THE COLORS OF 486958 2014 MU₆₉ ("ULTIMA THULE"): THE ROLE OF SYNTHETIC ORGANIC SOLIDS (THOLINS).

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Tholins as coloring agents on planetary surfaces:

Many Solar System bodies exhibit colors in the visible spectral region that range from yellow to red to brown. From color alone, and in the absence of diagnostic spectral bands, the composition of the chromophore(s) cannot be unequivocally determined, and many candidate materials have no strong absorption bands at λ<3μm wavelength. Some minerals are naturally colored, and others acquire color by space weathering processes that abstract iron from Fe- and Ni-bearing minerals and deposit nanometer-size blebs on regolith grains [1]. In cases of icy surfaces, the red or brown colors are interpreted as refractory complex organic solids synthesized by the photolysis or radiolysis of carbon-bearing components, particularly CH₄ ice [2,3]. In laboratory simulations of astrophysical settings, these complex organics are called refractory residues [4,5], while those synthesized in simulations of planetary environments are called tholins. In terms of composition, chemical structure, and origin, the definition of tholins is broadly encompassing. The colors of the Kuiper Belt object Ultima Thule (UT) emerging from a preliminary analysis of data returned from the New Horizons spacecraft within a few days of the flyby event of January 1, 2019, are described in [6,7] and compared with comets. Both of these investigations note that when all the data are available for analysis, the explanation for the red color UT will probably require a coloring agent in the form of a tholin made in simulated planetary conditions in the laboratory (see [8]).

Tholins are relevant both to atmospheres and surfaces of planetary bodies. They are created in the laboratory and are broadly characterized as relatively refractory (i.e., stable at T>100 K) organic complexes produced by energetic processing of simpler carbon-bearing and other molecules in the gas or solid phase. Tholins are disordered polymer-like materials made of repeating chains of linked subunits and complex combinations of functional groups. Khare et al., [9,10] showed that colored particles are made by UV photolysis of gaseous CH₄ and N₂ in simulated Titan atmosphere conditions. While the complex refractive indices of this "Titan tholin" published by Khare et al. [11] have been used in modeling spectra of the surfaces of many planetary bodies, the analytical techniques available in the laboratory at the time the tholin was synthesized were insufficient to reveal the full details of its complex structure (e.g., [9]). A more complete structural analysis of Titan tholins made over a range of gas pressures relevant to Titan's atmosphere showed that the quantity and size of aromatic ring compounds increases with decreasing pressure, and the abundance of saturated C-H bonds is less at low pressures, with a concomitant increase in N-H bonds [12,8]. Additionally, the C/N ratio is greater at high pressure because N is incorporated into the tholin less efficiently. Tholins formed at low gas pressures have clusters of N-substituted polycyclic aromatic compounds connected by C- and N- branched networks. The pressure also affects the degree of N-substitution in both aromatic and aliphatic structures. In terms of color, tholin films formed at low pressure show stronger UV/Vis absorptions and are reddish-brown, in contrast to yellow-colored tholins formed at higher pressure. The efficacy of using gas-phase tholins to model solid surfaces can be questioned, but the absence of optical constants for tholins made in conditions considered more appropriate has resulted in their use as the best available data. In addition, complex organics occurring as a component (together with minerals and ices) of the bulk composition of Kuiper Belt objects may reflect formation in a gas-rich environment in the nascent solar nebula. In terms of modeling planetary surfaces, we note that the particular radiative transfer model in which the optical constants of tholins are used can be a major factor in the interpretation of the results, because values for the derived relative concentrations, particle sizes and other parameters vary significantly [13].

Tholins that appear to be more directly related to the surfaces of planetary bodies that are mostly or entirely ice-covered and have extremely tenuous atmospheres (e.g., Pluto) or no atmosphere (e.g., Charon) can be synthesized in the laboratory by the energetic processing of ices of various compositions. Early ice experiments [3] produced tholins containing carboxylic acids, urea, HCN and other nitriles, alcohols, ketones, aldehydes, and amines, with other unidentified
planetary satellites, and comets, and the role of tholins can be modeled. See Fig. 2.


Acknowledgements: This work was funded by NASA. We thank NASA, the Deep Space Network, JPL, KinetX Aerospace, the entire present and past New Horizons team, and the Gaia and HST missions for making the flyby of MU69 successful.

Figure 1. Natural color and texture of Pluto ice tholin from [15], made by electron radiolysis of an ice mixture of N$_2$:CH$_4$:CO (100:1:1). Striations are scratches in Al foil substrate on which the ice was deposited. Scale bar 1 mm.

Figure 2. Ultima Thule from New Horizons. The color from a lower resolution Multispectral Visible Imaging Camera (MVIC) image was overlaid on a Long Range Reconnaissance Imager (LORRI) image taken on 1 Jan 2019, 05:01:47 UTC.