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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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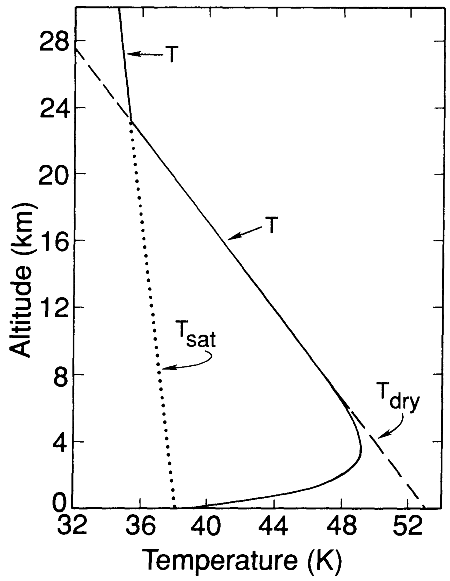

Fig. 1. Temperature profile for Triton's atmosphere controlled by hot spots at 53 K. The solid line is the temperature profile, which consists of three parts. The upper portion with dotted extension T_{sat} is the N_2 saturation curve. The middle portion with extension T_{dry} is a dry adiabat with surface temperature 53 K. The lower portion is an exponential (scale height 1.5 km) that decays upward from a surface temperature of 38 K (the frost temperature) and joins smoothly to the dry adiabat.

planet, the convection would turn itself off when the atmospheric temperature was that of the hottest hot spot. A weak heat sink will allow a few hot spots to continue convecting, and these will control the temperature of the atmosphere.

Figure 1 shows the temperature profile in an atmosphere above a patchy frost interspersed with hot spots. Since the parcels rise adiabatically, the steady-state temperature profile will follow a dry adiabat with a surface temperature that is closer to that of the hot spots than that of the frost. The lapse rate, $-dT/dz$ where z is altitude, is then g/c_p where g is the gravitational acceleration (0.79 m s^{-2} for Triton) and c_p is the specific heat at constant pressure (1040 J kg^{-1} K^{-1} for N_2). Thus temperature initially decreases with altitude at a rate of 0.76 K km^{-1}. Eventually the profile runs into the condensation boundary, the temperature at which the gas is saturated. Using the Clausius-Clapeyron equation for dP/dT and the hydrostatic equation for dP/dz, we find that the condensation point varies with altitude at a rate given by $dT/dz = -gT/L$. With $T = 38$ K and $L = 2.5 \times 10^5$ J kg^{-1} (*11*), this gives $gT/L = 0.12$ K km^{-1}, which is much less than the dry adiabatic rate. For a dry adiabat starting at a surface temperature of 53 K, saturation occurs at 27 km altitude. Convection will stop at this altitude unless the atmosphere is supersaturated—colder than the rising parcels.

Yelle *et al.* (*8*) argue that the atmosphere would be supersaturated if condensation nuclei were absent. Ignoring the possibility of hot spots, they invoke geyers to inject condensation nuclei into the atmosphere where the plumes are. The parcels then rise along the condensation curve, which is warmer than the surrounding supersaturated atmosphere. This produces extremely cold temperatures, 38 K at the surface with temperature decreasing upward, which is inconsistent with the published radio science results as described earlier. Yelle *et al.* also mention another problem with their model, namely, that the photodissociation of methane should produce abundant condensation nuclei. Hot spots eliminate both problems, as well as the need for geysers. But they have their own problem, namely, how to make the plume visible when the air is too warm for condensation.

Although a warm atmosphere [Fig. 1 and figure 5B of Tyler *et al.* (*14*)] cannot condense nitrogen frost, it can condense the hydrocarbon products of methane photodissociation, and it can pick up particles from the surface if the winds are strong enough. Thus, the existence of clouds and haze in the lowest 10 km does not necessarily imply that the atmosphere is cold there.

How large are the hot spots? Even under the most unstable conditions, the efficiency of heat transfer from the warm surface to the cold atmosphere is only about 1% (*15*, p. 168), so the area of the hot spots must be at least 100 times that of the plumes. Since the plume diameter is of order 1 km (*7*), the linear dimension of the hot spots must be of order 10 km or larger.

How does the atmosphere lose the heat that it gains from the hot spots? The temperature inversion in the radio occultation profile allows us to estimate the downward heat flux in the turbulent boundary layer. This flux is presumably balanced by the upward heat flux in the hot spots averaged over the planet. The estimate equates the inversion layer thickness to the Monin-Obukhov length, which is the altitude at which the work expended in mixing warm air downward is equal to the work done by the shear stress in the turbulent boundary layer (*15*). This length, which we call z_*, is given by $-u_*^3 \rho c_p T/(kgF)$, where $-F$ is the downward heat flux (a positive quantity), k is Von Karman's constant (a dimensionless number of order 0.4), ρ is the atmospheric density, and u_* is the friction velocity in the turbulent boundary layer. The surface stress is defined as ρu_*^2.

Setting z_* equal to 1.5 km, which is the e-folding height of the inversion layer in the radio occultation profile (*14*), we solve for $-F$ in terms of u_* and other known quantities. We can calculate the stress ρu_*^2 from the mass transport away from the subliming polar cap using standard Ekman layer theory (*15*, p. 97). The eddy viscosity, drag coefficient, and other poorly known quantities drop out of the problem and we are left with $u_*^2 = v_0 H\Omega$, where v_0 is the depth-averaged sublimation-driven velocity, ~0.32 m s^{-1} according to Ingersoll (*11*), H is the atmospheric scale height, ~14.8 km (11), and Ω is Triton's rotational angular velocity, ~1.24×10^{-5} s^{-1} (*11*). With these choices, we get $u_* = 0.24$ m s^{-1} and $-F = 1.5 \times 10^{-4}$ W m^{-2}.

The heat flux $-F$ is much less than the incident sunlight at the top of the atmosphere, ~1.52 W m^{-2}, but is much greater than the downward flux of energy from Triton's thermosphere. The latter flux is derived from the Voyager ultraviolet spectrometer observations (*8, 10*) and is approximately 1.6×10^{-6} W m^{-2}. Yelle *et al.* (*8*) did not allow for hot spots and discounted the radio occultation profile, so the thermospheric flux was the largest downward flux in their calculations. In fact $-F$ is a lower bound on the atmospheric heat sink, since heat could also be carried to the dark side by large-scale winds. Thus $-F$ is a lower bound on the heat flux from Triton's actively convecting hot spots.

We now come to the most difficult question, namely, what winds should we expect, and could they be strong enough to pick materials off the surface? Sagan and Chyba (*16*) have calculated the critical friction velocity u_* as a function of particle radius for saltation of grains on Triton. They use an empirical formula fitted to wind tunnel data taken at terrestrial and martian pressures (1 bar, 3 to 9 mbar). The formula includes the effects of hydrodynamic, gravitational, and interparticle cohesion forces. The form of the cohesion force, especially its dependence on particle size, is highly uncertain, so the extrapolation to Triton conditions is also uncertain. Sagan and Chyba find that the minimum critical u_* is about 10 m s^{-1}, corresponding to a particle radius r of about 150 μm. These are the particles that move first as the wind speed increases. If the particles on Triton were less cohesive than particles on Earth, the critical values of u_* and r would both decrease.

How strong are the winds? Searching the literature, we have not found a theory of terrestrial dust devils that could be applied directly to Mars or Triton. Dust devils violate the similarity relations for eddy velocity v and temperature fluctuation δT when the only input variables are the heat flux F and altitude z. According to Arya (*15*, p. 137), these relations are

$$\nu = 1.4 \left(\frac{Fgz}{\rho c_p T}\right)^{1/3} \quad (1)$$

$$\delta T = 1.3 \left(\frac{F}{\rho c_p}\right)^{2/3} \left(\frac{gz}{T}\right)^{-1/3} \quad (2)$$

For Earth with $F = 1000$ W m^{-2} and $z = 2$ m, we obtain $\nu = 0.54$ m s^{-1} and $\delta T = 3.1$ K. In contrast, Sinclair (*3*) measures $\nu = 10$ m s^{-1} and $\delta T = 5$ K at $z = 2$ m for several large dust devils. We conjecture that the similarity relations fail because the mixed layer thickness h is also entering the problem (*15*, pp. 137–138). Possibly the ground-to-air temperature difference ΔT is entering too. In any case, we adopt the formula

$$\nu_d = 0.5 \left(\frac{gh\Delta T}{T}\right)^{1/2} \quad (3)$$

as the velocity in a large dust devil. This expression is consistent with the similarity relations if we substitute h for z and ΔT for δT, eliminating $F/\rho c_p$ from the two equations, but the numerical constant is different. The constant above was chosen to give $\nu = 10$ m s^{-1} when $g = 10$ m s^{-2}, $h = 600$ m, $\Delta T = 22$ K, and $T = 320$ K (*3*). The above equation says that kinetic energy is proportional to the potential energy involved in lifting a parcel with vertical acceleration $g\Delta T/T$ through a distance h. The $h^{1/2}$ dependence is also consistent with the empirical results of Ryan and Carroll (*1*), and the numerical constant is consistent with the strongest dust devils they encountered.

The mixed layer is the zone of buoyancy-generated turbulence that develops during the day above the unstable surface layer (*15*). On Earth, its thickness is limited by the heat capacity of the atmosphere and is of order $h = F/(\rho c_p \Delta T \Omega) \approx 600$ m, where F is the solar flux reaching the ground. On Mars and Triton the above expression gives $h > 10$ km, indicating that the mixed layer could occupy most of the atmosphere. A more conservative estimate is that h is equal to the heights of the plumes, 6 km for Mars (*6*) and 8 km for Triton (*7*). With these choices and with $\Delta T/T = 0.25$, we obtain $\nu_d = 40$ m s^{-1} for Mars and 20 m s^{-1} for Triton.

It is not clear that winds of order 20 m s^{-1} could pick up material on Triton. The friction velocity u_* is likely to be 10 to 20 times smaller than the wind above the boundary layer (*15*, p. 168). If the latter is 20 m s^{-1}, the friction velocity is only 1 or 2 m s^{-1}. Then the interparticle cohesion forces would have to be 10^3 to 10^4 times smaller on Triton than on Earth, according to the formula of Sagan and Chyba (*16*). They regard such differences as possible. Certainly, the difference in temperature would tend to make water ice particles much less cohesive on Triton than on Earth.

The alternative is that the plumes are indeed geysers or eruptions of some sort (*17*). If so, the eruptions are fundamentally different from those on Io. The plume does not spread into an umbrella shape, nor does it rise above the atmosphere like the hypervelocity jets of Io. Instead, it spreads out horizontally at 8-km altitude, as if the density structure of the atmosphere were controlling its rise. In short, the plumes look like buoyant columns (*7, 8*), and their narrowness makes them look like atmospheric vortices. They might be dust devils.

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The Impact Cratering Record on Triton

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Impact craters on Triton are scarce owing to the relatively recent resurfacing by icy melts. The most heavily cratered surface has a crater density about the same as the lunar maria. The transition diameter from simple to complex craters occurs at a diameter of about 11 kilometers, and the depth-diameter relationship is similar to that of other icy satellites when gravity is taken into account. The crater size-frequency distribution has a differential −3 slope (cumulative −2 slope) and is the same as that for the fresh crater population on Miranda. The most heavily cratered region is on the leading hemisphere in Triton's orbit. Triton may have a leading-trailing asymmetry in its crater population. Based primarily on the similarity of size distributions on Triton and Miranda and the relatively young surface on Triton, the source of Triton's craters is probably comets. The very peculiar size distribution of sharp craters on the "cantaloupe" terrain and other evidence suggests they are volcanic explosion craters.

IMPACT CRATERS ON TRITON ARE RARE to nearly absent at the 3 to 1.8 km resolutions acquired on the mapping sequence of Voyager 2. The highest resolution (1.8 to 0.8 km) terminator images have various degrees of smear and, therefore, crater counts have not yet been performed. When these images have been desmeared they should provide useful information on the small crater population and extend the size distribution downward.

Although extensive resurfacing has left only a few late-forming impact craters, there are still enough craters to provide information on the size-frequency distribution and to locally derive relative terrain ages. However, the diameter range over which the size distribution can be reliably determined is very limited, making comparisons with most other outer planet satellites difficult to impossible. Furthermore, the identification of impact craters on certain terrains is extremely difficult due either to the complex nature of the terrain or the high sun angle under which it was viewed.

Triton's surface records the relatively recent impacts which have occurred since it was extensively resurfaced by internal processes. No reliable record of an early intense bombardment remains on the part of Triton imaged at relatively high resolution. The largest uncontested impact crater viewed by Voyager 2 on Triton (Mazomba) is only about 27 km in diameter. There are several larger quasi-circular features, but they may be of internal origin, particularly since there are numerous acknowledged circular volcanic structures present in most areas of the

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