New Horizons Encounter with the Pluto System: Atmospheric Opacities and Composition, Temperature, Pressure, and Haze Profiles – Overview

This dataset contains derived data products from the Atmospheres Science Theme Team of the New Horizons project. It includes the wavelength-dependent solar atmospheric occultation count rate and opacities, a model of the unocculted solar count rate, atmospheric composition profiles for the species N2, CH4, C2H2, C2H4, and C2H6 based on data taken from the Alice UV imaging spectrograph, lower atmospheric temperature and pressure profiles from the Radio EXperiment (REX) instrument, and vertical I/F haze profiles from the LOng Range Reconnaissance Imager (LORRI) instrument.

Note: *This document was reformatted from the content provided for the PDS3 version of these data, but not edited apart from layout. In the descriptions following, the directory names are likely preserved in same or similar form in the PDS4 data collection, and the PDS3 PRODUCT_ID values are similar to the file names of the respective products. Note that the case convention in PDS4 is typically lower rather than upper case for file and directory names.*

Processing

The data generated by the Atmospheres Science Theme Team of the New Horizons project can be grouped into a number of sub-specialities, and the data for these is grouped into subdirectories of:

ALICEOCC/ - solar occultations and an unocculted model
ATMOSCOMP/ - atmospheric composition profiles
HAZE/ - details of the Pluto haze layers
REXATMOS/ - lower atmospheric temperature and pressure profiles
STAROCC/ - stellar occultation and appulse data
THERMSCAN/ - diametric and polar thermscans of Pluto

The data content that resides in each subdirectory is detailed below.

ALICEOCC: Solar Atmospheric Occultation Count Rate and Opacities

Data from the Alice UltraViolet Imaging spectrograph aboard the New Horizons spacecraft was acquired during the occultations of the Sun by Pluto and Charon. The data have been binned in time to 1-second (MET - Mission Elapsed Time) resolution. The observed solar spectrum has been extracted and corrected for a variety of instrumental effects.

For a detailed description of the data analysis process, please see Young, et al. (2017).

The list of Raw files used in creating this product can be found in the first header of the fits file.

ATMOSCOMP: Atmospheric Composition Profiles

The Alice instrument on NASA's New Horizons spacecraft observed an ultraviolet solar occultation by Pluto's atmosphere on 2015 July 14. The transmission vs. altitude was sensitive to the presence of N2, CH4, C2H2, C2H4, C2H6, and haze.

Line-of-sight abundances and local number densities for the 5 molecular species, and line-of-sight optical depth and extinction coefficients for the haze, were derived. The UV occultation occured from approximately 2015 July 14 12:15 to 13:32 UTC (spacecraft time).

The line-of-sight abundance spreadsheet in data/atmoscomp holds data for N2, CH4, C2H2, C2H4, C2H6, and haze as a function of radius. The line-of-sight abundance N_s of species s as a function of tangent radius r' can be found in Section 3, Equation (6) in Young, et al. (2017).

Data acquisition

Data was acquired using the Alice instrument. Alice is an imaging spectrograph that has a bandpass from 52 to 187 nm, with a photocathode gap from 118 to 125 nm designed to decrease the count rate near Ly-alpha. For the Pluto occultation, the 'pixel list' data collection mode was used for higher time cadence. During the observation, the Sun was placed in the 'box' of the Solar Occultation Channel (SOCC) to avoid slit losses, to avoid oversaturation, and to observe the UV solar occultation simultaneously with the radio Earth occultation. The SOCC is roughly co-aligned with the field of view of REX Tyler, et al. (2008) to allow for simultaneous observations of the solar and the uplink radio occultations. During the Pluto solar occultation, the REX field of view was centered on Earth, which placed the Sun within a few tenths of a degree from the center of the 2x2 degree 'box'. Thrusters were fired to keep REX centered on the Earth within 0.0143 degrees (deadband half-width). Thus, the Sun moved only slightly within the 2x2 degree 'box' during the solar occultation observation. The Sun's diameter as seen from New Horizons in July 2015 was 0.016 degrees, which was much smaller than the size of the 'box' and slightly smaller than the Alice pixel size (Alice pixels subtend 0.019 degrees in the spectral axis, and 0.308 degrees in the spatial axis). Pluto, by contrast, was large compared to the box, varying from 3.0 degrees at 2015 July 14 12:41 UT, when Pluto first entered the box, to 2.2 degrees at 13:01 UT, when Pluto exited the box.

The locations probed by the solar occultation depended only on the relative positions of the Sun, Pluto, and New Horizons, and not on the pointing of the Alice field of view. Pluto passed across the Sun at a sky-plane velocity (that is, the component of the velocity perpendicular to the spacecraft-Sun line) of 3.586 km/s, so it took ~11 minutes for the solid body of Pluto to pass across the Sun. This is slightly faster than the Earth's sky-plane velocity of 3.531 km/s during the Earth occultation, Hinson, et al. (2017). Solar ingress occurred at 195.3 degrees E longitude, 15.5 degrees S latitude, while egress occurred at 13.3 degrees E longitude, 16.5 degrees N latitude Gladstone, et al. (2016). Thus, ingress probed the atmosphere just off of the southern tip of the left-hand side of the bright heart-shaped feature, named Sputnik Planitia, and egress probed the atmosphere near the transition between dark equatorial regions and the mid-latitude areas. Observations were taken in 'pixel list' mode, in which each detected photon is tagged with its location on the detector. Effectively, this location was a measure of which of the 1024 spectral and 32 spatial pixels was stimulated by each detected photon. The pixel resolution was 0.177-0.183 nm/pixel, which Nyquist samples the instrumental spectral resolution (0.35 nm when operated in pixel list mode). Timing was determined by the insertion of special 'time hack' values into the instrument's memory buffer every 4 ms. This 4 ms timing was much finer than that required for the analysis presented here, and the counts were summed into 1-second time bins. This resulted in a 1024 by 32 image of counts per second at each 1 second interval, called a count rate image.

Data analysis

In order to extract 1-second count-rate spectra from the pixel list data, the following analysis steps were performed.

1) Dead time correction in the raw pixel list stream were calculated. The detector electronics took a finite amount of time to process each count. During this time, the detector was 'dead' i.e., it was insensitive to any additional counts. Therefore each detected photon was weighted by a factor of 1 / (1 - tau_d * C), where tau_d = 18 microseconds, the dead time constant of the electronics, and C is the count rate measured over a 4 ms interval.

2) The pixel stream was summed to construct 2-D count-rate images at 1-second resolution. During one second, the tangent altitude probed by the Sun moved ~3.586 km through Pluto's atmosphere. The choice of 1-second binning was a balance between increasing signal-to-noise ratio per image and sub-sampling the 4 to 5 second (~16 km) smoothing caused by the Sun's finite size.

3) A 1-D solar spectrum was extracted from each 2-D count rate image. The Sun varied in its deadband by 0.0143 deg (half-width). Since this was much smaller than the pixel size of 0.308 deg/pixel in the spatial direction, the variation within the deadband did not change which detector row contained the counts from the Sun. The solar spectra was extracted by a simple sum of rows 19-22, inclusive, which accounted for the width of the spatial point-spread function (Stern, et al. (2008), Figure 12) and the motion within the deadband. The contribution of Pluto's nightside to the UV signal was negligible compared to the direct solar flux.

4) Alice 'stim pixels' Stern, et al. (2008) was used to correct the wavelength scale for temperature effects in the Alice detector. The mapping between the physical location of an event on the detector and its pixel number in data space depended on the resistivity of the readout anode, which itself depended on temperature. Essentially, the detector electronics produced counts at two known physical locations on opposite ends of the detector. These counts were then mapped into data space, allowing for a linear correction to the apparent position of detected photons.

5) Each one-second count-rate spectrum was then corrected for the wavelength dependence on the location of the Sun within the 2x2 degree 'box' portion of the slit. The Sun was offset slightly from the center line of the slit, which introduced an overall wavelength shift of 0.396 nm. There was some variation in wavelength as the Sun's position moved in the +/-0.0143 degree deadband, since a pixel subtended 0.019 degrees in the dispersion direction. For

unocculted spectra, the wavelength shift was determined by fitting a Gaussian line profile to five solar lines, including the Lyman-Alpha line at 121.6 nm. The shift was also calculated from the spacecraft attitude, and the two methods agreed to within 0.10 pixels; the shift calculated from the spacecraft altitude was used for spectra taken when the solar lines were obscured by Pluto's atmosphere. The resulting spectra were placed on a common wavelength grid using a sinc interpolation. Doppler shifts were ignored in this analysis. Pluto's heliocentric motion, which affected the interaction of the solar lines and absorption in Pluto's atmosphere, was at most 1.075 km/s during this observation (0.00035 nm shift at 100 nm). This was much less than the width of the solar lines Curdt, et al. (2001). The rate at which the spacecraft receded from Pluto, which affected how the spectrum is recorded on the Alice spectrograph, ranged from 11.66 to 13.60 km/s over the POCC observation (0.0038 to 0.0045 nm shift at 100 nm). This led to a shift of only ~2% of a pixel.

6) The gradual decrease in sensitivity of regions of the detector that saw the highest solar flux had to be corrected for. This localized phenomenon, known as 'gain sag', is a function of the total amount of charge extracted from the micro-channel plates, per unit area, over the lifetime of the detector Stern, et al. (2008). The magnitude of the sensitivity loss due to gain sag varied from zero at the short wavelength end of the detector, where the solar flux is low, up to several percent at the long wavelength end of the detector, where the solar flux is greatest. A correction for the gain sag during the occultation observation was derived, on a pixel by pixel basis, by fitting a line to the observed count rate when the sun was unocculted by Pluto or its atmosphere as a function of the total integrated number of counts during the observation, using both ingress and egress spectra.

7) After correcting for gain sag, the dark rate spectrum was subtracted. This was calculated from a composite dark spectrum, shifted (with sinc interpolation) to match the wavelength of each count-rate spectrum. The resulting extracted one-second count-rate spectra vs. tangent radius are shown in Figure 4A of Young, et al. (2017). The tangent radius was the closest distance between Pluto's center and the ray connecting the spacecraft and the center of the solar disk, and was calculated at each second using SPICE kernels supplied by the New Horizons KinetX navigation team for science analysis:

NH_PRED_20141201_20190301_OD122.BSP
NAVSE_PLU047_OD122.BSP
NAVPE_DE433_OD122.BSP

These SPICE kernels are archived with NAIF at JPL and can be found with the search keywords 'JPL NAIF data New Horizons.'

8) A reference solar spectrum for each one-second spectrum was created. Because of the small entrance aperture of the SOCC, the repeller grid, a lattice-like pattern of wires designed to remove stray ions (Stern, et al. (2008) figure 5) produced discrete shadows on the surface of the detector. Even a sub-pixel change in the Sun's position on the focal plane affected the observed shadow pattern on the detector, and caused up to a 40% variation in apparent throughput at certain regions of the spectrum. Failure to correct for this effect would leave

periodic reductions in counts that mimic absorption features. To correct for this, the spacecraft attitude information derived from the star trackers was used to derive the position of the Sun in the focal plane. For each one-second count rate spectrum, other spectra (in either the Pluto or Charon solar occultations) that (i) were obtained when the Sun was within 0.002 deg of the spectrum in question, and (ii) were unocculted, were identified. This selection gave a median of 60 reference spectra for each one-second sample. These were averaged to produce a reference solar spectrum for each one-second count-rate spectrum. Figure 4B in Young, et al. (2017) shows the result of dividing each one-second count rate spectrum by its reference solar spectrum at full one-second, 0.17 nm resolution.

Absorption cross sections

For the ultraviolet solar occultation by Pluto observed by New Horizons, the refraction of Pluto's atmosphere can be ignored Hinson, et al. (2017), simplifying the geometry of the occultation. The ray connecting the Sun and the New Horizons spacecraft has a minimum distance to the body center, called the tangent radius, r', which can be defined by the surface radius, r_s, and the height of the tangent point above the surface (the tangent height), h, by $r' = r_s + h$. At a distance along the ray, x, defined as 0 at the tangent point, the relationship between the radius in the atmosphere along the ray, r, and the tangent radius is simply $r^2 = r'^2 + x^2$. We can define the radius in the atmosphere as the sum of the surface radius and the altitude, z, by $r = r_s + z$.

The incident UV solar flux is diminished by the absorption of an occulting atmosphere (e.g., Smith and Hunten 1990). The line-of-sight transmission, Tr, is a function of the line-of-sight optical depth, which is itself a function of tangent radius, r', and wavelength, lambda. The cross-sections can be approximated as constant along the line-of-sight.

Equations and further details regarding the determination of cross-sections for N2, CH4, CO, C2H6, C2H2, C2H4, and Hazes can be found in Section 3, Young, et al. (2017).

Determination of line-of-sight abundances

The retrieval of N2, CH4, C2H6, C2H2, C2H4, and haze line-of-sight abundances was performed individually at each altitude, in a method very similar to that used in Gladstone, et al. (2016). Fitting for the hazes and hydrocarbons was first performed using only the wavelengths 100-180 nm, where the signal-to-noise of the occultation data was highest, and N2 did not contribute. In a later step, N2 was included to analyze the wavelengths below 65 nm. HCN and CO, while known to be present in Pluto's atmosphere, were not detected in the Alice solar occultation.

Retrievals were performed separately for ingress and egress. The retrieval started at a tangent height 2000 km altitude, above the first measurable absorption, and progressed downward toward the surface. To retrieve line-of-sight abundances from each spectrum, the spectrum at the next higher altitude step acted as the initial condition in a weighted Levenberg-Marquardt least-squares fit to minimize the weighted sum of squared residuals, (Press et al. 2007). Fitting to individual one-second spectra gave unacceptably large errors and unstable solutions to the non-linear least-squares fit, so multiple spectra were averaged before retrieving line-of-sight abundances. Because of the 3.586 km/s sky-plane velocity of the Sun, averaging in time corresponded to averaging in altitude. To investigate the impact of different averaging lengths, one retrieval was performed that averaged 23 seconds (82.5 km) for altitudes > 1000 km, 11 seconds (39.5 km) for 1000 to 800 km, and 5 seconds (17.9 km) below 800 km, scaling the errors per spectrum appropriately. A second retrieval averaged 23 seconds throughout the entire span. The 5-second averaging scale was matched to the angular size of the Sun as seen by New Horizons. At altitudes below 700 km, the 23-second averaging sampled less than one point per scale height. Using Eq. 8 Young, et al. (2017), line-of-sight abundances were retrieved that produced a transmission, Tr, that best matched the time-averaged data, D, when weighted by the solar rate, R, convolved by the line-spread function, k, normalized by the convolved solar rate, k*R, and multiplied by the time-averaged reference spectrum, Dref. For each averaged spectrum, the log of the line-of-sight abundance was fitted for, because that quantity guaranteed a positive N_s (N_s is the line-of-sight abundance of species s), and because the surfaces of chi^2 were more symmetric in ln(N) than in N itself.

Determination of local number densities

The line-of-sight abundance, N, is the integral of the local number density, n, along the line-of-sight. Under certain assumptions, one can invert this relationship to derive n given N (for details on how N were determined, see Young, et al. (2017)). By far, the most common assumption is that of local spherical symmetry (that is, within the region where the ray path intersects Pluto's atmosphere). For Pluto's upper atmosphere, spherical symmetry appeared to be a very good assumption. The Alice Pluto solar occultation data had close agreement between the ingress and egress lightcurves, and nearly identical profiles for ingress and egress for the line-of-sight abundances of all species considered here. Similarly, the REX Pluto Earth radio occultation Hinson, et al. (2017) showed similar density profiles for ingress and egress above 30 km altitude.

For these two New Horizons datasets, the ingress and egress latitudes differed by only ~30 deg, raising the possibility that the similarity is simply due to ingress and egress probing similar latitudes. Analyses of the main occultation drop in ground-based stellar occultations (probing ~10 km to 400 km altitude) do not show evidence for statistically significant ellipticity Person (2001) or only very rare cases of statistically significant dawn/dusk or summer/winter differences Zangari (2013). There are robust theoretical reasons to expect very small horizontal variations in temperature over all the body (at a given pressure level) in the part of the atmosphere not influenced by topography because of the very long radiative timescale of the atmosphere. This is predicted by 3D Global Circulation Models even when methane is not well mixed horizontally Toigo, et al. (2015), Forget, et al. (2017).

Data processing was performed with the assumption of spherical symmetry, with the caveat that this might lead to inaccuracies in derived number densities in the lowest 30 km. Given a spherically symmetric atmosphere, the classic method for deriving local number density from line-of-sight abundance is the Abel transform Roble and Hayes (1972). This method includes a derivative and an integral which amplify the noise in the profile. There are various methods for dealing with this noise, for example by imposing functional forms Roble and Hayes (1972) or by imposing a smoothness constraint using a Tikhonov regularization Quemerais, et al. (2006). Because data was already smoothed over 23-second (82.5-km) intervals, and a quality constraint of < 30% errors to define the valid altitudes was imposed, the unmodified Abel transform technique was used.

For the haze analysis, the relationship between line-of-sight optical depth, tau, and local extinction coefficient, xi, was mathematically equivalent to the relationship between N and n. The Abel transform formally includes an integral to infinity. Specifying the atmosphere above the highest valid data point was done by defining an altitude region over which a functional form N(r) is fitted, and then the function was extrapolated to a radius where the contributions to the integral were negligible (in practice, this was taken to be 2000 km altitude). The higher altitude of the fitting region, h_1, was near the top of the region of valid retrievals of the line-of-sight abundance (determined by the errors in the lower panel of Fig. 9 of Young, et al. (2017)).

Altitudes sampled every 23 seconds (~82.5 km) were used for the fit, to avoid fitting to correlated points, so the lower altitude of the fitting region, h_0, was a multiple of 82.5 km below h_1. This step required some judgment, to balance using a larger region to better constrain the fits, while using a smaller region to avoid non-exponential changes in the profile. Within the extrapolation altitudes, a simple function that assumed that each species has a constant ratio of temperature, T, to molecular weight μ, was used for the fit.

Two parameters were fitted for at the lower extrapolation altitude: the line-of-sight abundance, N_0, and the scale height H_0. The scale height increases proportionally with the square of the radius, $r = r_s + z$, due to variable gravity. The number density, n, is an exponential in geopotential (Eq. 13 of Young, et al. (2017)).

In order to define the scale height and number density at r0, a new geopotential referenced to $r_0= r_s + h_0$ was defined, $xi' = (r - r_0)r_0/r$ (or, for N(r'), substitute r' for r). Because the scale height was not small compared with the radius on Pluto, the line-of-sight column, N, was nearly but not quite an exponential in geopotential (Eq. 13, Young (2009)).

The functional form established from the fitting altitude range was used to calculate the densities up to 2000 km for use with the Abel transform. Errors on the density were calculated by propagation of errors on the line-of-sight abundances. As expected, the errors on the density were larger than those on the line-of-sight abundance. Whereas the altitudes on the line-of-sight abundance were selected to hold fractional errors to < 30%, the fractional errors on the densities for many of the species were near one. This means they are only measured to within a factor of ~2.7, or exp(1).

Quality Flags

The quality flags were defined for all species as:

Quality flag values:

0 = good
1 = out of HEIGHT/ALTITUDE range
2 = out of VALUE or ERROR CRITERIA range

4 = solution did not CONVERGE

and if multiple flags applied to a given value, the flags are added together (e.g., a flag of 3 = both 1 and 2 apply).

HAZE: Haze in Pluto's atmosphere:

Atmospheric haze was detected in images by both the Long Range Reconnaissance Imager (LORRI) and the Multispectral Visible Imaging Camera (MVIC) on New Horizons. LORRI observed haze up to altitudes of at least 200 km above Pluto's surface at solar phase angles from ~20 degrees to ~169 degrees. The haze is structured with about ~20 layers, and the extinction due to haze is greater in the northern hemisphere than at equatorial or southern latitudes. However, more haze layers are discerned at equatorial latitudes. A search for temporal variations found no evidence for motions of haze layers (temporal changes in layer altitudes) on time scales of 2 to 5 hours, but did find evidence of changes in haze scale height above 100 km altitude. An ultraviolet extinction attributable to the atmospheric haze was also detected by the ALICE ultraviolet spectrograph on New Horizons.

The haze particles are strongly forward-scattering in the visible, and a microphysical model of haze is presented which reproduces the visible phase function just above the surface with 0.5 micrometer spherical particles, but also invokes fractal aggregate particles to fit the visible phase function at 45 km altitude and account for UV extinction. A model of haze layer generation by orographic excitation of gravity waves is presented. This model accounts for the observed layer thickness and distribution with altitude. Haze particles settle out of the atmosphere and onto Pluto's surface, at a rate sufficient to alter surface optical properties on seasonal time scales.

Additional details of Pluto haze observations are presented in the literature (Gladstone, et al. (2016) and Cheng, et al. (2017)). LORRI is the panchromatic, long focal length visible imager on New Horizons mission to Pluto and Charon, and a full instrument description is given in Cheng, et al. (2008).

This dataset includes several categories of Pluto haze profile data:

- Azimuthally averaged profiles
- Temporal variation search
- Latitude variation search
- Phase angle variation

Azimuthally averaged profile data

Product ID: AZIMUTHAL_AVERAGE_PROFILE

Departure images of Pluto were obtained by New Horizons LORRI in forward scatter geometries at high solar phase angle, in order to observe atmospheric aerosols over the night side limb of Pluto and the thin illuminated crescent Pluto. The four images from the sequence P_LORRI_FULLFRAME_DEP included the full disk of Pluto at 3.85 km/px resolution and are shown in Figure 2 of Cheng, et al. (2017). These images show a bright ring of scattered light emission from atmospheric haze all around Pluto's limb, over the night side and the illuminated crescent. The present data appeared in Figure 3 of Cheng, et al. (2017). The four LORRI images were obtained with METs of 299236719, 299236749, 299236779 and 299236809, each exposure at 0.15 s in 1x1 unbinned mode, at a range of 775,278 km from Pluto and at a solar phase angle 166 degrees. The sub-observer longitude and latitude, or Pluto (longitude, latitude) at the center of the observed disk, is (288.7 degrees, -43.9 degrees). The sub-solar (longitude, latitude) is (91.1 degrees, 51.6 degrees). The images were scaled, shifted and co-added, after which a smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). The adopted Pluto radius was 1190 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

The azimuthally averaged I/F versus radius is obtained as in aperture photometry, using concentric circular apertures of successively larger radii from Pluto center. The I/F versus radius is found from the average DN per pixel within each of the annuli between successive apertures. This curve has been differentiated to find the scale height by H = -1/(dln[I/F]/dr) with r the radius. The center of Pluto is found by fitting a circle to the limb, with limb radius placed at the maximum brightness gradient.

The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F value, and the scale height in km. The noise floor in I/F is reached at ~1440 km.

Temporal variation search data

The New Horizons departure images, at sufficiently high resolution to characterize haze layering, covered a time base of several hours including the image sequences named P_MULTI_DEP_LONG_1, P_LORRI_DEP_0, P_MULTI_DEP_LONG_2, and P_LORRI_ALICE_DEP_1. These sequences (see Table 1 of Cheng, et al. (2017) were obtained at pixel scales of 2.3 km/pixel or less and phase angles in the range 166.6 degrees to 169 degrees. The New Horizons observations of haze above the limb of Pluto, obtained at different times by different image sequences, also measured haze over different locations on Pluto. The Pluto longitudes and latitudes seen at the limb in these sequences are shown in the limb traces of Figure 8 Cheng, et al. (2017). The intersection points of the limb traces corresponding to different image sequences indicated Pluto locations which were observed at the limb in more than one sequence. These limb trace intersections afforded an opportunity to study temporal variations in the haze layers, by comparing the haze seen over the same locations on Pluto at different times. Four such comparisons are shown in Figure 9 of Cheng, et al. (2017).

Product IDs: TEMPVAR_A_MULTI_DEP_LONG_2, TEMPVAR_A_MULTI_DEP_LONG_1

The present data (from Figure 9a of Cheng, et al. (2017)) compares two haze I/F profiles obtained over the location (longitude, latitude) = (334 degrees, 42.0 degrees) with a time interval between observations of 3.46 hours. The comparison is made between the image sequences P_MULTI_DEP_LONG_1 and P_MULTI_DEP_LONG_2. The adopted Pluto radius was 1190 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

From the sequence P_MULTI_DEP_LONG_2, the specific location on Pluto was found in the images MET 299206659 and MET 299206660 (these were both 0.15 s exposures, obtained one second apart), which were rescaled to a common range of 360779 km, shifted and co-added. The pixel scale became 1.79 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 56.7 degrees, a rectangular 600 x 12 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 12 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 6th order polynomial.

From the sequence P_MULTI_DEP_LONG_1, the specific location on Pluto was found in the images MET 299194487 and MET 299194497 (these were both 0.15 s exposures, obtained one second apart), which were rescaled to a common range of 193342 km, shifted and co-added. The pixel scale became 0.96 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 51.5 degrees, a rectangular 960 x 20 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 20 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 4th order polynomial.

Product IDs: TEMPVAR_B_LORRI_ALICE_DEP_1, TEMPVAR_B_MULTI_DEP_LONG_1

The present data (from Figure 9b of Cheng, et al. (2017) compares two haze I/F profiles obtained over the location (longitude, latitude) = (326 degrees, 43.2 degrees) with a time interval between observations of 5.43 hours. The comparison is made between the image sequences P_MULTI_DEP_LONG_1 and P_LORRI_ALICE_DEP_1. The adopted Pluto radius was 1190 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

From the sequence P_LORRI_ALICE_DEP_1, the specific location on Pluto was found in the images MET 299214015 and MET 299214045 (these were both 0.15 s exposures, obtained 30 s apart), which were rescaled to a common range of 458186 km, shifted and co-added. The pixel scale became 2.27 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 46.6 degrees, a rectangular 600 x 12 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 12 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is exponential with a scale height of 50.96 km.

From the sequence P_MULTI_DEP_LONG_1, the specific location on Pluto was found in the images MET 299194487 and MET 299194497 (these were both 0.15 s exposures, obtained one second apart), which were rescaled to a common range of 193342 km, shifted and co-added. The pixel scale became 0.96 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 51.5 degrees, a rectangular 960 x 20 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 20 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 4th order polynomial.

Product IDs: TEMPVAR_C_LORRI_ALICE_DEP_1, TEMPVAR_C_MULTI_DEP_LONG_2

The present data (from Figure 9c of Cheng, et al. (2017) compares two haze I/F profiles obtained over the location (longitude, latitude) = (314 degrees, 45 degrees) with a time interval between observations of 1.97 hours. The comparison is made between the image sequences P_MULTI_DEP_LONG_2 and P_LORRI_ALICE_DEP_1. The adopted Pluto radius was 1190 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

From the sequence P_LORRI_ALICE_DEP_1, the specific location on Pluto was found in the images MET 299214015, MET 299214045 and MET 299214075 (these were all 0.15 s exposures, obtained 30 s apart), which were rescaled to a common range of 458186 km, shifted and co-added. The pixel scale became 2.27 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 37.8 degrees, a rectangular 600 x 12 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 12 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend was a 3rd order polynomial.

From the sequence P_MULTI_DEP_LONG_2, the specific location on Pluto was found in the images MET 299206659, MET299206660, and MET 299206661 (these were all 0.15 s exposures, obtained one second apart), which were rescaled to a common range of 360779 km, shifted and co-added. The pixel scale became 1.79 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 41.9 degrees, a rectangular 600 x 12 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 12 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 3rd order polynomial.

Product IDs: TEMPVAR_D_LORRI_ALICE_DEP_1, TEMPVAR_D_LORRI_DEP_0

The present data (from Figure 9d of Cheng, et al. (2017)) compares two haze I/F profiles obtained over the location (longitude, latitude) = (133 degrees, -45.4 degrees) with a time interval between observations of 2.61 hours. The comparison is made between the image sequences P_LORRI_ALICE_DEP_1 and P_LORRI_DEP_0. The adopted Pluto radius was 1190.6 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

From the sequence P_LORRI_ALICE_DEP_1, the specific location on Pluto was found in the images MET 299213682 and MET 299213712 (these were both 0.15 s exposures, obtained 30 s apart), which were rescaled to a common range of 458186 km, shifted and co-added. The pixel scale became 2.27 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 37 degrees, a rectangular 600 x 12 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 12 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 6th order polynomial.

From the sequence P_LORRI_DEP_0, the specific location on Pluto was found in the images MET 299204282 and MET 299204283 (these were both 0.15 s exposures, obtained 1 s apart), which were rescaled to a common range of 328830 km, shifted and co-added. The pixel scale became 1.63 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter clock-wise rotation of the co-added image through 40.2 degrees, a rectangular 600 x 12 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 12 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend was a 5th order polynomial.

Product IDs: TEMPVAR_E_LORRI_ALICE_DEP_1, TEMPVAR_E_MULTI_DEP_LONG_2, TEMPVAR_E_MULTI_DEP_LONG_1

The present data (from Figure 10 of Cheng, et al. (2017)) compares three haze I/F profiles obtained over equatorial locations, one profile from each of the image sequences

P_MULTI_DEP_LONG_1, P_MULTI_DEP_LONG_2, and P_LORRI_ALICE_DEP_1. The times relative to closest approach for these sequences were 3.78 hr, 7.25 hr, and 9.21 hr, respectively (from Table 1 of Cheng, et al. (2017)). The phase angles for these sequences were 169.0 degrees, 167.1 degrees, and 166.6 degrees respectively (from Table 3 of Cheng, et al. (2017). The adopted Pluto radius was 1190 km (Gladstone et al. 2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

From the sequence P_LORRI_ALICE_DEP_1, a profile was obtained over the specific location on Pluto (longitude, latitude) = (33 degrees,-0.2 degrees), using the images MET 299213793, MET 299213823 and MET 299213853 (these were all 0.15 s exposures, obtained 30 s apart). These images were rescaled to a common range of 458186 km, shifted and co-added. The pixel scale became 2.27 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a clock-wise rotation of the co-added image through 60 degrees, a rectangular 60020 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 20 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is an exponential with scale height 43.0 km.

From the sequence P_MULTI_DEP_LONG_2, a profile was obtained over the specific location on Pluto (longitude, latitude) = (32 degrees, 5 degrees), using the images MET 299206714, MET 299206715 and MET 299206716 (these were all 0.15 s exposures, obtained 1 s apart). These images were rescaled to a common range of 360779 km, shifted and co- added. The pixel scale became 1.79 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a clock-wise rotation of the co-added image through 60 degrees, a rectangular 600 x 16 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 16 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is an exponential with scale height 45.1 km.

From the sequence P_MULTI_DEP_LONG_1, a profile was obtained over the specific location on Pluto (longitude, latitude) = (43 degrees, -0.5 degrees), using the images MET 299194661 and MET 299194671 (these were both 0.15 s exposures, obtained 10 s apart). These images were rescaled to a common range of 193342 km, shifted and co-added. The pixel scale became 0.960 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a clock- wise rotation of the co-added image through 54 degrees, a rectangular 600 x 20 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 20 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 6th order polynomial.

Latitude variation data

Haze brightness profiles were compared from the same observation sequence P_MULTI_DEP_LONG_1 and obtained over the most northern latitudes imaged (latitude 44 degrees) and over equatorial latitudes at the same resolution of 0.96 km/px and at the same solar phase angle. The New Horizons departure images from P_MULTI_DEP_LONG_1 were at sufficiently high resolution to characterize haze layering, at a pixel scale of 0.96 km/pixel, and the solar phase angle was 169 degrees (Table 3 of Cheng, et al. (2017)). The Pluto longitudes and latitudes seen at the limb in the New Horizons haze observation sequences are shown in the limb traces of Figure 8 Cheng, et al. (2017).

The present data (from Figure 11 of Cheng, et al. (2017)) compares two haze I/F profiles from the image sequence P_MULTI_DEP_LONG_1, one from an equatorial latitude and one from a northern latitude, using images obtained over a 184 s time span. The adopted Pluto radius was 1190 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm (Cheng et al. 2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

Product ID: LATVAR_N_P_MULTI_DEP_LONG_1

From the sequence P_MULTI_DEP_LONG_1, a profile was obtained over the northern location on Pluto (longitude, latitude) = (312 degrees, 44 degrees), using the images MET 299194487 and MET 299194497 (these were both 0.15 s exposures, obtained 10 s apart). These images were rescaled to a common range of 193342 km, shifted and co-added. The pixel scale became 0.96 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a counter-clockwise rotation of the co-added image through 36 degrees, a rectangular 600 x 20 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 20 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 6th order polynomial.

Product ID: LATVAR_E_P_MULTI_DEP_LONG_1

Also from the sequence P_MULTI_DEP_LONG_1, a profile was obtained over the specific location on Pluto (longitude, latitude) = (43 degrees, -0.5 degrees), using the images MET 299194661 and MET 299194671 (these were both 0.15 s exposures, obtained 10 s apart). These images were rescaled to a common range of 193342 km, shifted and co-added. The pixel scale became 0.96 km/pixel. A smoothly varying image background was subtracted to remove solar stray light (this subtraction did not completely remove the stray light, but left fine linear features directed toward the sun and low level ghost features). After a clock- wise rotation of the co-added image through 54 degrees, a rectangular 600 x 20 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 20 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the I/F, and the detrended I/F. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is a 6th order polynomial.

Phase Angle Variation Data

Day-side Limb phase angle variation data: Haze brightness profiles were compared from observations obtained over the 19 hr time span from 3.6 hour before closest approach to 15.6 hr afterwards, including back scatter and forward scatter geometries. The solar phase function was compiled using haze observations over the day side limb at similar northern latitudes > 40 degrees.

At low solar phase angles in approach imaging of Pluto, the haze above the limb of Pluto is much fainter than the sunlit surface of Pluto, and the instrumental stray light from the bright limb of Pluto must be removed to measure haze. This removal was accomplished empirically, using observations obtained in similar back scatter viewing geometries and at similar image resolution by the P_LORRI_L1 and PELR_C_LORRI sequences before closest approach (Table 1 of Cheng, et al. (2008)). A haze profile at 19.6 degrees solar phase angle was extracted using images of Charon and Pluto obtained in similar viewing geometries, where the Charon image from C_LORRI was used to remove stray light from the P_LORRI Pluto image, and the excess brightness in the Pluto image was characterized and attributed to haze. This method takes advantage of the absence of an atmosphere, as well as absence of haze, at Charon Stern, et al. (2017).

The present data appeared in Fig. 12 of Cheng, et al. (2017). The adopted Pluto radius was 1190.4 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

Product ID: PHASE_DAY_P_LORRI_L1

From the sequence P_LORRI_L1, a profile was obtained over the northern location on Pluto (longitude, latitude) = (312 degrees, 44 degrees), using the image MET 299168039 (an 0.15 s exposure). This image was rescaled to a range of 171200 km. The pixel scale was 0.85 km/pixel. A hard stretch of the image shows low level ghost features; a column-oriented artifact of readout smear removal is also visible. A rectangular 725 x 75 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 75 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the column-average DN profile before removal of the scaled Charon profile (PHASE_DAY_PELR_C_LORRI), and the corrected I/F after removal of the scaled Charon profile. This Charon profile is scaled by a constant factor and is then subtracted from the 'column-average DN profile' of PHASE_DAY_P_LORRI_L1 to generate the corrected I/F profile.

Product ID: PHASE_DAY_PELR_C_LORRI

From the sequence PELR_C_LORRI, the images MET 299169015 and MET 299169016 (these were both 0.15 s exposures, obtained 1 s apart) were rescaled to a common range of 172233 km, shifted and co-added. The pixel scale became 0.855 km/pixel. A hard stretch of the image shows low level ghost features; a column-oriented artifact of readout smear removal is also visible. A rectangular 725 x 75 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 75 rows). The Charon DN values are scaled by a factor 0.7 to account for the different average brightness within the sunlit portions of the profiles. The result is the DN profile attributed to stray light versus the number of pixels x from the bright limb to be subtracted from the Pluto profile. (The number of pixels x is defined as the profile of average DN versus column number in pixel units from the PHASE_DAY_P_LORRI_L1 data product.) The three columns of the table are, from left to right, the radius from Pluto center in km, the pixel number x in the Charon profile (x has an arbitrary zero; the limb is at x=675), and the scaled Charon DN profile, where radius is the radius in the Pluto image at the corresponding pixel number relative to the bright limb. The Charon profile in PHASE_DAY_PELR_C_LORRI is scaled by a factor 0.7 and then subtracted from the column-average DN profile of PHASE_DAY_P_LORRI_L1 to generate the corrected I/F after removal of stray light.

Night-side Limb phase angle variation data: At low or moderate solar phase angles in approach imaging of Pluto, the haze above the limb of Pluto is much fainter than the sunlit surface of Pluto, and the instrumental stray light from the bright limb of Pluto must be removed to measure haze. This removal was accomplished empirically, using observations obtained in similar back scatter viewing geometries and at similar image resolution by the P_LORRI_L1 and PELR_C_LORRI sequences before closest approach (Table 1 of Cheng, et al. (2017)). A haze profile at 19.5 degrees solar phase angle over the night side limb of Pluto was extracted using images of Charon and Pluto obtained in similar viewing geometries, where the Charon image from C_LORRI was used to remove stray light from the P_LORRI Pluto image, and the excess brightness in the Pluto image was characterized and attributed to haze. This method takes advantage of the absence of an atmosphere, as well as absence of haze, at Charon Stern, et al. (2017).

The present data appeared in Fig. 13 of Cheng, et al. (2017). The adopted Pluto radius was 1190 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

Product ID: PHASE_NIGHT_P_LORRI_L1

From the sequence P_LORRI_L1, a profile was obtained over the northern location on Pluto (longitude, latitude) = (260 degrees, 13 degrees), using the images MET 299167703 and MET 299167704 (both are 0.15 s exposures). These images were rescaled to a range of 175814 km, shifted and co-added. The pixel scale was 0.873 km/pixel. A hard stretch of the image shows low level ghost features. After a clockwise rotation of 56 degrees, a rectangular 341100 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 100 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the column-average DN profile before removal of the scaled Charon profile, and the corrected I/F after removal of the scaled Charon profile. If the radius is <1900 km, then the brightness is a haze-lit Pluto surface brightness, and the radius given is that at closest approach of the line of sight to Pluto center.

Product ID: PHASE_NIGHT_PELR_C_LORRI

From the sequence PELR_C_LORRI, the images MET 299169015 and MET 299169016 (these were both 0.15 s exposures, obtained 1 s apart) were rescaled to a common range of 172233 km, shifted and co-added. The pixel scale became 0.855 km/pixel. A hard stretch of the image shows low level ghost features. The Charon image was flipped horizontally to match the geometry of the Pluto image, and a rectangular 40585 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 85 rows). The bright limb of the Charon profile was aligned to the terminator of the Pluto profile, and the Charon profile DN values were scaled by a factor 0.70 to account for the average brightness within the sunlit portions. The Charon profile gives the numbers of DN attributed to stray light versus the number of pixels x from the bright limb (x has an arbitrary zero; the image has been flipped; Charon limb is at x=62). The three columns of the table are, from left to right, the radius from Pluto center in km, the pixel number x in the Charon profile, and the scaled Charon DN, where radius is the radius in the Pluto image at the corresponding pixel number relative to the bright limb.

Product ID: PHASE_P_MVIC_LORRI_CA, PHASE_PELR_C_MVIC_LORRI_CA

At low or moderate solar phase angles in approach imaging of Pluto, the haze above the limb of Pluto is much fainter than the sunlit surface of Pluto, and the instrumental stray light from the bright limb of Pluto must be removed to measure haze. This removal was accomplished empirically, using observations obtained in similar back scatter viewing geometries and at similar image resolution by the P_MVIC_LORRI_CA and C_MVIC_LORRI_CA sequences before closest approach (Table 1 of Cheng et al. 2017). A Pluto haze profile at 67.3 degrees solar phase angle was extracted using images of Charon and Pluto obtained in similar viewing geometries, where the Charon image from PELR_C_MVIC_LORRI_CA was used to remove stray light from the P_MVIC_LORRI_CA Pluto image, and the excess brightness in the Pluto image was characterized and attributed to haze. This method takes advantage of the absence of an atmosphere, as well as absence of haze, at Charon Stern, et al. (2017).

The present data appeared in Fig. 15 of Cheng, et al. (2017). The adopted Pluto radius was 1190.5 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

From the sequence P_MVIC_LORRI_CA, a profile was obtained over the approximate northern location on Pluto (longitude, latitude) = (104 degrees, 55 degrees), using the image MET 299179658 (a 0.01 s exposure). This image was rescaled to a range of 17297 km. The pixel scale was 0.0859 km/pixel. A hard stretch of the image shows artifacts of readout smear removal and low level ghost features. A rectangular 77290 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 90 rows). The three columns of the table are, from left to right, the radius from Pluto center in km, the column-average DN profile before removal of the scaled Charon profile, and the corrected I/F after removal of the scaled Charon profile.

From the sequence PELR_C_MVIC_LORRI_CA, the image MET 299180406 (a 0.01s exposure) was used, for which the target range was 31724 km, and the pixel scale was 0.1575 km/pixel. A hard stretch of the image shows artifacts of readout smear removal. A rectangular 77290 pixel selection box was defined within which a column-average profile was measured (the brightness was averaged over 90 rows). The limb of the Charon profile was aligned to the limb of the Pluto profile, and the Charon profile DN values were scaled by a factor 3.08 to account for the average brightness within the sunlit portions. The Charon profile gives the numbers of DN attributed to stray light versus the number of pixels x from the bright limb (x has an arbitrary zero; Charon limb is at x=218). The three columns of the table are, from left to right, the radius from Pluto center in km, the pixel number x in the Charon profile, and the scaled Charon DN, where radius is the radius in the Pluto image at the corresponding pixel number relative to the bright limb.

Product ID: PHASE_P_HIPHASE_HIRES

The sequence P_HIPHASE_HIRES obtained images after closest approach (Table 1 of Cheng, et al. (2017)). Image MET 299181359, a 0.01 s exposure obtained at a range of 18758 km and apixel scale 0.0931 km/px, was used to obtain a Pluto haze profile at 148.3 degrees solar phase angle. The present data appeared in Fig. 16 of Cheng, et al. (2017). The adopted Pluto radius was 1190 km Gladstone, et al. (2016). The image brightness from a pixel in data units (DN) was converted into I/F at the pivot wavelength 607.6 nm Cheng, et al. (2008), where I is the scattered radiance and Pi*F is the solar irradiance 1.76 W/m2/nm, according to: I/F = [DN/sec] * [7.5 e-5].

The image MET 299181359 was obtained over the approximate location on Pluto (longitude, latitude) = (160 degrees, -7 degrees). A rectangular 894 x 110 pixel selection box was defined within which a column- average profile was measured (the brightness was averaged over 110 rows). The four columns of the table are, from left to right, the radius from Pluto center in km, the I/F, the detrended I/F, and a notation as to whether the brightness is a Pluto surface brightness or a haze brightness. If a Pluto surface brightness is noted, the radius given is that at closest approach of the line of sight to Pluto center. The detrended I/F is the fractional deviation of I/F from a trend, defined as [(I/F) / trend] - 1, where the trend is an exponential with scale height 61.95 km.

REXATMOS: Lower Atmospheric Temperature and Pressure Profiles

On 14 July 2015 New Horizons performed a radio occultation (RO) that sounded Pluto's atmosphere down to the surface. This file contains the atmospheric pressure-temperature profile derived from measurements at occultation entry, which occurred at sunset near the center of the anti-Charon hemisphere. The sensitivity of the measurements was enhanced by a unique configuration of ground equipment and spacecraft instrumentation. Signals were transmitted simultaneously by four antennas of the NASA Deep Space Network, each radiating 20 kW at a wavelength of 4.2 cm. The polarization was right circular for one pair of signals and left circular for the other pair. New Horizons received the four signals and separated them by polarization for processing by two independent receivers, each referenced to a different ultra-stable oscillator. The two data streams were digitized, filtered, and stored on the spacecraft for later transmission to Earth. All subsequent steps of analysis were performed after the data had been received on the ground. We calibrated each signal to remove effects not associated with Pluto's atmosphere, including the limb diffraction pattern. We then applied a specialized method of analysis to retrieve profiles of number density, pressure, and temperature from the combined phase measurements. See Hinson, et al. (2017) for a detailed discussion of the procedure used for data analysis and profile retrieval.

STAROCC: Stellar Atmospheric Occultation and Appulse Count Rates

A few hours after its encounter with Pluto, Alice observed the simultaneous stellar occultation and appulse of two UV-bright stars, 69 Ori and 72 Ori, respectively. As during the solar occultation that occurred immediately prior, the transmission of starlight through Pluto's atmosphere was sensitive to absorption by N2, CH4, C2H6, C2H2, C2H4, and haze. The line of sight to each star passed over different areas of Pluto from those probed by the solar occultation, providing insight into the degree of spatial and diurnal variability of atmospheric composition on Pluto.

The data have been binned in time to 1-second (MET) resolution. The observed stellar spectra have been extracted and corrected for a variety of instrumental effects.

For a detailed description of the data analysis process, please see Kammer, et al. (2020).

THERMSCAN: Diametric and Winter Pole Thermscans Across Pluto By REX

The data contained in the thermscan directory gives the values in Kelvin for the diametric and winter pole scans across Pluto for both the Right Circularly Polarized (RCP) and Left Circularly Polarized (LCP) channels of the REX (Radio EXperiment) instrument on New Horizons. The document section of this dataset contains three REX documents that can be used to help interpret the data. Note the calibration document (v4.7) has the most recent calibration constants which were used to generate the Calibrated REX dataset in the PDS archive and the values given in that paper should be used as the best known calibration values. The Radio Brightness Temperature Measurement document (Linscott, et al. 2017) uses older values for these constants. See Bird, et al. (2019) for a discussion of the uncertainties.

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