**RESEARCH ARTICLE SUMMARY**

**PLANETARY SCIENCE**

The atmosphere of Pluto as observed by New Horizons


**INTRODUCTION:** For several decades, telescopic observations have shown that Pluto has a complex and intriguing atmosphere. But too little has been known to allow a complete understanding of its global structure and evolution. Major goals of the New Horizons mission included the characterization of the structure and composition of Pluto's atmosphere, as well as its escape rate, and to determine whether Charon has a measurable atmosphere.

**RATIONALE:** The New Horizons spacecraft included several instruments that observed Pluto's atmosphere, primarily (i) the Radio Experiment (REX) instrument, which produced near-surface pressure and temperature profiles; (ii) the Alice ultraviolet spectrograph, which gave information on atmospheric composition; and (iii) the Long Range Reconnaissance Imager (LORRI) and Multispectral Visible Imaging Camera (MVIC), which provided images of Pluto's hazes. Together, these instruments have provided data that allow an understanding of the current state of Pluto's atmosphere and its evolution.

**RESULTS:** The REX radio occultation determined Pluto's surface pressure and found a strong temperature inversion, both of which are generally consistent with atmospheric profiles retrieved from Earth-based stellar occultation measurements. The REX data showed near-symmetry between the structure at ingress and egress, as expected from sublimation driven dynamics, so horizontal winds are expected to be weak. The shallow near-surface boundary layer observed at ingress may arise directly from sublimation.

The Alice solar occultation showed absorption by methane and nitrogen and revealed the presence of the photochemical products acetylene and ethylene. The observed nitrogen opacity at high altitudes was lower than expected, which is consistent with a cold upper atmosphere. Such low temperatures imply an additional, but as yet unidentified, cooling agent.

A globally extensive haze extending to high altitudes, and with numerous embedded thin layers, is seen in the New Horizons images. The haze has a bluish color, suggesting a composition of very small particles. The observed scattering properties of the haze are consistent with a tholin-like composition. Buoyancy waves generated by winds flowing over orography can produce vertically propagating compression and rarefaction waves that may be related to the narrow haze layers.

Pluto's cold upper atmosphere means atmospheric escape must occur via slow thermal Jeans' escape. The inferred escape rate of nitrogen is ~10,000 times slower than predicted, whereas that of methane is about the same as predicted. The low nitrogen loss rate is consistent with an undetected Charon atmosphere but possibly inconsistent with sublimation/erosional features seen on Pluto's surface, so that past escape rates may have been much larger at times. Capture of escaping methane and photochemical products by Charon, and subsequent surface chemical reactions, may contribute to the reddish color of its north pole.

**CONCLUSION:** New Horizons observations have revolutionized our understanding of Pluto's atmosphere. The observations revealed major surprises, such as the unexpectedly cold upper atmosphere and the globally extensive haze layers. The cold upper atmosphere implies much lower escape rates of volatiles from Pluto than predicted and so has important implications for the volatile recycling and the long-term evolution of Pluto's atmosphere.

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The atmosphere of Pluto as observed by New Horizons


Observations made during the New Horizons flyby provide a detailed snapshot of the current state of Pluto’s atmosphere. Whereas the lower atmosphere (at altitudes of less than 200 kilometers) is consistent with ground-based stellar occultations, the upper atmosphere is much colder and more compact than indicated by pre-encounter models. Molecular nitrogen (N₂) dominates the atmosphere (at altitudes of less than 1800 kilometers or so), whereas methane (CH₄), acetylene (C₂H₂), ethylene (C₂H₄), and ethane (C₂H₆) are abundant minor species and likely feed the production of an extensive haze that encompasses Pluto. The cold upper atmosphere shuts off the anticipated enhanced-Jeans, hydrodynamic-like escape of Pluto’s atmosphere to space. It is unclear whether the current state of Pluto’s atmosphere is representative of its average state—over seasonal or geologic time scales.

Major goals of the New Horizons mission were to explore and characterize the structure and composition of Pluto’s atmosphere and to determine whether Charon has a measurable atmosphere of its own (1). Several instruments contribute to these goals, primarily (i) the Radio Experiment (REX) instrument (2), through uplink X-band radio occultations; (ii) the Alice instrument (3), through extreme- and far-ultraviolet solar occultations; and (iii) the Long Range Reconnaissance Imager (LORRI) and Multispectral Visible Imaging Camera (MVIC) (4, 5), through high-phase-angle imaging. The associated data sets were obtained within a few hours of the closest approach of New Horizons to Pluto at 11:48 UT on 14 July 2015. Pressure and temperature profiles of the lower atmosphere are derived from the REX data, the composition and structure of the extended atmosphere are derived from the Alice data (supported by approach observations of reflected ultraviolet sunlight), and the distribution and properties of Pluto’s hazes are derived from LORRI and MVIC images. This Research Article provides an overview of atmosphere science results.

A suggested atmosphere around Pluto (6–11) was confirmed by means of ground-based stellar occultation in 1988 (12, 13) and subsequently studied with later occultations (14–16) and spectra at near-infrared and microwave wavelengths (17, 18) and with models of increasing sophistication. These results revealed a primarily N₂ atmosphere with trace amounts of CH₄, CO, and HCN with complex surface interaction, an uncertain surface pressure of ~3 to 60 bar, and a warm stratosphere at ~100 K above a much colder surface (38 to 55 K). On the eve of the New Horizons flyby, critical questions remained about the atmospheric temperature and pressure profiles, dynamics, the presence and nature of possible clouds or hazes, the escape of Pluto’s atmosphere, and possible interactions with its large moon, Charon. The New Horizons flyby (19) enabled us to address these questions using radio occultations, ultraviolet occultations, and imaging at several phase angles between 15° and 165°.

**Pressure and temperature**

The New Horizons trajectory was designed to permit nearly simultaneous radio and solar occultations (20). The radio occultation was implemented in an uplink configuration by using 4.2-cm-wavelength signals transmitted by antennas of the NASA Deep Space Network and received by the REX instrument onboard New Horizons (2). The spacecraft passed almost diametrically behind Pluto as viewed from Earth, with ingress at sunrise near the center of the anti-Charon hemisphere and egress at sunset near the center of the Charon-facing hemisphere. Other characteristics of the REX observation are listed in table S1.

The location of Pluto’s surface is indicated by a characteristic diffraction pattern in the REX

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![Fig. 1. Pressure and temperature in Pluto’s lower atmosphere.](image)

These profiles were retrieved from radio occultation data recorded by the REX instrument onboard New Horizons. Diffraction effects were removed from the data (53), which greatly improves the accuracy of the results, and the conventional “Abel-transform” retrieval algorithm (2, 54, 55) was applied to the diffraction-corrected phase measurements. Each graph shows results at both entry (red line with circles) and exit (blue line with triangles), situated on opposite sides of Pluto. The profiles are most accurate at the surface, where the uncertainties in pressure and temperature are ~1 bar and 3 K, respectively. Temperature fluctuations at altitudes of >20 km are caused by noise; no gravity waves were detected at the sensitivity of these measurements. The dashed line indicates the saturation temperature of N₂ (29).
amplitude measurements (2). According to scalar diffraction theory (21), the limb of Pluto is aligned with the location where the amplitude is reduced by 50% from its “free space” value, as determined from data recorded well before or well after the occultation by Pluto. (The change in amplitude from refractive bending in Pluto’s atmosphere is negligible, in contrast to what occurs in stellar occultations observed from Earth.) At both entry and exit, the amplitude drops from 80 to 20% of its free-space value in a radial span of ~1.5 km. We used the solutions for the location of the surface at entry and exit to anchor the REX atmospheric profiles (Fig. 1), yielding an altitude scale with a relative uncertainty of ±0.4 km.

The absolute radii at entry and exit are much less certain, owing to limitations on the accuracy of the reconstructed spacecraft trajectory. Because the occultation was nearly diametric, the main concern is with any systematic bias in the position of the spacecraft along its flight path. This sort of error causes an underestimate in the position of the spacecraft relative to the surface at entry and exit to anchor the REX atmospheric profiles (Fig. 1), yielding an altitude scale with a relative uncertainty of ±0.4 km. This result is consistent with the global radius derived from images, 1187 ± 4 km (19). The difference, if real, could be a consequence of local topography or global flattening.

The atmospheric structure at altitudes of 0 to 50 km was retrieved from REX measurements of the Doppler-shifted frequency (or, equivalently, the phase) of the uplink radio signal (Fig. 1). We found that there is a strong temperature inversion at both ingress and egress for altitudes below ~20 km, which is qualitatively consistent with profiles retrieved from Earth-based stellar occultation measurements (16, 22, 23). However, there are two notable differences between the REX profiles at entry and exit, which indicate the presence of horizontal variations in temperature that had not been identified previously. First, the temperature inversion at entry is much stronger than its counterpart at exit; the derived mean vertical gradient in the lowest 10 km of the inversion is 6.4 ± 0.9 K km \(^{-1}\) at entry but only 3.4 ± 0.9 K km \(^{-1}\) at exit. Second, the temperature inversion at entry ends abruptly at an altitude of ~4 km, marking the top of a distinctive boundary layer. In contrast, the temperature inversion at exit appears to extend all the way to the surface, and we find no evidence for a boundary layer at that location. Because the radiative time constant of Pluto’s atmosphere is 10 to 15 Earth years (24), equivalent to ~700 Pluto days, these differences in temperature structure cannot be attributed to nighttime radiative cooling or daytime solar heating within the atmosphere. A boundary layer had been discussed on energetic grounds or as a way to connect stellar occultation profiles to conditions at an unknown surface radius (23, 25–28). REX results indicate that the boundary layer is not uniform across Pluto.

We estimated the surface pressure through downward extrapolation of the REX pressure profiles (Fig. 1), obtaining values of 11 ± 1 bar at entry and 10 ± 1 bar at exit. Analysis of stellar occultation data from 2012 and 2013 has yielded essentially the same result, a pressure of 11 bar at 1190 km radius (16). Hence, the mass of Pluto’s atmosphere has not changed dramatically in recent years.

Downward extrapolation of the REX exit profile yields a temperature adjacent to the surface of 45 ± 3 K. For comparison, a surface covered in N\(_2\) ice would have a temperature of 37.0 K to remain in vapor pressure equilibrium with the measured value of surface pressure (29). This may be indicative of a surface material less volatile than N\(_2\) ice. Occultation exit was closer than entry to the subsolar latitude—52°N at the time of the observation—which would contribute to a warmer surface temperature in the absence of N\(_2\) ice. (Where N\(_2\) ice is present, any increase in insolation is balanced largely by latent heat, with only a small change in the ice temperature (30).)

At occultation entry, the mean temperature temperature structure cannot be attributed to internal heating or to the observation of N\(_2\) ice at high pressures. (Where N\(_2\) ice is present, any increase in insolation is balanced largely by latent heat, with only a small change in the ice temperature (30).)

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Last, the vertical resolution of the entry profile in Fig. 1 is not sufficient to determine the temperature lapse rate in the boundary layer. The results to date cannot distinguish an isothermal layer from one with a wet or dry adiabatic gradient.

**Composition and chemistry**

Models indicate that photochemistry in Pluto’s upper atmosphere is similar to that of Titan and Triton (35–38). Methane (CH₄) is processed by far-ultraviolet sunlight into heavier hydrocarbons, and at Pluto’s distance from the Sun, interplanetary hydrogen scattering of solar Lyman α photons provides a comparable secondary source of CH₄ photolysis, which is also effective at night and in winter (39). Extreme-ultraviolet sunlight photolyzes molecular nitrogen (N₂), leading to nitrile production in conjunction with CH₄, which also leads to the production of high-altitude haze nuclei (40). Establishing Pluto’s atmospheric composition as a function of altitude is important for understanding its atmospheric chemistry, and the solar occultations by the New Horizons Alice ultraviolet spectrograph (3) provide an excellent data set for this purpose. The circumstances of the solar occultations by Pluto and Charon are presented in tables S2 and S3, respectively. The transmission of Pluto’s atmosphere is directly derived from the Alice ingress and egress data (Fig. 2; the full solar occultation light curve is presented in fig. S1). The transmission profile clearly indicates the altitude at which the tangent line-of-sight opacity reaches unity for a given wavelength and also provides a useful scale height at that level.

The Pluto solar occultation results are surprising in that the expected upper atmospheric opacity of N₂ at wavelengths ~65 to 100 nm is largely absent, and the opacity is mostly due to CH₄. At wavelengths longward of 100 nm, CH₄, C₂H₂, C₂H₆, C₃H₆, and H₂ account for a majority of the observed opacity. A model consistent with the observed transmission requires a much colder upper atmosphere than in pre-encounter models (Fig. 3). The absorption of sunlight in the 57- to 64-nm-wavelength range by N₂ at high altitudes (~850 to 1400 km) constrains the temperature of the upper atmosphere to be ~70 K. Such low temperatures are potentially achievable through cooling by C₂H₂ ν₅ band emission and HCN rotational line emission (if HCN is supersaturated, not in vapor pressure equilibrium at these cold temperatures). However, recent Earth-based observations by using the Atacama Large Millimeter/submillimeter Array (ALMA) suggest that the HCN abundances in Pluto’s upper atmosphere are many times less than would be required (16, 18). Currently, the details of exactly how Pluto’s upper atmosphere is being cooled are poorly understood. Also, the ALMA data provide a definitive observation of CO on Pluto, which has not been detected in the Alice solar occultation data.

**Hazes**

Extensive, optically thin hazes are seen in New Horizons images of Pluto (Fig. 4), extending to altitudes of >200 km, with typical brightness scale heights of ~50 km. Distinct layers are present, which vary with latitude but are contiguous over distances of >1000 km. Separated by ~10 km, the layers merge, separate (divide into thinner layers), or appear and disappear when traced around the limb. Using radial brightness profiles at various points around the limb, prominent haze layers are found in LORRI images at altitudes of ~10, 30, 90, and 190 km, but in the highest-resolution MVIC images (<1 km/pixel), about 20 haze layers are resolved. The haze scale height decreases to ~30 km at altitudes of 100 to 200 km, which is consistent with the decreasing atmospheric scale height (Fig. 3). Although most obvious at high phase angles (θ ~ 165° to 169°) with I/F values (observed intensity times π and divided by the incident solar flux) of ~0.2 to 0.3 at red wavelengths (in MVIC red, 540 to 700 nm, and LORRI images, 350 to 850 nm) and I/F values up to 0.7 to 0.8 at blue wavelengths (in MVIC blue images, 400 to 550 nm), the hazes are also seen at moderate scattering angles (for example, at I/F ~ 0.02 at θ ~ 38°, in MVIC red and blue images) and are just barely detectable at low phase angles (for example, at I/F ~ 0.003 at θ ~ 20°, in LORRI images) but are undetected at the lowest phase angles (θ ~ 15°) on approach. Although the blue haze color is consistent with very small (radii r ~ 10 nm) particles (Rayleigh scatterers), their large high- to low-phase brightness ratio suggests much larger particles (with r > 0.1 μm); it is possible that they are aggregate particles (randomly shaped particles of a fraction of a micrometer in radius, composed of ~10-nm spheres), which could satisfy both of these constraints. The MVIC blue/red ratio increases with altitude, which is consistent with smaller particles at higher altitudes. As seen in Fig. 4, the haze is brightest just above the limb, and from this and other images, the haze is brightest around the limb near the direction of Pluto north.

Haze optical properties can be roughly estimated as a function of particle size by using Mie theory—for example, with optical constants of n = 1.69 and k = 0.018 (where n and k are the real and imaginary parts of the complex refractive index, respectively), which are appropriate for tholin-like particles (41) at the LORRI pivot wavelength of 607.6 nm (although over the LORRI bandpass, n varies between 1.63 and 1.72, whereas k varies between 0.11 and 0.0024). For optically thin conditions, I/F ~ R(θ) τLOS/4, where P is the scattering phase function at phase angle θ and τLOS is the line-of-sight opacity. On the basis of their large forward/backward scattering ratio, which is met by Mie-scattering particles with radii no smaller than ~0.2 μm, P(165°) ~ 5, leading to τLOS ~ 0.16, or a vertical haze scattering optical depth of ~0.013. For particles of r ~ 0.2 μm, the scattering cross section of a single particle is...
produced in a manner similar to Titan’s hazes (40), an upper limit to their mass production rate is calculated to be $n_{\text{HAZE}} \sim 0.8$ particles/cm$^3$, or a column mass of $8 \times 10^{-8}$ g cm$^{-2}$ (assuming a particle density of 0.65 g cm$^{-3}$) (42).

If the haze particles are photochemically produced in a manner similar to Titan’s hazes (40), an upper limit to their mass production rate is given by the photolysis loss rate of methane; from photochemical models (37, 38), we estimate this at $\sim 1 \times 10^{-16}$ g cm$^{-2}$ s$^{-1}$. In steady state, this is also the loss rate, so (dividing the column mass by the production rate) the haze residence time is calculated to be $t_{\text{HAZE}} \sim 90$ Earth days. By comparison, the time expected for 10-nm particles to settle through the lowest 10 km of the atmosphere is ~400 Earth days (Fig. S2), whereas 0.2-μm particles would be expected to traverse this region much faster, in ~10 Earth days.

**Dynamics**

Pluto’s atmospheric pressure and composition is buffered by sublimation equilibrium with surface ices (principally $N_2$, with minor amounts of CH$_4$ and CO ices). Solar-induced sublimation of these ices drives transport to colder surface regions. Subsequent condensation constrains pressure variations in the atmosphere above the first 1/2-scale height to $\Delta p/\rho < 0.002$ for a surface pressure $\sim 10$ mbar (43, 44) and for ice $\Delta T/T < 0.002$ (44). For pressures $<5$ mbar, the radio occultation data exhibits global symmetry, as expected from sublimation-driven dynamics. Previously, ground-based stellar occultations also yielded symmetry within the error bars about the occultation midpoint (for example, as shown for the 2006 Siding Spring light curve) (45). With very little pressure variation in the current atmosphere on a global scale, horizontal winds are expected to be weak (no more than $\sim 10$ m s$^{-1}$). Radiative time constants ($\tau_{\text{RAD}}$) for Pluto’s atmosphere above its planetary boundary layer are on the order of 10 to 15 Earth years (24), or $\tau_{\text{RAD}} \sim 2.5 \times 10^{19}$ Hz. Diurnally driven dynamics with frequency of $\Omega = 2\pi/639$ days$^{-1} = 114 \times 10^{-6}$ Hz will be damped in amplitude by a factor $\sim Q^2/(Q_{\text{RAD}}^2 + Q^2) \sim 5.6 \times 10^{-6}$. Although the surface likely has a short thermal response time constant, surface radiative exchange with the atmosphere is very weak, and the very steep positive temperature gradient in the near-surface layer as seen both in REX occultation data (Fig. 1) and ground-based stellar occultation data (15) should suppress convection and inhibit the formation of a deep global troposphere.

Gravity waves have previously been investigated as a source for scintillations seen in Earth-based stellar occultation data (46, 47). Pluto’s atmospheric dynamics can generate internal gravity (buoyancy) waves driven by sublimation forcing (48) and orographic forcing (wind blowing over topography). Mountains and mountain ranges with heights of 2 to 3 km have been detected with New Horizons imagery (19, 49), and the distinct haze layers in Pluto’s atmosphere are possibly a result of orographic forcing. For example, a
\( w_0 = 1 \text{ m s}^{-1} \) wind blowing over topography with height amplitude of \( x_0 = 1.5 \text{ km} \), horizontal wavelength \( \lambda_x \approx 120 \text{ km} \) (zonal wavenumber \( k_x = 2\pi/\lambda_x \approx 600 \text{ km}^{-1} \)), meridional wavelength \( \lambda_y \approx 3600 \text{ km} \), and period \( T = 2\pi/|k_x|w_0 = 1.4 \text{ Earth days} \) yields a vertical forcing velocity \( w' = w_0 k_x x_0 \approx 0.008 \text{ m s}^{-1} \). Because of the small adiabatic lapse rate (~0.62 K km\(^{-1}\)) at the surface and decreasing with altitude), the gravity wave reaches saturation amplitudes by an altitude of 10 km. Saturation occurs when the buoyancy-restoring force vanishes—when the sum of the wave and mean temperature gradients render the atmosphere adiabatic, and the vertical parcel velocity \( w' \) is equal to \( w_0 \), the vertical group velocity (50). At 10 km altitude, with any surface vertical forcing velocity \( w_0 > 0.008 \text{ m s}^{-1} \), the solution to the gravity wave equation yields saturated amplitudes for the wave magnitude of \( T^* \approx 0.7 \text{ K} \). The solution to the gravity wave equation yields saturated amplitudes for the wave magnitude of \( T^* \approx 0.7 \text{ K} \). The solution to the gravity wave equation yields saturated amplitudes for the wave magnitude of \( T^* \approx 0.7 \text{ K} \).

**Conclusions**

Observations made from New Horizons have already greatly altered our understanding of how Pluto’s atmosphere works, even with many data remaining to be reduced and analyzed. LORRI, MVIC, and Linear Etalon Imaging Spectral Array (LEISA) imaging clearly reveal optically thin hazes extending to altitudes of at least 200 km. Photochemical models have long predicted the formation of higher hydrocarbons, and species such as acetylene (C\(_2\)H\(_2\)) and ethylene (C\(_2\)H\(_4\)) are clearly detected in the Alice solar occultation data (ultraviolet reflectance spectra also show the absorption signatures of C\(_2\)H\(_2\) and C\(_2\)H\(_4\)). Last, the escape rate of Pluto’s atmosphere is found to be much less than expected, although over time it may have left its signature on Charon (39, 31).

Although most of the results obtained to date agree with each other, there are several problems areas: Is cooling by HCN self-limited because of condensation? Are the haze layers consistent with transport by winds? Does the escape of much more methane than nitrogen agree with geologic evidence? The data obtained by the New Horizons mission are likely to provide the answers and allow the development of a fully self-consistent description of Pluto’s atmosphere.


G. R. Gladstone, W. R. Pryor, S. A. Stern, Lyss’s day.


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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/351/6279/aad8866/suppl/DC1

Materials and Methods

Figs. S1 and S2

Tables S1 to S3

New Horizons Science Team Author List

References (56–63)

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