Triton, Pluto, and the Origin of the Solar System

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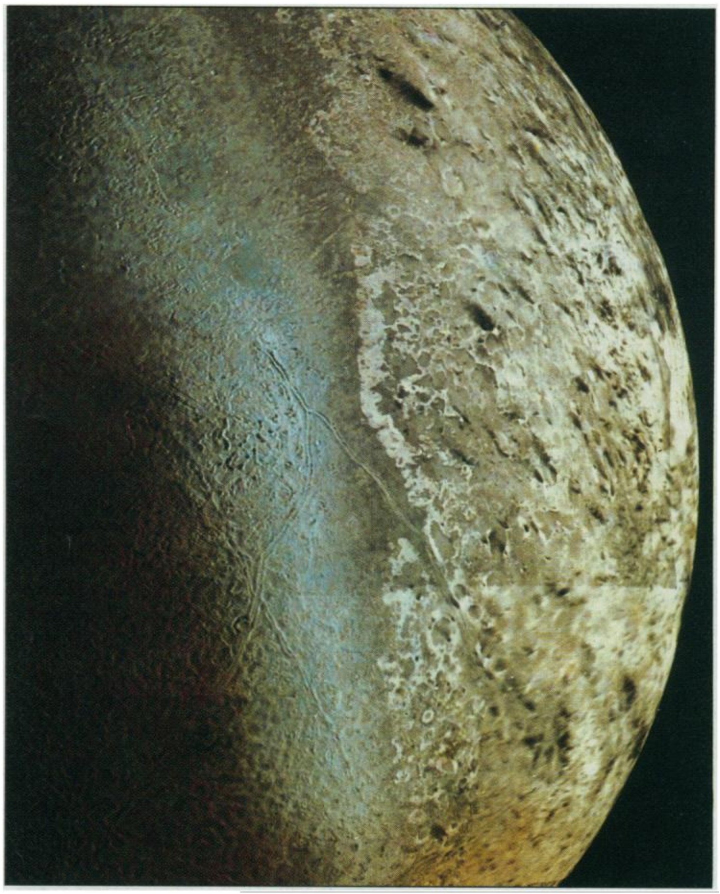
Star formation and evolution represent the fundamental processes of chemical evolution in galaxies, whereby lighter elements are progressively converted to heavier ones. Planet formation may represent a common by-product, and it is in the planets of our solar system that we search for chemical and physical clues to our beginnings. On pages 742 to 754 of this issue, four reports present just these kinds of clues about the composition of two icy bodies in the outer solar system (*1–4*).



Planetary puzzle. Montage of images of Triton's southern hemisphere from Voyager 2. Dark area on the left is the crust of the satellite, with exposed geologic features; the signature of water ice is presumably obscured by photochemical products of methane. The bright polar cap (to the right) is composed of primarily nitrogen ice with an admixture of methane and carbon monoxide. Carbon dioxide may be scattered over the icy and nonicy regions of the surface. The complexity of the pattern of light and dark regions makes interpretation of the Earth-based spectra, which include light from the entire visible hemisphere of Triton, a difficult and ill-constrained task. Ground-based studies suggest an equally complex surface for Pluto.

The story begins with ice-forming molecular species, such as methane, carbon monoxide, nitrogen, carbon dioxide, ammonia, and water, which are most readily observed in the giant molecular clouds that host the birth of stars and planets (*5*). The difference in chemical inventory between such clouds and our own solar system provides information on some of the physical processes associated with collapse of cloud cores to form protoplanetary disks.

In consequence, the composition of the solar system's most distant, and hence coldest, objects is of keen interest. Two of these, Triton (figure) and Pluto, provide uniquely valuable records of chemical inventories in the outer solar system. Pluto's composition reflects the molecular inventory in grains at 30 to 50 astronomical units (AU) from the forming protosun. Triton's retrograde path around Neptune argues for a capture from solar orbit at roughly 30 AU (*6*). Thus, two similarly sized solid bodies exist in the 30- to 50-AU region, albeit with distinct dynamical histories that hold in their chemical inventories information on conditions in the outer solar nebula.

Two indicators are used to infer the composition of these outermost solar system bodies. Direct spectroscopy of surfaces and atmospheres, mostly in the infrared part of the electromagnetic spectrum, is diagnostic of composition, provided one understands the degree to which these surficial ices are representative of the primordial bulk interior composition. Determination of the bulk density of an object yields a fair estimate of the so-called rock-to-ice ratio—where "rock" is defined to be silicate with an admixture of iron and the "ice" is presumed to be largely water—based on the thermodynamic stability of the latter and the large abundance of oxygen in so-called "solar" abundance material (which is representative of bulk elemental abundances in the sun and other stars of the same epoch).

The link between bulk density and molecular abundances comes through the fact that the carbon abundance is roughly one-half the abundance of oxygen in solar material, and carbon monoxide will tie up oxygen preferentially relative to water. Hence, the bulk density of an icy body is determined by how much carbon was locked up in the primordial gas as carbon monoxide (and secondarily carbon dioxide, which under relevant conditions is much less abundant than the monoxide). Molecular cloud gas is rich in carbon monoxide (*5*), and the same is predicted to be true for solar nebula gas; gas gravitationally bound to the forming giant planets would have been much denser than either medium and hence characterized by hydrogen-bearing molecules such as methane (*5, 7*). In the outermost solar nebula, where heating associated with the nebula was limited, the bulk gas composition likely was similar to that of the hot core regions of molecular clouds.

Complicating the issue is the abundance of carbon locked in involatile organic phases; it may represent half the carbon in interstellar clouds (*5*) and provides an additional contributor to the bulk density that renders nonunique the interpretation in terms of rock-ice ratios. Ignoring this problem for the moment and using the "traditional" carbon-to-oxygen ratio constructed from solar spectral observations by Anders and Ebihara (*8*), one predicts a silicate mass fraction of 0.7 for bodies formed from the solar nebula or molecular cloud gas and a number roughly half that for bodies formed in the gravitational sphere of influence of a giant planet.

The bulk density of Triton inferred from the close flyby of Voyager 2 (*9*) yields a rock mass fraction of roughly 0.7, fully consistent with an object formed from outer solar nebula gas. Although no spacecraft has yet visited Pluto, a rare and fortuitous series of eclipses and occultations ("mutual events") by Pluto and its moon Charon, observed from Earth in the late 1980s, enabled the radii of the two and the total mass to be determined; these yield a system rock mass fraction essentially identical to that of Triton (*10*).

On the basis of these numbers, the story

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seems remarkably simple: Triton and Pluto were objects formed from interstellar cloud–solar nebula material, their small size precluding significant loss of water or other volatiles after formation. Never mind that ground-based spectroscopy detected methane, the "wrong" molecular form of carbon, on both bodies and failed to see carbon monoxide (*11*).

This simple story failed completely when revised carbon and oxygen elemental abundances for the sun, published in 1989 and 1991 (*12*), brought the predicted rock mass fractions for solar nebula objects down to roughly 0.5 to 0.6. Planetary theoreticians have been loath to embrace the new abundances because they imply that both Triton and Pluto lost the same very large fraction of their water budgets to reach their present densities. Although these water losses are not impossible (*13*), the coincidence that both lost similar amounts in very different dynamical histories seems implausible.

A stellar occultation of Pluto in 1988 (*14*) provided the first evidence that the densities of Pluto and Triton are in fact dissimilar. The presence of methane in Pluto's atmosphere implies substantial solar heating and a predicted temperature profile that rises from some low surface value (30 to 50 K) to 100 to 110 K; the consequent atmospheric density profile, when applied to the stellar occultation data, forces the conclusion that the molecular weight of the gas is close to 28 and the atmosphere is dominated by nitrogen or carbon monoxide (*15*). Further analysis showed that the shape of the stellar occultation light curve could be reproduced by such a temperature-inversion model and that the radius of Pluto must be roughly 1200 km, 50 km larger than that given by the mutual events data (*16*).

A larger radius means a lower density for Pluto and a consequent rock mass fraction around 0.6, which implies much less (or even zero) loss of water ice early in Pluto's history. Importantly, it implies a qualitatively higher rock mass fraction for Triton than for Pluto. Pluto and Triton may have started out the same, but their early histories indeed dictated that their final ice contents were different.

In this context, the new discoveries of several volatile species on Triton (*1*) and Pluto (*2*) are of importance. The analysis of the highest resolution near-infrared spectra of these objects to date indicates that, on Triton, methane ice is present at 0.05% and carbon monoxide ice at 0.1% relative to nitrogen ice. All three of these ices are transported from pole to pole in response to the seasonal variation of sunlight; these ices may be mixed at the molecular or particulate level with each other. Carbon dioxide is also present but, at the low surface temperatures (40 K), would not sublimate seasonally and hence is probably separate from the other identified ices. On Pluto, methane and carbon monoxide ices weigh in at 1.5% and 0.5% relative to nitrogen ice. On neither body is water ice seen, not unexpected if sunlight converts atmospheric methane to dark organics that coat the surface and prevent all but the mobile, volatile ices from being detected.

The presence of carbon monoxide lends some credence to the density analysis given above, but what of the methane? In fact, methane is present in molecular clouds (*5*), and given its lower volatility compared with carbon monoxide, one expects it to dominate on preplanetary grains and hence in objects made up of such grains. The high nitrogen abundance relative to carbon monoxide on Triton and Pluto is a problem, however. In no chemical inventory associated with either molecular cloud or solar nebula models does nitrogen dominate over carbon monoxide. In fact, this abundance anomaly strongly suggests early outgassing of both Triton and Pluto, followed by substantial loss of carbon monoxide (*17*). Molecular nitrogen is more volatile than carbon monoxide, however; thus, it would be lost as well, and, hence, the nitrogen we see today on the two bodies must have been produced later in the histories of Pluto and Triton from a much less volatile nitrogen-bearing molecule. Interstellar and cometary abundances (*5*, *18*) indicate that ammonia or similar reduced forms of nitrogen were relatively abundant in the source material of the outer solar system. The inability to detect ammonia today on Triton and Pluto is not unexpected, given that water ice is not detected either; both are too involatile to avoid burial by a meter-thick detritus of methane photolysis.

Major uncertainties remain. In particular, the physical processes that determine the state of the surface ices are only beginning to be studied (*3*), yet they may have an important effect on spectral band shapes (*4*). There is as yet no prospect that Earth-based spectroscopy has reached its limit on these very dim objects: With improved resolution comes better information on the physical state of the ices. A proposed flyby mission to Pluto, which could be completed by the end of the next decade, would allow regional mapping of the ices. The efforts are well worth it if the end result is a firm understanding of how these cold icy bodies have chemically evolved from the primordial reservoirs that breed new planetary systems.

References and Notes

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