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TRITON: A HOT POTATO?; R. L. KIRK*, AND R. H. BROWN†, *U.S. Geological Survey, Flagstaff, AZ 86001, †Jet Propulsion Laboratory, Pasadena, CA 91109

Introduction Since the 1989 flyby of Triton by Voyager 2, considerable attention has been given to the effect of sunlight on the surface of that body: widely disparate models of the active geysers observed by Voyager have been proposed by us and by others, with a solar energy source almost their only common feature; other workers have struggled to explain the seemingly paradoxical distribution of surface frost, with an extensive polar cap in the hemisphere currently most heated by the sun but no visible cap in the less-illuminated northern hemisphere. Yet Triton derives more of its heat from internal sources than any other icy satellite, and perhaps more than any other solid body in the solar system except Io. On the one hand, Triton is located 30 times as farther from the sun than the Earth is, and reflects away the majority of the solar radiation incident upon it. On the other, the high bulk density of Triton indicates that rock substantially outweighs ice in its makeup, so that energy released by the decay of radioactive elements is correspondingly more important for Triton than for other icy satellites. We have begun to investigate how this relatively large internal heat source might affect the observable behavior of volatiles on Triton's surface.

The Global Energy Budget How much energy is liberated by the decay of radioisotopes in Triton's interior, and how much does the satellite receive on average from the sun? One of us (Brown) and coworkers have tried to answer these questions in a paper recently submitted to *Science*. Both quantities turn out to be uncertain by about a factor of two. The internal heat flux could be as low as $3.3\,\mathrm{mW\,m^{-2}}$ or as high as $6.6\,\mathrm{mW\,m^{-2}}$, depending mainly on whether the rock in Triton has a composition more like that of chondritic meteorites or like that of the Moon. (For comparison, the Earth's internal heat flow is roughly $60\,\mathrm{mW\,m^{-2}}$.) The incident solar energy is much greater, at $1.5\,\mathrm{W\,m^{2}}$, but only a fraction is absorbed (roughly one fifth by past estimates, but perhaps as little as one tenth according to Brown and coworkers), and, of course, only a part of the surface is illuminated at any time. The absorbed solar energy, averaged over the whole surface, is probably between 40 and $80\,\mathrm{mW\,m^{-2}}$. Internal heat thus amounts to somewhere between about 5% and 20% of Triton's global energy supply.

Inclusion of a spatially uniform internal heat supply in Triton's energy budget would not have any observable effect on surface frosts (although it would imply that, in order to maintain the surface temperature measured by Voyager, Triton's surface must radiate heat slightly more efficiently than previously thought). If the internal heat flux is spatially variable, however, frost stability will be enhanced in areas of low heat flux and decreased in areas of high flux. The relatively large *average* internal energy supply encouraged us to try to estimate the magnitude of internal heat flux *variations* and to evaluate their potential effect on the distribution of surface volatiles. We have considered the insulating effect of the polar caps, the nonuniform heat flow due to mantle convection, and the localized heating due to cryovolcanic activity.

Insulating Polar Caps We are ultimately interested in the effect of internal heat on the distribution of surface volatiles. The distribution of volatiles may, however, significantly influence the internal heat flux. The thermal conductivity of solid nitrogen at Triton temperatures is several hundred times less than that of water ice. A polar cap on the order of a kilometer thick may thus have an insulating effect comparable to the entire icy outer layer of Triton, which is probably about 350 km thick. We have constructed a simple analytic model to test this effect, assuming thermal conduction in a spherical shell (the thermal lithosphere) with a constant temperature maintained by the convecting ice mantle at its base and an insulating cap whose thickness varies smoothly with latitude from zero at the equator to a maximum at the poles. We find that for a nitrogen cap 1 km deep, the equatorial heat flux can be increased to as much as 1.4 times the global average, while the flux at the poles is reduced to only 0.3 of the average value in the extreme case.

Effect on Frost Stability Published models of the current energy balance on Triton (excluding internal heat but including the variation of albedo with latitude) predict the deposition of frost northward of 15° latitude; time-dependent models predict that seasonal frost deposits currently extend even farther south. Can we account for the absence of obvious bright frost deposits in Triton's northern hemisphere by including the concentration of internal heat toward the equator in the energy balance? The answer would appear to be no. We have performed a frost stability analysis similar to that by John Stansberry of the University of Arizona and coworkers. Adding a spatially varying internal heat flux shifts the current latitude of frost deposition by no more than 0°.5.

Somewhat less can be said with certainty about the effect of internal heat on the long-term stability of the polar caps. The seasonally averaged insolation varies much less strongly with latitude than the current diurnally averaged insolation, so that addition of internal heat should have a proportionally larger effect on frost stability. By an unfortunate coincidence, however, the seasonally averaged insolation curve has almost exactly the same shape as our simple model for the redistribution of heat by the polar cap. Including internal heat in our calculation thus has the same effect as would increasing the brightness of the sun: the latitude dividing long-term net sublimation from net deposition does not shift, although the rates of sublimation and deposition are increased. We are presently working on a numerical model that will incorporate more general cap thickness profiles (including an

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unfrosted equatorial zone that does not participate in the energy balance of the caps) and that will follow through time the feedback between cap thickness and the redistribution of internal heat. This feedback mechanism may well be an important (and previously overlooked) piece of the puzzle that is Triton's global frost distribution.

Mantle Convection We turn now to processes capable of producing more localized enhancement of heat flux and thus perhaps able to modify the pattern of frost deposition. One candidate is mantle convection: upward heat flux at the top of the mantle is concentrated over zones of upwelling. Lateral heat conduction in the thermal lithosphere will, however, act to smooth out or attenuate the variation in heat flux. We have modeled this attenuation, which depends on the thickness of the lithosphere, the horizontal scale of mantle convective cells (proportional to mantle thickness) and the planform of convection (one-dimensional rolls *versus* polygonal cells). For roll convection and our upper limit on average heat flux the variation in surface flux would be sufficient to shift the latitude of frost equilibrium by $\pm 2°$. If the mean flux is smaller, the variable portion will be much more strongly attenuated, resulting in a neglibable effect. We conclude that it is barely possible that mantle convection modulates the shape of the polar cap edges in an observable way.

Cryovolcanism Many of the surface features revealed by Voyager 2 on Triton have been interpreted as evidence of "cryovolcanism," that is, geologic activity analogous to volcanic eruption on the terrestrial planets but involving ices such as H_2O, NH_3, CH_4, or N_2 and occurring at much lower (though well above ambient) temperatures. Unlike the mechanisms discussed above, migration of "hot" cryovolcanic material toward or to the surface of Triton could result in heat fluxes that exceed the global average by a large factor. On the other hand, this enhancement would be transient and hence might not be observed at a given time. We have considered the possible effects of two very different types of cryovolcanic activity.

Linear ridges a few hundred meters high, tens of kilometers wide, and thousands of kilometers long are common in Triton's cantaloupe terrain and extend into the southern polar cap. They have been interpreted as the result of fissure eruptions. We have modelled the thermal effect of the warm material in the conduit feeding such an eruption, and we find that temporary heat flux enhancements comparable to or greater than the global average flux would occur in a zone extending 17 km to either side of the dike and would last up to 10^5 years. This result leads us to speculate that the narrow swath apparently cleared through the polar cap margin by one of the linear ridges may result in part from heating by the surface flow and its conduit. The critical problem with this suggestion is the low probability (on the order of 1%) of Voyager observing a ridge soon enough after its eruption that the heatflow

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is still enhanced. This difficulty might be overcome if openings in the permanent polar cap, once created, are able to persist for much longer than 10^5 years because the material exposed in this way is darker than the cap and absorbs enough more sunlight to remain significantly warmer.

We have also considered the thermal effects of diapirs: buoyant masses of warm ice or other cryomagma that are not confined to a conduit, but instead ascend through the lithosphere as roughly spherical "blobs." Because the viscosity of the lithospheric ice is very high (and increases dramatically with decreasing temperature) the diapirs propagate upward by softening and pushing aside a thin layer of the surrounding ice at the expense of their internal heat, in a kind of upside-down "China syndrome." Modeling this behavior, we find that a diapir typically ascends 1.0–1.5 of its own radii before running out of heat. The enhancement of surface heat flux depends on the depth at which the diapir stops; a diapir 70 to 100 km in radius will ascend far enough to double the heat flux in the region above it. The flux enhancement will last on the order of 50 to 100 million years, so that observation of the thermally active phase is far more probable than was the case for the linear ridges. We suggest that the three diffuse, roughly circular regions of lower albedo at latitude 5° S, longitudes 25°–50° on Triton may be the result of sublimation of the surface frost by diapiric activity. The features are roughly 50 km in radius, and at least two of them are clearly associated with cryovolcanic flooding of the surface. They may therefore constitute the clearest evidence for the modification of Triton's frost layer by localized internal heating.