HAZE LAYERS IN PLUTO'S ATMOSPHERE.

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Introduction: The New Horizons spacecraft made the first reconnaissance of the Pluto-Charon system on Jul 14, 2015, obtaining images of Pluto and its satellites on approach, near closest approach, and on departure. Departure images from the Long Range Reconnaissance Imager (LORRI) on New Horizons, obtained at high solar phase angles, unexpectedly revealed that Pluto's atmosphere is hazy [1].

The haze in Pluto's atmosphere was detected in images by both LORRI and the Multispectral Visible Imaging Camera (MVIC) on New Horizons [2], at solar phase angles ranging from ~20° to ~169°. The haze is detected to altitudes of at least 200 km above Pluto's surface. The haze is structured into as many as ~20 layers and exhibits a blue color at visible wavelengths. A UV absorption attributable to the atmospheric haze was also detected by the ALICE ultraviolet spectrograph on New Horizons [2]. The haze particles are strongly forward-scattering in the visible. The submicron-sized haze particles settle out of the atmosphere and fall to Pluto's surface, altering the surface optical properties on seasonal time scales.

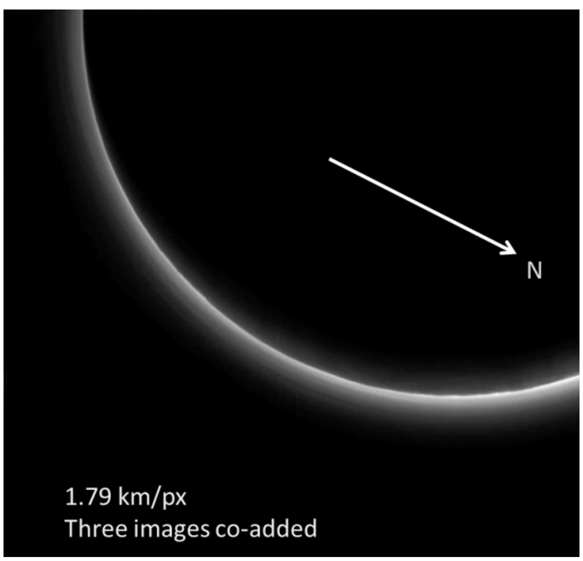

Figure 1. Stack of three LORRI images at phase angle 167° and at resolution of 1.79 km/pixel. The I/F peaks at the surface at a value *I/F*~0.22 (near right side of image) and decreases with altitude, with a scale height ~50 km below 150 km altitude. Haze layers are visible. N indicates Pluto north. The Sun is to the bottom of the image.

Observations: Haze in Pluto's atmosphere was discovered in the LORRI image obtained at MET 299206716, on July 14, 2015 at a range of 360800 km from Pluto. The LORRI images are panchromatic with pivot wavelength of 607.6 nm [3]. The solar phase angle was 167° so that the camera was pointed only 13° away from the Sun. Initially returned with lossy compression in the quick-look dataset, the image already suggested the presence of haze layers. The complete sequence of three images has been returned with lossless compression and is shown, with the three images stacked, in Fig. 1.

The atmospheric haze as shown in Fig. 1 peaks in brightness at the surface where *I/F* ~ 0.22, and the haze brightness decreases with altitude with an approximate exponential scale height ~ 50 km over the bottom 150 km. Fig. 2 shows an example of the *I/F* profiles.

The atmospheric haze is seen to extend completely around the limb in full disk images of Pluto at high phase angles. An example is given in Fig. 3, which is a stack of four LORRI images obtained at a range of 775300 km, for a resolution of 3.83 km /pixel, and at a solar phase angle 166°. Notable in Fig. 3 is that the haze is brightest toward Pluto north and not under the Sun. A distinct left-right brightness asymmetry is evident in the image.

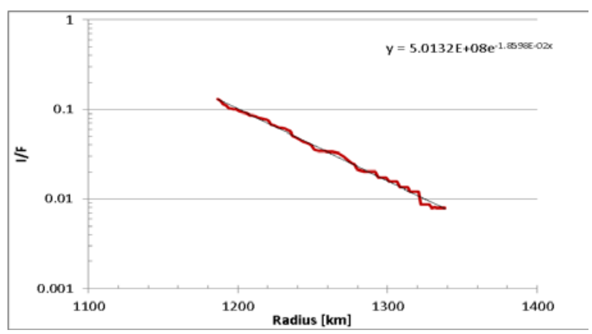

Figure 2. Example of I/F profile extracted from upper left corner of stacked image in Fig. 1, with peak *I/F*~0.13 and a scale height 54 km.

Haze layers can be discerned in Fig. 1 and in Fig. 3. They are approximately horizontal, and they can be traced over horizontal extents of hundreds of km. The layer structures are brought out in high resolution images obtained by LORRI and MVIC near closest approach. Fig. 4 is a high resolution, panchromatic MVIC image [4] obtained at high phase angle.

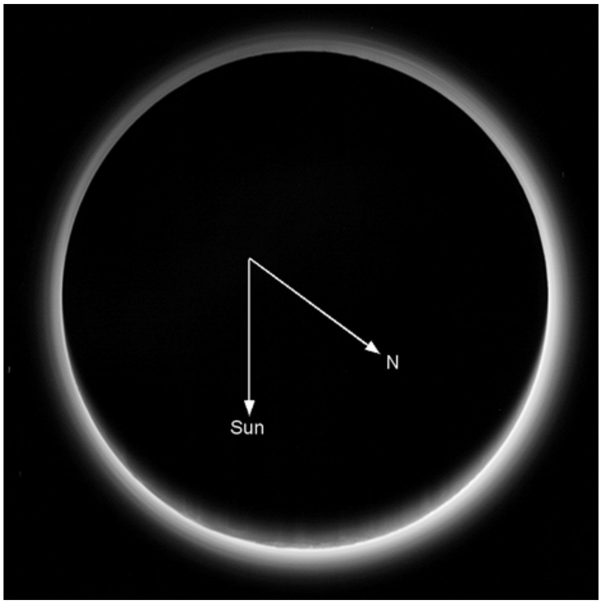

Figure 3. Stack of four LORRI images obtained July 15, 2015 at 3.83 km/px resolution. Haze is present all around the limb, brightest toward Pluto N and not toward Sun, and layers are seen. Image has been stretched and sharpened. Surface features are seen within the limb of Pluto.

Fig. 4 shows that haze layers merge, separate (divide into thinner layers), change in thickness, or appear and disappear, when traced around the limb. The minimum haze layer thickness is about 1 km, and the maximum horizontal extent of a haze layer is ~1000 km.

MVIC color images [4] show a blue color for the haze, with peak *I/F* reaching 0.7 to 0.8 in the blue, versus peak *I/F* ~ 0.2 to 0.3 in the red (similar to LORRI) at high phase angle [2]. As seen by LORRI, the peak *I/F* ~ 0.012 at 67° phase, while the peak *I/F* ~ 0.003 at 20° phase. Aggregate particles, that have structural feature sizes at small scales ~ 10 nm, as well as overall particle sizes ~400 nm, may be able to explain both the blue color and the strong forward scattering at visible wavelengths [2]. Under optically thin conditions, $I/F \sim P(\Theta)\, \tau_{LOS} /4$, where P is the scattering phase function at phase angle Θ, and τ_{LOS} is the line of sight scattering opacity. If the phase function P ~ 10 at high phase angle, giving a large forward/backward scattering ratio (e.g., Mie-scattering tholin-like particles [5] with radii no smaller than ~0.4 µm), we estimate $\tau_{LOS} \sim 0.08$. For particles of radius r~0.4 microns the scattering cross section of a single particle is $\pi r^2 Q_S$ or ~1×10^{-8} cm^2 (with Q_S ~2). Using $\tau \sim \pi r^2 Q_S\, n_{HAZE}\, H_{HAZE}$, where H_{HAZE} is the low altitude haze scale height of 50 km, the haze column mass is estimated as 2×10^{-7} g/cm^2. If the haze particles are photochemically produced like Titan's hazes [6], an upper limit to their mass production rate is given by the photolysis loss rate of methane [2], estimated at ~1×10^{-14} g/cm^2/s. This rate would be balanced by a haze residence time estimated to be t_{HAZE} ~ 200 terrestrial days. The time to accumulate a surface cover of cross section area in haze particles equal to the Pluto surface area (100% cover) is ~ 200 years.

References: [1] Stern S. A. et al. (2015) *Science*, **350**, aad1815. [2] Gladstone G. R. et al. (2015) *Science* in press. [3] Cheng A. F. et al. (2008) Spa. Sci. Revs. 140, 189. [4] Reuter D. C. et al. (2008) Spa. Sci. Revs. 140, 129. [5] Khare B. N. et al. (1984) *Icarus* **60**, 127. [6] Lavvas P. et al. (2013) *Proc. Nat. Acad. Sci.* **110**, 2729.

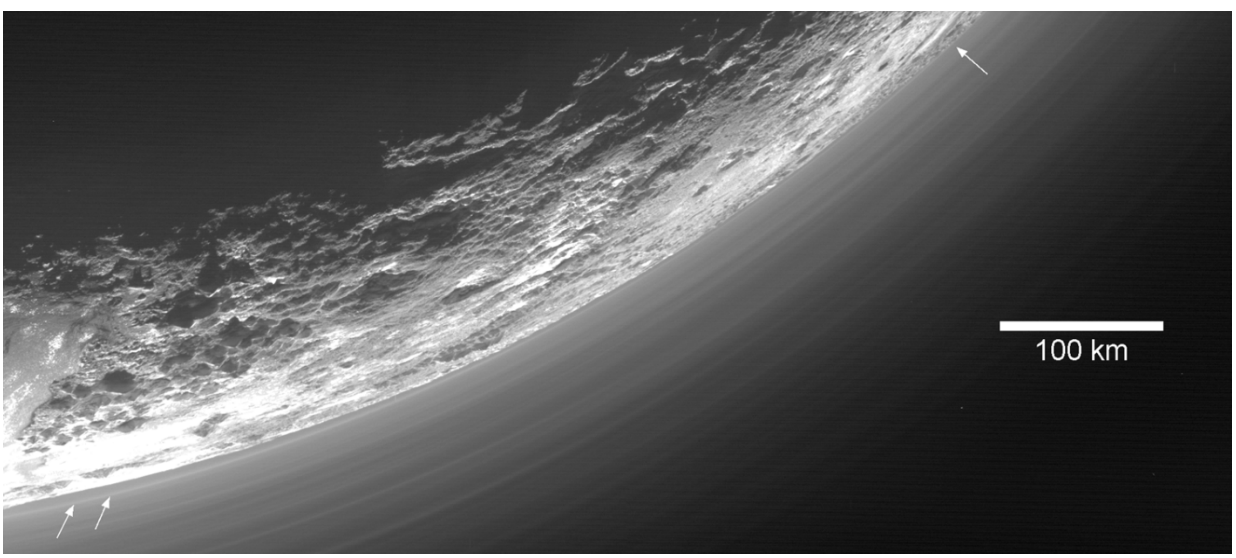

Figure 4. MVIC image at resolution 0.34 km/pixel and at phase angle 147°, stretched and sharpened. About 20 haze layers are seen. White arrows indicate a layer ~5 km above the surface at lower left merging wih the surface to upper right.