THE IDENTIFICATION AND DISTRIBUTION OF PLUTO'S NON-VOLATILE INVENTORY.

J. C. Cook[1], D. P. Cruikshank[2], C. M. Dalle Ore[2,3], K. Ennico[2], W. M. Grundy[4], C. B. Olkin[1], S. Protopapa[5], S. A. Stern[1], H. A. Weaver[6], L. A. Young[1] and the New Horizons Surface Composition Theme Team, [1]Southwest Research Institute, 1050 Walnut St, Suite 300, Boulder, CO 80302, [2]NASA Ames Research Center, [3]SETI Institute, [4]Lowell Observatory, [5]University of Maryland, [6]John Hopkins University, Applied Physics Laboratory (jc-cook@boulder.swri.edu)

Introduction: Prior to the arrival of *New Horizons* at Pluto, the detection of H_2O-ice on its surface had evaded scientists. Most ground based spectra before about 2000 relied on moments of excellent seeing in order to resolve Pluto from H_2O-ice-rich Charon [1, 2], which are separated by no more than 0.9″. Since then, adaptive optics and space based spectra have been helpful in obtaining separate spectra of Pluto and Charon [3, 4]. However, unlike in the case of Pluto's analog Triton [5], no observational effort has been successful in obtaining an unambiguous detection of H_2O-ice on Pluto [6]. Its non-detection suggests that H_2O-ice must be a small fraction of Pluto's observable surface.

Observations: On July 14, 2015, NASA's *New Horizons* spacecraft flew past Pluto at about 12,000 km from the surface. Using the Ralph [7] instrument, *New Horizons* successfully obtained images and spectra necessary to map the composition and distribution of Pluto's surface. 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. Some of the LEISA observations returned to Earth to date include two scans taken at approximately 100,000 km from Pluto and at a spatial scale of 6 to 7 km/pixel. [8] will discuss the mixing ratio of N_2 and CH_4 across Pluto. Our work will discuss the distribution of non-volatile ices such as H_2O.

Evidence for H_2O-ice: Observations returned in July 2015, shortly after closest approach, included images from LORRI, the LOng Range Reconnaissance Imager. It revealed mountain ranges several km high along the western perimeter of Sputnik Planum[1]. Based on the size of the mountains and the strength of Pluto's known composition (mainly N_2-ice), it is arguable that the ice is much too soft to form the observed mountains. Instead, H_2O-ice is stronger, and therefore a more plausible material. If this is the case, then H_2O-ice might be detected in small, isolated regions on Pluto. Spectroscopic evidence for H_2O-ice, however, would have to wait until at least September 2015, when LEISA scans of Pluto where scheduled to return.

Methodolgy: In order to find H_2O-ice, [9] used a model spectrum of crystalline H_2O-ice and calculated the Pearson correlation coefficient (ρ) for every spectrum on Pluto. The value of ρ is bound between –1 and 1. A value of 1 indicates a perfect correlation, and –1 an anti-correlation. Values near zero indicate little correlation. We show in Fig. 1 the map produce from calculating the correlation function. This map is shown with a linear stretch covering the range $-0.3 < \rho < 0.9$. This stretch reveals the seam running diagonally from the northwest to southeast where the two LEISA scans were merged. Regions off the limb of Pluto are set to zero and gives a sense of the zero-level.

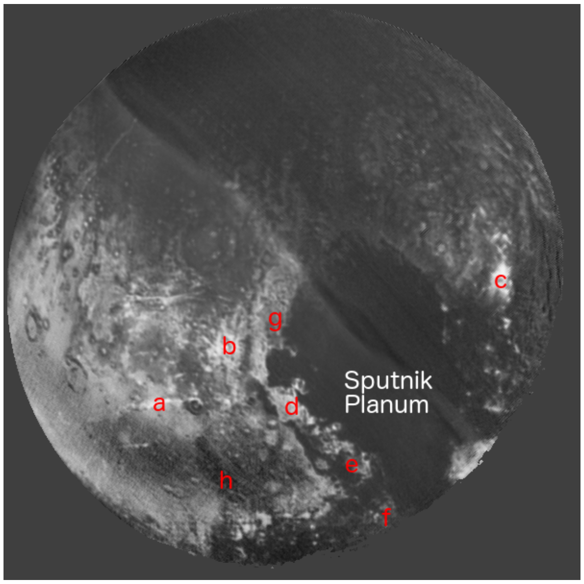

Figure 1: The H_2O correlation map produced by correlating every observed spectrum with a model crystalline H_2O-ice spectrum. We use a linear stretch from –0.3 (black) to 0.9 (white). The seam between the two LEISA scans is apparent running diagonally northwest to southeast. North is up, east is to the right. We indicate Sputnik Planum and regions *a*-*h*: (a) Virgil Fossa, (b) Viking Terra, (c) Pulfrich Crater, (d) Baré Montes, (e) Hillary Montes, (f) Norgay Montes, (g), al-Idrisi Montes and (h) central Cthulhu Regio.

Figure 1 shows there is little correlation with H_2O-ice in Sputnik Planum. The correlation also decreases as one moves from southern latitudes to northern latitudes. Cthulhu Regio appears to have varying amounts of H_2O ice and this region contains some of the lowest correlation seen on Pluto. This figure also clearly illustrates that there are isolated regions on Pluto where

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[1] all place names discussed here are informal

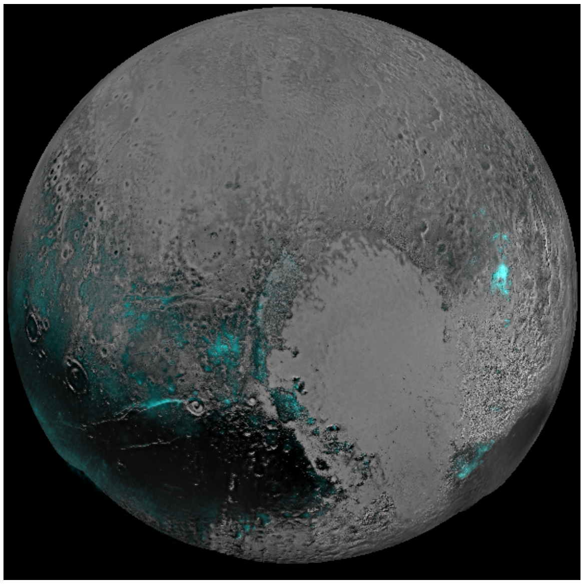

Figure 2: Here we show the panchromatic map from LORRI overlaid with the correlation map shown in blue. We use a cubic stretch on the H_2O correlation map to highlight regions that have a high correlation. North is up, east is to the right.

H_2O-ice is strongly correlated with the observations. We show the H_2O correlation map overlaid with the LORRI basemap in Fig. 2. The correlation map has a cubic stretch to highlight likely H_2O-ice-rich regions.

Analysis: We show in Fig. 3 the spectra (black dots) from 8 selected regions. We select regions that are highly correlated with H_2O-ice (spectra a-d), the mountain ranges (spectra e-g) and where H_2O-ice and CH_4-ice are absent (spectrum h).

Examination of spectra a-d shows a strong asymmetry in the 2.0 μm band of H_2O-ice. [10] noted a similar asymmetry in spectra of Iapetus and several other Saturnian satellites. They compared lab spectra of sub-μm grain H_2O-ice and found good agreement with models when Rayleigh scattering in included. We modify our Hapke code to account for Rayleigh scattering to obtain the results (red curves) in Fig. 3.

Spectra a to d have a sub-μm H_2O-ice fractions between 15 and 45% with most of the grains diameters at about 0.1 μm. Spectra e to g have a sub-μm H_2O-ice fraction between 10 and 25% with similar grain diameters. Spectrum h has a 25% sub-μm content, but with 10 nm grain sizes, significantly smaller than the other spectral regions. We find the region longward of $\sim$2.3 μm in h best matches C_3H_8-ice. Since we lack optical constants for many candidate hydrocarbons, we do not take this as a definitive detection of C_3H_8-ice.

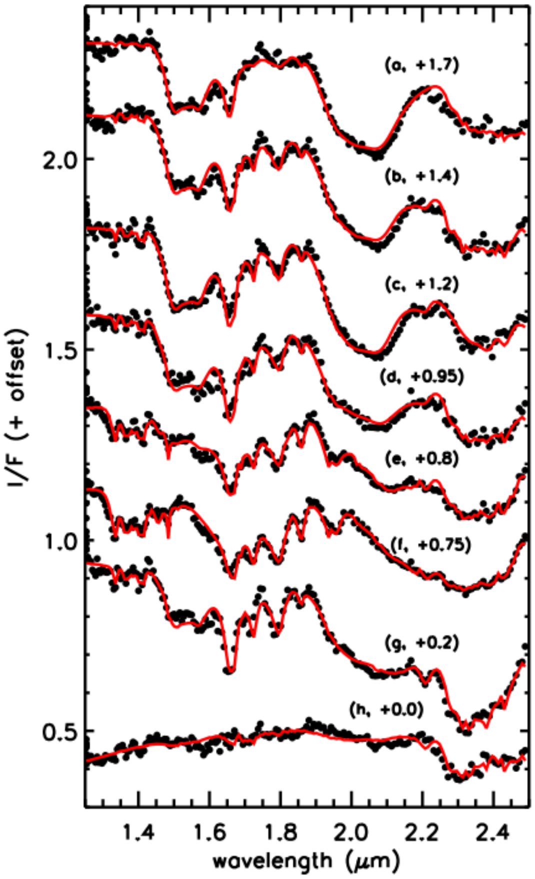

Figure 3: The spectrum of eights regions of interest. Informal names for regions a-h are listed in Fig. 1

Discussion & Conclusion: We show that there are regions on Pluto with fine grained H_2O-ice with a diameter $\sim$0.1 μm. In regions where the 1.5 and 2.0 μm bands are the strongest, the fine grained H_2O-ice may be up to 45% of the observed signal. H_2O-ice appears to be in the crystalline state, at about 55 K. There is no evidence for amorphous ice. We also show that heavy hydrocarbons such as C_3H_8 are likely present in Cthulhu Regio.

The presence of fine grain H_2O-ice on Pluto is in contrast to preliminary work on Charon, where the grains appear much larger [11]. In the Saturnian system, fine grained ice is thought to be evidence for ring material settling on icy satellites, or the cryovolcanic activity seen on Enceladus. The reason for fine grain H_2O-ice on Pluto, but not Charon, is unknown.

References: [1] Brown, M. E., et al. (2000) *Science* 287:107. [2] Dumas, C., et al. (2001) *Astron. J.* 121:1163. [3] Buie, M. W., et al. (2000) *Icarus* 148:324. [4] Cook, J. C., et al. (2007) *ApJ* 663:1406. [5] Cruikshank, D. P., et al. (2000) *Icarus* 147:309. [6] Grundy, W. M., et al. (2002) *Icarus* 157:128. [7] Reuter, D. C., et al. (2008) *Space Sci. Rev.* 140:129. `arXiv:0709.4281`. [8] Protopapa, S., et al. (2016) LPSC #47. [9] Grundy, W. M., et al. (2016) *Science*. [10] Clark, R. N., et al. (2012) *Icarus* 218:831. [11] Dalle Ore, C. M., et al. (2015) vol. 47 of *DPS* #210.27.