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TRITON'S POST-CAPTURE THERMAL HISTORY *or* HOW LONG DID TRITON STAY MOLTEN, AND DOES THIS HAVE ANYTHING TO DO WITH HOW TRITON LOOKS TODAY?

William B. McKinnon and Lance A.M. Benner, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130.

Among the major highlights of last summer's Voyager encounter with Neptune were the first close observations of the mysterious moon Triton. Planetary scientists had long suspected that Triton would be interesting because of its anomalous retrograde (backwards) orbit, but Triton's surface turned out to be nothing less than astonishing: the satellite is covered with fractures, icy lava flows and volcanic calderas (collapse craters), frost and plume deposits, and other features that remain puzzling. Subsequent analysis revealed ongoing volcanic eruptions or geysering, with probably methane and/or nitrogen gas being vented. Thus Triton, the first icy satellite of its size class in the solar system to be visited by spacecraft, is a geologically active world, and one that possesses features that have, by and large, never been seen on the other icy satellites of the solar system.

What can explain this diversity of features? What does it mean for Triton's composition, structure, and history? And what does it all mean for how the outer solar system assembled 4.5 billion years ago? These are the questions planetary scientists will struggle with in the years to come. At this meeting, William McKinnon and Lance Benner of Washington University (in St. Louis) present the results of recent calculations and modeling that suggest that massive tidal heating and melting, associated with Triton's capture by Neptune, could be largely responsible for Triton's geologically youthful appearance.

Background

Several workers, going back many years, have suggested that Triton's retrograde and tilted (with respect to Neptune's equator) orbit could be explained if Triton was a captured satellite. There are two two major ways for this to happen. The first is capture by *gas drag*. This was first suggested by James Pollack and co-workers at NASA-Ames Research Center in 1979, and involves a solar-orbiting Triton passing close to Neptune when the planet was forming and thus when it had a large amount of gas (mainly hydrogen and helium) in close proximity. Gas drag would slow Triton down just enough that it would become permanently gravitationally bound to Neptune. A more modern and detailed version of the gas drag hypothesis is presented by Andrew Leith and William McKinnon in a companion talk in the Triton session. In that work, Triton is captured by gas drag in a later phase of Neptune's evolution, one in which accretion of the planet is largely over, but in which there remains a compact disk (or nebula) of gas and solids that can form a satellite system similar to that which exists today around Uranus. The remnants of this original Neptune satellite system are seen close to Neptune. In any event, Triton passes through this disk, and is slowed enough to be permanently captured.

In all gas drag models there is substantial orbital evolution, due to gas drag, after the initial capture. In principle, Triton's orbit can shrink and completely circularize, attaining close to its present orbital configuration by gas drag alone. In fact, unless gas drag evolution halts, Triton's orbit will continue to decay, and it will eventually be torn apart by tides when it is very close to Neptune. This has not happened, of course, and thus gas drag models rely on the gas near Neptune being dispersed (such as by the T Tauri wind that is thought to have cleared away the solar nebula) before this could have happened, leaving Triton stranded in a retrograde, but uncircularized orbit. This is most plausible if Triton is captured close to the end of Neptune's accretion, so the version of the gas drag model by Leith and McKinnon is favored on this point.

Leith and McKinnon also show that gas drag capture by a protosatellite disk is favored because the time scale for gas drag evolution can be prolonged by two effects, thus making it more likely that Triton outlives the gas. The first effect is that solar perturbations cause Triton's eccentric and elongated capture orbit to markedly oscillate. Specifically, the point of closest approach, or pericenter, of Triton's orbit varies such that sometimes it is within Neptune's disk or nebula, and sometimes it is outside. If it is outside, then Triton's orbit doesn't evolve by gas drag at all during that orbit, and the overall effect is that Triton can take more than 10,000 years to spiral in. Furthermore, Triton is sufficiently massive compared with the estimated mass of the Neptune disk or nebula that it may be able to clear out zones or lanes within the nebula. Once this happens gas drag evolution will halt altogether. From this point on, Triton's orbital evolution will be controlled by tides (the topic of the talk by McKinnon and Benner), and be much slower.

The other capture mechanism is *collision* with an original "regular" Neptune satellite (one that would have formed from the Neptune nebula above). This was proposed by Peter Goldreich and co-workers at Caltech last year. Here, a collision, after Neptune's satellite system has formed, causes Triton to move from solar orbiting to Neptune orbiting in a single (cataclysmic) step. All further evolution is controlled by tides, or possibly by further collisions (and actually, during orbital evolution by gas drag, collisions may also occur with satellites that have formed or are in the process of forming). The post-collision orbit is a very elongated ellipse, taking Triton from several Neptune radii (R_N) from the planet to possibly greater than 2000 R_N. The post-gas-drag orbit would likely be similar, but not so elongated.

Tidal Heating

McKinnon was the first to point out, in a 1984 paper in the British journal *Nature*, that a captured Triton would likely undergo massive heating as its orbit was circularized and shrunk by tides raised on it by Neptune. In that paper, Triton was estimated to have completely melted, with the most volatile components of its possible makeup (CH_4, N_2, etc.) being driven to the surface. These volatile ices had been identified spectroscopically at the time, and their presence on Triton's surface was confirmed by Voyager. The possibility of a Triton melted by tidal energy was reiterated by Goldreich and co-workers in their paper of last year.

The time scale of tidal evolution is an important quantity to estimate. The simplest model of the dissipation of tidal energy assumes that Triton remains solid throughout its orbital evolution. It predicts that a Triton with an extremely elongated elliptical orbit, extending to the edge of Neptune's gravitational sphere of influence, takes almost 10^9 yr to evolve inward and have its orbit circularize. This is significant because (1) the time scale is more than twice as long as predicted in McKinnon's 1984 paper (because Triton's radius was then unknown but thought to be near 1750 km, whereas it is now known to be a much smaller 1350 km) and (2) the time scale is much longer than the estimated duration of heavy cratering in the outer solar system (~500 million years). Therefore, the "new," smaller Triton could have stayed hot well beyond the era of heavy cratering, and it could be predicted that little if any of the heavily cratered terrains seen on nearly all of the other icy satellites would be observed on Triton by Voyager. (It is significant that the icy satellites without heavily cratered terrains are Europa, Enceladus, and Ariel, all of which are being or have been tidally heated.)

These simple models, which assume that Triton remains solid, cannot be correct in detail, because so much of Triton's orbital energy is dumped into the satellite that it must melt. More complex models are necessary, the subject of this LPSC talk.

McKinnon and Benner first determine how soon Triton begins to melt once tidal evolution starts, that is, after the capture collision or after gas drag evolution ceases. It turns out that Triton is so rock-rich, approximately 70% rock by mass with the other 30% being ices, that it is likely that Triton would begin to melt its ice and unmix, or differentiate, spontaneously, because of the energy liberated within the satellite by radioactive element (U, K, and Th) decay. Only by deliberately choosing parameters that lower Triton's internal viscosity is it possible to build an internal model of Triton that convects without melting.

However, even for very elongated initial orbits that extend to the edge of Neptune's sphere of influence, the tidal energy dissipated during individual passes close to Neptune is, time-averaged, comparable to the power due to radioactive element decay. Therefore, it is very unlikely that melting can be significantly delayed. Only if Triton is captured cold will melting be put off, perhaps ~100 m.y. The best estimate is that Triton will begin to melt promptly. Incidently, Triton's rock abundance is very similar to that of slightly smaller Pluto, which is further evidence that Triton was born in solar orbit and was then captured.

Melting and differentiation are interesting because they are partially self-sustaining. The gravitational energy of unmixing liberated (by moving rock to the center and ice to the outside) is approximately 30% of that needed to melt Triton's ices. Therefore, continued radiogenic and tidal heating are necessary to push Triton all the way to complete differentiation. This is greatly aided by the fact that the tidal dissipation in a differentiating body increases wildly compared with that in a solid one. The dissipation increases because of abundant "hot" ice (ice near the melting point), transient multiphase regions such as ascending slush and descending mud diapirs, and because the opening up of an internal ocean allows greater tidal flexing. Calculations suggest that Triton will differentiate in under 10^7 yr, and possibly much less. The result is a liquid water ocean, approximately 350–400 km deep, capped by a thin, conductive ice shell, overlying a rock core.

Continued tidal heating in the core causes it to heat up and melt as well. The ultimate tidally heated configuration for Triton is nearly totally molten. A thin water-ice shell tops a liquid water mantle, and thin rock shell tops a liquid silicate core; this lower shell may be negatively buoyant, though, and may turn over as on a lava lake. There may be an inner core of liquid iron-sulfur, but no iron shell because the freezing point of the core is less than that of the molten rock mantle. We ignore for the time being any other ices, such as methane (CH_4) and nitrogen (N_2), that might form a surface ocean.

Once Triton melts, and it needs only a small portion of the total orbital energy potentially available to it, its orbital evolution actually slows. This seeming paradox results from the fact that dissipation in a liquid Triton is largely confined to the thin solid shells described above. The hot, near-melting portions of both shells are quite dissipative under tidal forcing, but the shells are at most only a few km thick. Of course, tidal flexing is at its maximum for a liquid body, but the total effect is still to stretch out Triton's orbital and thermal evolution due to tidal heating. Thus McKinnon and Benner conclude that a nearly totally molten Triton may stay hot for an extended length of time, greater than 500 million years. Therefore, as with the simple model of tidal heating above, it is predicted that Triton should not have retained any early record of heavy cratering. This conclusion was originally presented by McKinnon at the Fall 1988 AGU Meeting, in advance of the

Voyager Neptune encounter, but the results presented at this (LPSC) conference take advantage of the new knowledge of Triton's size and mass.

The Evidence from Triton

The question now is whether tidal heating and melting are *required* to explain the absence of heavily cratered terrains on Triton. This depends on the composition of the surface. If at least portions of Triton's surface are made of close to pure water ice, as in the models discussed here, then ancient craters could survive in these cold, rigid regions in the absence of tidal heating and associated geologic activity. Thus tidal heating would be required to explain Triton's present appearance. If, however, there is a crust of lower melting point ices (such as nitrogen and methane, mentioned above) greater than a few km thick, then continuing volcanic and other activity in this relatively soft layer driven by present-day radiogenic heating inside Triton could, by itself, probably destroy any ancient crater population. In this case, tidal heating is not required. Hence, in order to use Triton's appearance to determine whether massive tidal heating actually occurred, detailed geological analyses will be necessary to constrain the composition of Triton's surface layers.

Further work should also involve more detailed characterization of the volatile ices during the tidal heating epoch. This may lead to new constraints on the amount of tidal heating Triton experienced. During the time when Triton was mostly liquid, a surface ocean of CH_4 and N_2 liquid probably existed, overlying the water-ice shell described above. It may have been capped by a CH_4-ice shell, but this would have been too thin to affect the tidal heating and orbital evolution of the satellite. However, a tidally heated Triton would have a hotter surface than it does now, which means a substantial CH_4–N_2 greenhouse atmosphere, so it may have been too hot for surface methane ice.

There are many questions for the future. What chemical processing occurred in the hotter, thicker early atmosphere, and could this be linked to the absence of atmospheric carbon monoxide (CO) today? CO is predicted to occur, based on the composition of comets, and a captured Triton may represent the largest surviving cometary body known in the solar system. What chemical processing occurred in Triton's early water ocean? What happened to the abundant organic material that was likely a part of the satellite (>10% by mass according to the cometary model) during the era of extreme tidal heating? Study of this marvelous moon is only beginning.