TRITON'S EVOLUTION WITH A PRIMORDIAL NEPTUNIAN SATELLITE SYSTEM. R. Rufu[1] and R. Canup[2], [1]Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot Israel 76100 (raluca.rufu@weizmann.ac.il), [2]Planetary Science Directorate, Southwest Research Institute, Boulder, Colorado 80302, USA (robin@boulder.swri.edu).

Introduction: Neptune has substantially fewer and mostly smaller satellites than the other gas planets. The one massive satellite, Triton, is thought responsible for this. Triton's retrograde orbit implies that it is a captured object, likely from a separated KBO binary [1]. If Neptune had a primordial satellite system with a mass ratio of $M_{sat}/M_{Nep} \sim 10^{-4}$ (as suggested by some satellite accretion models of gas planets [2]), then Triton's mass seems near the minimum value required for a retrograde object to have destroyed the system. Thus, the existence of Triton places an upper limit on the total mass of such a primordial system.

The high initial eccentricity of Triton's orbit may decay by tidal circularization in less than 10^9 years [3, 6]. Ćuk and Gladman [4] argue that Kozai cycles increase the average pericenter, increasing the circularization timescale beyond the age of the Solar System. That study proposes that perturbations on the prograde satellites induced by Triton lead to mutual disruptive collisions between those satellites. The resulting debris disk interacts with Triton and drains angular momentum from its orbit, reducing the circularization timescale to less than 10^5 years. Such fast circularization can preserve the irregular satellites, such as Nereid, that are otherwise lost during Triton's circularization [4]. However, it is unclear whether Triton can induce mutual collisions among the satellites before it experiences a disruptive collision. Due to its retrograde orbit, collisions between Triton and a prograde moon would have higher relative velocities than those between two prograde moons. A disruptive collision onto Triton would be inconsistent with its current inclined orbit, as Triton would tend to re-accrete in the local Laplace plane.

The objective of this study is to explore how interactions (scattering or collision) between Triton and putative prior satellites would have modified Triton's orbit and mass.

Methods: We performed N-body integrations [5] of a newly captured Triton together with a hypothetical prograde satellite system for 10 Myr including effects of Neptune's oblateness. We considered a primordial (pre-Triton) satellite system comparable to that at Uranus, i.e., with a mass ratio relative to the planet of 10^{-4} (e.g., [2]). The SyMBA code resolves close encounters among the bodies and perfect merger is assumed when an impact is detected. Triton's initial conditions (semimajor axis, eccentricity and inclination) are chosen from previous studies of typical initial captured orbits [6]. We test the collision history onto Triton and between the prograde moons. Tidal evolution over the simulated time is small and thus neglected. Initially we do not include Kozai perturbations in these preliminary simulations, although they may be relevant.

We use Movshovitz *et al*. [7] scaling laws to analyze impact outcomes. These disruption scaling laws were derived for non-hit-and-run impacts between two bodies in an isolated space. Their disruption estimation is an upper limit because material that escapes from two colliding satellites has to only reach sufficient velocity to escape their Hill sphere, which is smaller than the mutual two-body escape velocity. Impact geometry is also important, for example, grazing impacts (high impact angles) require higher energies to disrupt a body, since the velocity is not tangential to the normal plane.

Results: In 200 simulations, the overall likelihood of Triton's survival after 10 Myr is ~40%. The typical collision timescale is less than ~Myr, and in most scenarios Triton experiences at least one impact.

Different sets of initial conditions have different probabilities for Triton's loss (either by escaping the system or falling onto Neptune). For example, a high inclination Triton (175°) does not survive more than 10^4 yr, due to the near alignment of its orbit with Neptune's equatorial plane which contains the prograde satellites. In this case, after a final Triton-satellite collision, the orbital angular momentum of the merged pair is small, leading to collapse onto Neptune.

In scenarios that resulted in a final stable Triton, the median velocity of impacts onto Triton is 6.7 V_{esc} (±2.3 V_{esc}), whereas impacts between the prograde satellites have a median of 1.8 V_{esc} (±1.5 V_{esc}). Mutual collisions among the prograde moons are almost always (~98%) non-disruptive (Fig 1). The mass ratio between Triton and the prograde satellites is <0.4, hence disruption is predicted only at high velocities (>10 V_{esc}) [7]. Triton impacts are more disruptive than the mutual collisions between the prograde satellites, nevertheless most (~80%) of Triton's impacts fall below the threshold for catastrophic disruption [7].

Most of Triton's final orbits lie within the Nereid's periapsis (Fig. 2). In these cases, Nereid-type satellites may remain stable for the subsequent Triton circularization [4, 6]. Moreover, for orbits with apoapses smaller than 70 R_{Nep}, perturbations to Triton's orbit due to Neptune's shape are bigger than the Kozai induced cycles, and beyond this point, the subsequent evolution proceed at relatively constant inclination [6].

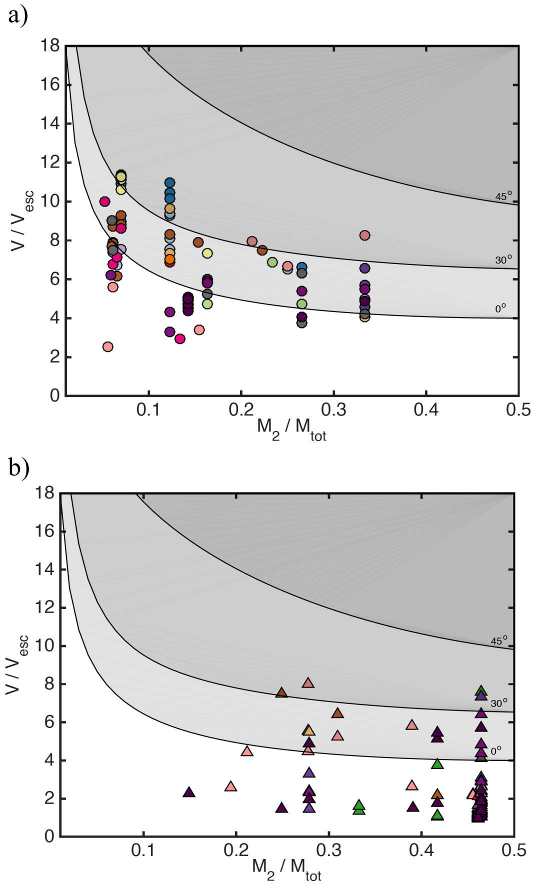

Fig. 1 – Impact parameters (mass ratio vs. the impact velocity normalized to the mutual escape velocity, V_{esc}) from scenarios with a final surviving Triton onto a) Triton; b) prograde satellites. The black curves represent the transition to the disruptive regime [7] at impact angles of 0, 30 and 45 degrees respectively. Colors represent different initial conditions.

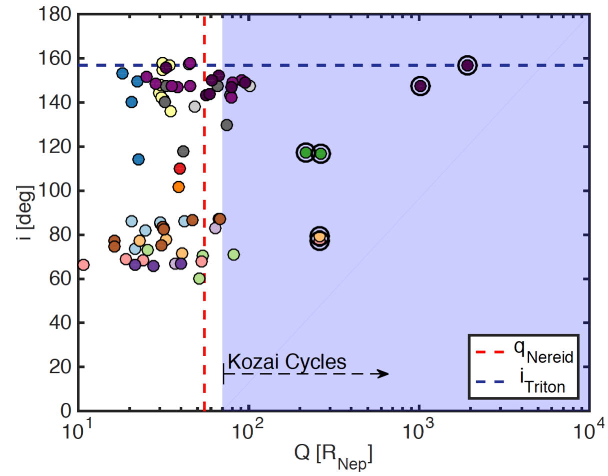

Fig. 2 – Triton's final apoapsis in Neptune Radii vs. its final orbital inclination. The red vertical dashed line represents the current Nereid's periapsis. The dark blue horizontal line represents the Triton's current inclination. The light blue region represents the regions where Kozai perturbations are important, for lower orbits, tidal evolution proceeds with constant inclination [6]. Simulated Triton analogs that did not encounter any impacts are indicated by the black circles. The colors represent different initial conditions.

Discussion: The majority of impacts with Triton appear non-disruptive, and therefore Triton can survive several collisions with pre-existing prograde satellites. Mutual impacts among the prograde moons are even less disruptive, suggesting that a debris disk as envisioned by Cuk & Gladman [4] is unlikely.

Non-disruptive collisions onto Triton may provide a mechanism for Triton to lose angular momentum and reduce its semi-major axis over a short timescale. In this case, the collisional evolution could lead to the preservation of small and irregular satellites (Nereid-like), that might otherwise be lost during a protracted Triton circularization via tides alone, echoing Cuk & Gladman's [4] findings although through a different mechanism.

References: [1] Agnor C. B. and Hamilton D. P. (2006) *Nature, 441,* 192–194. [2] Canup R. M. and Ward R. W. (2006) *Nature, 441,* 834–839. [3] Goldreich P. *et al.* (1989) *Science, 245,* 500–504. [4] Cuk M. and Gladman B. J. (2005) *ApJ, 626(2),* L113-L116. [5] Duncan M. J. *et al.* (1998) *ApJ, 116,* 2067-2077. [6] Nogueira E. *et al.* (2011) *Icarus, 214,* 113-130. [7] Movshovitz N. *et al.* (2016) *Icarus, 275,* 85-96.