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# Complex Organic Solid Matter in the Outer Solar System

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Complex organic molecular material of non-biological origin is found in abundance in the interstellar dust in our Galaxy, and is also detected in other galaxies. Some of this material was incorporated into the solar nebula and is now found in some Solar System bodies. While some pre-solar organic material has been preserved, synthesis of complex organics in planetary atmospheres and on icy surfaces has been in progress for the entire age of the Solar System. Refractory organic solids have proven difficult to detect by traditional spectroscopic techniques, and their presence is usually inferred from the low albedo and (often) red color of the surfaces of small bodies in the outer Solar System (OSS). Color in complex organic molecules, such as polymers and polycyclic aromatic hydrocarbons, is caused by absorption in the UV and visible spectral regions arising from electronic transitions connected primarily with C-C and C-O bonding. In particular, large hydrocarbon molecules with conjugated (alternating pairs of double and single) C-C bonds have color because the electronic transitions of the de-localized pi electrons extend into the visible spectral region; the longer the conjugated chain, the further is the extension to longer wavelength, with the result that especially large molecular material appears black.

Rigorous scattering models of the diffuse spectral reflectance in the visible and near-infrared wavelength region of OSS bodies are calculated using the complex refractive indices of the known or suspected component materials and with plausible assumptions about the physical structure of the surface. This technique depends on the availability of measured refractive indices of ices, minerals, and solid organic materials, such as tholins; with the work of investigators around the world, the library of such data continues to grow. Tholins are complex, refractory mixtures of heteropolymers, polycyclic aromatic hydrocarbons, nitrogen heterocycles, and other structures that readily form when mixtures of gases (or ices) are subjected to irradiation by charged particles or UV light (or both). They are identified with the photochemical atmospheric hazes on Titan, Triton, and Pluto, and in the atmospheres of the giant planets. Small amounts of tholins have a strong coloring effect on ices on the surfaces of various planetary satellites.

The principal results of spectral reflectance modeling studies with organic materials in combination with minerals, ices, and elemental carbon are:

1. Low-albedo and reddish colored asteroids in the Main Belt and in the Jovian Trojan populations may contain organic solids, but such material is not required because their spectra can also be matched with mixtures of common igneous rock-forming minerals.

2. The extremely red members of the Kuiper Belt and Centaur populations cannot be matched with plausible minerals and ices, and require organic solids (e.g., tholins) to achieve fits to their spectra.

3. The very red Centaur object 5145 Pholus shows absorption bands that are well modeled with water and methanol ices, while the red color is modeled with a tholin, elemental carbon, and the mineral olivine; all of these components are common in comets.

4. The low-albedo, red-colored leading hemisphere of Saturn's satellite Iapetus is well modeled with a nitrogen-rich tholin, elemental carbon, and water ice.

5. The relatively high-albedo icy satellites of the giant planets, and Pluto have weak red coloration that can be modeled with small amounts of tholins; such organic material may have formed in situ by particle and UV irradiation of the ices, or it may have precipitated from a tenuous atmosphere, or it may be acquired from exogenous sources.

Complex organic matter is emerging as the third major component of small Solar System bodies, together with ices and minerals. The chemical characterization of this material and the identification of its sources present continuing challenges to investigators.