MIXING AND PHYSICAL STATE OF PLUTO'S SURFACE MATERIALS FROM NEW HORIZONS LEISA SPECTRO-IMAGES.

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Introduction: Several decades ago near infrared observations of Pluto established that there is solid CH_4 on Pluto's surface as well as CO and N_2, with the later dominating the ices abundances. The red slope evidenced in the visible observations pointed to the presence of tholins-like compounds. Since then a number of visible, near and mid-infrared disk-integrated observations with increasing spectral resolution have tried to identify new molecules, to better constrain the relative abundance of the ices and other materials and to understand their longitudinal distribution as well as possible temporal evolutions.

The physical state and abundance of the volatile ices N_2, CH_4 and CO have been studied by [1] who evidenced the presence of two methane phases, one highly diluted in solid beta-nitrogen (together with CO) and another CH_4-rich phase that is either present as spatially segregated patches or as a segregated layer on top of the diluted phase, or both. The longitudinal spatial distribution of Pluto's material has been studied using rotation resolved observations and monitoring over almost 2 decades [2]. In July 2015 the New Horizons mission reached Pluto and its satellite system and recorded a large set of data. First results on the composition and distribution of ices from preliminary analysis of the Ralph instrument have been reported in [3]. In this abstract we analyze the first high spatial resolution spectro-image from LEISA instrument covering half of the illuminated disk with a resolution of 6.2 km/pixel.

Exploration of data with PCA analysis: In order to assess the spectral content of the data set and its spatial distribution we run a Principal Component Analysis. The result of this analysis is about 8 Principal Component axes (PC) containing significant physical information (Fig. 1). The first PC dominated by noise and instrumental effects is only PC#7, which assess the high quality of the data, even at the current stage of the data calibration.

[1]All surface feature names mentioned in this abstract are informal.

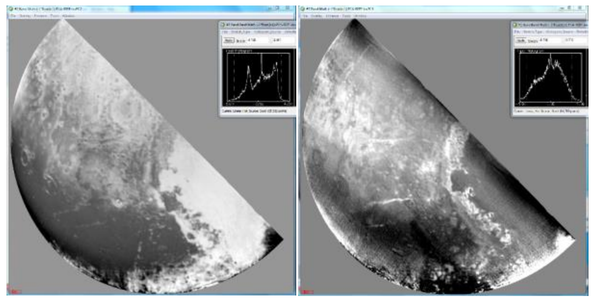

Figure 1: Two of the main principal components of the PCA: #2 and #3 that will be attributed to CH_4-containing ice and H_2O ice respectively.

De-noised cube reconstruction: Another step necessary before analysis is to assess that most of the physically significant signal is contained in the first axes. We reconstructed a de-noised spectro-image cube by an inverse PC rotation on a limited number of axes (16). The result is a conservation of most of the spectral energy (except in the N_2 band) and a clear enhancement of the sharpness of the spectro-image due to the removal of most of the noise and instrumental effects (Fig. 2).

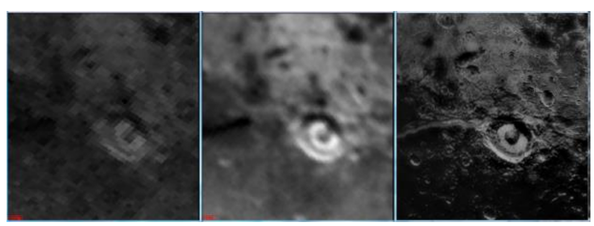

Figure 2: Comparison between raw (left) and PCA de-noised LEISA images (center) at 2.00 µm and the LORRI image convolved at 10 times better resolution than LEISA (right). The image is centered on the Elliot crater[1].

Analysis of the PC: We analyzed the occurrence and spatial distribution of the different principal materials present on the surface of Pluto, i.e. N_2-rich, CH_4-rich, and H_2O ices as well as the dark reddish material, using the Principal Components as well as specific spectral indicators and their correlations. It is demonstrated that each of these materials are well described, but only qualitatively, with one or two PC. The assignements are summarized below:

- PC #1 = albedo * photometric behavior
- PC #2 = CH_4-containing ices
- PC #3 & #9 = H_2O ice
- PC #4 = CH_4-rich ice
- PC #5 = ‘dark reddish material’
- PC #6 & #8 = N_2 and/or CO ices ? - noisy

Study of the material mixing lines: The state and degree of mixing of all these materials are assessed using specific correlations between these PC and/or specific spectral indicators that best display the mixing lines of these materials.

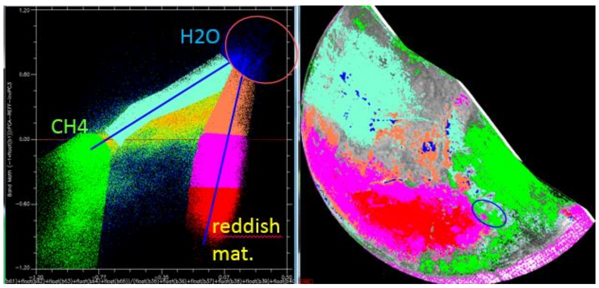

Figure 3: H_2O-CH_4 and H_2O-reddish material mixing lines. *Left*: correlation plot of PC#3 vs 2µm H_2O band depth with 6 classes (colors). The lines visualize the trends. *Right*: Location of the six classes on Pluto. The blue ellipse show the sharp CH_4 – reddish material boundary.

The H_2O ice – reddish material mixing line

This mixing line in Figure 3 is progressive and continuous from the purest dark reddish material, that appears to contain no visible trace of water ice (pure end-member), to the purest H_2O. This mixing line appears as a spatial mixing of the two non-volatile components (at the surface temperature of Pluto), most probably the reddish material covering H_2O ice, as expected from the atmospheric production of this organic material [4].

No CH_4 ice – reddish material mixing line

Figure 3 clearly shows the absence of a mixing line between the purest reddish material and CH_4-containing ice. The distribution of these materials on the map shows very sharp transitions between CH_4-containing ice and this non-volatile materiel. This points out an exclusion process which may originate from the higher temperature reached by the dark-reddish material that should lead to the fast sublimation of any CH_4-rich or N_2-rich ices possibly condensed on it during the night or the long polar night (southern polar regions).

The CH_4-rich – N_2-rich ices mixing line

The correlation between PC#4 (global CH_4) and PC#2 (CH_4-rich ice) allowed us to separate the CH_4-rich ices from the N_2-rich:CH_4 ices (Figure 4) [5]. However there is a mixing line that connect both physical states of CH_4, pointing to an evolution process that transforms one type of ice to another. Due to the large difference in volatility [6] the most probable process is the progressive sublimation of N_2 (and CO) from N_2-rich:CH_4:CO mixtures and the formation of either a N_2-rich – CH_4-rich binary phase mixture at the surface of the N_2-rich ice layer, or an upper CH_4-rich ice crust as we demonstrated experimentally [7]. Such a segregation process may led to the formation of a CH_4-rich layer that may get optically thick at the wavelengths of the N_2 band and thus hide its presence.

The H_2O ice – CH_4:N_2 ices mixing lines

Two relatively separated mixing lines of H_2O with CH_4-containing ices occurs (Figure 4): one with CH_4-rich ices and another with N_2-rich:CH_4 ices. It seems thus that both CH_4-rich ices and N_2-rich ices can be spatially segregated at the pixel level with the water ice bedrock. A sublimation process should be found to explain this behavior.

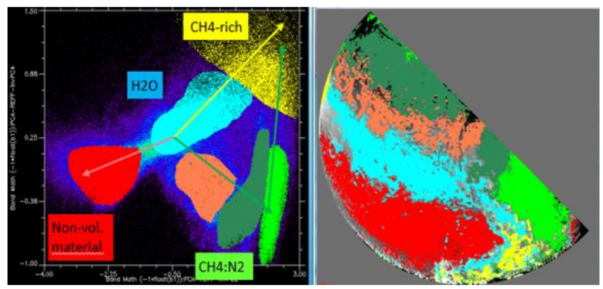

Figure 4: Distribution of pure and diluted CH_4. *Left*: correlation plot of PC#4 vs PC#2 with a classification in 6 classes (colors). The lines visualize the trends. *Right*: Location of the six classes on Pluto.

Conclusion: The qualitative spatial distributions and mixing modes of the main materials constituting the surface of Pluto have been derived. This allows to better constrain the surface representation necessary to model the spectra for the derivation of quantitative information on the surface composition and texture [8,9]. The occurence, or not, of mixing lines between two materials also provide interesting information to constrain the evolution processes of the different ices and non-volatile materials at the surface of Pluto.

Acknowledgments: This work was supported by NASA's New Horizons Project. B. Schmitt, S. Philippe and E. Quirico acknowledge the Centre National d’Etudes Spatiales (CNES) for its financial support.

References: [1] Douté S. et al. (1999), *Icarus*, 142, 421-444. [2] Grundy W. M. et al. (2013), *Icarus*, 223, 710-721 [3] Grundy W. M. et al. (2016) *Science*, submitted. [4] Cruikshank et al. (2016) *LPSC 47.* [5] Philippe et al. (2016) *LPSC 47.* [6] Fray N. & Schmitt B. (2009) PSS, 57, 2053-2080. [7] Stansberry et al. (1996) PSS, 44, 1051-1063. [8] Protopapa S. et al. (2016) *LPSC 47.* [9] Cook et al. (2016) *LPSC 47.*