Condensation of Nitrogen: Implications for Pluto and Triton

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We have observed in the laboratory that nitrogen condenses initially as a transparent layer, if the deposition rate is less than about 2.88 $\mu m/hr$. To correlate our laboratory results with the Voyager observations of Triton and ground-based observations of Pluto, we have calculated the nitrogen deposition rates on these bodies. The maximum deposition rate for Pluto (with 40 K icy surface temperature) is calculated to be about 4,57 $*$ 10^{-8} cm/s (or $\approx$ 1.65 $\mu m/hr$) and for Triton is $\approx$ 3.83 $*$ 10^{-8} cm/s at 38 K. This implies that nitrogen on these bodies presently condenses as a transparent layer. Voyager 2 observations in August, 1989 revealed that Triton's northern hemisphere had overall 10W% albedo than the southern hemisphere. This was surprising since at that time deposition of the fresh N_2 should have taken place over most of Triton's northern hemisphere (subsolar point was at 45 s). On the contrary, the subliming southern cap was seen as a bright feature. Our new approach to this problem is based on the combination of the energy balance calculations and the laboratory results. We explain the darker northern hemisphere by the condensation of an initially transparent layer on a dark substrate, which might be dark organics produced by UV light or charged particle bombardment of CH_4 ice. The bright southern cap can be a result of N_2 shattering due to the earlier passage of the cubic hexagonal phase transition fronts. If there is a similar puzzling North/South albedo asymmetry on Pluto, as was indicated by two independent sets of observations (Buie *et al.* 1992; Young and Binzel 1993), our results offer an explanation for it. We also infer an original grain size of N_2 ice on Triton and, possibly, on Pluto. The role of impurities is discussed.

Introduction

During the Voyager 2 encounter with Triton in August 1989 the subsolar point was at 45 deg S and was moving southward its extreme of 52 deg S for the current seasonal cycle. The observed 10W% albedo of the northern regions on Triton was surprising because (like on Pluto) volatile transport models predicted that there would be bright frost which had recently condensed in Triton's northern hemisphere during autumn there (Spencer 1990, Yelle 1992, Hansen and Paige 1992). To explain this discrepancy, a transparent, solid nitrogen layer on Triton has been postulated in several studies (Smith *et* al. 1989,

Moore and Spencer 1990, Eluszkiewicz 1991, Helfenstein *et al.* 1991, Helfenstein *et al.* 1992, Lee *et al.* 1992). Helfenstein *et al.* (1992) reached this conclusion after detailed analysis of the Voyager 2 images. A extensive southern cap with the albedo of about 0.8 was also unexpected during the southern spring on Triton.

According to the albedo maps derived from the mutual event lightcurves (Buie *et al.* 1992; Young and Binzel 1993), Pluto's northern hemisphere is much darker than the southern. (WC use Pluto's angular momentum vector to define North). At the time of the mutual eclipses with its satellite Charon, Pluto was approaching perihelion in 1989. Buie *et al.* (1992) conducted regular observations of mutual eclipses for about 6 years to produce the Pluto albedo map. The Pluto subsolar point has crossed the equator in 1986 moving north with a speed of about 2 deg per Earth year. Hence prior to 1986 the south pole has been in continuous sunlight during the last $\approx$ 124 years (northern autumn and winter), and currently it is the beginning of spring in the northern hemisphere. Since the Hubble Space Telescope images (Stern *et al.* 1996) were taken later (in June 1994), the subsolar point was at $\approx$1 G deg N and the south polar regions to $\approx$ 74 S were in continuous darkness in those images.

Ground-based infrared spectroscopy (Owen *et al.* 1 993) revealed that nitrogen ice was the most abundant ice ($\approx$ 98%) on Pluto's surface. It was surprising to find an extensive bright feature near the south pole, because it should have sublimed during the southern summer (by the beginning of southern autumn) and incorporated at the north pole. Even more puzzling was why the north polar regions (where the fresh bright nitrogen frost should have naturally condensed during the winter season) appeared much darker than tile south polar regions (Spencer *et al.* 1996). Similar albedo asymmetry was revealed by Voyager 2 images (August 1989) for Triton. We proq Km a solution to this seasonal frost puzzle as well as to tile southern cap's brightness based upon the physics of solid N_2. We also estimate an original grain diameter for the present condensation of N_2 frost on Pluto and Triton.

The following two long-term cycles are important for the transport of Pluto's volatiles: the precessional cycle of the Pluto's spin axis with a period of 3 Myr (Dobrovolskis and Harris 1983) and the precession of Pluto's orbital longitude of perihelion (according to

Williams and Benson 197'1, 360 degrees in 3.7 Myr). Considering these two cycles, it is plausible that at some times Pluto has only one polar cap (Binzel 1990, 1992). If a cap experiences summer at perihelion for a sufficiently long time, it may totally sublimate away. Hence we suggest using the term "perennial" for Pluto's caps instead of "permanent" which was used for Triton's caps (Duxbury and Brown 1992, 1993, 1995). Spencer *et al.* (1996) calculations confirm that the incident insolation (note that this is not an absorbed insolat ion, since albedos are not well constrained) averaged over t he past 1 My r is about twice as high at Pluto's north pole as at its south pole. It is therefore reasonable to conclude that the residual large, bright southern polar cap at the beginning of southern autumn (after experiencing summer sublimation) must be perennial. Though the precessional cycle (which is the superposition of the 3 Myr and the 3.7 Myr cycles and has a period equal to the least common multiple of the two) explains the current existence of a large southern cap (Binzel 1992), it does not account for the lack of bright fresh frost (Spencer *et al.* 1996) in the northern hemisphere at the end of the northern winter. It also does not explain the brightness of the southern cap.

Calculations and Laboratory Experiments

Initially, we make calculations for Pluto and then generalize these for Triton. From the energy balance equation at the surface of nitrogen ice on Pluto, we calculate the highest condensation rate (which occurs whew absorbed insolation is equal to zero, i.e. at night or in permanently shadowed areas) at the present time. We assume that Pluto's surface and at mosphere are in global vapor-pressure equilibrium and use the equation:

$$\frac{\partial h(\theta,\Phi,t)}{\partial t} = \frac{\sigma\epsilon T_{ice}^4 - S(\theta,\Phi,t) - H(\theta,\Phi,t)}{L\rho}.$$

Here $\partial h/\partial t$ is the rate of change in nitrogen thickness h due to deposition ox sublimation; θ, Φ, t are latitude, longitude and time, respectively; σ is the Stefan-Boltzmann constant ($5.67051 * 10^{-8} W/m^2 K^4$); ϵ is t he emissivity (0.8 for the β phase of nitrogen, acceding t o Stansberry *et al.* 1996); T_{ice} = 40 K has been determined spectroscopically as the present solid nitrogen surface temperature on Pluto (Tryka *et al.* 1994); S is the absorbed insolation and is taken as zero; the latent heat of the solid-gas phase transition is taken

for the β phase of N_2 as 2.5 $*$ 10^5 J/kg (Brown and Ziegler 1979); and the bulk density ρ at 40 K is about 989 kg/m^3 (Scott 1976). Following Brown and Kirk (1994) calculations for Triton, Duxbury and Brown (1996) calculated that H=2.97 $*$ 10^{-3} W/m^2, which is the lower limit for the radiogenic heat flow at Plut o's surface, corresponding to the specific radiogenic heat production measured from chondrit ic meteorites. Therefore, the calculat ed upper limit for the current nitrogen condensation rate on Pluto is about 4.57 $*$ 10^{-8} cm/s (01 $\approx$ 1.65 $\mu m/hr$).

From laboratory experiments we found that, at about 2.88 p7~2/~17 or lower, nit rogen condenses as a transparent layer. The experiments were conducted at t hc Ext raterrestrial Ice Facility at the Jet Propulsion Laboratory. As in Tryka *et al. (1995),* the experimental set up included a Fourier t ransform spectrometer, a closed-cycle He refrigerat or, a t emper-at ure controller and a vacuum chamber. The laboratory measurements were performed o n thin-film samples of nitrogen grown on a sapphire substrate. The procedure was to introduce nitrogen gas of **99.999** % purity (supplied by Alphagaz) into the cryo chamber through a nozzle pointed at t he sapphire subst rate using a calibrat ed leak valve assembly. Material was deposited at a constant rate by maintaining a constant, low pressure in the line leading to the nozzle in the cryo chamber. The deposition rat e was measured by a HeNe laser. We used a photodiode to measure the intensity of tile laser beam specularly reflected from the front surface of the A^{T}_{2} layer and from the substrate. This produced an accurate measurement of the film thickness and deposition rate by measuring the passage of interference fringes in the reflected beam as the film thickened. The sapphire substrate did not interact with the condensed nitrogen, therefore it did not influence the groin growth.

The wavelength of the laser was 0.6328 microns and the accuracy of the measurement was 1/2 of a fringe or better. The typical thickness of the layer, when 1 fringe cycle was seen, is about 1/2 of the wavelength (depending upon the index of refraction of t he layer and the angle of incidence of the laser beam). We used a t echnique that assumed a two-frequency sinusoidal function for the intensity modulation seen in the scat tered laser light, thus in principle, we achieved accuracies bet t er than 1/2 of a fringe. When we condensed a A^{T}_{2} layer and observed 10 fringe cycles, we had a worst case accuracy of about 1 part in 20, ignoring systematic errors in our knowledge of the index of refraction, uneveness of t he

film, and uncertainty in our knowledge of the angle of incidence of the laser beam.

The average deposition rate for the samples measured was about 0.0008 microns per second or about 2.5 cm/yr. Typical total deposition times were such that" the average thickness of the resulting nitrogen films was about 5 microns with a maximum of 11 microns (the latter required about 3.S2 hours). If we would deposit A^{T}_{2} longer, then the grains could have sintered (i.e., neck growth between the grains would occur) and subsequently annealed at the base. Therefore, the layer would remain transparent. The clarity of the thin films was measured by obtaining transmission spectra of the substrate before film deposition, after film deposition and again after evaporative removal of the film. A Mattson Galaxy Series Fourier transform spectrometer was used. In all cases, any attenuation of the spectrometer beam in addition to that expected from purely specular reflection at the film-substrate interface was unmeasurable. Typical signal-to-noise ratios for the spectra obtained were in the range of 400-500, with the maximum of 1000. For more clet ailed description of the equipment setup aud calibrat icm we refer to the work 1)y Tryka *et al.* (1995).

We calculated the thickness of tile N_2 frost, which condensed during Pluto's northern autumn and winter ($\approx$ 120 Earth yrs) at the rate of 1.65 $\mu m/hr$, to be about 180 cm. This is still a reasonable thickness for the layer to be transparent. Increasing the condensation rate in the laboratory shows that scattering centers appear gradually in the condensed layer, hence speaking about the maximum critical condensation rate has little meaning. In summary, we conclude that what we see in Pluto's northern hemisphere is probably a relatively dark substrate under a clear layer of nitrogen ice. The dark substrate is likely a lag deposit of organics produced by phot on and charged particle bombardment of less volatile (at the same temperature as nitrogen) methane ice.

Trit on

Our results are moreover applicable to Triton because N_2 is also the dominant sulfate ice three ($\approx$99 % acceding to Cruikshank *et al.* 1993) and the A^{T}_{2} surface t emperat ure on Triton is currently lower than on Pluto ($\approx 38^{+1}_{-1}$ **K** according to Tryka *et al.* **1994).** We calculated the upper limit for the current condensation rate on Triton to be about

3.83 $*10^{-8}$ cm/s, which is less than the corresponding rate on Pluto and thus sufficient to form an initially clear nitrogen layer. This explains the relative darkness of the northern regions up to 45 deg N seen in the Voyager 2 images taken in August 1989. The polar regions above 45 deg N were not seen since they were beyond the terminator.

The mist ence of bright regions, adjacent to the large, dark areas that can be identified in the Voyager 2 images of areas north of Triton's equator, could be seen as a possible problem for the clear-layer hypothesis. Nevertheless, the bright regions may be the regions where A^{T}_{2} condensed earlier during northern autumn than clear A^{T}_{2} did. The time interval from the epoch when the subsolar point crossed the equator going south to the epoch of tile Voyager 2 encounter is about 50 Earth years. If at that time $T_{ice} > 40$ K, then the condensation rate was higher than the rate sufficient for the condensation of a transparent layer. Thus, the frost condensed as a bright layer and evidently did not have enough time to anneal into a clear ice. This explanation is applicable to Pluto>s bright regions in the mostly dark northern hemisphere. Alternatively, the bright areas on Triton may in fact be areas of exposed CO_2 or CH_4, whose lower volatility (at the same temperature as N_2 ice) would result in little or no transport or sintering during a typical Triton seasonal cycle, and thus would likely remain bright.

Initial N_2 groin size

We also have constrained the present initial N_2 grain size on the surfaces of Pluto and Triton by calculating the current maximum condensation rate, and combining the observations of Buie *et al.* (1 992), Young and Binzel (1993), Helfenstein *et al.* (1992), our laboratory experiments and Eluszkiewicz's (1991) calculations. Fortunately from the laboratory observations, we have determined the sufficient condition for a N_2 layer to be deposited as a transparent layer in terms of the condensation rate. Eluszkiewicz (1991) studied the process of sintering during deposition on Triton. He treated it as a process similar to epitaxial growth, which is an oriented overgrowth of a crystalline material upon the surface of another crystal with a similar structure. His calculations showed that if $d_{grain} > 0.3\mu$m, then an initially formed layer is non-transparent. Those "large" particles will be buried before they merge with the substrate to form a clear layer. This is equivalent

to saying: if the layer is initially transparent, then $d_{grain} < 0.3\mu m$. The current deposition rates for Pluto and Triton, which we calculated above, will cause a N_2 deposit to form as a transparent layer (according to our laboratory observations), and hence the original grain size at which N_2 frost currently forms on these bodies is less than 0.3 pm. Therefore, the laboratory observations demonstrate a sufficient condition for the condensation of an initially transparent solid nitrogen layer, providing the missing link, which allows all pieces of the puzzle to be put together.

Finally, our thermal numerical modeling (Duxbury and Brown 1992, 1993, 1995) can explain the observed lightness of Triton's and Pluto's southern perennial polar caps. We conclude that crystalline α - β nitrogen phase transition fronts shattered the solid N_2 in the southern polar regions of these icy bodies when the surface temperature dropped Mow 35.61 K. This resulted in the formation of many scattering centers in the nitrogen ice. Although the southern perennial caps had enough time to anneal into a transparent layer (Eluszkiewicz 1991) prior to this event, they are now seen as high albedo features due to the fracturing.

Discussion

It is not completely clear whether the controlled conditions of the laboratory experiments are directly applicable to the surfaces of Triton and Pluto. On one hand, the deposition of nitrogen frost on Pluto and Triton is slower than that, used in our laboratory experiments, which would argue that transparent layers could rosily form on these bodies, at least for thin layers on time scales much shorter than seasonal. On the other hand, it is not known whether other long-term processes operating on Triton and Pluto such as photochemically and cosmic ray altered impurities (especially CH_4 ice), formation of scattering bubbles and precipitation of dust particles from tile atmosphere can prevent the formation of clear layers on these bodies as thick as 1 meter.

A definitive answer to this question will likely have to be preceded by spacecraft exploration. Two spacecraft are currently planned to be launched to Pluto in March 2001 (Pluto Express mission). Our purpose here is simply to point out that, in the absence of competing processes, the very small deposition rate of nitrogen frost during a typical

season on Triton and Pluto is more likely to produce layers of clear ice rather than layers of scattering frost.

Recent Hubble Space Telescope images of Pluto, taken in June 1994, show albedo patterns similar to the mutual event albedo maps in the equatorial regions, but they show an opposite brightness pattern in the polar regions. As Stern *et al.* (1996) pointed out, systematic errors in the treatment of the HST data are the largest near a planet's limb, and the polar legions of Pluto presently lie at the limb. Whether there is indeed a contradiction between these two data sets will be decided by further observations.

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