COMPOSITION OF PLUTO'S SMALL SATELLITES: ANALYSIS OF *NEW HORIZONS* SPECTRAL IMAGES J. C. Cook[1], R. P. Binzel[2], D. P. Cruikshank[3], C. M. Dalle Ore[3,4], A. Earle[2], K. Ennico[3], W. M. Grundy[5], C. Howett[6], D. J. Jennings[7], A. W. Lunsford[7], C. B. Olkin[6], A. H. Parker[6], S. Philippe[8], S. Protopapa[9], D. Reuter[7], B. Schmitt[8], J. A. Stansberry[10], S. A. Stern[6], A. Verbiscer[11], H. A. Weaver[12], L. A. Young[6], the New Horizons Surface Composition Theme Team and the Ralph Instrument Team, [1]Pinhead Institute, Telluride, CO, [2]Massachusetts Institute of Technology, Cambridge, MA, [3]NASA Ames Research Center, Moffat Field, CA, [4]SETI Institute, Mountain View, CA, [5]Lowell Observatory, Flagstaff, AZ, [6]Southwest Research Institute, Boulder, CO, [7]NASA Goddard Space Flight Center, Greenbelt, MD, [8]Institut de Planétologie et Astrophysique de Grenoble, Grenoble, France, [9]University of Maryland, College Park, MD, [10]Space Telescope Science Institute, Baltimore, MD, [11]University of Virginia, Charlottesville, VA, [12]John Hopkins University, Applied Physics Laboratory, Laurel, MD. (jasoncampbell-cook@gmail.com)

Introduction: Orbiting Pluto are 5 satellites: Charon, Styx, Nix, Kerberos and Hydra, in order of increasing distance from Pluto. Charon ($r \sim 600$ km) has been studied from the Earth [1, 2, 3] as well as from *New Horizons* [4, 5]. The remaining satellites are much smaller ($r \lesssim 50$ km), irregular in shape [6] and were discovered by Hubble Space Telescope during the construction and cruise of *New Horizons* [7, 8, 9]. Learning about these satellites from Earth is difficult. On July 14, 2015, *New Horizons* made its closest approach to the Pluto system. Among its many tasks were spectroscopic observations of Nix, Hydra and Kerberos.

Observations: Using the Ralph [10] instrument, *New Horizons* successfully obtained images and spectra of Pluto's small satellites. Ralph is a dual channel instrument with MVIC (Multi-spectral Visible Imaging Camera), the visible color imager, and LEISA (Linear Etalon Imaging Spectral Array), the near infrared spectrograph. LEISA covers the spectral range 1.25 to 2.50 μm at a resolving power ($\lambda/\Delta\lambda$) of 240, and 2.10 to 2.25 μm at a resolving power of 560. *New Horizons* obtained 1 LEISA scan of Kerberos at 394,000 km away, 2 LEISA scans of Hydra at 240,000 and 370,000 km away and 2 LEISA scans of Nix at 60,000 and 162,000 km away. Styx was not observed with LEISA.

Methodology: In addition to the standard LEISA pipeline to flat field and flag bad pixels, our analysis includes a step for removing an electronic noise pattern that changes in each LEISA frame. We take advantage of the fact that the pattern repeats in each quadrant of the frame. By masking out the target and median stacking each quadrant we produce a fairly reliable estimate of the background noise pattern.

After the data are cleaned, we remove motion distortion. Thrusters may be fired during the scan if the target reaches a deadband. We use the known spacecraft trajectory to correct for its motion. Finally, we build a cube. This step does not resample the data, it just reorders the pixels such that each plane of the cube is a single wavelength.

We examine the disk integrated spectrum of each target and the disk resolved spectrum of Nix using Hapke theory. We assume a simple model with an intimate mixture of amorphous H_2O-ice [11], crystalline H_2O-ice [12] in three size ranges, a Triton tholin [13] and a Pluto tholin [14, 15]. H_2O-ice is assumed to be 50 K.

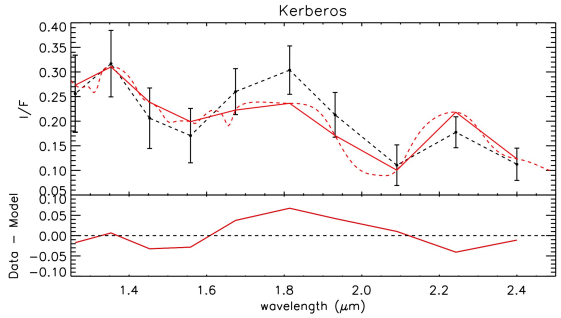

Figure 1: The spectrum of Kerberos (black points) resampled down to 10 points to increase signal-to-noise. Two absorption bands appear in the spectrum near 1.5 and 2.0 μm. A Hapke model (red solid line) containing H_2O-ice best matches the data. A model spectrum at the native LEISA sampling is shown as the red dashed line. The residual (data-model) is shown below the spectrum.

Results: Kerberos is the smallest and most distant satellite *New Horizons* observed with LEISA. We extract the signal of Kerberos following the description of optimal extraction [16] modified for a cube. Fig. 1 shows the spectrum and evidence for H_2O-ice.

We extract Hydra's spectrum from both LEISA scans and show the weighted average spectrum in Fig. 2. The spectrum shows evidence for crystalline H_2O-ice and an absorption band at 2.2 μm that is likely related to NH_3. CH_4, which shares a band at 2.2 μm, has more bands that are not seen in the data and its presence is unfavored by the Hapke models.

Nix was the most favorable small satellite for observing with *New Horizons*. Fig. 3 shows the spectrum and LEISA image from closest approach. The disk is resolved by ∼130 pixels. The spectrum shows crystalline H_2O-ice and a band at 2.2 μm. The 2.2 μm band is deeper on Nix than on Hydra, or the most NH_3-rich places on Charon [5]. Analysis of the disk resolved spectra show little variation in the 2.2 μm band depth.

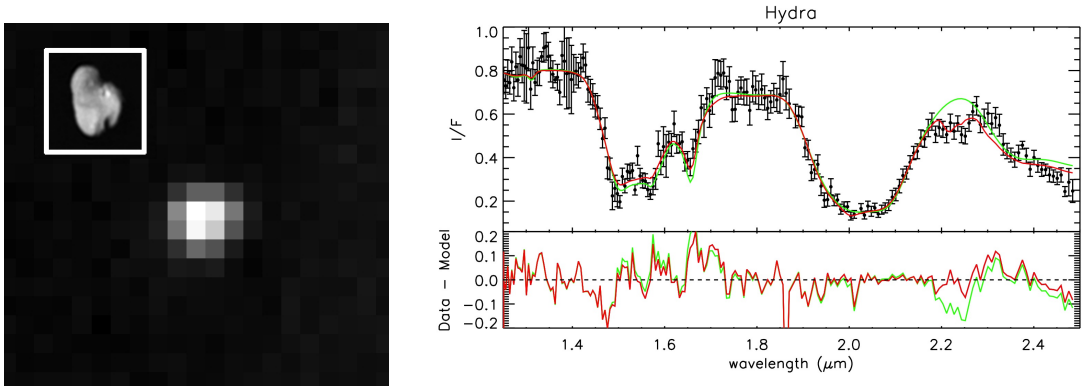

Figure 2: (Left) A LORRI (inset, upper left) and LEISA image of Hydra at closest approach. (Right) The spectrum of Hydra (black points) is a weighted average of the two LEISA observations. The spectrum clearly shows absorption bands at 1.5, 1.65, 2.0 and 2.2 μm. We attribute the first three bands to crystalline H_2O-ice and the latter to NH_3-hydrate. A Hapke model containing NH_3-hydrate (red line) agrees more closely with the observations than a NH_3-free model (green line). Residuals for both cases are shown below the spectrum.

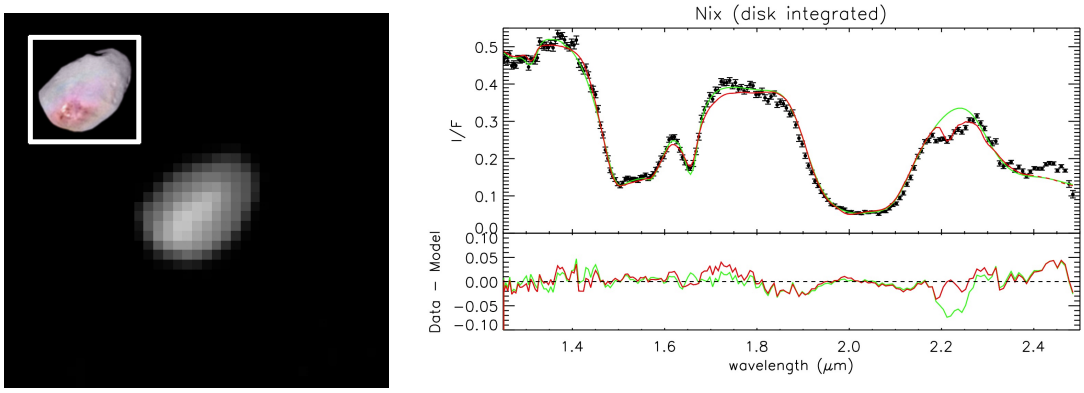

Figure 3: (Left) A LORRI + MVIC enhanced color (inset, upper left) and LEISA image of Nix at closest approach. (Right) The disk integrated spectrum of Nix (black points) from the closest approach to Nix. The spectrum clearly shows absorption bands at 1.3, 1.5, 1.65, 2.0 and 2.2 μm. We attribute the first four bands to crystalline water ice, and the later to NH_3-hydrate. A Hapke model containing NH_3-hydrate (red-line) agrees more closely with the observations than a NH_3-free model (green line). Residuals for both cases are shown below the spectrum.

Discussion & Conclusion: This work reports on the composition of Kerberos, Hydra and Nix. These observations show H_2O-ice is present on all three. The greater signal-to-noise of the Nix and Hydra spectra show that the H_2O-ice is in the crystalline phase via the 1.65 μm band. We also find an absorption band at 2.2 μm. The strength of the band appears to be uniform over the disk of Nix. This band is likely due to an NH_3-H_2O-ice mixture or possibly other NH_3-enriched material, such as those identified on Ceres [17].

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