

Evidence that Pluto's atmosphere does not collapse from occultations including the 2013 May 04 event



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ABSTRACT

Combining stellar occultation observations probing Pluto's atmosphere from 1988 to 2013, and models of energy balance between Pluto's surface and atmosphere, we find the preferred models are consistent with Pluto retaining a collisional atmosphere throughout its 248-year orbit. The occultation results show an increasing atmospheric pressure with time in the current epoch, a trend present only in models with a high thermal inertia and a permanent N₂ ice cap at Pluto's north rotational pole.

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1. Introduction

Pluto has an eccentric orbit, $e = 0.26$, and high obliquity, $102\text{--}126^\circ$ (Dobrovolskis and Harris, 1983), leading to complex changes in surface insolation over a Pluto year, and, therefore, in surface temperatures. When the first volatile ice species, CH₄, was discovered on Pluto's surface, researchers quickly recognized that these insolation and temperature variations would lead to large annual pressure variations, due to the very sensitive dependence of equilibrium vapor–pressure on the surface temperature.

Pluto receives nearly three times less sunlight at aphelion than perihelion, prompting early modelers to predict that Pluto's atmosphere would expand and collapse over its orbit (Stern and Trafton, 1984). More sophisticated models were made in the 1990s (Hansen and Paige, 1996), after the definitive detection of Pluto's atmosphere in 1988 (Millis et al., 1993) and the discovery of N₂ as the dominant volatile in the atmosphere and on the surface (Owen et al., 1993). Similar models were run recently (Young, 2013), systematically exploring a range of parameter space. These models predict changes on decadal timescales, dependent on the thermal inertia of the substrate and the total N₂ inventory. Only in a subset of the models did pressures increase by a factor of two between 1988 and 2002/2006, consistent with observations (Sicardy et al., 2003; Elliot et al., 2003; Young et al., 2008a). These models include important physical processes including the global

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migration of N_2 through a seasonal cycle and the varying heat sources which include insolation changes due to Pluto's varying heliocentric distance, the effect of time varying albedo patterns on insolation, the obliquity of Pluto which changes the frost pattern facing the Sun and finally the heat flow from or to the substrate. These are described in more detail in [Young \(2013\)](#). Over the course of a Pluto year, changes in global insolation drives the migration of 1 m of frost, therefore, seasonal changes in frost distribution are likely. Continuing observations of Pluto's atmospheric pressure on decadal timescales constrain thermal inertia, providing insight into deeper layers of the surface that are not visible in imaging.

2. Observations

Stellar occultations, where a body such as Pluto passes between an observer and a distant star, provide the most sensitive method for measuring Pluto's changing atmospheric pressure. Pluto was predicted to occult a 14th magnitude (R filter) star on May 4, 2013 ([Assafin et al., 2010](#)). This was one of the most favorable Pluto occultations of 2013 because of the bright star, slow shadow velocity (10.6 km/s at Cerro Tololo), and shadow path near large telescopes. An unusual opportunity to refine the predicted path of the shadow presented itself in March 2013 when Pluto passed within 0.5 arcsec of the occulted star six weeks before the occultation. The Portable High-Speed Occultation Telescope group (based at Southwest Research Institute, Lowell Observatory and Wellesley College) coordinated observations of the appulse from multiple sites including the 0.9-m astrograph at Cerro Tololo Inter-American Observatory (CTIO), the 1-m Liverpool Telescope on the Canary Islands, as well as the Las Cumbres Observatory Global Telescope Network (LCOGT) sites at McDonald Texas, CTIO Chile, SAAO South Africa, SSO Australia and Haleakala Hawaii. The appulse observations improved the knowledge of the shadow path location such that the final prediction was within 100 km of the reconstructed location.

Occultation observations were obtained from the three 1.0-m LCOGT telescopes at Cerro Tololo ([Brown et al., 2013](#)). The three telescopes have 1.0-m apertures and used identical instrumentation, an off-axis Finger Lakes Instrumentation MicroLine 4720 frame transfer CCD cameras, unfiltered. The cameras have a 2-s readout time, and autonomous observations were scheduled with different exposure times to provide adequate time resolution and minimize data gaps in the ensemble observation. We measured the combined flux from the merged image of Pluto, Charon and occultation star as a function of time using aperture photometry, and accounted for variable atmospheric transparency using differential photometry with five field stars. The light curves were normalized using post-occultation photometry of the field stars relative to the occultation star.

Observations were also attempted from the Research and Education Cooperative Occultation Network (RECON) from the western United States. This was an excellent opportunity to test the network and provided backup observing stations in case the actual path was further north than predicted. Observations were attempted at 14 sites and data were acquired at all sites, although in the end, all RECON sites were outside of the shadow path.

3. Modeling

In order to interpret an occultation light curve we need to have accurate knowledge of the precise location of the star relative to Pluto. The geometric solution was obtained by a simultaneous fit to 7 light curves from the following five sites: Cerro Burek Argentina, LCOGT at Cerro Tololo Chile (3 light curves), Pico dos Dias Brazil, La Silla Observatory Chile and San Pedro de Atacama Chile.

The observation at San Pedro de Atacama was made using Caisey Harlinton's 0.5-m Searchlight Observatory Network Telescope. Details of the geometric solution will be given in a future paper. These sites span ~ 900 km across the shadow covering more than 35% of Pluto's disk with chords both north and south of the centerline. The reconstructed impact parameter for LCOGT at Cerro Tololo (i.e., the closest distance of that site from the center of the occultation shadow) is 370 ± 5 km with a mid time of $08:23:21.60 \pm 0.05$ s UT on May 4, 2013.

We fit the three LCOGT light curves simultaneously using a standard Pluto atmospheric model ([Elliot and Young, 1992](#)) that separates the atmosphere into two domains: a clear upper atmosphere with at most a small thermal gradient, and a lower atmosphere that potentially includes a haze layer. This model was developed after the 1988 Pluto occultation, which showed a distinct kink, or change in slope, in the light curve indicating a difference in the atmosphere above and below about 1215 km from Pluto's center. The lower atmosphere can be described with either a haze layer, or by a thermal gradient ([Eshleman, 1989](#); [Hubbard et al., 1990](#); [Stansberry et al., 1994](#)) or a combination of the two to match the low flux levels in the middle of the occultation light curves. We focus on the derived upper atmosphere parameters in this paper, but give the lower atmospheric parameters for completeness. [Fig. 1](#) shows the LCOGT light curves and the best fitting model with a pressure of 2.7 ± 0.2 microbar and a temperature of 113 ± 2 K for an isothermal atmosphere at 1275 km from Pluto's center. The lower atmosphere was fit with a haze onset radius of 1224 ± 2 km, a haze extinction coefficient at onset of $3.2 \pm 0.3 \times 10^3 \text{ km}^{-1}$ and a haze scale height of 21 ± 5 km (see [Elliot and Young, 1992](#), for details). This atmospheric pressure extends the trend of increasing surface pressure with temperature since 1988.

Previous work ([Young, 2013](#)) combined stellar occultation observations from 1988 to 2010 and new volatile transport models to show that Pluto's seasonal variation can be fit by models that fall into one of three classes: a class with high thermal inertia, which results in a northern hemisphere that is never devoid of N_2 ice (Permanent Northern Volatile, PNV, using the rotational north pole convention where the north pole is currently sunlit), a class with moderate thermal inertia and moderate N_2 inventory, resulting in two periods of exchange of N_2 ice between the northern and southern hemispheres that extend for decades after each equinox (Exchange with Pressure Plateau, EPP), and a class with moderate thermal inertia and smaller N_2 inventory, where the two periods of exchange of N_2 ice last only a short time after each equinox (Exchange with Early Collapse, EEC). These models do not include longitudinal variation in frost distribution and the runs in [Young \(2013\)](#) investigated only one value for the substrate albedo (0.2). All of the low-albedo substrate models have a low-albedo terrain at the south pole in 1989 during the mutual event season. However, the mutual event maps show a high albedo surface in the south pole. We have expanded the parameter-space search to include a high value for the substrate albedo (0.6) and find Permanent Northern Volatile models with substrate albedo of 0.6 on the south pole and volatiles with an assumed albedo of 0.4 on the northern hemisphere. This pattern would appear to have a brighter southern pole at the epoch of the mutual events (equinox in 1989). We present these model runs only to demonstrate that the models can produce solutions with a bright southern pole. Another consideration is the source of the bright south pole at equinox. The south pole could be bright due to CH_4 ice at the south pole and this would not be reflected in the volatile-transport models because the models only consider the dominant volatile, N_2 .

With this most recent stellar occultation of May 4 2013, we are able to distinguish between these three classes ([Fig. 2](#)) of seasonal variation. The new data clearly preclude the EEC ([Fig. 2C](#)) and EPP ([Fig. 2B](#)) classes. Only the PNV class is consistent with the

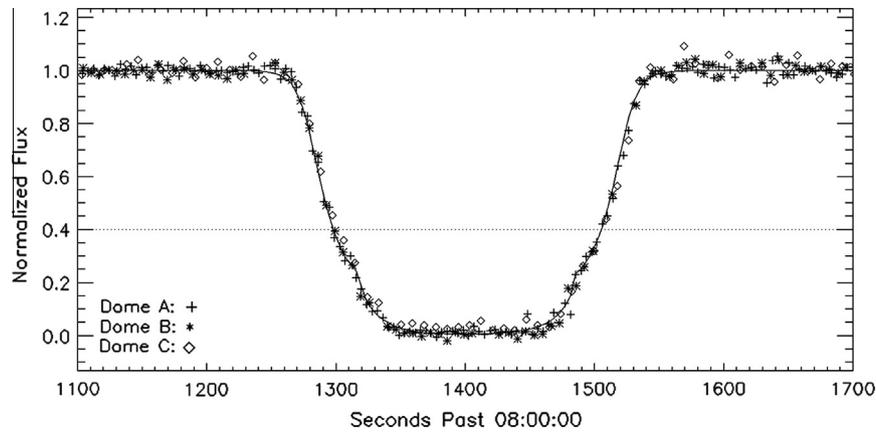


Fig. 1. The observed occultation light curves overlaid with the best fitting model. Time plotted is seconds after 2013 May 04 08:00:00 UTC. The line at normalized flux of 0.4 corresponds to 1275 km in Pluto's atmosphere. The transition from the upper atmosphere to the lower atmosphere in the fitted model occurs at a flux level of ~ 0.25 in these data (see text for details). All three telescopes are 1.0-m telescopes located at the Cerro Tololo LCOGT node. The WGS 84 Coordinates of the three telescopes are (1) Dome A: Latitude: $30^{\circ}.167383S$, Longitude: $70^{\circ}.804789W$, (2) Dome B: Latitude: $30^{\circ}.167331S$, Longitude: $70^{\circ}.804661W$ and (3) Dome C: Latitude: $30^{\circ}.167447S$, Longitude: $70^{\circ}.804681W$. All telescopes are at an altitude of 2201 m. The Dome A telescope used a 2-s integration time; Dome B used a 3-s integration time and Dome C used a 5-s integration time.

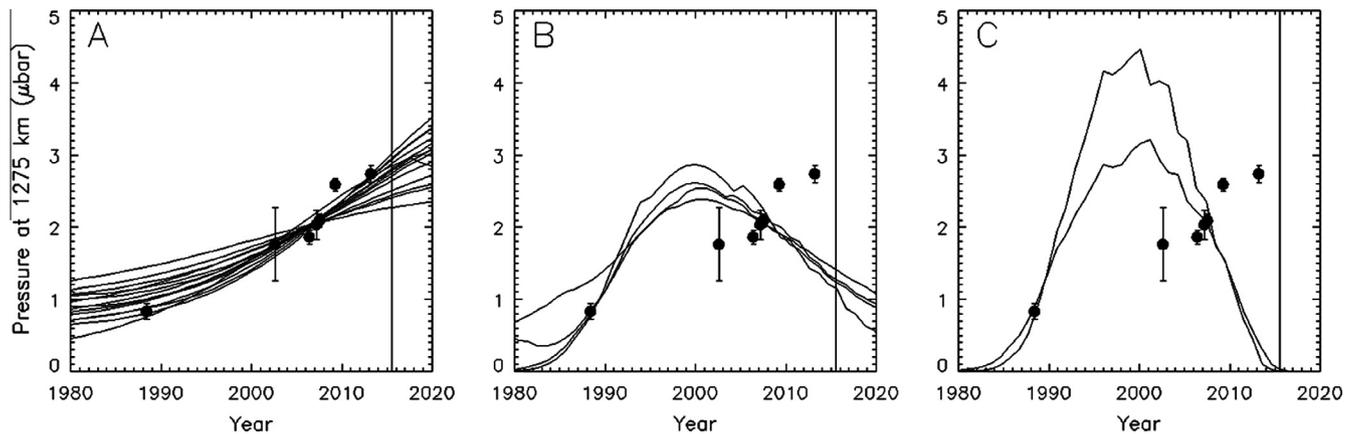


Fig. 2. Comparison of pressures derived from occultation measurements to pressures from volatile transport models that are consistent with the 1988 and 2006 occultations, and also roughly consistent with visible, infrared, and thermal measurements (the preferred runs of Young, 2013). Points indicate pressures in Pluto's atmosphere at 1275 km from Pluto's center, derived from fits of occultation data using the model of Elliot and Young (1992), and the points are repeated in each panel. These include six previously published measurements (Young, 2013) and the new measurement reported here. Lines correspond to modeled pressures for the Permanent Northern Volatiles (PNV) cases (2A), the Exchange with Pressure Plateau (EPP) cases (2B), and the Exchange with Early Collapse (EEC) cases (2C). As the pressures throughout the Pluto year for EPP1 (Young, 2013) resemble the PNV cases (with a minimum pressure of 21 microbars for EPP1), and the pressures for PNV8 resemble the EPP cases, these two models are plotted with the alternative category. The only class of model consistent with the increasing pressure from 1988 to 2013 is the Permanent Northern Volatile class. The vertical line in each panel is the closest approach of the New Horizons spacecraft to Pluto in July 2015.

observations that show an increasing surface pressure in the current epoch. Both the EEC and EPP classes result in condensation of Pluto's atmosphere after solstice with surface pressures at the nanobar level or less (Young, 2013). The PNV model has a high thermal inertia, such that the atmosphere does not collapse over the course of a Pluto year with typical minimum values for the surface pressure of roughly 10 microbar. At this surface pressure the atmosphere is collisional and present globally, and we conclude that Pluto's atmosphere does not collapse at any point during its 248-year orbit. We consider that an atmosphere has not collapsed if it is global, collisional, and opaque to UV radiation. An atmosphere that is global and collisional can efficiently transport latent heat over its whole surface. The cutoff for a global atmosphere is ~ 0.06 microbars (Spencer et al., 1997) or more than 2 orders of magnitude smaller than the typical minimum pressure for PNV models.

4. Discussion

The PNV model runs that show an increasing atmospheric pressure with time over the span of stellar occultation observations

(1988–2013) have substrate thermal inertias of 1000 or $3162 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ (tiu). These values are much larger than the thermal inertia measured from daily variation in temperature on Pluto of 20–30 tiu for the non- N_2 ice regions (Lellouch et al., 2011), or on other bodies such as Mimas, 16–66 tiu (Howett et al., 2011). The range of thermal inertias derived for Pluto from this work is comparable to that for pure, non-porous H_2O ice at 30–40 K, 2300–3500 tiu (Spencer and Moore, 1992). This points to a variation of thermal inertia with depth on Pluto. The variation of temperature over a day probes depths of ~ 1 m, while the seasonal models depend on conditions near 100 m, indicating that the thermal inertia is lower near the surface (~ 1 m) than at depth (~ 100 m).

Evidence for large thermal inertias at the depths probed by seasonal variation has also been seen on Triton. Models that best explain the presence of a N_2 cap on the summer hemisphere of Triton during the 1989 Voyager encounter have thermal inertias greater than 1000 tiu (Spencer and Moore, 1992). Also large-thermal inertia models for Triton (Spencer and Moore, 1992) are further supported by the large increase in atmospheric pressure observed

on Triton from 1989 to 1995 (Olkin et al., 1997; Elliot et al., 2000). Pluto and Triton are similar in size, density and surface composition. They may also be similar in size in their substrate thermal inertia properties.

Pluto's atmosphere is protected from collapse because of the high thermal inertia of the substrate. The mechanism that prevents the collapse is specific to Pluto, because it relies on Pluto's high obliquity and the coincidence of equinox with perihelion and aphelion. In the PNV model, volatiles are present on both the southern and northern hemispheres of Pluto just past aphelion. Sunlight absorbed in the southern hemisphere (the summer hemisphere)

from aphelion to perihelion powers an exchange of volatiles from the southern hemisphere to the northern (winter) hemisphere. Latent heat of sublimation cools the southern hemisphere and warms the northern hemisphere, keeping the N_2 ice on both hemispheres the same temperature. This exchange of volatiles continues until all the N_2 ice on the southern hemisphere sublimates and is condensed onto Pluto's northern hemisphere. Once this occurs at approximately 1910 in Fig. 3b and 1890 in Fig. 3d, the northern (winter at this time) hemisphere is no longer warmed by latent heat, and begins to cool. However, the thermal inertia of the substrate is high, so the surface temperature on the northern

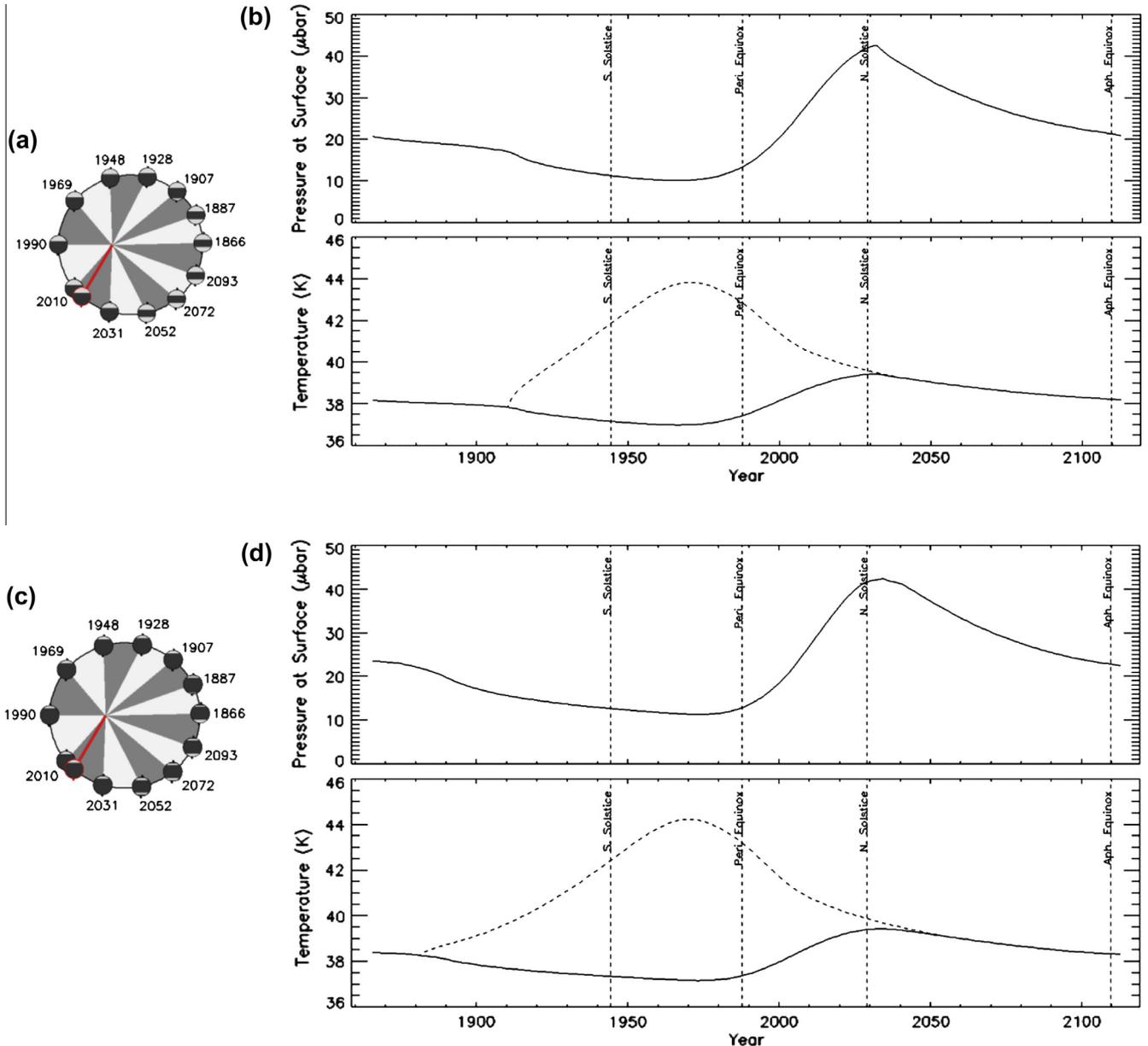


Fig. 3. Results for two different PNV runs (PNV9 and PNV12 from Young (2013)). Both of these cases have a high thermal inertia (3162 tui), but one case has a large inventory of N_2 (16 g cm^{-2} for PNV9) and the other has a small inventory of N_2 (2 g cm^{-2} for PNV12). For each run, the plot on the left shows Pluto over a season. The circles represent Pluto at each of 12 equally spaced times in the orbit, indicated by date. The short vertical bar behind the circles represents the rotational axis, oriented so that the axis is perpendicular to the Sun vector at the equinoxes, with the northern pole at the top (currently pointed sunward). Latitude bands are colored with their geometric albedos. The red line indicates the globe at the time of the New Horizons encounter (July 2015). The plots on the right show surface pressure and temperature as a function of year. The temperatures of the N_2 ice (solid line) and of a mid-southern latitude (-60° , dashed line) are indicated. At any given time, all the N_2 ice on Pluto's surface is at the same temperature due to the transfer of energy from condensation and sublimation. Bare, N_2 -ice free regions can have temperatures higher than the ice temperature, as seen from 1910 to 2030 in panel (b). The surface pressure reaches a minimum of ~ 10 microbar for each of these cases and this is typical for PNV models. Southern solstice, equinox at perihelion, northern solstice, and equinox at aphelion are indicated for the current Pluto year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hemisphere does not cool quickly. The ice temperature drops by only a few degrees K before the N₂-covered areas at mid-northern latitudes receive insolation again, in the decades before perihelion, as shown in Fig. 3b from 1910 to 1970 or in Fig. 3d from 1890 to 1980.

Near the perihelion equinox, the southern hemisphere surface is warm, ~42 K, because the N₂-free substrate was illuminated for the preceding eight decades (1910–1990, in Fig. 3a and b, 1890–1990 in Fig. 3c and d). Approaching and after equinox (at perihelion), the southern hemisphere receives less sunlight, and radiatively cools slowly due to high thermal inertia. Once the surface cools to the N₂ ice temperature (in approximately 2035–2050, see Fig. 3), the N₂ gas in the atmosphere will condense onto the southern hemisphere, and there begins a period of exchange transferring N₂ from the summer (northern) hemisphere to the winter (southern) hemisphere. However, this period of flow lasts only until equinox at aphelion. The period of exchange is not long enough to denude the northern hemisphere, thus as Pluto travels from perihelion to aphelion, N₂ ice is always absorbing sunlight on the northern hemisphere keeping the ice temperatures relatively high throughout this phase and preventing collapse of Pluto's atmosphere.

5. Robustness of the results

Unfortunately, we cannot measure the atmospheric pressure at the surface of Pluto from the ground so we need to use the pressure at a higher altitude as a proxy for the surface pressure. We investigated the validity of this proxy measurement. We started with synthetic occultation light curves derived from GCM models (Zalucha and Michaels, 2013) at a variety of different methane column abundances and surface pressures ranging from 8 to 24 mbars. We fit the synthetic light curves with the Elliot and Young (1992) model to derive a pressure at 1275 km. We found that the ratio of the pressure at 1275 km to the surface pressure was a constant within the uncertainty of the model fit (0.01 mbar). Because of this, we concentrate on those occultations for which the pressures at 1275 km have been modeled by fitting Elliot and Young (1992) models, which is a subset of the occultation results presented in Young (2013).

We have also considered whether there are intermediate cases where there is an increase in atmospheric pressure in the current epoch (as the occultation data show) and then a collapse of the atmosphere in later years. We have found no set of conditions that is consistent with this. In order for the pressure increasing currently, one must have increasing insolation on the ices in the northern hemisphere (current summer pole) while there is not yet formation of a southern pole. If the gases could condense on the southern pole currently, this becomes a sink and the atmosphere would be decreasing in bulk pressure. One might ask if there is a case where there is currently no condensation onto the south pole but that it would begin in the next few decades and lead to significant reduction in the bulk atmospheric pressure. For this to happen the atmosphere would have to collapse approximately before the year 2080 because that is when the southern pole starts to be illuminated by the Sun given the obliquity of Pluto. At this time, the south pole begins sublimating and supplying the atmosphere. Such a case would require a very specific combination of thermal inertia and N₂ inventory. In fact, we have not yet found any such cases in our parameter-space searches.

Fig. 3 shows two different cases of Permanent Northern Volatile models. A significant difference between the top panel (PNV9) and the lower panel (PNV12) is the mass of N₂ available for the surface and atmosphere. PNV9 has 16 g/cm² while PNV12 has only 2 g/cm². The effect of this difference is seen in the globes that indicate

the distribution of N₂ frost on the surface. There is obviously less N₂ available in the second case and yet the pressures and temperatures have very similar variation over the Pluto year.

6. Conclusions

The PNV model is testable in multiple ways. In 2015, The New Horizons spacecraft will fly past Pluto providing the first close-up investigation of Pluto and its moons (Stern et al., 2008; Young et al., 2008b). The infrared spectrometer on New Horizons will map the composition across Pluto's surface. New Horizons will observe all of Pluto's terrain that is illuminated by the Sun and will attempt an observation of Pluto's winter pole using reflected Charon-light. We will be able to compare the N₂ ice distribution predicted by the Permanent Northern Volatile model with the observed ice distribution determined by New Horizons including perhaps even the southern pole of Pluto to determine if frost is present on the currently winter pole. The REX instrument on New Horizons will provide thermal measurements to compare with the surface temperatures predicted by the PNV models. From the UV solar and stellar occultations of Pluto, the New Horizons mission will determine the composition of Pluto's atmosphere as well as the thermal structure in the thermosphere. From the Radio Science experiment, the pressure and temperature profiles in Pluto's lower atmosphere will be determined. All of these data provide a test of the PNV model.

In addition to this close-up comprehensive investigation of Pluto by the New Horizons spacecraft, the model results can be tested by regular stellar occultation observations from Earth. The current epoch is a time of significant change on Pluto. Most of the PNV models show a maximum surface pressure between 2020 and 2040. Regular observations over this time period will constrain the properties of Pluto's substrate and the evolution of its atmosphere.

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