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Composition of Pluto's small satellites: Analysis of *New Horizons* spectral images

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ABSTRACT

On July 14, 2015, NASA's *New Horizons* spacecraft encountered the Pluto-system. Using the near-infrared spectral imager, *New Horizons* obtained the first spectra of Nix, Hydra, and Kerberos and detected the 1.5 and 2.0 µm bands of H_2O-ice on all three satellites. On Nix and Hydra, *New Horizons* also detected bands at 1.65 and 2.21 µm that indicate crystalline H_2O-ice and an ammoniated species, respectively. A similar band linked to NH_3-hydrate has been detected on Charon previously. However, we do not detect the 1.99 µm band of NH_3-hydrate. We consider NH_4Cl (ammonium chloride), NH_4NO_3 (ammonium nitrate) and $(NH_4)_2CO_3$ (ammonium carbonate) as potential candidates, but lack sufficient laboratory measurements of these and other ammoniated species to make a definitive conclusion. We use the observations of Nix and Hydra to estimate the surface temperature and crystalline H_2O-ice fraction. We find surface temperatures < 20 K (<70 K with 1-σ error) and 23 K (< 150 K with 1-σ error) for Nix and Hydra, respectively. We find crystalline H_2O-ice fractions of 78^{+12}_{-22}% and > 30% for Nix an Hydra, respectively. *New Horizons* observed Nix and Hydra twice, about 2–3 hours apart, or 5 and 25% of their respective rotation periods. We find no evidence for rotational differences in the disk-averaged spectra between the two observations of Nix or Hydra. We perform a pixel-by-pixel analysis of Nix's disk-resolved spectra and find that the surface is consistent with a uniform crystalline H_2O-ice fraction, and a ~ 50% variation in the normalized band area of the 2.21 µm band with a minimum associated with the red blotch seen in color images of Nix. Finally, we find evidence for bands on Nix and Hydra at 2.42 and possibly 2.45 µm, which we cannot identify, and, if real, do not appear to be associated with the ammoniated species. We do not detect other ices, such as CO_2, CH_3OH and HCN.

1. Introduction

Five satellites are known to orbit Pluto: Charon, Styx, Nix, Kerberos, and Hydra, in order of increasing distance from Pluto. Charon ($r = 606 \pm 1$ km; Nimmo et al., 2017), known since 1978 (Christy and Harrington, 1978), has been well studied from the Earth (*i.e.*, Buie and

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Grundy, 2000; Sicardy et al., 2006; Cook et al., 2007; Merlin et al., 2010; Holler et al., 2017) as well as *New Horizons* (Stern et al., 2015; Grundy et al., 2016; Dalle Ore et al., 2018). Hubble Space Telescope observations found (Weaver et al., 2006; Showalter et al., 2011; 2012) the remaining smaller ($r \lesssim 50$ km) and irregularly shaped (Weaver et al., 2016) satellites during the construction and cruise phases of *New Horizons*. Learning about these small satellites from Earth has been difficult and limited to mainly their orbital properties (*i.e.*, Showalter and Hamilton, 2015) because of their size and faintness. *New Horizons* provided several *in situ* observations which have broadened our understanding of the small satellites and thus the Pluto system.

New Horizons images of the small satellites revealed their shapes and sizes (Weaver et al., 2016). Kerberos and Hydra are possibly bilobate, similar to comet 67P/Churyumov-Gerasimenko (Massironi et al., 2015), while the other satellites appeared oblong. Several craters could be seen on the surfaces of Nix and Hydra, the more favorably observed targets, indicative of ancient surfaces (Robbins et al., 2017). Color images revealed a red blotch surrounding an apparent impact crater on Nix, while Hydra was neutral in comparison. *New Horizons* also made near-infrared spectral observations of Nix, Hydra, and Kerberos, but did not observe Styx spectroscopically.

In this paper, we present the first near-infrared spectra of Kerberos, Hydra, and Nix from *New Horizons*. H_2O-ice is present on these objects, and it is confirmed to be in the crystalline phase for the latter two objects. We find an additional absorption band at 2.21 µm on Nix and Hydra, which we attribute to an ammoniated species. We use the spatially and temporally resolved spectra of Nix to search for variations in H_2O-ice crystallinity and the 2.21 µm band depth. We compare our results to Charon (Brown and Calvin, 2000; Buie and Grundy, 2000; Dumas et al., 2001; Cook et al., 2007; Verbiscer et al., 2007; Merlin et al., 2010; DeMeo et al., 2015; Holler et al., 2017) and to several other objects in the outer Solar System where the 2.21 µm band may be present.

2. Observations

NASA's *New Horizons* spacecraft encountered Pluto and its system of satellites on July 14, 2015, after a 9.5-year-long trip across the solar system. *New Horizons*' closest approach to Pluto was nearly simultaneous to its closest approach to the other satellites because of the near "pole-on" orientation of the system. *New Horizons* obtained images and spectra of Pluto's small satellites using LORRI (LOng Range Reconnaissance Imager; Cheng et al., 2008) and Ralph (Reuter et al., 2008). LORRI is the monochromatic imager used for long distance observations, and Ralph (Reuter et al., 2008) is a dual-channel instrument composed of a color imager and near-infrared spectrograph. Ralph's color imager, MVIC (Multi-spectral Visible Imaging Camera), has blue (0.40-0.55 µm), red (0.54-0.70 µm), near infrared (0.78-0.98 µm), a narrow CH_4-band (0.86-0.91 µm) and two panchromatic (0.40-0.98 µm) filters. Ralph's near-infrared spectrograph, LEISA (Linear Etalon Imaging Spectral Array), covers the 1.25 to 2.50 µm spectral range at a resolving power ($\lambda/\Delta\lambda$) of 240, and the 2.10 to 2.25 µm spectral range at a resolving power of 560 (Reuter et al., 2008). LEISA obtained the first-ever spectra of the small satellites: Nix, Hydra, and Kerberos. We list the observations used in this work in Table 1.

Encounter plans included observations of Nix and Hydra because they were discovered in 2005 (Weaver et al., 2006). At the time of closest approach, Nix was nearest the spacecraft, and thus it was observed at higher signal-to-noise (SNR) and spatial scales than the other small satellites. The discovery of Kerberos and Styx (Showalter et al., 2011; 2012), however, happened much later. Encounter plans included several "TBD" observations for satellites discovered during cruise and approach phases, but the location of Styx and Kerberos relative to *New Horizons* during the encounter was not optimal. As a result, *New Horizons* did not observe Styx using LEISA.

3. Data reduction

In the following section, we shall describe some of the steps performed to reduce the data. With a few exceptions, we follow the data reduction techniques as described in Cook et al. (2018) and we refer the reader there for additional details. We provide a summary of similar steps and describe those steps that are unique to reducing this dataset in greater detail.

The standard data reduction steps to all LEISA data include applying the flat field, flagging bad pixels, and converting the data from DN to reflectances, *I/F*, the ratio between the radiance received by the instrument and the incident solar irradiance. The LEISA data pipeline handles most of these steps, but we perform additional steps to remove a background pattern noise before building the image cube and extracting the signal. Each step described below is designed to maximize signal-to-noise of the final spectrum.

3.1. Pattern noise cleanup

In every LEISA frame, there exists a background pattern noise that is likely due to something cyclic in the instrument electronics. We characterize the pattern noise as an increase of signal running (usually) diagonal across the field, regardless of wavelength (*i.e.,* frame row) and it is unique in each LEISA frame. Since the target's location within the field sweeps across all wavelengths (*i.e.,* frame row), a simple median average of several LEISA frames does not sufficiently remove the pattern noise without losing wavelength precision. We take advantage of the fact that the pattern noise repeats in each quadrant of the LEISA frame. When the target is faint or small, as was the case of all small satellite observations except the best Nix observation, a median of each quadrant can be used to make a template for the pattern noise. If a target is bigger or brighter, as in the case of the best Nix observation, it must be masked out before taking a median of each quadrant with only a minor impact on accuracy, typically a small background level offset within in the masked out region.

3.2. Building an image cube

In Cook et al. (2018), we examined image cubes that were built using United States Geological Survey's (USGS) software Integrated Software for Imagers and Spectrometers (ISIS, https://isis.astrogeology.usgs.gov/). This software, however, was not ideal for irregular shaped targets lacking the accurate shape model that would be required for map projection. Instead, we rely on a simpler code we built in IDL (Interactive Data Language) and neglect the spatial information.

Our code takes the LEISA frames and converts them into an image cube. Each LEISA frame combines spatial information along the *x*-direction and spatial-spectral information along the *y*-direction (scan direction, or along-track direction) where each row of a LEISA frame is a different wavelength. The scan rate is set such that the object should move one row between LEISA frames. Using the housekeeping telemetry for the pointing and motion of the spacecraft, we disentangle the spatial and spectral information and remove motion distortion from the data to build our image cube. The image cube has two spatial dimensions and one independent spectral dimension. Our code only performs integer pixel shifts when constructing the image cube to preserve the measured flux in each spatial element. However, integer pixel shifts can also serve to blur the resolution by up to a 1/2 pixel. When thrusters fire, they may cause the along-track motion to change. If the along-track motion increases, then single row wide gaps will appear in the image cube and traverse the field of view as one moves along the spectral dimension of the final image cube.

3.3. Optimal extraction on a cube

When dealing with low SNR spectra, as in the case of Hydra and