that this could have occurred.

First, Triton's own internal engine, powered by radiogenic energy release alone, may after 4.5 Gyr still generate mantle temperatures exceeding 200 K (Stevenson & Gahndi 1990; McKinnon, Lunine, & Banfield 1995). Such conditions are possibly significant enough to power widespread, low-temperature cryovolcanism that accounts for the recent resurfacing. This cryovolcanism could in principle also be related to Triton's observed plume vents (Kirk et al. 1995) and global color changes (Buratti et al. 1999).

Alternatively, it is possible that Triton's recent geologic activity is instead due to residual tidal heat resulting from a late-epoch capture into Neptunian orbit. This scenario would imply that Triton was a resident of the EKB or SKB until relatively recently (i.e., within the last Gyr), and as discussed above, that it likely would then have possessed a substantial atmosphere until even more recently. This scenario would in turn favor Triton's capture by collision with an original satellite (Goldreich et al. 1989), rather than by means of gas drag in a proto-Neptunian nebula (McKinnon & Leith 1995). Nevertheless, the a priori likelihood of such an event late in solar system history, and from such a depleted reservoir as the present-day EKB or SKB, is low.

While a late capture is not impossible, it might seem simpler to accept that Triton is big enough, and composed of mobile enough ices, to be geologically active, as in the first scenario sketched above. Given the accumulating evidence for warmth and activity inside the Galilean satellites as revealed by the Galileo mission (e.g., McKinnon 1997), this should not be seen as so surprising. Perhaps Triton is telling us that somewhat smaller icy bodies, such as Pluto, can also remain geologically active at late times.

6. CONCLUSIONS

Combining *Voyager*-derived Triton crater counts and improved cratering flux estimates for Triton, we have derived the following findings:

1. The impactor population reaching Triton today is most probably dominated by the Kuiper belt.

2. Triton's extant surface craters require an impactor flux that contains a substantial population of subkilometer impactors; plausible 0.1–10 km impactor populations appear to exhibit power-law slope size indices in the range -2.5 to -3, with the steeper slope being more likely.

3. Findings 1 and 2 together imply a strong (if circumstantial) case for a significant, unseen population of kilometer-scale and subkilometer scale bodies in the Kuiper belt, as predicted by both dynamical and collisional models (see Weissman & Levison 1997; Farinella et al. 2000).

4. Unless the areas of Triton imaged by *Voyager* are not representative of the object as a whole, Triton's global average surface age may be of order 100 Myr, though older ages cannot be formally ruled out. Regardless, this implies surface ages for the imaged units that are at least a factor of 2, and perhaps over a factor of 10, younger than the 1 Gyr derived at the time of the *Voyager* flyby (Smith et al. 1989). Even if unimaged terrains are more heavily cratered than the terrains seen by *Voyager*, the units already mapped indicate very recent resurfacing over large regions of Triton.

5. As such, Triton appears to have been geologically active throughout at least 90%, and perhaps over 98%, of the age of the solar system. These estimates are conservative, in that some dateable units on Triton may well be significantly less than 100 Myr old. It is plausible that Triton's internal engine still supports sufficient ongoing activity capable of generating large-scale (perhaps episodic) resurfacing.

6. Triton's high rate of resurfacing may indicate its capture and subsequent, tidally driven thermal catastrophe occurred relatively recently; alternatively, the high rate of resurfacing may imply that we understand less than had been thought about the interiors of icy objects like Triton and Pluto.

7. Owing to the fact that the derived time-average volumetric resurfacing rate, $\dot{V}_{TR}$, exceeds 0.01 $km^3\ yr^{-1}$, geologic processes are clearly the dominant large-scale surface modification process operating on Triton.

8. Triton's inferred volumetric resurfacing rate exceeds all other satellites in the solar system except Io, Europa, and possibly Titan (whose rate is unknown). The time-average resurfacing rate at late epoch is comparable to or exceeds the lunar resurfacing rate during the Moon's active, mare-filling era.

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