PHOTOMETRIC PROPERTIES OF ICES IN THE KUIPER BELT OBSERVED BY NEW HORIZONS.

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Introduction: Robust determinations of the scattering properties of ices in the Solar System can be obtained from reflectance measurements that span the full range of viewing and illumination angles. These include incidence and emission angles from 0° to 90° and solar phase angles from 0° to 180°. Such data sets are often impractical or impossible to acquire, even in laboratory settings, yet scattering properties can be constrained by observations that span the widest range of viewing angles. The large heliocentric distances at which Kuiper belt objects (KBOs) and dwarf planets orbit the Sun preclude observations of them at solar phase angles $\alpha > 2°$ from Earth or Earth-orbit. Since 2007, NASA's New Horizons spacecraft that made the first close exploration of the Pluto system and a KBO [1-2] has used its LOng Range Reconnaissance Imager (LORRI) [3-4] to observe dozens of KBOs and dwarf planets [5-7] from unique vantage points in the Kuiper belt at solar phase angles from 8° to 153°. When combined with Earth-based, low phase angle observations, these 'high phase' observations from New Horizons have enabled construction of the most complete solar phase curves for KBOs and dwarf planets to date (Fig. 1).

Phase Curves of Icy Surfaces: Using the extended phase angle coverage provided by the New Horizons observations, we fit the Hapke photometric model [8] to the phase curves of several KBOs from all dynamical classes and dwarf planets. These fits are described by sets of parameters that include the single scattering albedo, macroscopic surface roughness, and directional scattering properties in addition to parameters that describe the phase curve near opposition at small phase angles. Many of these objects have ices on their surfaces and these fits enable evaluation of their photometric properties and comparison with those of ices on surfaces elsewhere in the Solar System. Some have the more volatile CH_4, N_2, and C_2H_6, ices while others exhibit less volatile H_2O and CH_3OH ices. The surface of cold classical KBO Arrokoth has CH_3OH ice but no H_2O ice [9]. The expanded range in phase angles enables the evaluation of phase integrals q and Bond albedos ($A=pq$) for objects whose geometric albedos p are known. Figure 1 shows all phase curves of KBOs, dwarf planets, and satellites observed by New Horizons, normalized to 0 at opposition to facilitate comparison of their shapes. Three groupings emerge, highlighted by the grey region in Figure 1: shallow, intermediate, and steep phase curves that correspond to surface ice composition.

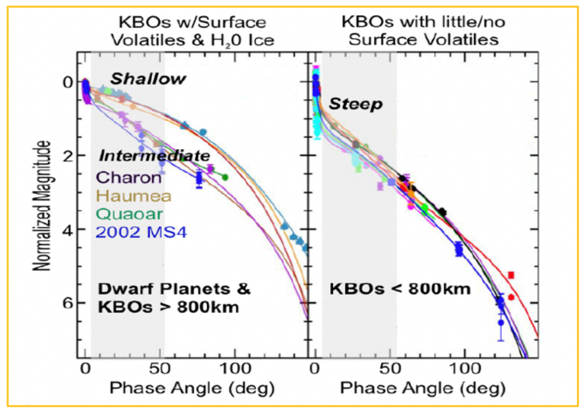

Figure 1: Solar phase curves of KBOs, dwarf planets, and satellites Charon and Triton from Earth-based and New Horizons LORRI observations. All data at phase angles $\alpha < 2°$ are from Earth-based observations and all data at phase angles $\alpha > 2°$ are from New Horizons (circles) and Voyager 2 (triangles). All phase curves are normalized to magnitude 0 at $\alpha = 0°$ to enable direct comparison of their shapes. All lines are the solar phase curve fits to the Hapke photometric model [8]. Error bars represent one standard deviation from the mean reflectance in all images at each visit.

Conclusions and Future Work: New Horizons' observations of a variety of the surfaces of KBOs and dwarf planets at intermediate and high phase angles have revealed differences in their scattering properties that correlated with the volatility of KBO surface ices. Objects with highly volatile ices (CH_4, N_2, C_2H_6) have shallow phase curves, large phase integrals ($q > 0.8$), and correspondingly high Bond albedos. KBOs and dwarf planets that do not have hypervolatile-dominated surfaces, but do have significant amounts of water ice on their surfaces have steeper phase curves, smaller phase integrals ($0.4 < q < 0.6$), and correspondingly smaller Bond albedos. KBOs that do not have volatile ices on their surfaces have the steepest solar phase curves with small phase integrals (q<0.4) and low Bond albedos.

During its second extended mission, New Horizons plans to acquire additional observations of Eris, Haumea, Makemake, at even higher phase angles to constrain further the scattering properties of ices on their surfaces. New Horizons also plans to observe smaller, still more distant KBOs, particularly those from the scattered disk population, at high phase angles. These include KBOs discovered in a ground-based search for New Horizons targets using the Hyper Suprime-Cam on the Subaru Telescope [10].

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