INVESTIGATIONS OF THE ORIGINS OF PLUTO'S SURFACE DARK MATERIALS: COMPOSITIONAL MAPPING OF CTHULHU MACULA AND SPUTNIK PLANITIA.

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Introduction: The dwarf planet and Kuiper Belt object Pluto exhibits volatile nitrogen (N_2), methane (CH_4), and carbon monoxide (CO) ices at its surface, as well as non-volatile water (H_2O) ice, and non-ice organic refractory materials [1]. The spatial distribution of these surface materials is associated with the surface geologic processes on the planet and seasonal interactions with its tenuous atmosphere driven by climate dynamics [2]. Thus, mapping the distribution of surface compositions and their relationship with the geology is important for understanding the volatile transport mechanism on the dwarf planet [3-4]. Here we present new spectral maps of the surface composition of the eastern part of Cthulhu Macula (CM) and Sputnik Planitia (SP) on Pluto, generated from the analysis of near-infrared (NIR) *New Horizons* spectral data using an unsupervised machine-learning clustering technique.

Method: We have analyzed spectral images from the Linear Etalon Imaging Spectral Array (LEISA) instrument onboard the *New Horizons* spacecraft to map the surface composition of CM and SP. LEISA is a hyperspectral imager in NIR wavelengths (1.25–2.5 μm). For CM, we used the highest spatial resolution image scene (P_LEISA_HIRES), while for SP, we used two next-best spatial resolution image scenes (P_LEISA_Alice_2a and P_LEISA_Alice_2b). The images were calibrated using the mission data pipeline processing routine and further processed following Emran et al. [3].

We used the principal component reduced Gaussian mixture model (PC-GMM) to map these two areas on Pluto. The PC-GMM is an unsupervised machine learning technique that first employs a principal component analysis (PCA) to reduce data dimension, followed by an application of the Gaussian mixture model (GMM). The same approach has successfully been utilized to map the surface compositions on Pluto at the global scale [3]. The optimal numbers of clusters in both cases were determined using the Akaike information criterion (AIC) and Bayesian information criterion (BIC) values and their gradients.

Results: We have classified the CM into seven classes (Fig. 1), and the SP into six classes (Fig. 3). We have also extracted the average I/F spectra from all pixels of each class for CM (Fig. 2) and SP (Fig. 4). CH_4 ice has several characteristic absorption bands at NIR wavelengths. N_2 and CO ices can be identified using weak absorption bands at 2.15 μm and 1.58 μm, respectively (see [3-4] for details). For the convenience of interpretation, in Figs. 2 and 4, each I/F spectrum corresponding to a surface clustering unit is labeled as C followed by the assigned unit number.

Cthulhu Macula (CM): Although visible images (MVIC or LORRI) returned from the *New Horizons* spacecraft revealed very little diversity in the color (mostly red) of the surface in the CM area, the compositional mapping resulting from our analysis of NIR images exhibits a diversity in compositions at the local scale and displays contrast with visible images.

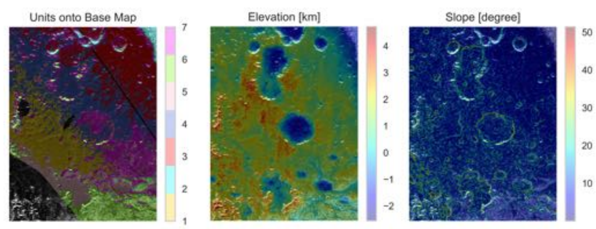

Fig. 1: *(Left)* Distribution of the surface compositional units within CM obtained using the PC-GMM clustering technique; *(Center)* Elevation and *(Right)* Slope maps.

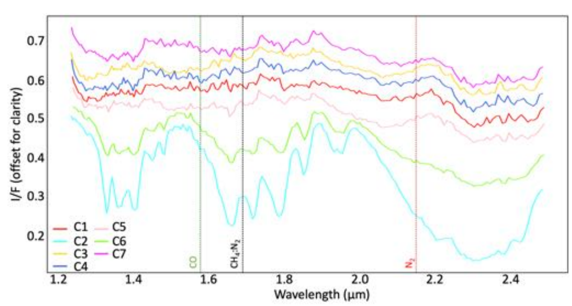

Fig. 2: Average I/F spectra extracted from the CM surface units. The colors of the spectra correspond to the colors of the surface units in Fig. 1. The dashed vertical lines indicate N_2 (red, 2.15 μm), CO (green, 2.58 μm), and CH_4:N_2 absorptions (black, 1.69 μm).

Interestingly, the north-facing walls of some of the craters in CM (cyan color unit in left panel of Fig. 1, C2 in Fig. 2) exhibit the presence of a CH_4-rich— perhaps pure—ice signature. Other North-facing walls also have CH_4 ice (green color unit, C6) but the cyan color unit (C2) is different as it has very strong CH_4 absorption bands compared to the green unit. In any case, the presence of CH_4 ice at the north-facing walls highlights a seasonal effect of CH_4 condensation [5].

The mountains in the CM area, e.g., Pigafetta and Elcano Montes (C6, green color unit in left panel of Fig. 1), exhibit the presence of CH_4 ice mixed probably with a small fraction of H_2O ice – indicative of a thin veneer of CH_4 lying above the H_2O ice bedrock. A similar result has also been reported by Emran et al. [3]. This demonstrates that mountains in that area are physically supported by H_2O ice. As mentioned above a similar compositional deposit is seen on the north-facing walls of some craters— meaning similar nature of composition as the deposits on top of Pigafetta and Elcano Montes (green color unit, C6). The other surface units in CM show similar compositions with slight variations in the composition of the organic refractory material.

Sputnik Planitia (SP): From a compositional viewpoint, the main part of SP consists of three different surface units with varying abundances of N_2 and CO ices. The central region of SP (C6, light green unit in left panel of Fig. 3) exhibits spectral features that indicate the highest abundances of volatile N_2 and CO. However, the northern (C4/blue unit) and southern (C1/magenta unit) portions of SP have slightly lower abundances of N_2 and CO. Based on this evidence (also echoing Emran et al. [3]) we assert that an active sublimation of N_2 may happen in northern and western SP, which is then atmospherically deposited in the central part of SP — in agreement with the volatile transport model in [6]. This model [6] confirmed that sublimation likely only occurs in the northern and western part (C4/blue unit) of SP at the time of the New Horizon's flyby in 2015. The lower latitudes are likely dominated by condensation (C6/green unit), according to models [6]. The magenta unit (C1) region is likely dominated by condensation due to its location (far south, receiving little sunlight) but condensation may involve different amounts of contaminants (haze, methane, etc.) and other processes may be at play to affect the ice composition. However, this remains to be investigated in detail.

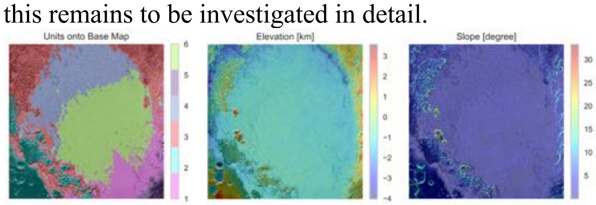

Fig. 3: *(Left)*: Distribution of the surface compositional units within SP obtained using the PC-GMM clustering technique. *(Center)* Elevation and *(Right)* Slope maps.

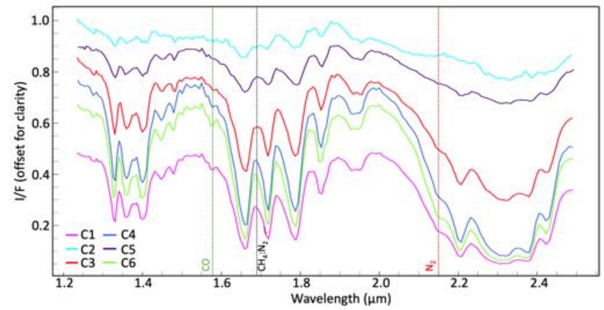

Fig. 4: Average I/F spectra extracted from the SP surface units (offset for clarity). The colors of the spectra correspond to the colors of the surface unit in Fig. 3. The dashed vertical lines indicate N_2 (red, 2.15 µm), CO (green, 1.58 µm), and CH_4:N_2 absorptions (black, 1.69 µm).

Discussion: Mapping the distribution and spectral characterization of surface compositions on CM and SP provides an understanding of the geographic distribution of ices at the local scale. The results also help in understanding the volatile sublimation and transport mechanism on Pluto. The spectral results from this study can be modeled with radiative transfer models [7] and laboratory spectral data [8] for a quantitative assessment of the distribution of the volatile and organic refractory materials on the dwarf planet, which will pave the way for an improved understanding of the surface materials found on Pluto [9].

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References:
[1] Stern A. et al. (2015). Science 350, aad1815. https://doi.org/10.1126/science.aad1815.
[2] Moore et al. (2016). *Science* 351, 1284–1293. https://doi.org/10.1126/science.aad7055
[3] Emran A. et al. (2023). *PSJ, [accepted]*.
[4] Cruikshank D. P. et al. (2021) in In *Pluto System After New Horizons*, pp 165-193.
[5] Bertrand et al. (2020). *Nature comm.* 11(1), 1-7.
[6] Bertrand et al. (2018). *Icarus*, 309, 277-296.
[7] Cook, J. C., et al. (2023) 54th *LPSC*.
[8] Sciamma-O'Brien, E., et al. (2023a) 54th *LPSC*.
[9] Sciamma-O'Brien, E., et al. (2023b) 54th *LPSC*.