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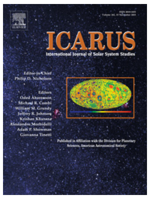

Ices on Charon: Distribution of H_2O and NH_3 from New Horizons LEISA observations

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ABSTRACT

Charon, the largest moon of Pluto, appeared as a fairly homogeneous, gray, icy world to New Horizons during closest approach on July 14th, 2015. Charon's sub-Pluto hemisphere was scanned by the Ralph/LEISA near-IR spectrograph providing an unprecedented opportunity to measure its surface composition. We apply a statistical clustering tool to identify spectrally distinct terrains and a radiative transfer approach to study the variations of the 2.0-µm H_2O ice band. We map the distribution of the ices previously reported to be present on Charon's surface, namely H_2O and the products of NH_3 in H_2O. We find that H_2O ice is mostly in the crystalline phase, confirming previous studies. The regions with the darkest albedos show the strongest signature of amorphous-phase ice, although the crystalline component is still strong. The brighter albedo regions, often corresponding to crater ejecta blankets, are characterized by larger H_2O grains, possibly an indication of a younger age. We observe two different behaviors for the two absorption bands representing NH_3 in H_2O. The 2.21-µm band tends to cluster more in the northern areas compared to the ~2.01-µm band. Both bands are present in the brighter crater rays, but not all craters show both bands. The 2.21-µm band is also clearly present on the smaller moons Hydra and Nix. These results hint that different physical conditions may determine the appearance or absence of these two different forms of NH_3 in H_2O ice in the Pluto system. We also investigate the blue slope affecting the spectrum at wavelengths longer than ~1.8 µm previously reported by several authors. We find that the slope is common among the objects in the Pluto system, Charon, the smaller moons Nix and Hydra, and the darkest terrains on Pluto. It also characterizes the analog ice tholin obtained from irradiation of Pluto-specific materials (a mixture of N_2, CH_4, and CO ices) in the laboratory. Our modeling results show that Pluto ice tholins are widespread almost uniformly on Charon suggesting a common distribution possibly part of the original reservoir of materials that made up Charon. This was irradiated over the years to yield the gray color characteristic of Charon today. On top of the 'primordial' Pluto ice tholin there is the redder component produced by irradiation of the CH_4 provided by Pluto's atmospheric contribution as illustrated by Grundy et al. (2016a).

1. Introduction

During the closest approach of the New Horizons spacecraft to the Pluto system on July 14th 2015 Charon, the largest satellite of Pluto, appeared as a gray-colored icy world to the Long Range Reconnaissance Imager (LORRI) camera. LORRI Images revealed a surface with terrains of seemingly different ages and a moderate

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degree of localized albedo variations. Charon's normal reflectances range from 0.2 to 0.73 (Buratti et al., 2016) showing little correlation with topographic and geological surface features.

According to modeling by Canup (2011), Charon and Pluto would have formed from a grazing collision of partially differentiated/undifferentiated bodies consisting of a uniform rock-ice core and a thin ice mantle. Furthermore, Canup also suggests the possibility that Nix and Hydra could have aggregated from debris originating from the collision. The alternative (e.g., Lithwick and Wu, 2008) has the small moons originating from material captured into the Pluto's orbit after the Pluto-Charon forming event. The compositions and densities of Pluto's satellites are critical to determining the mechanisms at play in their formation. For Charon, detailed measurements have not been available until recently (Weaver et al., 2016) and are becoming available for the other moons only now with New Horizons data (Cook et al., 2016).

Prior to the last decade the detailed determination of Charon's surface composition had been elusive. Ground-based observations of Charon are scarce due to its close proximity to Pluto. In the period between 1985 and 1990, because of the position of Pluto and Charon on the ecliptic, the two bodies alternately eclipsed one another during the diurnal cycle of 6.4 days, allowing observations of 'pure' Pluto and therefore determination of a residual spectrum that corresponded to Charon's (Buie et al., 1987). From these observations it was determined that Charon's surface was rich in water ice, a fact also inferred by Marcialis et al. (1987) making use of broad band photometry of Pluto eclipsing Charon and comparing it to that of the combined system. Dumas et al. (2001) were able to extract and model Charon's spectrum in Hubble Space Telescope data and reported presence of crystalline H_2O ice on both its hemispheres and $NH_3 \cdot H_2O$ on its leading side.

Buie and Grundy (2000), Brown and Calvin (2000) also observed and modeled Charon independently of Pluto. Making use of the Hubble Space Telescope Near Infrared Camera and Multi-Object Spectrometer (HST/NICMOS), Buie and Grundy (2000) obtained 1.4–2.5 µm spectra of Charon only, without contamination of Pluto, at four longitudinal locations. Their models indicated the preponderant presence of H_2O in crystalline form varying weakly with longitude and showing slightly stronger absorption bands on the leading hemisphere. While they discussed the presence of NH_3 and its hydrates previously suggested by Brown and Calvin (2000), they could not present any hard evidence for it. However, they were the first to put forth the presence of a contaminant whose absorbance increased with wavelength longer than ~2 µm. To satisfy the need to model Pluto's spectrum without a Charon contamination, Buie and Grundy (2000) derived notional optical constants for the 'blue slope material' and published a standard spectrophotometric model to be used to remove Charon's contribution from observations of the unresolved system. The ultimate goal of this exercise had been to determine the presence of water ice on Pluto. This objective was later achieved unambiguously by making use of high spatial resolution observations by New Horizons (Cook et al., 2017; Protopapa et al., 2017; Schmitt et al., 2017).

Dumas et al. (2001) (leading hemisphere) and Verbiscer et al. (2007) (trailing hemisphere) reported ammonia hydrate on Charon. Charon's sub and anti-Pluto hemispheres were also observed and modeled by Cook et al. (2007). Cook et al. (2007) attributed the band at ~2.21 µm to ammonia in varying hydration states over the surface. The presence of ammonia in conjunction with H_2O in its crystalline form prompted Cook et al. (2007) to suggest cryovolcanism as a favored mechanism of resurfacing the satellite.

More recently, Merlin et al. (2010) also modeled the spectrum of Charon and reported presence of ammonia species along with H_2O ice in both crystalline and amorphous phases. Their data taken during two successive nights were approximately 60° apart in longitude. The second night, corresponding to the anti-Pluto hemisphere, shows a slightly lower (~5%) continuum in the 2.2–2.3-µm region and shallower depth of the 2.21-µm band. The difference is within the errors making it difficult to infer whether the slope is different. They assume that the slope is constant and to model it they adopt, analogous to Buie and Grundy (2000), an *ad hoc* component, featureless, and present at the 12% level in their best fit. Merlin et al. (2010) also reported a strong 1.65-µm band indicative of crystalline H_2O ice. Most recently, an analysis of ground base data by DeMeo et al. (2015) further supported variations in band depth and center of the 2.21-µm band, an indication of variability of ammonia hydrate over Charon's surface.

Here we present an analysis of Charon spectral images obtained by the New Horizons Linear Etalon Imaging Spectral Array (LEISA) instrument during closest approach yielding detailed mapping of water ice, ammonia products, and a still unidentified material that best fits the blue slope characteristic of Charon spectral signature.

2. Data description

New Horizons observed Charon at high spatial resolution (4.87 km/pixel) from a distance of 81,257 km at mid-observation with the LEISA imaging spectrometer on July 14, 2015 at 10:30:32 (UTC). LEISA is part of the Ralph instrument (Reuter et al., 2008) and offers a spectral resolving power of 240 in the wavelength range 1.25–2.5 µm, and 560 in the range 2.1–2.25 µm.

LEISA data are acquired while rotating the spacecraft slowly around the *Z*-axis so as to sweep LEISA's field of view across the target scene in the wavelength dispersion direction. Images are read out and recorded at a frame rate corresponding to the scan rate, such that a new image is recorded each time the scene has shifted by approximately one pixel on the focal plane. The spacecraft attitude and motion are controlled by hydrazine thrusters fired automatically whenever the spacecraft's attitude drifts beyond a specified deadband limit. The resulting impulses impose a slight zig-zag motion as the instrument pointing bounces back and forth within the cross-track deadband. Although these corrections are predominantly perpendicular to the scan direction, they are not perfectly orthogonal to it, so they also cause small changes in the scan rate.

Integrated Software for Imagers and Spectrometers (ISIS, https://isis.astrogeology.usgs.gov) software provided by the United States Geological Survey (USGS) uses the spacecraft attitude history along with its LEISA camera model and the reconstructed spacecraft trajectory to accurately determine where each LEISA pixel falls on the target body as a function of time. The ISIS software was adopted to perform an orthographic projection of the LEISA data to a sphere at the target's size and location relative to the spacecraft as of the mid-time of each scan.

This reprojection was done to a target grid with a spatial scale of 2 km/pixel at the center of the object, a higher resolution than the native LEISA pixel scales. The intention of this sub-sampling was to minimize degradation of spatial information as a result of the nearest neighbor re-sampling. A LEISA cube when compared to the much higher resolution LORRI base map projected to the same geometry showed mismatches of the order of a few LEISA pixels, but consistency across LEISA wavelengths. An average correction was performed by globally shifting the LEISA data using the ISIS "translate" routine. Higher order corrections were then done using the ISIS "warp" routine, based on a control network constructed using features that were recognizable in both LEISA and LORRI data.

These corrections resulted in LEISA cubes estimated to be geometrically accurate to a little better that a single LEISA pixel. The geometry is not perfectly static during the course of each LEISA scan due to the spacecraft motion along its trajectory at approximately 14 km/s relative to the Pluto system. This Charon scan