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Past epochs of significantly higher pressure atmospheres on Pluto

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A B S T R A C T

Pluto is known to have undergone thousands of cycles of obliquity change and polar precession. These variations have a large and corresponding impact on the total average solar insolation reaching various places on Pluto's surface as a function of time. Such changes could produce dramatic increases in surface pressure and may explain certain features observed by New Horizons on Pluto's surface, including some that indicate the possibility of surface paleo-liquids. This paper is the first to discuss multiple lines of geomorphological evidence consistent with higher pressure epochs in Pluto's geologic past, and it also the first to provide a mechanism for potentially producing the requisite high pressure conditions needed for an environment that could support liquids on Pluto. The presence of such liquids and such conditions, if borne out by future work, would fundamentally affect our view of Pluto's past climate, volatile transport, and geological evolution. This paper motivates future, more detailed climate modeling and geologic interpretation efforts in this area.

1. Introduction

Binzel (1990a,b; Binzel 1992) and Spencer et al. (1997) described how Pluto's high obliquity currently causes the planet's poles to receive more solar insolation than does the equator over the course of an orbit. There are also longer-term insolation cycles driven by the perihelion subsolar latitude variation on Pluto. Within each such long-term insolation cycle is a phase at which the perihelion subsolar latitude falls nearest to the poles, for example being as high as 75°N 0.9 Myrs ago in what we call an "extreme summer." The southern hemisphere's equivalent but less extreme configuration most recently occurred ~2.35 Myrs ago when the subsolar latitude reached only 60° S (the 75°N versus 60°S latitude asymmetry arises from the beat frequency between Pluto's 3 Myr obliquity period and 3.7 Myr longitude of perihelion precession period; see Dobrovolskis et al., 1997; Earle and Binzel 2015; Earle et al. 2016). Fig. 1 shows how the perihelion subsolar latitude varies over Pluto's 3 Myr obliquity period.

Our primary goal here is to show how these "extreme seasons" can plausibly drive large changes in Pluto's atmospheric pressure. Some of what we do here follows pioneering work by Trafton (1984), who considered a similar but not identical problem for a CH_4-dominated atmosphere once thought to exist at Triton. The concepts and equations in Trafton (1984) provide a context with which to study "super seasons". However, our work differs from Trafton's in several key respects, including (i) it concerns a different object, Pluto, (ii) it primarily concerns an N_2 rather than CH_4-dominated atmosphere, (iii) it is driven by different polar dynamics, and (iv) it includes Pluto surface imaging from New Horizons that bolsters the case for past epochs of much higher atmospheric pressures. We begin by modeling the atmospheric pressure response to a range of assumed polar cap extents, albedos, and emissivities.

2. Pluto's insolation cycles and atmospheric response

To determine the surface vapor pressure on Pluto, we first determine the subsolar latitude and instantaneous heliocentric distance at any given time, based on Dobrovolskis et al. (1997). Specifically, in what follows we modeled the CH_4 and N_2 surface vapor pressure variation over one Pluto orbit for each of three different epochs: Pluto's current "equinox" epoch, Pluto's "extreme northern summer" that occurred 0.9 Myrs ago, and Pluto's "extreme southern summer" that occurred 2.35 Myrs ago. These epochs each rep-

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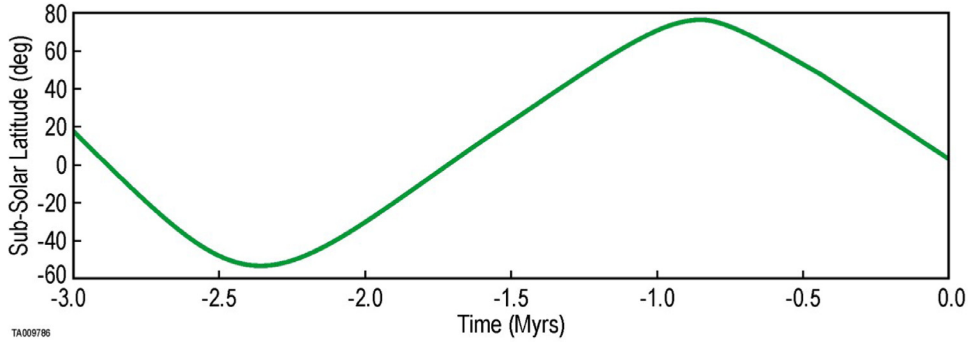

Fig. 1. Subsolar latitude on Pluto at perihelion over the past three million years; based on the analysis of Dobrovolskis et al. (1997); adapted with permission from Earle and Binzel (2015).

resent states that have occurred repeatedly in Pluto's history as a consequence of the planet's precession and obliquity cycles. The two historical epochs we examine below correspond to the two inflection points in the subsolar latitude at perihelion shown in Fig. 1.

In modeling Pluto's volatile distribution, we follow Earle et al. (2016), using a simple model accounting for the first order surface albedo variegation, and assume either CH_4 or N_2 ice is on Pluto's surface, depending on the model run. Within the equatorial zone, we model the informally named Tombaugh Regio as an additional volatile source region, simplifying its extent to range from 45° N to 30°S and being 45° wide in longitude. We assume a constant albedo of 0.6 for Tombaugh Regio. The remaining equatorial band in this simple model is assumed to be absent of volatiles. We tested various different areal extents for the poles, performing trials with the polar caps extending down to ±60° and ±45° latitude. For the thermal properties of the poles we considered three scenarios that span a wide parameter space: a high albedo where the poles are fresh (0.6 albedo), an intermediate albedo where the poles are partially depleted of fresh volatiles (0.3 albedo), and a low albedo (0.1 albedo) representing the case that an underlying, darker volatile base is being insolated; such a base is consistent with the dark material seen underground in numerous craters and scarps across Pluto (e.g., see Fig. 6). We used two different values of emissivity, 0.9 and 0.6, for each albedo case in order to span the range of likely emissivities. Our model calculates the vapor pressure for each case, in which the volatile distribution, albedos, and emissivity are held static. More sophisticated models that couple polar cap properties to the atmosphere as well as volatile transport as a function of time are warranted in the future, but for our simple purposes of illustrating that Pluto can display high-pressure atmospheric states over time, the static model we use here suffices.

For each specific value of subsolar latitude and heliocentric distance at any given epoch, we follow Pluto for one orbit, and calculate temperature based on the energy balance equation given in Trafton (1984). We note, however, that the energy balance equation (Eq. (10) of that paper) uses a different definition of A* than what is written in the text of that paper; to correct the equation to match the text's definition of A* we remove the extra factor of A from the equation. Additionally, the original equation also only accounts for the poles as source regions, so additional modifications were made to include Tombaugh Regio as a third source region, giving us:

$$(2A_P + A_{TR})\varepsilon\sigma T^4 = \pi F_\odot \quad \left[(1 - a_P)\left(A^*_{NP} + A^*_{SP}\right) + (1 - a_{TR})A^*_{TR}\right] \tag{1}$$

where ε is the emissivity, $\pi F_\odot$ is the solar flux at Pluto, a_i is the given region's albedo, A_i is given region's area, and $A_i{}^*$ is the effective insolation area of that region, i.e., the area normal to the solar insolation. The subscript P denotes the polar region; NP indicates the spin angular momentum North Pole, SP indicates the spin angular momentum South Pole, and TR indicates the bright equatorial patch representing Tombaugh Regio. Both poles are assumed to have equal area in our model. Once we have the calculated temperature, we use the algorithm from Brown and Ziegler (1980) to calculate the saturation vapor pressure for both methane and molecular nitrogen. See Earle et al. (2016) for additional details.

Our main model results are displayed in Figs. 2–4, which each span the parameter space described above for methane and nitrogen, respectively. Fig. 2 provides model results for CH_4 cases; Figs. 3 and 4 provides model results for N_2 cases.

The scenario for a polar cap extending to ±45° with albedo 0.3 and emissivity of 0.9 gives a maximum temperature of 37° K and a global average N_2 surface pressure of 10.5×10^{-3} mbar, i.e., like the present epoch. Figs. 2 and 3 also show interesting features on both the single orbit timescale and across the three different epochs. Most notable over the single orbit time scale is how the peak pressure is offset from perihelion, as is currently observed from decades of ground based stellar occultations (Olkin, 2015). We also find, as Earle and Binzel (2015) previously noted, that the peak insolation any region receives can be more strongly driven by constant illumination (e.g. "midnight sun" at the poles) than by changing heliocentric distance. Young (2013) shows how the offset from perihelion of the peak pressure can also be offset by the volatile distribution across Pluto's surface.

Notice the nearly two orders of magnitude difference in peak pressure that the model produces. The current pressure on Pluto is 1.1×10^{-2} mbar (e.g., Stern et al., 2015 a). Interestingly, the lowest peak pressure found in our model runs occurs for the current "equinox" Pluto epoch. The highest peak pressure arises during Pluto's "extreme northern summer" under the assumption that all fresh volatiles have been removed, leaving a low albedo base layer of the active volatile being insolated, with polar caps extending to ±60° and emissivity of 0.6.

These various results indicate that it is plausible for Pluto to have repeatedly reached very high atmospheric pressure states compared to the present epoch. Our results also indicate that the present epoch is near the minimum atmospheric pressure state of the entire parameter space we explored. Further, because Pluto's obliquity and precession cycles that produce these large pressure variations have occurred 1000s of times over 4 Gyr, we conclude that Pluto could have experienced 1000s of such high-pressure atmospheric epochs.

We do note, however, that our assumption of a static (i.e., non-time-dependent) polar cap extent, despite growing and decreasing atmospheric pressures, is non-physical. Nonetheless, the results from this model generate interest in more sophisticated, time-dependent modeling, which we plan as a next step.

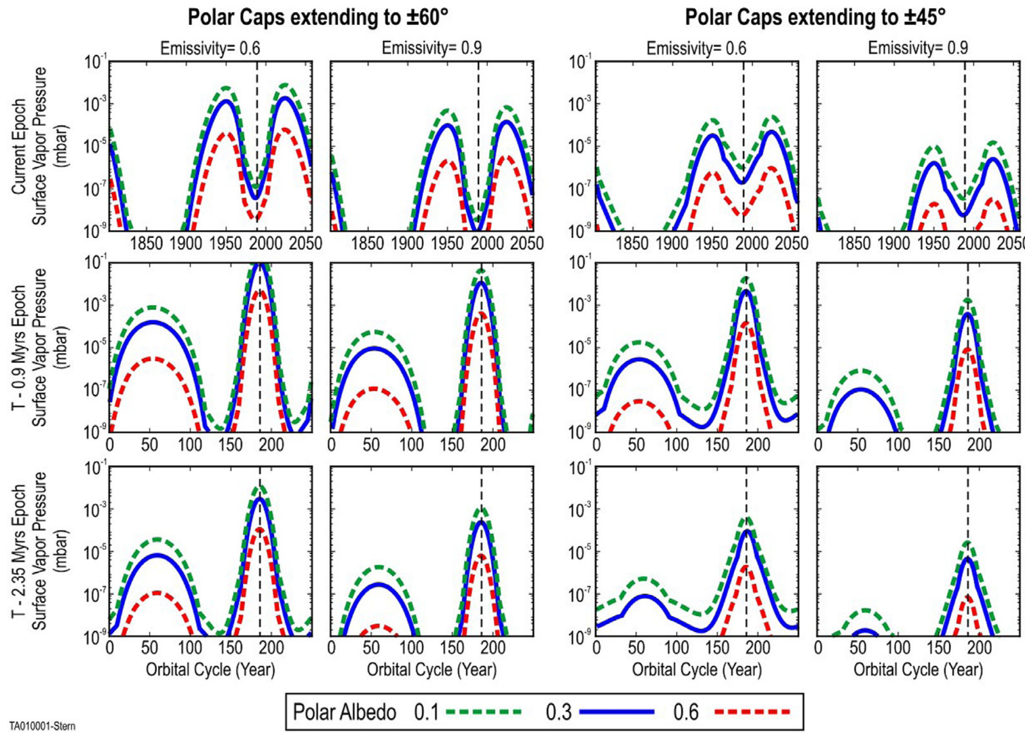

Fig. 2. Model variation in atmospheric methane pressure over a single Pluto orbit, at three different epochs. (Top row) Current epoch where perihelion occurs at "equinox." (Middle row) "Extreme Northern Summer" epoch occurring 0.9 Myrs ago where the subsolar point is at high northern latitudes when Pluto reached perihelion. (Bottom row) The "Extreme Southern Summer" epoch 2.35 Myrs ago where the subsolar latitude is furthest south when Pluto reached perihelion. Modeled with polar caps extending to ±60° latitude (first and second columns) and ±45° (third and fourth columns) and an emissivity of 0.6 (first and third columns) and 0.9 (second and fourth columns). In Figs. 2 and 3 perihelion is marked with a black vertical dashed line.

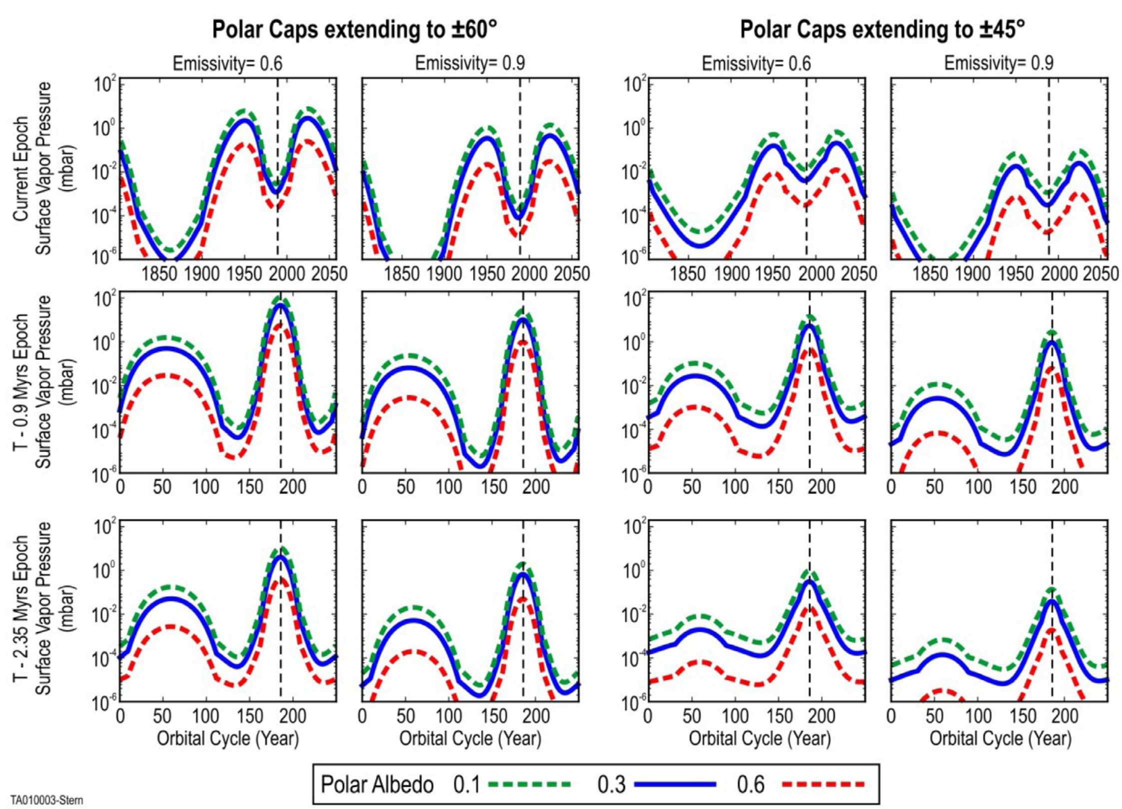

Fig. 3. Model variation in atmospheric nitrogen pressure over a single Pluto orbit at three different epochs. (Top row) Current epoch where perihelion occurs at "equinox." (Middle row) The "Extreme Northern Summer" epoch occurring 0.9 Myrs ago where the subsolar point is at high northern latitudes when Pluto reached perihelion. (Bottom row) The "Extreme Southern Summer" epoch 2.35 Myrs ago, where the subsolar latitude is furthest south at perihelion. Modeled with polar caps extending to ±60° latitude (first and second columns) and ±45° (third and fourth columns) and an emissivity of 0.6 (first and third columns) and 0.9 (second and fourth columns). Perihelion is marked with a black vertical dashed line in each plot.

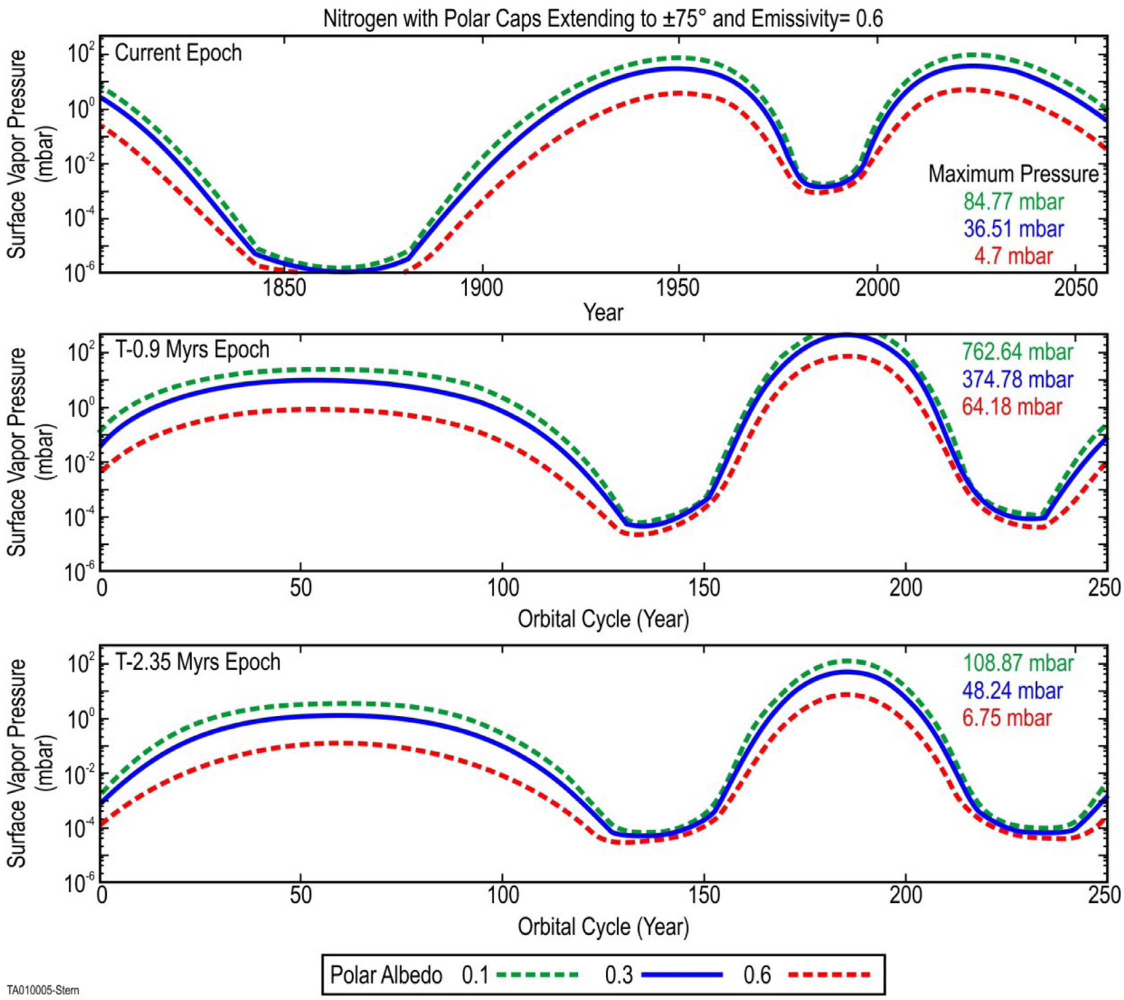

Fig. 4. Model of atmospheric molecular nitrogen pressure over a single Pluto orbit at three different epochs. (Top row) Current epoch where perihelion occurs at "equinox." (Middle row) The "Extreme Northern Summer" epoch occurring 0.9 Myrs ago where the subsolar point is at high northern latitudes at perihelion. (Bottom row) The "Extreme Southern Summer" epoch occurring 2.35 Myrs ago, where the subsolar latitude is furthest south at perihelion. These model polar caps extend to ±75° latitude and have an emissivity of 0.6.

We have tested the need for this modeling and the sensitivity of our present model to the static polar cap assumption it makes by rerunning our model with asymmetric poles. As expected, this significantly lowers the resultant peak pressures. As shown in Fig. 5 these asymmetric pole cases, which are likely intermediate to what a fully time dependent calculation will show, still gives peak pressures over order 1 mbar—two orders of magnitude higher than the currently observed pressure.

3. Surface features showing possible evidence for past eras of significantly higher atmospheric pressure

The flyby of Pluto by New Horizons revolutionized our knowledge of this planet (e.g., Stern et al., 2015a). Among the many datasets obtained, New Horizons provided essentially complete imagery of its close approach hemisphere at a resolution of 850 m/pixel, with higher resolution swaths obtained at resolutions ranging from 480 to 76 m/pixel. Charon's close approach hemisphere was also mapped.

These imaging datasets have revealed a wide variety of landforms and geomorphologies (Moore et al., 2016). From these data, it is now apparent that there are surface features that may indicate evidence of higher-pressure atmospheres in the past. Specifically, the following intriguing feature types on Pluto are noteworthy:

- *Dendritic Channels on Pluto*. Moore et al. (2016) identified several locations of likely dendritic channels and valley networks (see Fig. 6a, b). These branching networks appear to be erosional and can be seen in many cases to originate from higher topography, such as plateaus or mountains. Multiple hypotheses are under investigation to explain these features, including the fact that they are similar to valley networks on Earth formed by liquid runoff, glacial erosion, and basal melting (Moore et al., 2016; Howard et al., 2017). If these channels were in fact formed by liquid N_2, CH_4, or CO at Pluto's surface, then their stability would require significantly higher pressures than the current atmospheric pressure (Gladstone et al., 2015). Specifically, the requisite surface pressure needed to allow liquid N_2, CO, or CH_4 on the surface are all in the range 120–150 mbar.
- *Cryovolcanism on Pluto*. The feature informally named Wright Mons (see Fig. 6c) has been identified as a possible cryovolcano by Moore et al. (2016) due to (i) its topographic extent and vertical profile (see also Schenk et al., 2016) are characteristic of a volcano, (ii) the deep caldera structure near its summit has been identified by stereo-derived topographic profiles, and (iii) the young crater retention age of its flanks. The largest known terrestrial volcanic eruptions have emitted $\sim 10^{17}$–3×10^{18} g of material in individual eruptions. Pluto's current day atmospheric mass is near 3×10^{16} g. Such

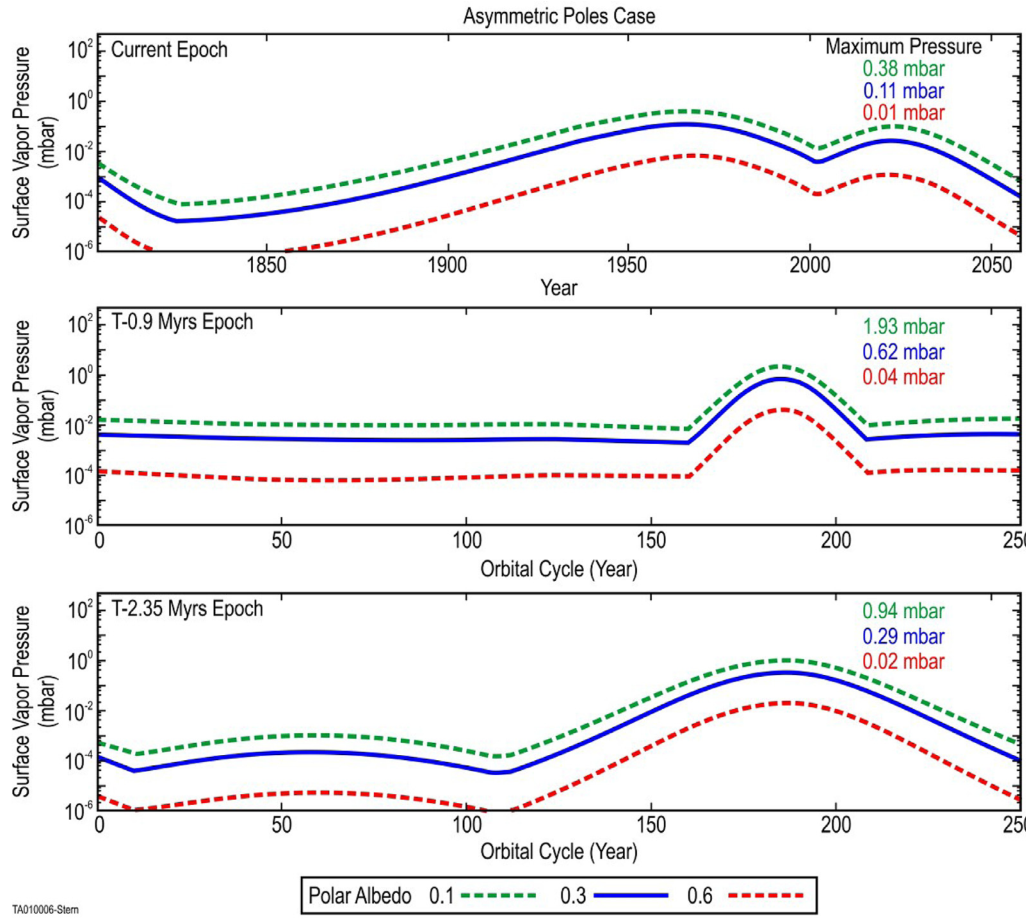

Fig. 5. Model of atmospheric molecular nitrogen pressure over a single Pluto orbit at three different epochs for the case of asymmetric polar cap extents. (Top row) Current epoch where perihelion occurs at "equinox." (Middle row) The "Extreme Northern Summer" epoch occurring 0.9 Myrs ago where the subsolar point is at high northern latitudes at perihelion. (Bottom row) The "Extreme Southern Summer" epoch occurring 2.35 Myrs ago where, the subsolar latitude is farthest south at perihelion. For these models the emissivity is 0.6, the northern polar cap extends to 60° latitude, and the southern polar cap extends to the equator, covering the entire southern hemisphere.

releases on Pluto would generate resulting transient pressure levels of order ~0.1–1 mbar**.** While it is not currently known if the largest cryovolcanic eruptions on Pluto's surface generated this much vapor, it is clear that Wright Mons and similar putatively cryovolcanic features identified on Pluto (see Moore et al., 2016) may have episodically enhanced the atmospheric pressure, perhaps by large amounts, compared to the present day atmospheric mass and pressure.

- *Charon's Dark Polar Deposit*. The reddish color of Charon's northern polar region informally called Mordor Macula (see Fig. 6d) is thought to be due to cold trapping of gases from Pluto that were subsequently photolyzed by solar UV and various charged particle radiations to become a heavier, involatile tholin (Grundy et al., 2016a,b). The required supply rate of such gas from Pluto is uncertain, but the current day escape rate only produces a flux to Charon of 2.7×10^{11} molecules m^{-2} s^{-1}, corresponding to a maximum tholins layer depth of ~5 m, which is arguably shallower than the observed polar deposit depth on Charon. If Charon's polar deposit depth is indeed much thicker, it would suggest past Pluto atmospheric environments with pressures and hence escape rates far higher than currently extant.
- *A Possible Paleo-Lake on Pluto:* As shown in Fig. 6e, a ponded deposit of an approximately 30 km length informally called Alcyonia Lacus has been identified on Pluto. This feature may have once been a lake that held ponded liquids, as supported by its topographic flatness and distinct, apparent shoreline (Moore et al., 2016). This identification is also consistent with the fact that this feature exists in a topographic low, which would naturally collect runoff (Schenk et al., 2016). Because ponded liquids would require N_2 or CH_4 atmospheric pressures of 120–150 mbar or higher to exceed the triple points of these substances and therefore be thermodynamically stable, this feature argues for one or more past epochs of such pressures.
- *Layering in Mountain Blocks and in Craters on Pluto*. As shown in Fig. 7a, there is clear evidence of dark, horizontal layering in many of the informally named al-Idrisi Mountain blocks bordering Sputnik Planitia. Similar layering is also seen on some of Pluto's scarp faces and crater walls (see Fig. 7b, c). These layers, some of which are several kilometers thick, have been interpreted to potentially indicate past epochs of increased atmospheric aerosol fall out, in turn indicating past epochs of higher atmospheric pressure (Moore et al., 2016).
- *Possible Dust Devil Tracks on Pluto*. As shown in Fig. 7c, various dark, quasi-linear and curvilinear features on Pluto's surface appear to some workers (Moore et al., 2016) as potential dust devil tracks. Dust devil formation is not favored in Pluto's current low-pressure atmosphere, but does take place at Mars and Earth at pressures of 6 and 1000 mbar, respectively. As such, if these features are due to dust devils, then they also argue for dramatically higher surface pressures in Pluto's past, though their visible presence today is constrained by subsequent volatile transport that could have covered them since their formation.

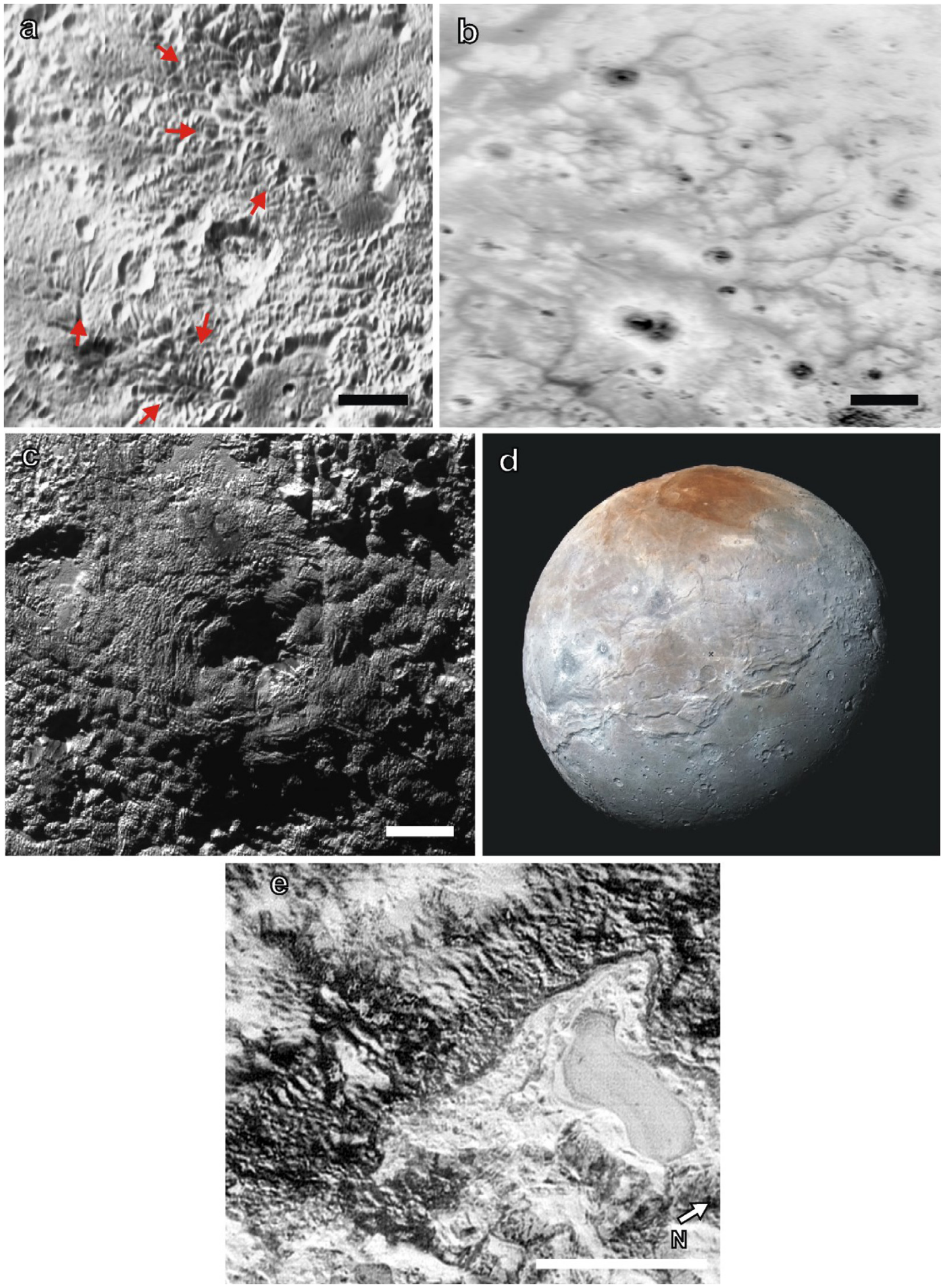

Fig. 6. (a) Dendritic networks northeast of the informally named feature Sputnik Planitia on Pluto. (b) Other network terrain to the northwest of Sputnik Planitia. (c) Pluto's informally named Wright Mons, a 4 km high, 150 km wide, likely cryovolcanic construct. (d) Color full disk view of Charon showing the dark red polar region. (e) Isolated ponded, lake-like feature just north of Sputnik Planitia on Pluto. All scale bars are 30 km and images are oriented with north up unless otherwise noted. Image sources: (a–c) ~320 m/px MVIC coverage from the P_MVIC_LORRI_CA (MVIC) observation; (d) ~1.5 km/pix C_Color_2 (MVIC) observation; (e) ~130 m/pix P_MPAN_1 (LORRI).

Table 1 summarizes the relationship of these various intriguing surface features to the likelihood that each required or argues for past epochs of far higher atmospheric pressure.

Although some of the surface feature types described above may not require epochs of higher atmospheric pressure, we believe that Occam's Razor argues that it is unlikely that none of them did.

Table 1
Geomorphologic evidence summary for past epochs of substantially higher pressure.

Feature type	Requires higher pressure epochs?
Dendritic channels	Yes, if created by surface flowing liquids
Cryovolcanism	Yes, but the resultant pressure increase is uncertain
Charon's polar deposit	Perhaps, depends on layer depth
Alcyonia Lacus	Yes, if further established as a paleo-lake
Mountain block layering	Consistent, but not required
Wind streaks	Yes, but minimum required pressure uncertain

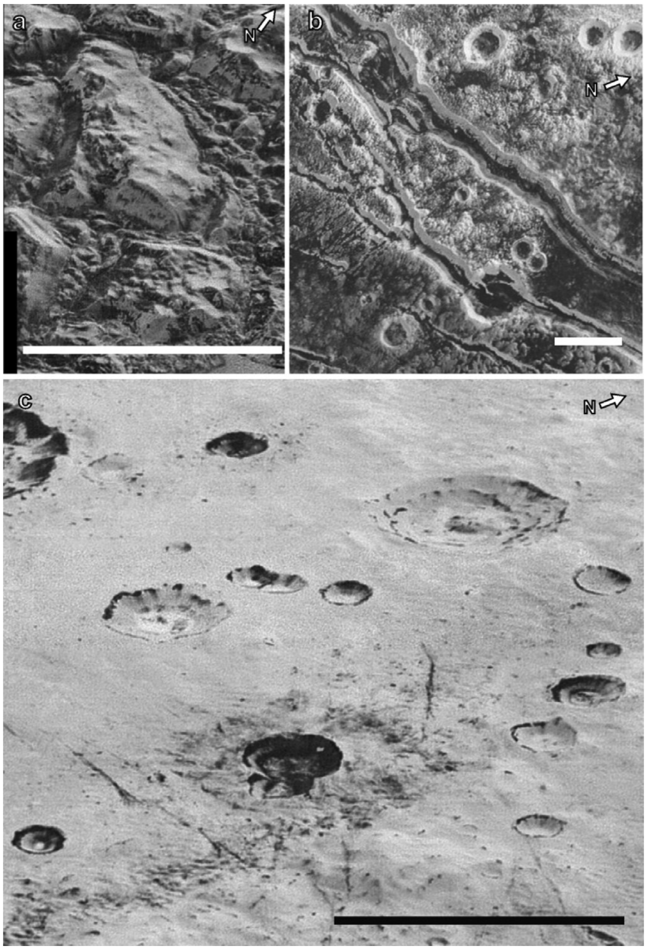

Fig. 7. Subsurface layering on Pluto up to several kilometers thick are seen in these and other images exposed in (a) chaotic mountain block scarps, (b) normal faults scarps, and (c) crater walls on Pluto. All scale bars shown here are 30 km in length. Image sources: (a, c) ~80 m/pix coverage from P_MVIC_LORRI_CA (LORRI); and (b) ~230 m/pix coverage from P_LEISA_HIRES (LORRI).

4. Conclusions

This paper has described for the first time, various kinds of geomorphological evidence consistent with far higher-pressure atmospheric states in Pluto's geologic past than is seen in the present $\sim 10^{-2}$ mbar era. This paper is also the first to provide a mechanism (and a simple, first order model) for potentially producing past high-pressure conditions on Pluto—i.e., polar obliquity and precession cycles.

Our model calculations have also shown that the current $\sim 10^{-2}$ mbar surface pressure state is in fact near the lowest surface pressures that Pluto likely experiences. Other mechanisms, including post-Charon forming giant impact thermal conditions and local thermal hot spots after basin forming impacts on Pluto can also plausibly generate transient epochs of similarly high atmospheric pressure.

These results, if borne out by further geomorphological analysis and higher fidelity modeling, would fundamentally change our view of Pluto's past. We therefore believe this initial work motivates further geologic interpretation efforts in this area, as well as time-dependent obliquity-climate modeling, including the coupled time-dependent escape losses of volatiles.

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