CH_4 SNOWLINE ON THE MOUNTAINS OF PLUTO DURING NASA'S NEW HORIZONS FLYBY. A. Emran[1], V.F. Chevrier[1], and C. Ahrens[1]. [1]Center for Space and Planetary Sciences, University of Arkansas, 332 N Arkansas Ave. Fayetteville, AR 72701 (alemran@uark.edu).

Introduction: The surface of Pluto is primarily composed of methane (CH_4), nitrogen (N_2), carbon monoxide (CO), and photochemically formed organic hydrocarbon called tholins with a trace amount of ethane (C_2H_6) and water-ice (H_2O) [e.g., 1-4]. CH_4 was first detected by ground-based techniques [1] and the subsequent studies (based on the observations of Pluto's changing viewing geometry) found its heterogeneous distribution on the surface of the dwarf planet [e.g., 5]. The flyby mission of NASA's New Horizons (NH) spacecraft also confirmed the surface heterogeneity of the dwarf planet [6-8]. While the top of the mountains, e.g., Pigafetta and Elcano Montes, Cthulhu Macula, and eastern Tartarus Dorsa, shows a high concentration of methane, the lower altitudes are mostly materially depleted [Fig. 1; 9].

Albeit N_2 and CH_4 precipitate simultaneously in lower elevations, the temperature and atmospheric pressure at higher altitudes only allow CH_4 to condense on the higher elevations [10]. Abundant pure methane deposits are detected at an elevation above 2 km from spectral analysis of Multispectral Visible Imaging Camera (MVIC) images [9]. This is because of the temperature inversion at the Plutonian lower atmosphere the makes it too warm for N_2 to precipitate while CH_4 can. Determination of methane snowline on mountains, thus, would provide an excellent clue for the lower atmospheric condition, volatile transport mechanism, and the climatic environment involved and its spatial differences. Though the existing literature explained condensation of CH_4 at higher altitude [e.g., 9 and references therein], however, the methane snowline in the mountains has not been delineated yet. This study determines the lower snowline (elevation) limit of CH_4 capped mountains from statistical analysis (2D kernel density estimation) between the elevation and CH_4 band depth maps. Though snowline depends on the climatic and seasonal dynamics and its delineation needs time-series analyses, we determine the lower snowline elevation on the mountains at a certain time (e.g., during the NH flyby) using statistical analysis.

Observations and methods: The elevation data were derived from the digital elevation model (DEM), produced from the NH's Long Range Reconnaissance Imager (LORRI) and MVIC images [11]. We used the integrated CH_4 band depth map computed from the Linear Etalon Imaging Spectral Array (LEISA) data [12]. While the band depth values are not the actual measure of CH_4 concentration, however, these values can be used to derive snowline elevation since the band depth values confirm the presence of methane concentration. CH_4 band depth, used in this study, was chosen between 1.58 and 1.83 µm (called band group of 1.7 µm) over a group of 3 CH_4 bands at about 1.67, 1.72, and 1.79 µm. The integrated band depth over 1.7 µm CH_4 band is calculated as [12]:

$$BD_{\lambda 1,\lambda 2}(CH_4) = 1 - \frac{\int_{\lambda 1}^{\lambda 2} RF(\lambda)\, d\lambda}{\int_{\lambda 1}^{\lambda 2} Cont(\lambda)\, d\lambda}$$

where λ_1, λ_2 are the integration limits of the bands, RF(λ) the reflectance factor inside the band, and Cont(λ) a linear interpolation of the continuum between λ_1, and λ_2. The band depth over 1.7 µm group was chosen since this CH_4 bands compromise between the signal to noise ratio and, thus, effectively detects methane on the surface of Pluto [12]. A threshold band depth value of -0.05 at the 1.7 µm CH_4 bands was set as a positive detection of methane [12]. However, this threshold value can not help in delineating the snowline in the mountains. We applied, therefore, a simple approach of using statistical analysis to extract the lower limit of CH_4 snowline.

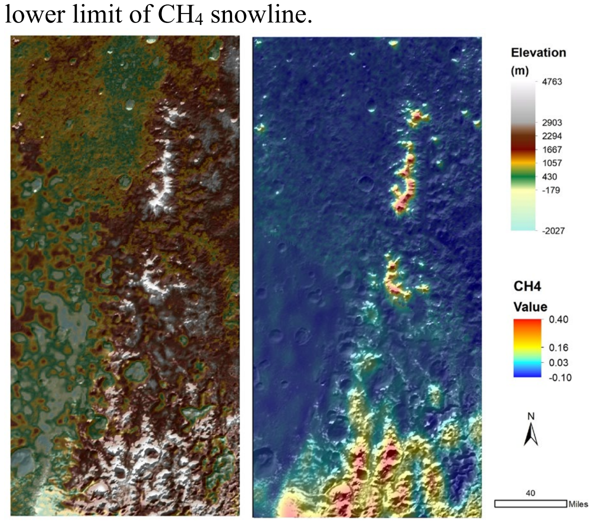

Fig. 1: LORRI-MVIC DEM and LEISA CH_4 integrated band depth map overlain on the LORRI base map of the chain of mountains at the Cthulhu Macula. Image is centered at 10°S, 145°E.

The spatial resolution of DEM and CH_4 band depth maps were 300 m/pixel and 1000m/pixel, respectively. To keep consistency between the dataset, we resampled the DEM map to 1000m/pixel using a nearest neighbor re-sampling algorithm since the algorithm minimizes changes to the pixel values. The values from each pixel of DEM and corresponding CH_4 band depth pixel values were extracted. We applied a *Pearson* product-moment correlation analysis between the elevation and methane band depth maps. The lower snowline limit (elevation) was derived by applying a two-dimensional (2D) kernel density estimate algorithm. 2D kernel density uses an axis-aligned bivariate normal kernel that displays the result on contours.

Results and discussion: Within the specified area (between 140°-150°E longitude and 0°-20°S latitude), the ranges of elevation and CH_4 band depth values were a minimum of -2027 m to maximum 4763 m and a minimum of -0.14 to a maximum of 0.39, respectively. The correlation analysis results in a sample estimate correlation coefficient (r^2) value of 0.45 with a 95 percent confidence interval between 0.447 and 0.458. This indicates that a moderately positive correlation between the elevation and CH_4 concentration on the chain of mountain. We plotted elevation and CH_4 band integrated depth values against each other in Fig. 2. The plot shows two distinct trends between elevation and methane band depth. Interestingly, a cluster of CH_4 band depth values around -0.05 is seen around elevation ranges of 0 m to 2000 m (up to the 2 km). There is another weaker trend that stretches from CH_4 band depth values more than zero and covers mostly the elevation ranges around 2000 m. However, the higher band depth values (around 0.3) also span to lower elevation around 0 m to the highest peak of the mountains at around 5 km. Therefore, a 2D kernel density map can appropriately be used for delineating the methane snowline in the mountains (Fig. 3).

The cluster density of bivariate (elevation and CH_4 integrated band depth) normal kernel in Fig. 3 shows two enclosed clusters centers: around -0.05 and 0.05. Since our goal is to find the snowline on the mountain cap (e.g., higher concentration of methane at higher altitude), therefore, we used the enclosed contour centered around 0.05 as the proxy for identifying the snowline. Our interested kennel density contour shows a lower elevation of 1800 m. We, therefore, state that the lower limit of CH_4 snowline on the mountain chains of the Cthulhu Macula region is 1800 m or 1.8 km. However, this lower limit does not rule out the possibilities of snowline above this elevation. The snowline can start from any elevation with the lowest possible elevation of 1.8 km on the mountain cap. Based on the 2D kernel density map it can be inferred the lowest CH_4 band depth value of 0.03 as the minimum methane band depth value at the lower limit of the snowline. However, this inference is more susceptible to a wrong determination of snowline since a range of values is found in different elevation ranges and can not necessarily be applied to other mountains, e.g., Tartarus Dorsa.

Conclusion: Based on statistical analyses (plot density and 2D kernel density estimation) we found the lower limit of CH_4 snowline at an elevation of 1800 meter or 1.8 km in the mountains. Since CH_4 concentration is controlled by a vertical temperature profile, this snowline altitude indicates the lowest elevation in the Cthulhu Macula where the atmosphere is warm enough to suppress the deposition of N_2. Moreover, this snowline information would provide a useful constraint on volatile transport modeling (e.g., seasonal) in the mountains. Note that determination of snowline was done without considering climate and atmospheric variables, rather we adopted a simple method of using 2D kernel density estimation between elevation and CH_4 band depth values in determining the snowline.

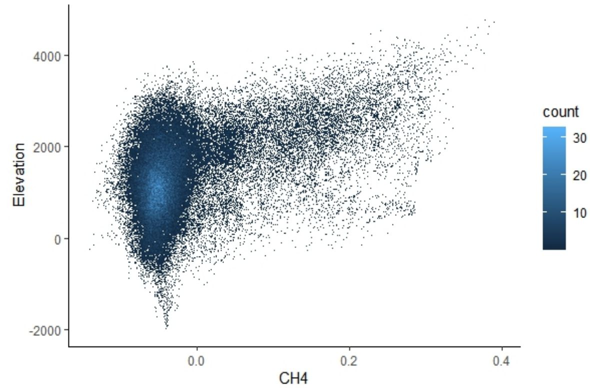

Fig. 2. The correlation plot between CH_4 integrated band depth map and elevations in the mountain chain. The elevation values were recorded in meters

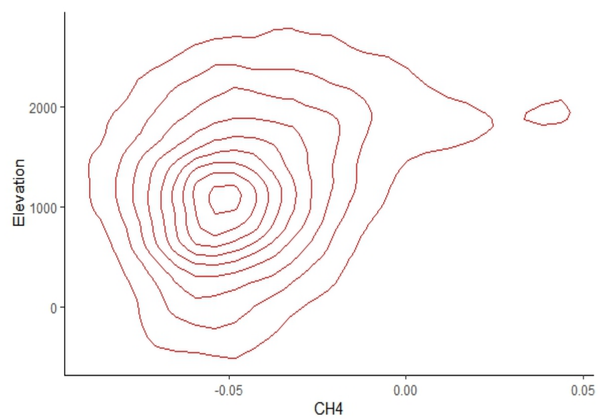

Fig. 3. 2D kernel density estimation (displays in contours) between CH_4 integrated band depth map and elevations in the mountain chain. The elevation values were recorded in meters.

References: [1] Cruikshank D.P. et al. (1976) *Science* 194, 835–837. [2] Owen T.C. et al. (1993) *Science* 261, 745–748. [3] Merlin, F. (2015) *A&A* 582, A39. [4] Cruikshank D.P. et al. (2016) *LPSC* 47, 1700. [5] Grundy W.M. and Buie M.W. (2001) *Icarus* 153, 248–263. [6] Stern S.A. et al. (2015) *Science* 350. [7] Protopapa S. (2017) *Icarus* 287, 218–228. [8] Grundy W.M. (2016) *Science* 351. [9] Earle A.M. et al. (2018) *Icarus* 314, 195–209. [10] Moore J.M. (2018) *Icarus* 300, 129–144. [11] Schenk P.M. et al. (2018) *Icarus* 314, 400–433. [12] Schmitt B. et al. (2017) *Icarus* 287, 229–260.