Perspective

Voyager at Triton

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THE SOLID BODIES OF THE OUTER SOLAR SYSTEM LIKELY contain key chemical and physical records of the early evolution and formation of the planets, and yet they remain poorly understood (*1*). Before the Voyager 2 flyby of the Neptune system, little was known about Neptune's satellite Triton (*2*). Earth-based spectra revealed that methane and possibly nitrogen are present on the surface (*3*). But the radius of Triton was uncertain to a factor of 2, its mass was very poorly constrained, and the nature of the atmosphere unknown. A variable atmosphere supported by polar caps of methane was advanced on the basis of the complex orbital modulation of solar illumination (*4*). Ten reports (pp. 410–443) in this issue of *Science* summarize a year's worth of analysis of the data collected during the flyby of Triton in August 1989.

Nitrogen is now known to be Triton's major atmospheric constituent (*5*), with a surface pressure in the 10- to 20-μbar range (*6*) and surface temperature of 34 to 41 K (*7*). These conditions are consistent with N_2 ice being present on the surface and that it buffers the atmospheric pressure through sublimation on the summer hemisphere and condensation on the winter side. Additionally, CH_4 is present in the atmosphere (*5*) and on the surface (*3*), but its volatility is 10^4 times less than that of N_2. Analysis of color images shows areas that are bright but with a yellow to peach color; these are very likely regions in which CH_4 and N_2 frost have been partially converted to more complex organic compounds by cosmic ray and solar ultraviolet chemistry (p. 415).

Triton's surface-atmosphere system is thus remarkably like that of Mars, with N_2 taking the place of CO_2 and CH_4 replacing water. Key differences are that Triton has more extensive frost deposits, which appear to extend to the equator, a much smaller ratio of atmospheric mass to seasonal frost mass (*8*), and the presence of active geysers or plumes in the summer high latitude regions. Discovery of the plumes in Voyager images was one of the highlights of the encounter, and five of the reports cover the properties, origin, and atmospheric effects of this intriguing phenomenon.

At least four active plumes have been identified in the data; two are well documented in several images (p. 410). They consist of particulate material embedded in narrow columns of N_2 gas (a few kilometers in diameter) which rise to an altitude of roughly 8 km, where the material then trails westward. The nature of the particulates is unclear; they are darker than the surface ices beneath (p. 410), and may be entirely composed of hydrocarbon debris or a mixture of N_2 condensate and dark particulates. Some discrete cloud features are also seen, mostly at latitudes poleward of 30°S, and altitudes from 0 to 6 km (p. 440). While it is tempting to associate these with other, unseen plumes, these clouds are brighter than the plume material (p. 440). The clouds may be due to condensation processes unrelated to plumes, or they could represent a later stage in which the brighter condensate dominates the plume material.

The plumes are poleward of the current subsolar point on Triton (p. 410). This suggests that the mechanism by which they are generated is associated with absorption of solar visible radiation (p. 410). Two reports (pp. 424, 431) detail a novel mechanism for powering surface "geysers" or "fumaroles" to explain the plumes.

The high transparency of clean N_2 ice in the visible part of the spectrum creates a so-called "solid-state greenhouse" effect (p. 431). Here, sunlight is thermalized well below the surface of the N_2 layer, and relatively high opacity in the thermal infrared creates elevated temperatures below the surface of the N_2 ice. The result may be an overpressure of N_2 vapor, which could drive plume activity (p. 431). Eruption for long periods requires more energy than can be collected in an area equal to the plume column cross section. A model in which thermalized solar energy and N_2 gas flow laterally into plume regions from surrounding areas of the surface can explain plume lifetimes of a few Earth years (p. 424), a time scale estimated from the frequency of surface streaks near active plumes (p. 421). This "heat pipe model" requires a permeable layer of N_2 ice. The picture of geyser formation put forth in these reports depends on the size distribution of N_2 grains as well as their permeability.

The properties of the atmosphere may also be crucial in understanding the appearance of the plumes; their narrow columnar nature is suggestive of atmospheric processes that create positive buoyancy relative to the surrounding air. A model in which the plumes are akin to terrestrial dust devils (p. 435) is advanced. Strong solar heating of unfrosted hot spots on the surface, in the absence of geysering effects, may create regions of convective upwelling. The model is consistent with preliminary analysis of the radio occultation data (*6*), which imply that the atmospheric temperature is as much as 10 K higher than the temperature of the N_2 frost, 38 K. However, N_2 condensation is predicted to occur only at 20 km and above in this model. The presence of discrete clouds at lower altitudes (p. 440), if they are N_2, suggests a different interpretation of the radio data, in which atmospheric temperatures decrease from the surface value (*9*). In this case the plumes, powered initially by geysers or dry convection, gain neutral or positive buoyancy because of condensation within the column, which is warmer than the surrounding supersaturated atmosphere.

Several reports in this issue address the boundary conditions for global N_2 transport. Imaging data were analyzed to yield a global albedo or reflectivity of roughly 0.8 (p. 419). Analysis of the photopolarimeter data yields a significantly lower value of 0.6 (p. 429). Resolution of this discrepancy is crucial to constraining the details of global transport as well as the solid-state greenhouse effect.

Triton's surface shows evidence for substantial activity early in its history. The highest crater density seen is comparable to that of the lunar maria (p. 437), indicating resurfacing during the first 1/2 to 1 billion years. The size distribution and forms of certain craters on the surface suggest a volcanic origin (p. 437). Such volcanism, occurring in the water ice crust of Triton, is distinctly different from the geysering activity seen in the N_2 polar frosts and likely ended a long time ago. Nonetheless, it is suggestive of a period in Triton's history during which much of the CH_4 and N_2 now on the surface may have been outgassed from the interior.

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