consistent with the UVS and IRIS results only for emissivities of ~0.5, whereas the results of Nelson *et al.* (*5*), with the combined PPS and ISS data sets, are consistent with Triton being a blackbody (emissivity = 1).

It is commonly assumed that the emissivity of a material is related only to its spectral reflectance. At ultraviolet, visual, and near infrared wavelengths the spectral reflectance is determined by chemical composition. We note, however, that the wavelength of the peak of the thermal emission of a blackbody at Triton's 37.5 K surface temperature is ~80 μm. Most of Triton's thermal emission is longer than that wavelength. We suggest that even at these long wavelengths, the texture of the surface plays an important role in determining the emissivity.

The net heat flux from a surface depends on the emissivity of the surface material and the fourth power of the temperature. The apparent emissivity (and the brightness) of a surface are closely related to the geometric properties of the surface as well as the composition. It has long been recognized that the emissivity of a cavity radiator is essentially independent of the emissivity of the material from which the cavity is constructed. If the frost on Triton's surface has the geometric properties of a cavity radiator (depth of cell >> opening of cell; that is, similar to a honeycomb) then the emissivity of the surface will approach unity, without a strong relationship to the reflectance properties of the material from which the surface is composed.

It is strongly believed from other Voyager investigations that much of Triton's surface is freshly deposited. For example, Hansen and colleagues (*9*) have presented convincing evidence for rapid resurfacing of Triton as a result of currently active geyser-like processes. We would expect that the precipitated deposits would be loosely compacted and not smooth, resembling the "fairy castle" analogy often invoked in discussions of reflectance properties of candidate materials of planetary surfaces. This would be consistent with Triton having a rough surface at the >100-μm scale. The thermal energy emitted from such a surface at a wavelength of ~100 μm would closely approximate the radiation emitted from a blackbody which is inconsistent with the low emissivity required to explain the ISS data (*10*).

In order for Triton's emissivity to be consistent with the ISS photometry, two conditions need to be satisfied. First, the spectral reflectance of the ices which dominate Triton's surface must be very high (emissivity is low) at wavelengths ~80 μm and longer. Second, Triton's surface must be smooth at the ~100-μm scale.

An alternative explanation is that there may remain some uncertainties in the absolute calibration applied to the ISS results. If the ISS phase curves more closely approximated the PPS phase curves, then Triton's surface could easily be approximated by a blackbody.

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11. This work was performed at Jet Propulsion Laboratory under contract with NASA.

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Energy Sources for Triton's Geyser-Like Plumes

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Four geyser-like plumes were discovered near Triton's south pole in areas now in permanent sunlight. Because Triton's southern hemisphere is nearing a maximum summer solstice, insolation as a driver or a trigger for Triton's geyser-like plumes is an attractive hypothesis. Trapping of solar radiation in a translucent, low-conductivity surface layer (in a solid-state greenhouse), which is subsequently released in the form of latent heat of sublimation, could provide the required energy. Both the classical solid-state greenhouse consisting of exponentially absorbed insolation in a gray, translucent layer of solid nitrogen, and the "super" greenhouse consisting of a relatively transparent solid-nitrogen layer over an opaque, absorbing layer are plausible candidates. Geothermal heat may also play a part if assisted by the added energy input of seasonal cycles of insolation.

SEVERAL HYPOTHESES REGARDING the energy sources of Triton's geyser-like plumes involve absorbed insolation or combinations of absorbed insolation and geothermal heat (*1*). Although it may seem unreasonable that a surface absorbing only 20% of the incident sunlight at 30 AU (*1, 2*) could manifest effects as dramatic as Triton's plumes, we will show that there are indeed ways to trap and store enough solar energy in Triton's surface such that it is quite conceivable that Triton's plumes are a direct result of the impending maximum summer solstice in Triton's southern hemisphere. We will not attempt to discuss the physical or thermophysical characteristics of the eruptions here, nor the mechanisms whereby fluids and gases are delivered to the volcanic vents; these subjects will be discussed in separate papers in this issue by Soderblom *et al.* (*3*) and Kirk *et al.* (*4*).

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It has been known for several years that Triton has frozen volatiles on its surface, the most spectrally dominant being methane and nitrogen (*5–7*). From ground-based observations made in the 2.0- to 2.5-μm spectral region, Cruikshank *et al.* (*7*) concluded that molecular nitrogen must be present over most of Triton's visible surface in a layer at least 50 to 100 cm thick to explain the depth of a 2.15-μm absorption band in Triton's spectrum. Lunine and Stevenson (*8*) correctly concluded that nitrogen on Triton was mostly solid rather than liquid as originally proposed by Cruikshank *et al.* (*7*). Voyager 2 found nitrogen to be the dominant constituent of Triton's atmosphere with trace amounts of methane also present (*9*). Triton's ~15-μbar surface pressure (*9, 10*) is consistent with the vapor pressure equilibrium of nitrogen gas over the solid at the 38 K global average temperature observed by the Voyager IRIS experiment (*11*). The basal atmospheric pressure on Triton is thus sufficient to buffer, via global

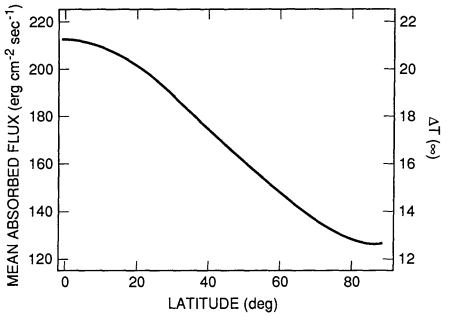

Fig. 1. Seasonally averaged, absorbed insolation and accompanying maximum, seasonally averaged greenhouse temperature as a function of latitude on Triton assuming a bolometric Bond albedo of 50% and $\zeta/\kappa = 0.1$. See the text for an explanation of the relevant assumptions for this calculation.

volatile transport, the temperature of the nitrogen ice on Triton's surface such that it is nearly isothermal (*12*). For a detailed discussion of global volatile transport on Triton the reader is referred to papers by Spencer (*13*) and Stansberry *et al.* (*14*). The overall direction of volatile transport on Triton over seasonal and multiseasonal time scales, however, is important to a determination of whether insolation can plausibly supply the energy for geyser-like plumes on Triton; thus we will discuss the essential aspects as they relate to our problem.

Because volatile transport on Triton is driven primarily by insolation (*12*), any net transport will be proportional to the mean value of absorbed insolation over many seasonal cycles. Using the results of Jacobson (*15*) to specify the subsolar latitude on Triton as a function of time, we calculated the mean value of incident insolation as a function of latitude on Triton, averaged over the period ± 3000 years about the present. That calculation indicates that the equatorial regions on Triton on average receive about 65% more incident sunlight than do the polar regions (see Fig. 1), suggesting that in the absence of latitudinal albedo variations the long-term average volatile transport on Triton is from the equator to the poles. Over time the equatorial regions on Triton should then be stripped of any initial cover of nitrogen ice and only seasonal deposits of ~ 1 m thick should remain (*13, 14*). In fact, because the long-term average insolation decreases monotonically toward the poles, in the absence of other effects all the nitrogen will migrate identically to the poles (*13, 14*). Nevertheless, because Triton's global average albedo is quite high, even small regional differences in Bond albedo will result in large differences in absorbed energy. Thus albedo differences could eliminate or reverse the tendency otherwise for systematic migration of volatiles toward the poles (*13, 14*).

What is envisioned here, thus, is a global surface layer of solid nitrogen on Triton contaminated with small amounts of methane and dark organics. This layer is some tens of centimeters to hundreds of meters thick, in places optically translucent or transparent in the visible region of the solar spectrum, and relatively opaque in the thermal infrared (*16*) (here being the $\sim$30- to $\sim$300-μm region for the 38 K temperature of Triton). In Triton's polar regions the nitrogen deposits could be hundreds of meters thick and permanent, while in its equatorial regions perhaps only meter-thick seasonal layers are present, possibly disappearing completely by early spring and late fall. In addition, solid nitrogen has a low thermal conductivity [$\sim 2.0 \times 10^4$ erg cm^{-1} s^{-1} K^{-1} (*17*)]. As we will show, layers of transparent or translucent, low-conductivity nitrogen ice that are meters to tens of meters thick are necessary for plausible models of geyser-like plumes driven entirely by insolation.

Another essential aspect of invoking insolation-only or insolation-triggered mechanisms for Triton's plumes involves the distribution, sizes and physical characteristics of the myriad dark streaks on Triton's south polar caps. The dark streaks are fan-shaped, kilometers to many tens of kilometers long, and seem to emanate from dark regions on Triton's south polar cap (*1*). They also seem to be closely associated with boundaries between the lighter and darker materials that form the distinctive patchwork patterns of albedo over much of Triton's south polar cap (*1*). Sagan and Chyba (*18*), in an analogy to wind streaks on Mars, argued that the dark streaks on Triton could be a similar phenomenon, if Tritonian dust grains are less than a few micrometers in size and have low cohesion; for grains as cohesive as those found on Earth, however, the required wind speeds are implausibly high. Sagan and Chyba also concluded that dust settling times combined with expected wind velocities on Triton (*19*) yield streak lengths in good agreement with the observed streak lengths. Thus, this, combined with the presence of active plumes on Triton at latitudes near $-50°$ (*1, 3*) whose ejecta fans are very similar in appearance to the streaks, suggests that streaks result when dust particles injected into Triton's atmosphere by geyser-like plumes are carried downstream from the vent by the prevailing winds. Therefore, we conclude that most of Triton's streaks are remnants of extinct or dormant plumes. That the streaks are confined almost entirely to areas south of $-20°$ latitude (*1*) strongly implicates insolation as a major driver for Triton's plumes.

Thus it seems that sunlight plays a dominant role in providing the energy for Triton's geyser-like plumes. Although it may seem implausible that a body as cold as Triton could support eruptive phenomena driven by sunlight, with the solid-state greenhouse effect (*20, 21*) enough solar energy can be trapped in Triton's near subsurface to induce the required thermal gradients. Energy stored as specific heat in solid nitrogen (or under some conditions liquid nitrogen) can then be released as latent heat of sublimation by venting of nitrogen gas through fissures (either preexisting or created by large pressure differences).

There are two basic types of greenhouse models that could supply the thermodynamic temperature differences. The first is the classical greenhouse mechanism where insolation is absorbed exponentially with depth in a visually translucent layer of solid nitrogen by trace impurities dissolved in or dispersed throughout the nitrogen (for example, methane, ethane, ethylene, acetylene and polycyclic, aromatic hydrocarbons). Because the nitrogen layer is relatively opaque to thermal radiation in the 30- to 300-μm spectral region, the dominant heat-transport mechanism within the layer is diffusion of subsurface heat to the surface where part is radiated to space and the rest carried away as latent heat of sublimation.

A variation on the classical greenhouse is loosely termed a "super" greenhouse. The major difference between it and the classical greenhouse is that insolation traverses a layer of solid nitrogen largely unattenuated, and is absorbed in a dark, opaque layer at the base of the nitrogen ice. Thus, the thermal gradients can be somewhat larger, and the nitrogen ice layer equivalently thinner for a given amount of absorbed insolation, in order to support the required thermodynamic temperature differences.

Brown and Matson (*20*) and Matson and Brown (*21*) have described the classical solid-state greenhouse model and have explored its application to icy surfaces in the outer solar system. More recently, Brown and Matson (*22*) obtained observational evidence for a mild solid-state greenhouse operating on Jupiter's satellite Europa. For Europa, Brown and Matson find that temperature inversions as large as 40 K are consistent with observations of Europa's thermal flux as it goes into and out of eclipse by Jupiter. Here we apply a similar model, albeit with different model parameters, to the case of Triton. Specifically, we look at the case of a layer of solid nitrogen trapped in a depression, with a total depth of 50 to 100 m. Absorption of sunlight within the nitrogen layer is accomplished by a trace amount of visually dark particles uniformly distributed throughout the ice. We assume that these absorbers are spectrally gray and have a low single-scattering albedo so that sunlight is absorbed exponentially with depth over a scale length independent of wavelength.

In their 1990 paper, Matson and Brown (*21*) derived an expression for the steady-state increase in temperature with depth for the classical solid-state greenhouse:

$$\Delta T = \overline{S}\frac{\zeta}{\kappa}\left(1 - e^{-z/\zeta}\right) \quad (1)$$

where $\overline{S}$ is the time average of the absorbed insolation (for either diurnal or seasonal time scales), ζ is the propagation scale length for absorption of sunlight, κ is the thermal conductivity, and z is depth below the surface. This expression is valid for the case of no lateral heat loss from the greenhouse (a reasonable assumption for seasonal time scales, but problematic for diurnal time scales) and can scope the plausible range of diurnal and seasonal average subsurface temperatures in a Triton solid-state greenhouse.

The seasonal mean greenhouse temperature on Triton at depths greater than 3ζ ($\Delta T \approx \overline{S}\zeta/\kappa$), depends partly on the seasonal mean absorbed insolation at a given latitude and partly on the ratio ζ/κ. The absorption scale length (ζ) for sunlight in clear nitrogen ice can be estimated by analogy to terrestrial water ice. The propagation scale length of ~20 meters for sunlight in terrestrial glare ice (*22*) provides a useful estimate for that of nitrogen glare ice on Triton, because the bulk of the sunlight absorption in either case will be effected by dark particles suspended within the ice. Terrestrial glare ice is typically contaminated with about a part per million by mass of mostly soot particles (*22*), and this level of contamination could be easily achieved for nitrogen ice deposits on Triton (*23*). For example, if multiple scattering within the ice layer is negligible (that is, only dark particles are present in an otherwise transparent ice layer), the number density of spherical particles required for a given propagation scale length for sunlight is given by:

$$N_p = (\pi\zeta r^2)^{-1} \quad (2)$$

where ζ is the propagation scale length and r is the particle radius. For ζ = 2000 cm and 1-μm particles this yields a number density of ~6.4×10^4 cm^{-3}. If the intrinsic particle density is ~2.5 g cm^{-3}, the result is a concentration of about 1 part in 10^7 by mass. The concentration of methane in the nitrogen ice on Triton is probably at least 1 part in 10^4 (*9*) and perhaps as high as 1 part in 100 (*24*), so only about 1 part in 10^3 to 10^5 of the methane need be converted to dark organics to provide the necessary concentration of visual absorbers.

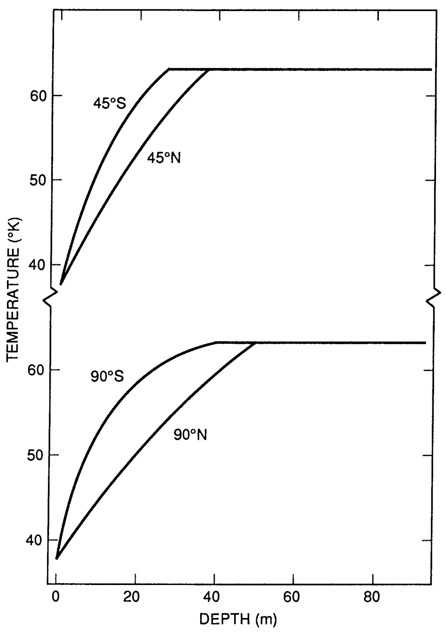

Fig. 2. Present transient temperatures in a deep, classical nitrogen greenhouse as a function of depth for several latitudes. This calculation shows transient temperatures in a classical nitrogen greenhouse on Triton whose effective albedo is 35% and whose optical properties are such that the absorption scale length for insolation is ~20 meters. At the top are curves for ±45° latitude; at the bottom are curves for the north and south poles. Note that the 63 K melting point of nitrogen is reached in all cases at some depth (see text).

Thus, with the appropriate values for the parameters specified, in Fig. 1 we plot the seasonal average temperature rise in a nitrogen greenhouse as a function of latitude for an effective albedo of 50%, and for our nominal value of ζ/κ = 0.1. An effective albedo of 50%, though probably much higher than that of pure nitrogen glare ice, is typical of the darker areas on Triton's south polar cap (*1*). Thus, we assume in this model that there is a scattering layer at the surface of the ice deposit that scatters 50% of the insolation back to space while the remaining 50% of the insolation penetrates to the mostly transparent nitrogen ice underlayers where it has an absorption scale length of ~20 meters. As can be seen from Fig. 1, for the nominal case of ζ/κ = 0.1 the average seasonal temperature at the base of a greenhouse layer on Triton is between 50 and 54 K for latitudes south of the subsolar point (~45° south latitude)—a temperature rise of 12 to 16 K above the nominal surface temperature of 38 K. This is the long-term average temperature upon which diurnal and seasonal transient temperatures will be superimposed and as such (for the assumed parameters) is a lower limit to the transient temperatures expected in a classical nitrogen greenhouse on Triton at or near summer solstice.

The transient temperatures that would obtain in a classical greenhouse, however, can be higher. To demonstrate this we again follow the approach of Brown and Matson (*20*) in constructing a model. In Fig. 2 is displayed the results of a calculation of the transient temperature profiles in 100-m-deep nitrogen ice layers with an effective albedo of 35%, with ζ/κ = 0.1 at various latitudes on Triton. As can be seen from Fig. 2, the transient temperatures for areas near the present subsolar point can reach the melting point of nitrogen fairly close to the surface, raising the possibility that the geyser-like plumes on Triton result from liquid nitrogen working its way from depth to the surface where it explosively vaporizes in the tenuous atmosphere. As Fig. 2 shows, the liquid nitrogen region in this model is nearest the surface in the mid-latitudes, at depths ≥~20 meters. Thus, this model predicts that active, geyser-like plumes will presently be erupting at latitudes near the highest seasonal average insolation input and thickest permanent nitrogen deposits; that is, in Triton's southern mid-latitudes.

As was previously mentioned, the super greenhouse model involves thinner, mostly transparent layers of nitrogen ice. In this model sunlight propagates through nitrogen ice largely unattenuated to depths of 2 to 5 m where it is absorbed by a dark layer, perhaps a lag deposit of dark organics. The layer of nitrogen ice is thus heated at its base and the resulting thermal gradient conducts heat upward toward the surface where it is eventually carried away both as latent heat of sublimation and as radiant energy to space. If insufficient solar energy is absorbed (that is, the thermal gradient is too shallow to supply the required energy to maintain a 38 K temperature), then the surface will cool slightly and nitrogen gas will condense, delivering just enough latent heat to the surface to maintain the 38 K surface temperature.

Again following the approach of Brown and Matson (*20*), we have constructed a numerical model of this "super" greenhouse for Tritonian conditions and display the results in Fig. 3 for various layer thicknesses, assuming ζ = 20 m, and for a 5% albedo absorbing layer at the base. Because the assumed thickness of the ice layer is less than 5 m, the thermal gradient reaches quasi-steady state in about a year, so we use the present subsolar latitude in these calculations and allow the solar input to vary on a diurnal time scale only. As can be seen, a substantial, nearly linear thermal gradient is induced, and, depending on the thickness of the layer, the temperature at its base can exceed 50 K. A consequence of the induced thermal gradient is that higher temperatures

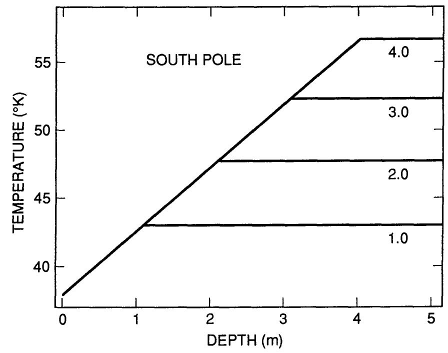

Fig. 3. Temperature versus depth for a "super" greenhouse at the south pole having a base absorbing layer of 5% albedo (see text).

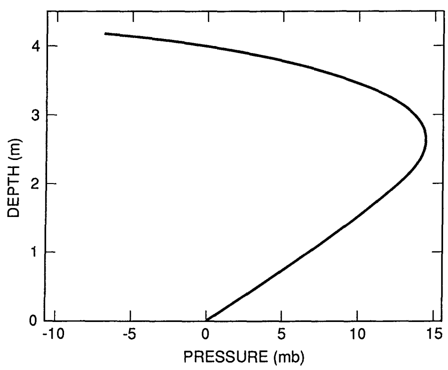

Fig. 4. Overburden pressure minus vapor pressure in millibars versus depth for the greenhouse model of Fig. 3. Note that the vapor pressure equals the overburden pressure near 4-m depth and exponentially exceeds the overburden below that point, suggesting that explosive shedding of a well-sealed overlayer would occur for layers much thicker than 4 m.

at depth result in a substantial increase in the nitrogen vapor pressure at depth relative to the ambient surface pressure of ~15 μbar. To demonstrate the magnitude of this pressure difference, in Fig. 4 we plot the net pressure difference between the overburden (which consists of the ambient atmospheric pressure plus that of the ice overburden above a given point) and the vapor pressure of the nitrogen ice at a given depth for the thermal gradient illustrated in Fig. 3. At a depth of about 4 m, the nitrogen vapor pressure exceeds that of the overburden and exponentially increases at depths greater than 4 m. It is clear from this plot that at depths greater than 4 m the vapor pressure can easily exceed the combined effects of the overburden pressure and the intrinsic strength of the overlayer such that an explosive release of gas into Triton's atmosphere is possible. More likely, however, the gas will find its way through defects in the ice layer to be released in a more gradual fashion, but with similarly dramatic consequences (*3*).

Although we have argued that the distribution of the streaks and the locations of the active plumes on Triton suggest a driving mechanism correlated with solar input, and we have discussed a couple of plausible models based on that thesis, there may be other mechanisms capable of supplying the required temperature gradients and reproducing the observed spatial distribution. For example, there is ample evidence in the Voyager images that Triton has had a geologically active past (*1*), and simple models of the thermal history of Triton, based on considerations of its bulk silicate fraction and the accompanying radiogenic heating, suggest that the present, near-surface geothermal gradient inside Triton is ~0.3 K km^{-1} (*1*). At about 200 km below the surface in these models the ammonia-water eutectic melting temperature is reached, possibly providing a supply of cryogenic lava that can intrude into Triton's near surface. It is certainly the case that cryogenic lavas with temperatures ≥173 K, either erupted under a nitrogen ice layer or extruded into regions close to the surface underlying a nitrogen ice layer, could provide the necessary temperature gradients to drive geyser-like plumes on Triton. What is not clear, at least to us, is whether mechanisms involving only geophysical heat sources can plausibly explain the spatial distribution of the streaks and active plumes on Triton's south polar cap. One way of removing this objection would be to postulate that the seeming correlation of the plume and streak locations with areas of high solar input is artificial. For example, if an active plume were found in Triton's northern latitudes near the present northern-most extent of the terminator, it would clearly be a problem for theories relying mostly or completely on insolation as a driver. Presently, however, there is no evidence for plume activity anywhere but in the mid- to high latitudes in Triton's southern hemisphere, and that mitigates against models that employ only geophysical heat sources.

More plausible is a model involving a solid-state greenhouse whose temperature gradient is made steeper by the global average geophysical heat flow originating from Triton's interior. For example, if the south polar cap on Triton is composed of mostly nitrogen, and if the crust below the cap is composed of water ice, then for internal heat flow to be globally isotropic, the thermal gradient in the cap material must be ~50 times that in Triton's assumed water ice crust (directly proportional to the ratio of thermal conductivity of water ice to that of nitrogen at 38 K). Under these conditions, the temperature at the base of a 1-km-thick polar cap would be ~15 K higher than at the surface, and at the base of a 100-m-deep layer the corresponding temperature rise would be 1.5 K. Under these conditions, geyser-like plume activity could be more easily triggered by seasonal cycles of insolation and would still be correlated with thick layers of nitrogen ice and small solar zenith angles. As such, this mechanism is poorly distinguishable from purely insolation-driven mechanisms.

As for the relative merits and drawbacks of the two greenhouse models presented here, it is difficult to distinguish between them without more data. One possible distinction is that the "super" greenhouse model would be most effective in areas receiving the highest diurnal average insolation which is presently Triton's south pole. This results because a layer of a few meters thickness reaches quasi-equilibrium with absorbed insolation in about a year or two. Thus, active plumes on Triton driven by a "super" greenhouse would be most numerous near Triton's south pole. In contrast, a classical greenhouse in deep nitrogen layers should produce geysers in areas having the thickest nitrogen deposits weighted toward areas receiving the highest seasonal average insolation; that is, in the mid-latitudes. This presumes, of course, that Triton's surface inventory of nitrogen increases away from the equator and that the optical properties of the nitrogen ice layer are what we assume them to be. A drawback of both of these models, but more so for the deep, classical greenhouse, is that the nitrogen layers must be relatively transparent to support a significant greenhouse temperature inversion. A crucial piece of information regarding the viability of our assumptions regarding the optical properties of nitrogen on Triton is whether nitrogen condenses as a fine-grained frost (~100-μm grains) or as a macro-crystalline ice, with crystals tens of centimeters in size. Grain growth rates for nitrogen frost at 38 K are too slow to produce large grains in recent frost deposits (*4*), but the slow seasonal deposition rate of ~1 cm of ice per year suggests that large crystals may in fact result. The effective pathlength required to explain the depth of the 2.15-μm nitrogen absorption in Triton's spectrum also argues for large crystals with few internal scattering centers (*7*). Nevertheless, we are not presently aware of any laboratory data that would bear upon this question.

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Triton's Plumes: The Dust Devil Hypothesis

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Triton's plumes are narrow columns 10 kilometers in height, with tails extending horizontally for distances over 100 kilometers. This structure suggests that the plumes are an atmospheric rather than a surface phenomenon. The closest terrestrial analogs may be dust devils, which are atmospheric vortices originating in the unstable layer close to the ground. Since Triton has such a low surface pressure, extremely unstable layers could develop during the day. Patches of unfrosted ground near the subsolar point could act as sites for dust devil formation because they heat up relative to the surrounding nitrogen frost. The resulting convection would warm the atmosphere to temperatures of 48 kelvin or higher, as observed by the Voyager radio science team. Assuming that velocity scales as the square root of temperature difference times the height of the mixed layer, a velocity of 20 meters per second is derived for the strongest dust devils on Triton. Winds of this speed could raise particles provided they are a factor of 10^3 to 10^4 less cohesive than those on Earth.

Dust devils are atmospheric vortices that occur under clear skies and unstable conditions. They are common at midday in desert areas, where the ground temperature exceeds the air temperature at an elevation of 0.3 m by 20°C or more (*1*). Dust is apparently an incidental component, carried aloft by the wind but having little effect on the dynamics (*2*). On Earth, a large dust devil is 10 m in diameter, rises to an altitude of 600 m, and has vertical and horizontal wind speeds of 2 and 10 m s^{-1}, respectively (*1–4*). The diameters and wind speeds are a factor of 20 less than those of tornadoes (*5*), which grow downward from cumulonimbus clouds and are associated with latent heat release and dense overcast. Large dust devils are observed on Mars (*6*), where they rise to altitudes of 6 km.

Planetary bodies with thin atmospheres are more likely to have dust devils than those with thick atmospheres. To see this, note that the vertical acceleration of an air parcel is given by $g\delta T/T$, where g is the gravitational acceleration and $\delta T/T$ is the fractional temperature difference between the parcel and its surroundings. This difference is proportional to the temperature lapse rate in the lowest few meters of the atmosphere, which is the best predictor of dust devil size and frequency (*4*). On Earth, favorable conditions include flat topography, light winds, dry soil (low thermal inertia), and a clear atmosphere (strong radiative heating). Mars, with a surface pressure of 6 mbar (strong radiative forcing and low atmospheric heat capacity), is a more favorable location than Earth. Although the properties of its surface are uncertain, Triton's atmospheric pressure of 15 μbar would tend to make it a favorable location. Moreover, Triton's plumes look like buoyant columns, as pointed out by Smith *et al.* (7) and Yelle *et al.* (*8*).

However, if nitrogen frost were blanketing Triton's surface, the diurnal temperature range would be small and dust devils would seem unlikely. On Triton the frost temperature is controlled by vapor equilibrium with the N_2 atmosphere at $T = 38$ K (*9–11*). Any sunlight absorbed by the frost goes immediately into latent heat of sublimation, and the frost temperature does not change. But if the frost were patchy, any exposed "soil" of water ice or other involatile substance would heat up during the day. At the subsolar point (noon at −45° latitude during the Voyager encounter) a powdery soil with a thermal inertia of 13 J m^{-2} $s^{-1/2}$ K^{-1} (*12*) and an albedo of 0.6 would reach temperatures of 53 K. Even if the albedo were 0.8, which is typical of much of the polar region (*13*), the surface temperature would reach 44 K, which is 6 K above the mean temperature (*9*). In both cases, $\delta T/T$ is potentially larger than it is under the most extreme conditions on Earth. These unfrosted patches are the "hot spots"—the potential source regions for dust devils on Triton.

Finding places where the surface temperature is ≥48 K would help explain a puzzling feature of the atmospheric temperature profile derived from the radio science experiment on Voyager (*14*). Basically, the derived temperature is too warm for a surface that is uniformly covered by frost at 38 K. The radio science team derived 48 ± 5 K for the atmosphere up to 50 km altitude, with evidence of an inversion layer (temperature increasing upward) in the lowest 3 km. Yelle *et al.* (*8*) showed that such a profile would cool as a result of turbulent mixing of heat downward. Their warmest model atmosphere, assuming a surface temperature of 38 K, is colder than 38 K up to 20-km altitude. The turbulence is present because the sun is constantly subliming frost at the summer pole and driving large-scale winds toward the dark hemisphere (*11*).

Yelle *et al.* argued that the radio science data are consistent with their cold-atmosphere model when allowance is made for errors in the data. Here we accept the data at face value and show that hot spots can account for the 48 ± 5 K temperature. Since the radio science team described their published result as preliminary (*14*), the issue may be settled when the data are reanalyzed.

Our explanation hinges on the assumption that the unfrosted areas heat the atmosphere by convection. If the atmosphere had no way to get rid of its heat, either by infrared radiation, turbulent mixing downwards, or transport to the dark side of the

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