OBSERVATIONS AND THEORY FOR WAVES IN PLUTO'S ATMOSPHERE. A Jacobs[1], M. Summers[1], G.R. Gladstone[2], A.F. Cheng[3], D. F. Strobel[4], C. Lisse[3], L. Young[5], D. Pesnell[6], P. Gao[7], J. Kammer[2], H. Weaver[3], T. Bertrand[8], [1]George Mason University, MSN 3F3, George Mason University, Fairfax, VA 22030, ajacob12@masonlive.gmu.edu, [2]Southwest Research Institute, San Antonio, TX, [3]The Johns Hopkins University Applied Physics Laboratory, [4]The Johns Hopkins University, Baltimore, MD, [5]Southwest Research Institute, Boulder, CO, [6]NASA Goddard Space Flight Center, Greenbelt, MD, [7]University of California, Berkeley, Berkeley, CA, [8]NASA Ames Research Center, Mountain View, CA.

Introduction: Observations during the New Horizons spacecraft flyby of Pluto in July 2015 revealed that Pluto's atmosphere has an extensive background haze with as many as 20 relatively bright embedded layers. Several mechanisms that include possible microphysical and/or dynamical processes operating in the atmosphere have been proposed to produce these layers. The purpose of this poster is to use the New Horizons observations, along with microphysical models and atmospheric scattering simulations, to analyze the existing observations in a manner that allows testing of the proposed mechanisms.

The existence of gravity (buoyancy) waves and Rossby (planetary) waves in Pluto's atmosphere have been proposed to explain the wave-like structure. Two forcing mechanisms to produce gravity waves and explain observed structure are currently proposed— (1) tidal oscillations driven by geographic differences in surface ice sublimation over Pluto's diurnal cycle, and (2) orographically generated oscillations by flow over mountain ridges or large topographic features (applicable to both gravity and Rossby waves here). Only the latter mechanism has been used to model direct correspondence between wave dynamics and the observed haze layering through generation of haze particle density perturbations [1,2]

In addition, the haze layer associations with geographic variation are characterized in the context of evaluating the generation of a range of possible wave types in Pluto's atmosphere. Atmospheric gravity (buoyancy) waves - both tidally and orographically driven, as well as Rossby waves, have been previously proposed as the source of density perturbations observed in stellar occultations before the New Horizons flyby of Pluto [3].

Stellar occultation measurements of waves in Pluto's atmosphere before the flyby of New Horizons predicted density amplitudes of ~0.006 for 8km vertical wavelength gravity waves and ~0.015 for 20km vertical wavelength gravity waves [4], and ~0.01 for ~35km vertical wavelength Rossby waves [4]. These measurements and predictions were for higher altitude waves (>150km) than the altitude range for which LORRI images contained best S/N (~0-200km), however some consistency should still exist.

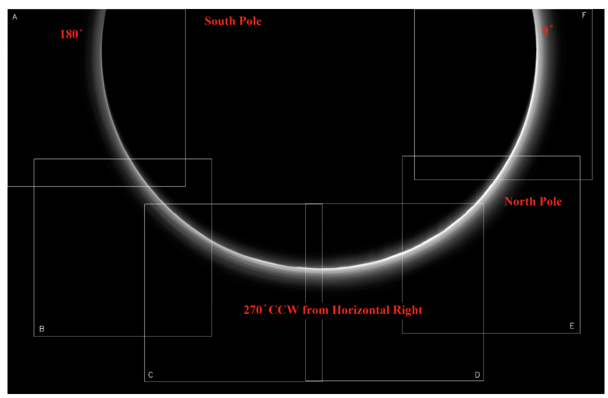

Figure 1. Simulation mosaic of all 6 unique FOV images within the P_MULTI sequence showing clock angle locations (red text) and frame boundary positions with labels A-F for reference in examining the unwrapped mosaic features. Image frames B and C (blue and orange diamonds in Figure 1) contain the layering that is most distinct. Pluto North and South directions are also indicated in red.

The LORRI observed background relative density amplitudes for the P_MULTI image sequence ~20km vertical wavelength signal are around 5x larger than that predicted by the stellar occultations measurements (~ 0.05 for altitudes of 0-150km), but the FULLFRAME sequence amplitudes are more consistent with the previously measured signal (~ 0.01-0.04, for altitudes 0-250km). The PSD 18-20km signal in Hubbard et al. 2008 is also consistent with that found as the large-scale oscillation in both the P_MULTI and FULLFRAME sequences.

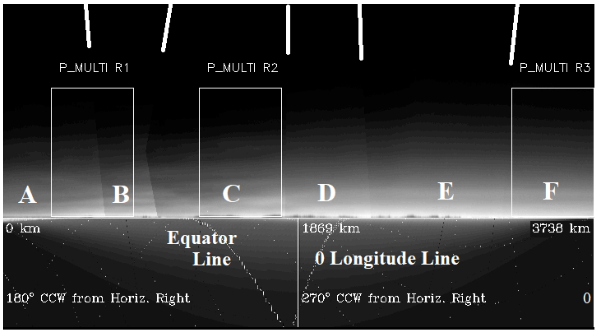

Figure 2. Unwrapped LORRI image mosaic from the P_MULTI sequence with the locations of regions P_MULTI R1-3 outlined. Pre-whitening was done by subtracting regional row averages from the columns to generate waveforms and PSDs were extracted. Frame borders are indicated at top with bold white lines corresponding to the frame letters A-F defined in Figure 1.

A signal below 200km in the stellar occultations (~10km) is also consistent in vertical wavelength with the P_MULTI sequence signals. In the HIRES sequence, much larger amplitudes were observed, in the range of 0.2 - 0.3. Oscillation amplitudes in this image were observed to grow with altitude from ~ 5km to the profile extent, 60km. A vertical wavelength signal ~ 8km was also identified.

Thermal tides and Rossby wave models need to be reconsidered with the more recent New Horizons constrained temperature and pressure profiles by the REX instrument measurements. The upper atmosphere was found to be much cooler than anticipated, and the surface pressure considerably larger than implemented in the thermal tides model. Resulting Global Climate Model (GCM) zonal mean winds reach speeds as great as 10 m/s by 40km altitude [4], directly challenging Rossby wave vertical propagation with horizontal scales that compare well with observed layer slopes. The thermal tides model also assumed negligible wind speeds—another feature that limits the application of the current model results. Once the models are updated and run for the atmospheric state measured by New Horizons, perturbations should then be calculated and extended to resulting perturbations in haze particle number densities (or some other variable that can manifest itself as haze brightness variations) to validate structure and amplitudes calculated by the models. A scattering model adapted in a companion study acts as a bridging tool between the orographic gravity wave model calculations to facilitate direct comparisons of the characteristic/criteria outlined here

Conclusions: We investigated the vertical and horizontal structure of the complex haze layers using three Long Range Reconnaissance Imager (LORRI) image sequences at high phase angles (148°- 169°) and three different resolutions (0.093 km/pix, 0.96 km/pix, and 3.86 km/pix). This analysis allowed a picture of the horizontal structure of the individual layers along the limb to be characterized. Several haze characteristics were extracted, i.e., their slope, amplitude, as well as their waveforms and power spectral densities (PSDs). Observational criteria to which model calculations predicting certain wave dynamics can be compared and validated. Initial comparisons between orographic gravity wave model slopes and observed slopes indicate that the horizontal wavelength may need to be increased, and that a sufficient increase may lead to waves that are evanescent (trapped) below Pluto's temperature inversion close to the surface More modeling of the layers needs to be done to confirm projection effects are not significant. However, the observations contained in this study, combined with GCM output and established theory on gravity and/or Rossby waves [5] may also indicate the presence of new wave dynamics than previously considered in Pluto's atmosphere.

References: [1] Gladstone et al. (2016), *Science*, 351, 1026-1039. [2] Cheng et al., (2017), *Icarus*, 290, 112-133. [3] McCarthy et al. (2008), *Astron. J.* 136, 1519–1522. [4] Bertrand, T. & Forget, F. (2017), *Icarus* **287,** 72–86. [5] Holton, J. R. (2004), 4th ed.; New York, NY: Elsevier/Academic.