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Supplementary Material for

The atmosphere of Pluto as observed by New Horizons

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Materials and Methods

Solar Occultation Reduction and Density Retrieval Method

Ingress and egress occultations were performed separately, with a gap (labeled "No Data") between them when the Alice instrument power was intentionally cycled (to mitigate against any unfortunately timed safing events). Occultation circumstances are provided in Table S2. The Alice instrument (*3*) recorded the solar occultation data in photon counting ("pixel list") mode at a temporal resolution of 4 ms, and the observed count rate is a product of the solar spectral flux (which increases by a factor of ~1000 across the Alice bandpass of 52-187 nm) and the Alice effective area, which peaks at ~0.25 cm^2 near 100 nm (*3*). The count rate is corrected for instrumental effects, including 1) dark count (about 120 counts s^{-1} distributed over the microchannel plate (MCP) detector, of which ~100 counts s^{-1} are from New Horizon's radioisotope thermoelectric generator), 2) detector dead time (counts closer in time than 18 μs cannot be distinguished by the detector electronics), and 3) repeller grid transmission (shadowing of solar port photons by a high-voltage wire grid located just above the detector surface), 4) spacecraft deadband pointing corrections, and 5) charge depletion of the MCP, resulting in a ~2% approximately linear decrease in sensitivity over the ~70-minute course of the occultation, primarily at the longest wavelengths.

For retrieval of line of sight abundances, an optimal estimation routine is applied. Beginning at the level where absorption of sunlight is first noticeable (a tangent altitude of ~1500 km), fits are made to each 1-second transmission spectrum in turn (the tangent altitude of the Sun during the occultation changed at a rate of 3.5 km s^{-1}). Above a tangent altitude of 900 km, the only species fitted for are CH_4 and N_2. Retrievals of C_2H_2 and C_2H_4 are possible from a tangent altitude of 900 km all the way down to the surface. Sensitivity to CH_4 absorption is lost before reaching the surface, at about 150 km. Ethane (C_2H_6) also has an effect on the transmission, but, since it has a very similar absorption cross section to that of methane, they are strongly cross-correlated, and we only extract ethane abundances below a tangent altitude of 400 km. Retrievals are performed independently for both ingress and egress, and the similar results obtained for each are evidence for their robustness and suggest that Pluto's atmosphere is highly symmetric.

Method for Deriving Pluto's Atmosphere Structure from New Horizons Data

The model atmosphere in Fig. 3 was constructed under the assumption that Pluto has a global, nearly spherically symmetric atmosphere above the first half scale height of the surface and characterized by $\Delta p/p < 0.002$ (Dynamics section, main text). The temperature profile was constructed with an analytic expression (*56*) for the radial coordinate, which ensures that the temperature profile is smooth and all its derivatives continuous. The temperature at the surface is set to 37 K and coefficients are selected to replicate the average REX profile from z = 10–60 km. The surface pressure is set to 11 μbar and the ideal gas law is used to obtain the N_2 density. The atmosphere is assumed to be in hydrostatic equilibrium, with a surface CH_4/N_2 mixing ratio of 0.008, and the density profiles of N_2 and CH_4 are calculated with a homopause selected to match the solar occultation data above 500 km. From the inferred escape rates, we expect that the upper atmosphere will be isothermal, as the threshold for adiabatic cooling to be important (*33*) requires a loss rate of 3×10^{27} amu s^{-1} (= 2×10^{26} CH_4 s^{-1}), ~3 times larger than our inferred escape rate of 5×10^{25} CH_4 s^{-1}.

From the solar occultation data, the most accurately derived quantity is the line of sight (LOS) CH_4 column density profile from $z \sim 500$-1300 km and of higher quality than the CH_4 number densities illustrated in Fig. 3, which are derived by differentiating the LOS column densities. If CH_4 were in diffusive equilibrium, the inferred isothermal temperature in this region would be 62 K. Given the LOS CH_4 column density profile, we infer the N_2 LOS column density profile from the combined transmission light curves of the solar emission features of He I 58.4 nm, O V 63 nm, Mg X 63 nm, after subtracting the contribution from CH_4. The opacity of Pluto's atmosphere is dominated by N_2 absorption at these wavelengths. The resulting N_2 LOS column density profile can be fit with an isothermal 65 K atmosphere, quite close to the 62 K inferred from CH_4. However, CH_4 is not completely in diffusive equilibrium at 500 km. We adopt an expression (an empirical modification of an exact solution for an isothermal atmosphere with constant scale heights and eddy diffusion coefficient) for the CH_4 volume mixing ratio with respect to N_2,

$$\mu(CH_4) = 0.008\left[1+\exp\left(\frac{r-R_h}{H_c\dfrac{r}{R_h}}\right)\right]^{1-\gamma}$$

in which the mass ratio $\gamma = 16/28$, r is the radius from the center of Pluto, $H_c = 67$ km is the constant scale height, and $R_h = 1570$ km is the radius at the homopause level. All coefficients are derived by an iterative process that yields an isothermal atmosphere of 68.8 K as providing the best fit to the LOS CH_4 column density profile. When $\mu(CH_4)$ is extrapolated to the surface, it validates our choice of 0.008 for the surface CH_4/N_2 mixing ratio. But an acceptable range of this ratio spans 0.006-0.0084.

An alternate interpretation may be considered, where CH_4 is escaping Pluto at the Hunten limiting rate (*57*), which for the surface CH_4/N_2 mixing ratio of 0.008 is ~ 3×10^{26} CH_4 s^{-1} (only 6 times larger than our inferred CH_4 escape rate), and would be well mixed throughout the entire atmosphere with the scale height of N_2. However, under this circumstance the CH_4 LOS column density profile derived from the Alice solar occultation would yield an isothermal atmosphere at 110 K and a much expanded N_2 atmosphere (as predicted before arrival of New Horizons), which is incompatible with the solar occultation data.

Finally, to complement our derived atmospheric structure, a 1-D transport code for a multi-component atmosphere (*58*) was used in conjunction with the previously derived temperature profile and an eddy diffusion coefficient profile with 7.5×10^5 cm^2 s^{-1} at the surface and asymptotically reaching 3×10^6 cm^2 s^{-1} at $z = 210$ km, which yields a homopause at $z = 390$ km and the N_2 and CH_4 density profiles presented in Fig. 3.

Method For Estimating Particle Sedimentation

Haze particle sizes will be representative of the processes governing their formation and evolution. Pluto's background haze extends to at least 200 km altitude with a scale height ranging from 45 to 55 km. If formed by a similar process to that thought to be responsible for the detached haze layer on Titan, it will be composed of tholins (*59-61*). The tholin particles likely range in size from nanometers to perhaps as large as 0.5 micron and have mostly fractal structures. This extended haze has as many as 20 embedded thin haze layers with thicknesses ranging from 1 km to 3-4 km, and have a mean separation of 10.5 km. The haze layer nearest the surface (at a typical of altitude ~6 km) may be direct condensation of photochemical products in the low temperature region of the atmosphere near Pluto's surface. This last population of haze particles may be initially spherical, but will evolve if they interact with falling fractal particles from higher altitudes. The size and abundance of haze particles in the near-surface layer will be dependent upon the abundance of condensation nuclei. If nuclei are present in high numbers, then these photochemical haze particles may be small but numerous.

We estimate the sedimentation timescales of the haze particles by using a functional form for the sedimentation velocity that has been used extensively for Titan's atmosphere (*62,63,60*). Titan's atmosphere is also dominated by nitrogen with similar photochemical hydrocarbons and nitriles as minor gases. We change the values of gravity, pressure and temperature in the Titan formulation to match those for Pluto's atmosphere described above. Fig. S2 shows the resulting sedimentation timescale of spherical haze particles in Pluto's atmosphere over an altitude range that encompasses the observed haze. Normally, the sedimentation timescale is the timescale for a particle to fall a distance equal to either the scale height of the background atmosphere or the scale height of the haze. Because of the rapid sedimentation of the haze particles, we use here a vertical scale equal to the mean separation of the haze layers, i.e., 10.5 km. The sedimentation timescale shown in Fig. S2 is the sedimentation velocity divided by this mean distance. For reference, the vertical red line shows the length of Pluto's day, i.e., 6.4 Earth days, and the locations of six of the brightest layers are indicated with horizontal lines.

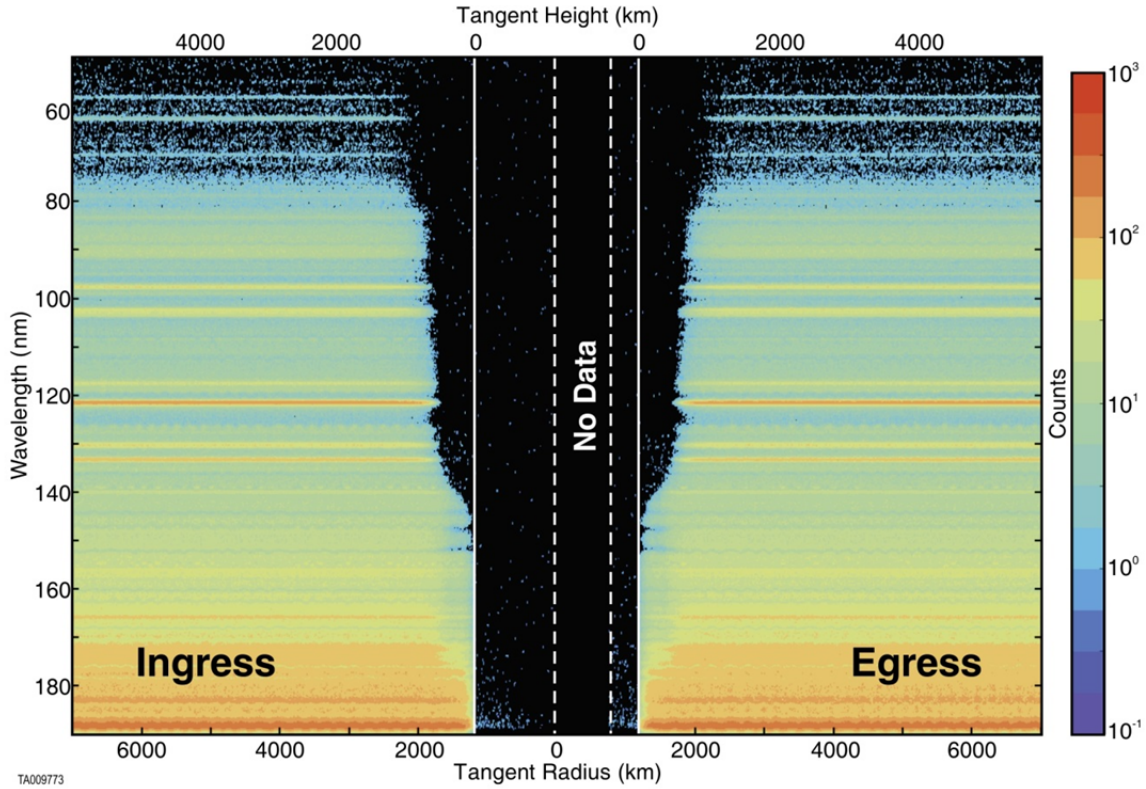

Fig. S1. Pluto Solar Occultation Light Curve. Alice count rates are shown as a function of tangent altitude / radius and ultraviolet wavelength for the ingress and egress of the Pluto solar occultation observed from the New Horizons spacecraft. Bright horizontal lines correspond to prominent solar emission features (e.g., Lyman α at 121.6 nm). Ingress and egress occultations were performed separately, with a gap (labeled "No Data") between them when the Alice instrument power was intentionally cycled (to mitigate against any unfortunately timed safing events). Occultation circumstances are provided in Table S2. The observed count rate is a product of the solar spectral flux (which increases by a factor of ~10^3 across the Alice bandpass of 52-187 nm) and the Alice effective area, which peaks at ~0.25 cm^2 near 100 nm (*3*).

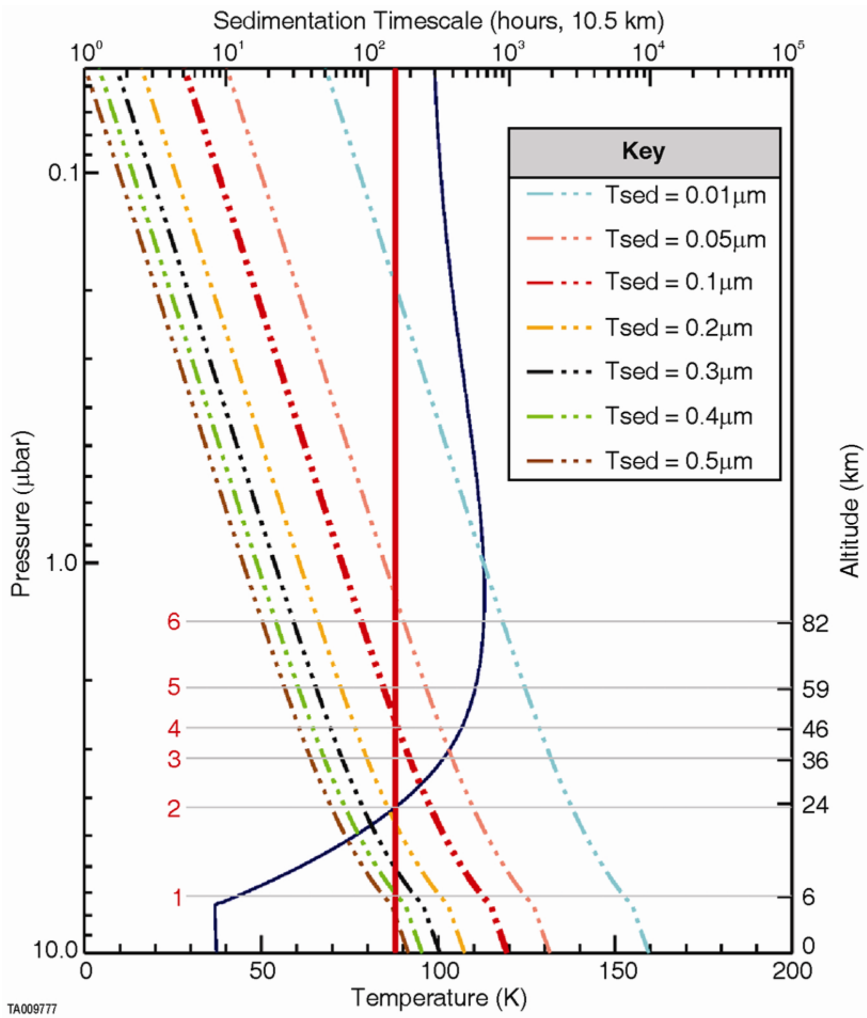

Fig. S2. Pluto Haze Sedimentation Timescales. Settling times for different sized particles to descend 10.5 km (the average separation between observed haze layers), are shown as a function of altitude in Pluto's atmosphere (triple-dot-dash curves). For example, r=0.2 µm particles at an altitude of 24 km take ~150 hours to fall to an altitude of 13.5 km. The horizontal lines indicate the altitudes of 6 prominent haze layers. The blue line shows the model temperature profile, and the vertical red line represents 1 Pluto day.

Table S1. Circumstances of the REX Pluto Radio Occultation. Universal time (UTC) at the New Horizons spacecraft on July 14, 2015 is provided for several epochs of interest, along with the range of the spacecraft from the center of Pluto, the tangent point (defined as the closest point to the center of Pluto along the line of sight from the New Horizons spacecraft to the center of the Earth) location and local time (based on a 24-hour clock with the Sun above the noon meridian at 12:00).

Epoch	UTC Time (hh:mm:ss)	Range (km)	Tangent Point Longitude (º)	Tangent Point Latitude (º)	Tangent Point Altitude (km)	Tangent Point Local Time (hh:mm)
Ingress Start	12:16:05	25559	195.7	-16.2	6182	16:36
Earthset Limb	12:45:15	48859	193.5	-17.0	0	16:31
Center	12:50:51	53333	97.0	-35.0	-1154	10:10
Earthrise Limb	12:56:29	57819	15.7	15.1	0	04:42
Egress End	13:25:32	81038	13.5	15.9	6159	04:38

Table S2. Circumstances of the Alice Pluto Solar Occultation. Columns are as in Table S1, except that the tangent point is the closest point to the center of Pluto along the line of sight from the New Horizons spacecraft to the Sun. Note that the Sun is a somewhat extended object as seen from Pluto, with an angular diameter of 0.016º.

Epoch	UTC Time (hh:mm:ss)	Range (km)	Tangent Point Longitude (º)	Tangent Point Latitude (º)	Tangent Point Altitude (km)	Tangent Point Local Time (hh:mm)
Ingress Start	12:16:35	25987	195.7	-15.9	5971	16:36
Sunset Limb: First Contact	12:44:18	48105	195.3	-15.5	7	16:32
Sunset Limb: Last Contact	12:44:22	48158	195.3	-15.4	-7	16:32
Ingress End	12:49:38	52361	212.6	-2.3	-1137	16:11
Center	12:49:51	52534	273.6	34.0	-1168	16:06
Egress Start	12:53:15	55247	12.9	16.9	-455	04:49
Sunrise Limb: First Contact	12:55:20	56910	13.3	16.5	-7	04:43
Sunrise Limb: Last Contact	12:55:24	56963	13.3	16.5	7	04:43
Egress End	13:25:30	80981	12.8	16.1	6483	04:38

Table S3. Circumstances of the Alice Charon Solar Occultation. Columns are as in Table S1, except that the tangent point is the closest point to the center of Charon along the line of sight from the New Horizons spacecraft to the Sun. Note that the Sun is a somewhat extended object as seen from Charon, with an angular diameter of 0.016º.

Epoch	UTC Time (hh:mm:ss)	Range (km)	Tangent Point Longitude (º)	Tangent Point Latitude (º)	Tangent Point Altitude (km)	Tangent Point Local Time (hh:mm)
Ingress Start	13:51:15	95140	13.7	-14.7	4717	16:43
Sunset Limb: First Contact	14:14:16	113669	49.0	13.0	15	19:07
Sunset Limb: Last Contact	14:14:30	113857	52.1	15.2	-15	19:20
Center	14:16:07	115159	86.3	32.8	-127	21:37
Sunrise Limb: First Contact	14:17:45	116474	130.4	38.2	-15	00:34
Sunrise Limb: Last Contact	14:17:58	116648	134.8	37.8	15	00:51
Egress End	14:41:30	135595	182.9	20.5	4829	04:07

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