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Emissivity and the Fate of Pluto's Atmosphere

J. A. Stansberry[1]

Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, Arizona 86001
E-mail: stansber@as.arizona.edu

and

R. V. Yelle[2]

Center for Space Physics, Boston University, Boston, Massachusetts 02215

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We present a simplified model for seasonal changes in Pluto's surface–atmosphere system. The model demonstrates the potential importance of the solid-state phase transition between α-N_2 and β-N_2, and the accompanying change in emissivity, for predicting the seasonal bulk of Pluto's (and Triton's) atmosphere. Specifically, the model shows that under simplified but not unreasonable assumptions Pluto may have nearly the same atmospheric pressure at aphelion as it does now, near perihelion. The emissivity change which accompanies the α–β phase change should be included in the next generation of Pluto and Triton seasonal models for the purposes of understanding the evolution of their atmospheres over seasonal and climatic timescales. © 1999 Academic Press

Key Words: **Pluto; Pluto, atmosphere; Pluto, surface; Triton; atmospheres, evolution.**

INTRODUCTION

Pluto's orbital eccentricity (0.25) means that it recieves 2.8 times as much sunlight at perihelion (which occurred in 1989) as it does at aphelion. The idea that this extreme insolation variation might lead to extreme changes in the bulk of the atmosphere followed close on the heels of the realization that Pluto posesses an atmosphere. Cruikshank *et al.* (1976) discovered absorption features in Pluto's near-IR spectrum which were eventually attributed to the presence of CH_4 ice (Cruikshank and Apt 1984). Although the observed spectrum was due solely to absorption by ice, it meant that Pluto had at least a tenuous CH_4 atmosphere because CH_4 has a significant (0.1–100 μbar) vapor pressure at temperatures then predicted for Pluto (Cruikshank and Silvaggio 1979, Trafton 1980). Stern and Trafton (1984) pointed out that the vapor pressure of such an atmosphere would undergo large pressure changes as the temperature of the ice on the surface changed in response to eccentricity-driven changes in insolation. The subsequent discovery that N_2 ice is much more abundant on Pluto than CH_4 ice (Owen *et al.* 1993) means that Pluto's atmosphere is dominated by N_2 (its vapor pressure is $\simeq 10^4$ times larger than that of CH_4 at Pluto temperatures (Brown and Ziegler 1979)), but does not change the expectation of seasonally induced pressure oscillations, because N_2 will also form a vapor-pressure atmosphere.

Observations pertaining to the pressure of Pluto's atmosphere and the temperature of its N_2 ice are consistent with vapor-pressure equilibrium. A stellar occultation by Pluto in 1988 set a lower limit on the perihelion surface pressure of 3 μbar (Elliot *et al.* 1989, Hubbard *et al.* 1989, Elliot and Young 1992, Millis *et al.* 1993). Stansberry *et al.* (1994) argued that the occultation may not have reached Pluto's surface, and that Pluto posesses a deep ($\sim$50 km) troposphere. This hypothesis, strengthened by recent results indicating that Triton's atmosphere may now posess a troposphere approximately 50 km deep (Elliot *et al.* 1999) implies that the true surface pressure of N_2 on Pluto is nearer 19 μbar. Tryka *et al.* (1993) also argued for a higher surface pressure, near 60 μbar, on the basis of the observed shape of the N_2 ice absorption feature. These pressures correspond to the vapor pressure of N_2 over a temperature range of 35–40 K (Brown and Ziegler 1979). This is in excellent agreement with temperatures calculated on the basis of surface energy balance (Stansberry *et al.* 1994), and is not inconsistent with temperatures derived from far-IR observations of emission from Pluto (Altenhoff *et al.* 1988, Jewitt 1994, Stern *et al.* 1993, Tryka *et al.* 1994, Spencer *et al.* 1997).

Phase equilibrium is usually encountered in systems considerably smaller than the entire surface–atmosphere interface of a planet (although Triton is another example of such a situation). Despite the large scale of this system, the conditions of vapor–solid phase equilibrium, namely a single pressure and

[1] Current address: Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721.

[2] Current address: Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ 86011.

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temperature, have been theoretically shown to apply to the entire ice–atmosphere interface (Leighton and Murray 1966, Trafton 1984, Yelle *et al.* 1995). Thus, a variety of observations and theory are consistent with the idea that Pluto's near-perihelion atmosphere is in equilibrium with the surface N_2 ice. We note that the dual-volatile seasonal model of Trafton (1990) leads to atmospheric pressures of N_2 considerably lower than those derived from the single-volatile considerations above, and that the Trafton model gives results consistent with a 3-μbar surface pressure for Pluto (Trafton *et al.* 1998). That model is also of interest because, like the model we present here, it predicts that under certain conditions Pluto's atmosphere may not freeze out at aphelion. However, the other dual-volatile model for Triton and Pluto (Stansberry *et al.* 1996b, Trafton *et al.* 1998) comes to different conclusions, so for current purposes we will assume that single-phase vapor-pressure equilibrium is an adequate paradigm for exploring the seasonal evolution of Pluto's atmospheric pressure.

THERMAL MODEL

Nitrogen ice everywhere on the surface of Pluto is at the same temperature because sublimation, atmospheric transport, and condensation act to efficiently redistribute energy across the globe (e.g., Spencer *et al.* 1997 and references therein). The usual equation for the diurnally averaged equilibrium temperaure of the surface, as a function of latitude (λ),

$$\epsilon\sigma T_{\mathrm{eq}}^4(\lambda) = \frac{1}{\pi} S_0(1-A)\int_{-\phi_{\mathrm{T}}}^{\phi_{\mathrm{T}}} d\phi\cos\theta, \tag{1}$$

where ϵ is the emissivity of the ice, σ is the Stefan–Boltzmann constant, T_{eq} is the radiative equilibrium temperature of the surface, S_0 is the solar flux at Pluto, A is the bolometric albedo of the ice (which we set to 0.8), ϕ is longitude, ϕ_{T} is the longitude of the terminator at a given latitude, and θ is the local solar zenith angle, must be modified to account for the latent heat flux in the equation of local energy balance. Writing the cossine of the diurnally averaged solar zenith angle (the integral in Eq. (1)) as $\bar{\mu}$ gives

$$S_0\bar{\mu}(1-A) = \epsilon\sigma T^4 + L\dot{m}, \tag{2}$$

where L is the latent heat of sublimation per unit mass of N_2 (2.6×10^9 erg/g^{-1}) (Brown and Ziegler 1979), and $\dot{m}$ is the sublimation mass flux. For current conditions on Pluto the temperature of the N_2 is the same everywhere to within a small fraction of a Kelvin (Yelle *et al.* 1995, Spencer *et al.* 1997). The N_2 temperature can be found by integrating Eq. (2) over all of the the N_2 deposits on the surface and applying the constraint that the globally averaged latent heat flux ($L\dot{m}$) is zero. This yields the globally constant temperature of the N_2 ice as

$$T_{\mathrm{N}_2} = \left(\frac{S_0(1-A)}{\gamma\epsilon\sigma}\right)^{1/4}. \tag{3}$$

The term γ is the ratio of the total area of the N_2 ice to its cross-sectional area as viewed from the Sun; i.e., it is the ratio of the area over which thermal reradiation from the ice occurs to the area receiving sunlight.

We wish to use these relations to predict the seasonal variability of the temperature of Pluto's N_2 ice, and thereby the atmospheric pressure. In order to do so we must know the values of the albedo, emissivity, and γ as a function of time. Volatile tranport models have been used to predict the distribution of N_2 ice, i.e., γ, as a function of time under the assumption of constant frost albedo and emissivity (Spencer 1990; Stansberry *et al.* 1990; Hansen and Paige 1992, 1996; Brown and Kirk 1994). In general these models do a poor job of both explaining the observed albedo patterns on Triton and predicting the changes in atmospheric pressure which have now been detected on Triton (Elliot *et al.* 1997, 1998). There is no reason to expect them to perform better on Pluto. Because our primary interest in this study is to examine the effect of emissivity on the seasonal frost temperature, and because existing volatile transport models are of limited utility in predicting the time behavior of γ, we simply take $\gamma=4$ in our models, equivalent to assuming that the entire planet is covered by N_2 ice. Later we discuss how changes in γ due to volatile transport would influence our results. We further assume that N_2 ice has a bolometric albedo of 0.8, based on *Voyager* imaging results from Triton (Stansberry *et al.* 1990) and mutual event albedo maps of Pluto (Stansberry *et al.* 1994). The detailed emissivity behavior of the N_2 is discussed below.

As noted above, Eqs. (1)–(3) are only applicable if the condition of frost isothermality is satisfied. The amount of latent heat that can be transported around the globe by winds of a given velocity dependens upon the atmospheric density: as the atmospheric pressure falls, winds will grow stronger. When the wind speed begins to approach the sound speed, significant pressure gradients will be required to drive the flow (Trafton and Stern 1983, Yelle *et al.* 1995). The presence of significant pressure differences in the atmosphere implies temperature differences between different regions of N_2 ice on the surface with which the atmosphere is in contact; i.e., the condition of isothermality is violated. Spencer *et al.* (1997) show that the condition of isothermality breaks down when the N_2 ice temperature falls below about 31 K, with a corresponding atmospheric pressure of 0.1 μbar.

EMISSIVITY AND THE α–β PHASE TRANSITION

The N_2 α–β solid phase transition occurs at $T_{\alpha\beta}=35.6$ K, where the vapor pressure is 4.2 μbar (Brown and Ziegler 1979). N_2^β, the high-temperature phase, posesses a hexagonal crystal structure in which the molecular orientations are disordered, while N_2^α, the low-temperature phase, posesses a cubic crystal structure in which the molecules are highly ordered (Scott 1976). N_2^β is characterized by broad, weak absorption bands both in the near and the far infrared, while N_2^α is characterized by narrow, weak absorption bands in both spectral regions (St. Louis and

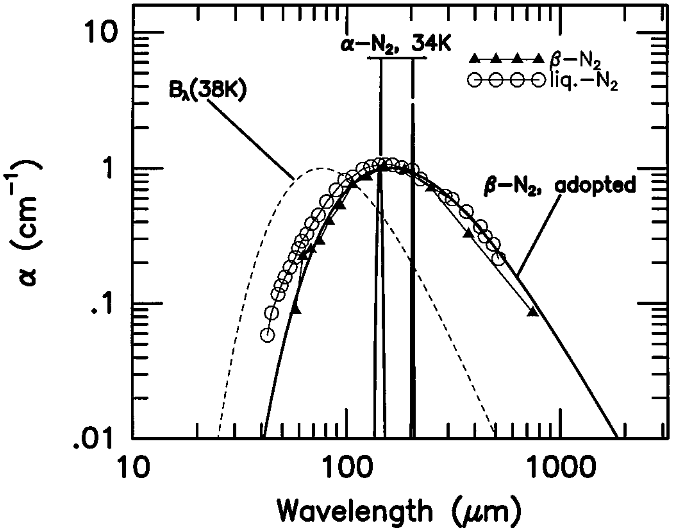

FIG. 1. The absorbtion coefficients of α, β, and liquid N_2 in the far-IR. The heavy solid lines show the analytical approximations of the absorption data used in computing the emissivities used in this paper. Reproduced from Fig. 1 of Stansberry *et al.* (1996a) with permission from Elsevier Science.

Schnepp 1969). Figure 1 shows the far-IR absorption coefficients for the two solid phases and liquid N_2. Since $T_{\alpha\beta}$ is well above the temperature where N_2 ice isothermality is expected to break down (31K), the above thermal model is appropriate for studying seasonal effects of the α–β phase change.

Duxbury and Brown (1993) investigated the seasonal stability of N_2^α and N_2^β, as a function of depth, at two selected latitudes on Triton's polar caps. They prescribed a surface temperature fluctuation and found that phase-transition "fronts" propagated into and out of the subsurface in response. Their model accounted for the latent heat of the α–β phase change (4% of the latent heat for the solid-to-vapor transition (Brown and Ziegler 1979); however, note that the expressions for the latent heat in that paper are incorrect: latent heats must be calculated using the vapor pressure relations and the Clausius–Clapeyron equation), but because the surface temperature variation was imposed and because they did not examine the global energy balance of the N_2 ice along with its phase, their model has no predictive ability for the seasonal behavior of N_2^α and N_2^β.

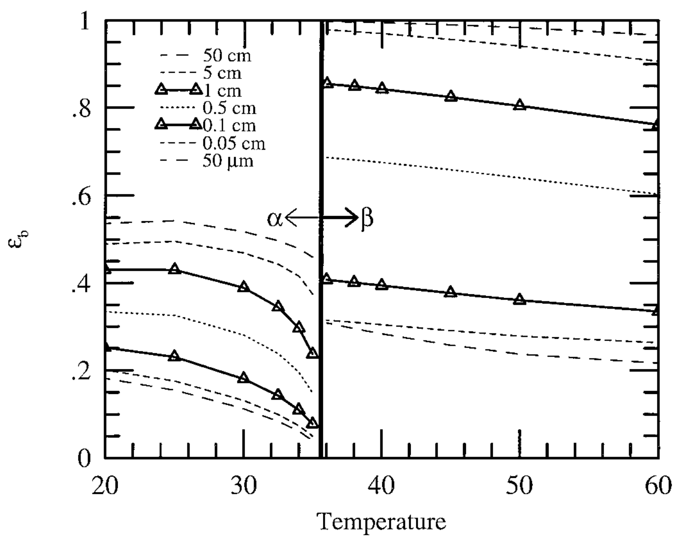

FIG. 2. The Planck-mean bolometric emissivity of N_2 ice as a function of temperature and particle size. The double vertical line marks the α–β phase transition temperature at 35.6 K. The dotted lines show the emissivity for nominal grain sizes deduced from visible and near-IR spectroscopy of Pluto and Triton. Reproduced from Fig. 3 of Stansberry *et al.* (1996a) with permission from Elsevier Science.

TABLE I

N_2 ice albedo	0.8
N_2^α emissivity	0.3
N_2^β emissivity	0.75
Solar constant	1587 erg cm^{-2} s^{-1} (@29.58 AU)

No Pluto or Triton seasonal study has accounted for the different optical properties of N_2^α and N_2^β in the thermal infrared. Their weak absorption bands in this spectral region (20–400 μm) means that they will have low emissivities. Figure 2 shows the bolometric emissivities of N_2 ice computed using Hapke theory (Hapke 1993) and the data in Fig. 1 (Stansberry *et al.* 1996a). N_2 grain sizes on Pluto (and Triton) are thought to be in the range 0.1–1 cm, determined from near-IR spectral modeling (Cruikshank *et al.* 1993; Owen *et al.* 1993; Grundy *et al.* 1993; Tryka *et al.* 1993, 1994). From Fig. 2, the bolometric emissivity of a surface composed of grains in this size range is 0.11–0.30 (N_2^α) and 0.40–0.85 (N_2^β). Here we adopt $\epsilon_\alpha = 0.3$ and $\epsilon_\beta = 0.75$ as our nominal emissivities for the two phases. As will be seen below, the value of ϵ_β determines the pressure we predict for the perihelion atmosphere and the timing of the onset of formation of the α phase. The value of ϵ_α determines the temperature of Pluto's N_2 ice when overall absorbed insolation is low, and so is more important for determining the fate of Pluto's atmosphere at aphelion. Our nominal value for ϵ_α is intentionally biased toward the upper end of the range in Fig. 2, so we predict an aphelion temperature and atmospheric pressure somewhat lower than those we would obtain if we used a more central value, such as 0.2. As discussed in detail by Stansberry *et al.* (1996a), contaminants such as CH_4 or its photolysis products may slightly increase ϵ_α, so in effect we are allowing for some contamination of the N_2 ice by choosing $\epsilon_\alpha = 0.3$. The nominal values we assume for the quantities in Eqs. (1)–(3) are summarized in Table I.

EMISSIVITY AND SEASONAL BEHAVIOR

The sudden change in the emissivity of N_2 at $T_{\alpha\beta}$ has interesting implications which can be illustrated by considering the idealized case of N_2 ice in radiative equilibrium with sunlight. Assuming that 50 erg cm^{-2} s^{-1} of solar radiation is absorbed by

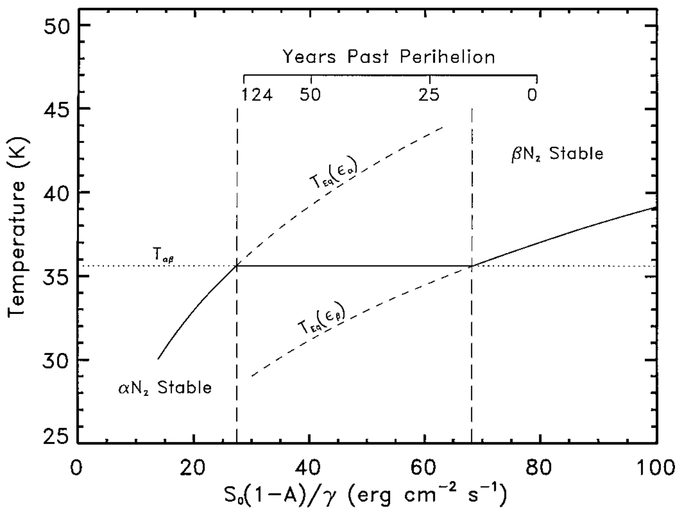

FIG. 3. Pluto's globally averaged equilibrium temperature as a function of time past perihelion passage or absorbed insolation. Insolation decreases as Pluto recedes from the Sun, but the equilibrium temperature remains constant at the solid-N_2 α-to-β transition temperature, 35.6 K, because of the emissivity contrast between the two phases.

the ice (appropriate for Pluto's surface ~40 years past perihelion), that the emissivities of N_2^α and N_2^β are as above, and that the ice is in its α phase, we find that its equilibrium temperature is $T_{\rm eq} = 43$ K, well above $T_{\alpha\beta}$: the ice cannot be in the α phase. Computing the equilibrium temperature under the assumption that the ice is in its β phase, we find $T_{\rm eq} = 33$ K, which is well below $T_{\alpha\beta}$. We are forced to conclude that for some values of insolation there is no radiative equilibrium solution involving either of the pure phases of N_2 ice: N_2^α would be too warm to exist and N_2^β would be too cold.

Figure 3 shows how these considerations apply to Pluto's entire surface–atmosphere system under the condition of vapor-pressure equilibrium. The figure shows solutions to Eq. (3) for $\epsilon = \epsilon_\alpha$ and $\epsilon = \epsilon_\beta$. As for an isolated patch of N_2 ice, there are values of the globally averaged insolation for which the ice cannot all be in either the α or the β phase: $T_{N_2} > T_{\alpha\beta}$ (Eq. (3)) if we plug in ϵ_β and $T_{N_2} < T_{\alpha\beta}$ if we use ϵ_α. This apparent conflict between thermal balance and phase equilibrium is resolved by allowing both N_2^α and N_2^β to be present on Pluto's surface and in contact with the atmosphere. Then, so long as all three phases are present and the atmosphere is thick enough to be hydrostatic, the Gibs phase rule requires that $T_{N_2} = T_{\alpha\beta}$. When both solid phases are present, the globally averaged emissivity will lie somewhere between ϵ_α and ϵ_β, and will have the value which satisfies $T_{N_2} = T_{\alpha\beta}$. As illustrated by the figure, this condition can persist for a large fraction of Pluto's orbit and will pertain even at aphelion for the nominal emissivity, albedo, and γ values assumed in our model. The predicted aphelion atmospheric pressure in this case is 4.2 μbar. If the emissivity of N_2^α were the same as that of N_2^β, at aphelion T_{N_2} would instead be about 28 K, and the atmospheric pressure about 5 nbar.

How can Pluto's climatic system satisfy the dual constraints of global energy balance and phase equilibirum between the gas and two solid phases of N_2? Figure 4 shows the equilibrium temperature of N_2^α and N_2^β as a function of latitude approximately 40 years after perihelion. Pluto's surface can be broken up into three different zones. Where the local diurnally averaged equilibrium temperature, $T_{\rm eq}^\beta$, is greater than $T_{\alpha\beta}$, N_2^β is the stable phase, and it is subliming. Where $T_{\rm eq}^\alpha$ is less than $T_{\alpha\beta}$, N_2^α is the stable phase, and it is condensing from the atmosphere. In these two zones (α- and β-stable) the fluxes of latent heat adjust the local ice temperature from $T_{\rm eq}$ to $T_{\alpha\beta}$. Within the third region of Fig. 4 (between the vertical dotted lines) $T_{\rm eq}^\alpha$ is greater than $T_{\alpha\beta}$, and $T_{\rm eq}^\beta$ is less than $T_{\alpha\beta}$. We now consider how the physical state of the N_2 ice within this region can evolve in order to achieve an emissivity that satisfies the global constraint that $T_{N_2} = T_{\alpha\beta}$.

The physical state and evolution of the N_2 ice within the region where neither N_2^α nor N_2^β is stable depends upon the relative timescales for sublimation and solid-state conversion between the α and β phases. If solid-state conversion happens more quickly, the phase composition of the ice will be able to readily adjust itself to local energy balance requirements. If sublimation happens more quickly, the molecules of the solid will not have time to rearrange themselves into the preferred solid phase in response to changes in local energy balance (this might result in the formation of layers of N_2^α and N_2^β). We believe that the solid-state phase change will be the preferred mode of evolution for two reasons. First, the latent heat of the solid state phase change in only 4% of that associated with the solid-to-vapor phase change: a given energy imbalance will drive the solid-state phase change 25 times more rapidly than it will drive sublimation. Second, when the local equilbrium temperature is close to $T_{\alpha\beta}$, as it typically is during the time when the ice is first

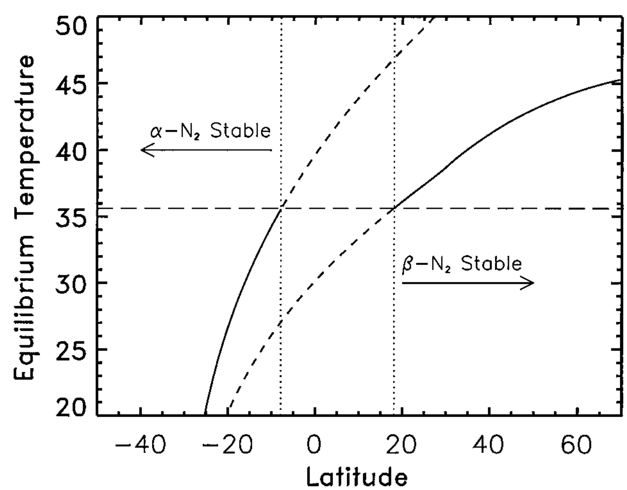

FIG. 4. Diurnally averaged equilibrium temperatures as a function of latitude on Pluto circa AD 2030, 40 years after the most recent perihelion passage. The pure α and β phases are thermodynamically stable in the regions indicated by the vertical dotted lines and arrows. Between the vertical dotted lines neither phase is stable, but a mixture of the two phases is.

begining to transition from one phase to the other, the sublimation rate will be very small (and the timescale correspondingly large). The slowness of sublimation during this stage increases the likelihood that the solid-state phase transformation dominates the evolution of the physical state of the N_2 ice.

The above arguments will not hold if there is significant kinetic inhibition of the solid-state phase change. However, no strong kinetic effects have been observed in a variety of laboratory experiments involving passing samples of N_2 ice through the phase transition temperature (W. M. Grundy, personal communication). Despite the lack of obvious kinetic effects in the laboratory setting, there is a finite energy penalty associated with the initial formation of cubic N_2^α crystals within hexagonal N_2^β, and vice versa. This energy penalty will result in some kinetic inhibition of the phase change, with the result that the two phases will be metastable over a small temperature range surrounding $T_{\alpha\beta}$. When the temperature is within this metastable range the two phases can exist in contact with one another, i.e., as a mixture of grains. This conclusion is supported by the phase-diagram work of Prokhvatilov and Yantsevich (1983). The finite width (in temperature space) of the metastable zone means that the grains of the two phases can be at slightly different temperatures.

A mixture of grains of N_2^α and N_2^β will have an emissivity intermediate between ϵ_α and ϵ_β, with its exact value depending on the mixing ratio of the two phases in the solid and the grain sizes associated with each phase. Considering the energy balance of such a mixed solid we find that its phase composition will be driven toward a state such that its equilibrium temperature will be equal to $T_{\alpha\beta}$. If the solid is too α rich (i.e., its emissivity is too close to ϵ_α), it will have an equilibrium temperature greater than $T_{\alpha\beta}$, and in particular the α grains will be at a temperature somewhat higher (but metastable) than that of the β grains. This will drive a decrease in the number of the α grains via the solid-state phase transformation to the β phase, simultaneously increasing the emissivity and absorbing a small amount of latent heat and thereby lowering the equilibrium temperature till it is equal to $T_{\alpha\beta}$. Conversely, if the solid is too rich in β, its emissivity will be high, and its equilibrium temperature below $T_{\alpha\beta}$. This will drive a decrease in the number of the β grains via the solid-state phase change to the α phase, with a resultant decrease in emissivity and simultaneous release of latent heat, thereby increasing the equilibrium temperature till it is equal to $T_{\alpha\beta}$. An alternative and perhaps more likely configuration for the N_2^α and N_2^β is that of layers. Because N_2 ice is so transparent in both the visible and the far-IR, both deposition of sunlight and emission of thermal radiation will peak below the surface, probably at around a few centimeters depth. If the depths of absorption and reradiation are different, temperature gradients will form, and N_2^α and N_2^β will tend to be vertically segregated. In this case emissivity adjustment could occur through changes in the thickness of the layers rather than in the number of particles of either phase.

The ability of the "mixed-phase" portions of the surface to attain equilibrium temperatures equal to $T_{\alpha\beta}$ by changing their emissivity has potentially important implications for volatile transport models. Because mixed-phase regions are able to attain a state of thermal equilibrium with absorbed insolation, they will not sublime nor will fresh ice condense onto them from the atmosphere: volatile transport in these areas comes to a halt. This could have the effect of stabilizing the N_2 ice distribution. Although we have not explored this issue in any detail so far, we do discuss some implications of it below.

We have calculated the latitudinal extent of the N_2^α and N_2^β stability zones, and the extent of the mixed-phase zone, as a function of time over one Pluto orbit. The calculation was not a seasonal transport model; rather we have simply used the equations of energy balance (Eqs. (1)–(3)). The lack of measurements or calculations for the emissivity of an intimate mixture of α- and β-N_2 grains and a model for the sizes and numbers of grains of each phase that will form preclude us from accurately modeling the exact phase composition within the mixed-phase zone. We have approximated a solution by assuming that the emissivity of the surface in the mixed-phase zone is linearly dependent on the fraction of each phase present.

Figure 5 shows the α and β stability zones and the mixed-phase zone as a function of the time past Pluto's perihelion. Shading indicates the mixing ratio of N_2^β in the ice. An obvious feature of the map is that N_2^β never completely disappears from the surface. For our nominal ϵ_α a portion of Pluto's surface is still in the mixed-phase state at aphelion, with the temperature of the N_2 pinned at $T_{\alpha\beta}$, and the atmospheric pressure equal to 4.2 μbar. At aphelion the maximum N_2^β mixing ratio, which occurs near Pluto's equator, falls to 0.32. From Eq. (3) we find that some N_2^β will be present at aphelion so long as $\epsilon_\alpha \leq 0.31$. If ϵ_α is greater than 0.31, Pluto will experience a period around perihelion where the atmosphere will no longer be buffered by the presence of both solid phases. If $\epsilon_\alpha = 0.35$, all of the N_2^β will disappear 87 years past perihelion, and the atmospheric pressure will begin to fall. However, for $\epsilon_\alpha = 0.35$ the perihelion temperature will be 34.6 K, implying an atmospheric pressure of 2.0 μbar. This is still well above the minimum pressure of 0.1 μbar required for the atmosphere to be in hydrostatic equilibrium (Spencer *et al.* 1997). If ϵ_α is as high as 0.5, the aphelion N_2 temperature will be 31.7 K, with a corresponding atmospheric pressure of 0.19 μbar, and Pluto's atmosphere may not be hydrostatic.

DISCUSSION

The ability of the N_2 α–β emissivity contrast to keep Pluto's atmosphere from freezing out is subject to a number of caveats due to the simplifying assumptions we have used in our model. If one takes issue either with the measured absorption coefficients of N_2 or with the application of Hapke's theory of emission to the problem of emission from Pluto's N_2 ice (Stansberry *et al.* 1996), then perhaps the emissivity contrast is suspect. Unfortunately it is difficult to prepare and measure either the reflectivity or the emissivity of a large enough sample of N_2 ice to directly determine its bolometric emissivity. In the absence of such

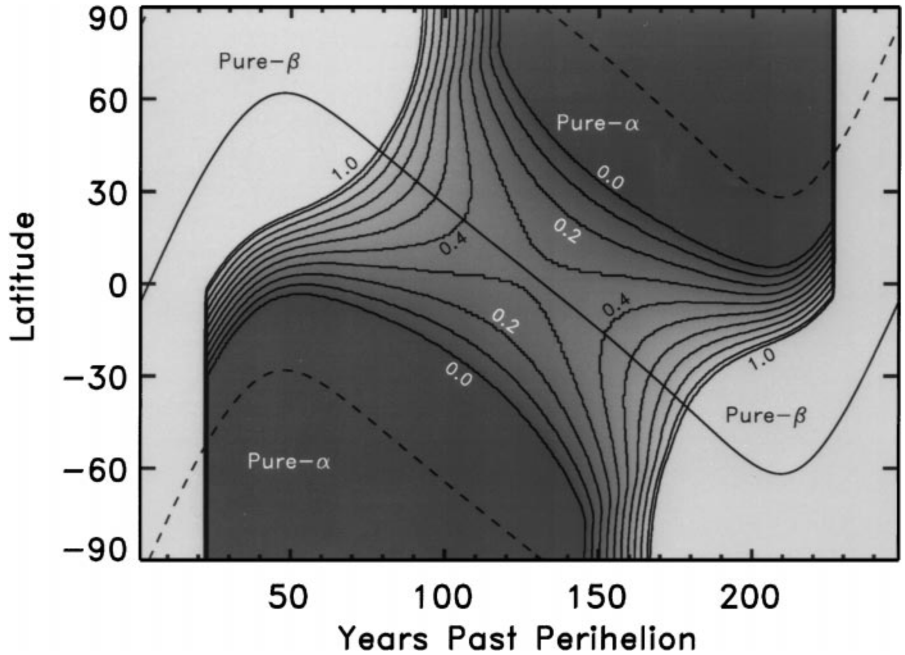

FIG. 5. The latitudinal distribution of β-N_2 on Pluto as a function of time: the brightest areas are pure β-N_2, the darkest pure α-N_2, and the shading indicates intermediate fractions of the β phase mixed with the α phase. The solid line shows the subsolar latitude as a function of time; the dashed lines show the limit of the unilluminated portion of the surface.

measurements, we are forced to rely on the simpler measurements of absorption coefficients and the use of radiative transfer theory.

Grain-size changes resulting from seasonal processes could have potentially important effects on the emissivity of both phases of N_2, as could the nature of the solid-state phase change itself. As the N_2 ice ages it is plausible that the grains become larger, and that the emissivity of older, coarse-grained surfaces will be correspondingly higher than that for younger surfaces (Fig. 2). However, the typical grain size is constrained by the near-IR spectroscopic measurements, so the values we have used should be approximately correct for the bulk of the visible N_2 ice. It has also been suggested that N_2 freezes out as a nongranular or large-grained glaze (e.g., Hansen and Page 1992), and a model of sintering of N_2 ice shows that glazes may form under certain deposition conditions (Eluszkiewicz 1991). Such a glaze would have a high emissivity (in Fig. 2 $\epsilon \to 1$ as the grain size becomes arbitrarily large), and if it turns out that N_2^α preferentially freezes out as a glaze or as very large grains, the emissivity contrast between it and N_2^β could be reduced or possibly even reversed. If so, the atmosphere would be unstable to freeze-out as has previously been predicted by others. On the other hand, N_2^α is denser than N_2^β, and it is likely that when the α–β phase transition occurs in the solid state the change in volume may damage grains of N_2 ice, resulting in a smaller grain size for N_2^α than what we have assumed, and a correspondingly lower emissivity for it. This would have the effect of enhancing the emissivity contrast between the two phases, and would strengthen the conclusion that this contrast will tend to keep the atmosphere from freezing out. Ice metamorphism and volatile transport also probably have some impact on the albedo of the N_2 ice, and we have ignored these effects as have nearly all existing studies of seasonal effects on Pluto and Triton.

Another aspect of volatile transport that we have not modeled is its impact on the distribution of the surface ice and therefore on the amount of sunlight the ice receives and on the area over which it radiates thermally. We neglected modeling this aspect of the volatile transport largely because previous models of seasonal transport have not convincingly reproduced the albedo, and presumably N_2 ice, distribution on Triton or Pluto. We concluded that any results we obtained by including seasonal transport in this study would be subject to greater, not less, uncertainty as a result. We can explore the potential impact of volatile transport on our model by considering a couple of scenarios. The dependence of T_{N_2} on the ice configuration is contained in the parameter γ of Eq. (3); for large values of γ the ice is predominantly in poorly lit and/or unilluminated areas, and T_{N_2} is low. For smaller values of γ the ice is at least partially in sunlight, and T_{N_2} is higher. Some endmember values of γ range from 4 (for an ice-covered body or, in fact, for many other reasonable configurations of the surface ice) and 2 (for ice only on the sunlit hemisphere) to values approaching ∞ (for all of the ice in the unilluminated area of the body, e.g., if the N_2 ice layer is extremely thin and sublimes completely during the summer). For a single patch of ice at the subsolar point, and no other ice on the body, $\gamma = 1$.

It is unlikely that γ approaches 2 given the natural tendency of the N_2 ice to sublime and move into dark regions: this volatile transport will tend to favor values of $\gamma > 2$. It is also improbable that γ approaches ∞: this would require that Pluto's N_2 layer is so thin that it sublimes entirely during the summer (or even during the daytime). A significant fraction of Pluto's sunlit regions must be covered with N_2 ice, else we would not see its absorption bands in the reflectance spectrum (Owen *et al.* 1993, Grundy 1995, Grundy and Fink 1996). Also, if there is too little ice in the sunlit hemisphere the vapor pressure over the ice would currently be much lower than the atmospheric pressure, which is probably in the range 10–60 μbar (Stansberry *et al.* 1994, Tryka *et al.* 1994, Young 1994, Yelle and Elliot 1997, Young *et al.* 1999; although, cf. Elliot *et al.* 1989, Elliot and Young 1992, Millis *et al.* 1993, Trafton *et al.* 1998, Yelle and Elliot 1997). Also, Pluto, like Triton, tends to be brightest in the hemisphere where insolation has been strongest over the past couple of decades (Spencer *et al.* 1997, Trafton *et al.* 1998, Young *et al.* 1999). The foregoing points regarding atmospheric pressure make it difficult to imagine that the well-illuminated high-albedo areas on Triton and Pluto are not repositories of N_2 ice. In addition, low-albedo areas have fairly high equilibrium temperatures even when they are well away from the subsolar latitude, and N_2 will preferentially sublime from them. While it is possible that some low-albedo areas do have some N_2 ice on them, this can only be true if the atmospheric pressure is high enough to stabilize the N_2 there, again requiring the presence of N_2 ice in the well-illuminated high-albedo areas. Two additional factors that argue against efficient removal of N_2 ice from the sunlit portions of Pluto, especially near aphelion, are: (1) as the insolation drops, more N_2 ice will be deposited on the surface, tending to keep existing high-albedo, sunlit, volatile-ice deposits from subliming, and (2) as discussed earlier, N_2 in the mixed-phase region may well become decoupled from the seasonal transport, tending to create a volatile distribution more static than that would exist otherwise.

The above reasoning bolsters the supposition that volatile ice deposits will probably be widespread in the sunlit regions of Pluto, and that γ will be larger than 2, but probably not much greater than 4. A realistic upper limit on γ, representative of the thermal balance if large portions of Pluto's sunlit regions become denuded of N_2 ice at some point in a seasonal cycle, might be represented by setting $\gamma = 8$ in Eq. (3). Using this assumption we can estimate a plausible upper limit to the potential cooling effect of volatile transport on N_2 ice energy balance over a seasonal cycle. Doing so we find that at aphelion $T_{N_2} = 29.1$ K, with a corresponding atmospheric pressure of 0.02 μbar. This is well below the values of T_{N_2} and P_{N_2}, 31 K and 0.1 μbar, respectively (Yelle *et al.* 1995, Spencer *et al.* 1997), where Pluto's atmosphere will become nonhydrostatic, so in this case "freeze out" will occur despite the N_2^α–N_2^β emissivity contrast. However, we note that because of the low emissivity of N_2^α, even for $\gamma = 8$, T_{N_2} will not drop to 31 K until Pluto is 43.5 AU from the Sun, 70 years after perihelion passage. The critical value of γ that gives $T_{N_2} = 31$ K at aphelion is 7.3: if γ remains below that value throughout Pluto's orbit, this model predicts that the atmospheric pressure will always be larger than 1 μbar, and that the atmosphere will remain in its hydrostatic state.

The effects we have discussed in this paper should also apply to the thermal balance of Triton's N_2 ice. We have chosen to focus on Pluto because the eccentricity-induced insolation forcing is so much stronger than Triton's obliquity-induced forcing that it is reasonable to expect other factors, such as the details of the ice distribution on the surface, to produce much smaller perturbations to the basic conclusions than would be the case if we had attempted to model Triton. Nonetheless, observations of Triton and Pluto both offer the potential to test the hypotheses presented here.

CONCLUSIONS

We have outlined a simplified model for studying the effect of the N_2^α–N_2^β phase change, and the associated change in emissivity predicted by Stansberry *et al.* (1996a), on the seasonal changes in Pluto's atmospheric pressure. Under the assumption that volatile transport does not greatly affect the overall energy balance of the N_2 ice ($\gamma < 7.3$ throughout the orbit) we show that the emissivity contrast between the two phases calculated by Stansberry *et al.* (1996a) will prevent Pluto's atmosphere from freezing out as Pluto recedes from the Sun. If volatile transport does largely denude Pluto's subsolar regions of N_2 ice as aphelion approaches ($\gamma > 7.3$) the atmosphere will freeze out, but the life of the atmosphere will still have been greatly prolonged by the emissivity contrast. This conclusion is subject to uncertainties related not only to volatile transport, but also relating to the evolution of other potentially important factors such as albedo, grain size, and vertical stratification of the phases. Telescopic observations of Triton and Pluto will be capable of detecting the α phase of N_2 ice only after significant amounts of it have formed because it will tend to be present mostly in poorly lit or unilluminated portions of the surface. In situ spacecraft observations would be much more effective for detecting N_2^α early on. Stellar occultation and/or spacecraft measurements should allow us to monitor Pluto's atmospheric pressure in coming decades, providing a direct test of the predictions of this model. More detailed modeling is possible, and probably desireable, in view of the possibility of a spacecraft being sent to Pluto with the express intent of studying the neutral atmosphere.

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