Global warming on Triton

J. L. Elliott‡, H. B. Hammel*, L. H. Wasserman‡, O. G. Franz†, S. W. McDonald*, M. J. Person†, C. B. Olkin†, E. W. Dunham, J. R. Spencer†, J. A. Pasachoff‡, M. W. Buli†, J. M. Pasachoff‡, B. A. Babcock‡ & T. H. McCone

* Department of Earth, Atmospheric, and Planetary Sciences, ‡ Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA
‡ Lowell Observatory, Flagstaff, Arizona 86001, USA
§ Astronomy-Department, Physics Department, Williams College, Williamstown, Massachusetts 01267-2565, USA

Triton, Neptune’s largest moon, has been predicted to undergo significant seasonal changes that would reveal themselves as changes in its mean frost temperature. But whether this temperature should at the present time be increasing, decreasing or constant depends on a number of parameters (such as the thermal properties of the surface, and frost migration patterns) that are unknown. Here we report observations of a recent stellar occultation by Triton which, when combined with earlier results, show that Triton has undergone a period of global warming since 1989. Our most conservative estimates of the rate of temperature and surface-pressure increase during this period imply that the atmosphere is doubling in bulk every 10 years — significantly faster than predicted by any published frost model for Triton. Our result suggests that permanent polar caps on Triton play a dominant role in regulating seasonal changes on Triton.

The 4 November 1997 occultation of the star Tr180 (also known as Tycho 651672 and GSC6321–01030) was successfully observed with the Hubble Space Telescope (HST) in daylight over the northwestern Pacific Ocean; Astrometer 3 of the Fine Guidance Sensors (FGS) was used to record the event. Details of the HST data are given in Table 1 along with information about other observing stations; the immersion and emission data (disappearance and reappearance of the star) are shown in Fig. 1. A central flash (the focusing of light rays by Triton’s atmosphere) was recorded, but will be analysed and elsewhere.

We modelled the HST light curve with a standard small-planet model that allows for a power-law temperature gradient (Table 2). The background from dark counts and Triton (determined by the FGS in September and adjusted for Triton’s different distance) was subtracted, and the remainder was divided by the flux from the star (also determined by the FGS in September) so that the full range of stellar flux corresponded to values between 0.0 and 1.0. In the light-curve model fits, the zero level was fixed, but the full-scale signal from the star was a free parameter. The difference of the fitted values from 1.0 shows that our calibration error is only a few tenths of one percent.

From fitting the entire light curve, the closest-approach distance between the centre of Triton’s shadow and the HST was determined to be 224 ± 4 km (first column of results in Table 2). This value places the shadow somewhat further north than predicted, but it is consistent with no detectable occultation at our Oahu station (Table 1). Using the closest-approach distance determined from the entire light curve, we fitted the main immersion and emission sections of the light curve both separately and together (next three columns of results in Table 2). As a test of the self-consistency of our light-curve models, we fixed the atmospheric model parameters ("half-light radius", "lambda at half-light," and the "thermal-gradient exponent"; see ref. 8) at their values determined from

![Figure 1 Triton occultation light curves from the HST. Data before and after the occultation were used to establish the modulation of the signal due to the astrometer scan, which was then removed from the entire data set. The zero and full-scale stellar flux levels were established with photometric data from an earlier FGS visit to these objects on 11 September 1997. At that time, Triton’s magnitude as observed by the FGS was 13.4 and the magnitude of Tr180 was 10.6. The FGS data have been averaged at 10 s. a, immersion data (filled circles) and light-curve model fit (line); b, immersion data (filled circles) and light-curve model fit (line; see fits in Table 2). The zero point of the abscissa is arbitrary. The light-curve model used a power-law thermal gradient; residuals from the fit in a are shown in c, and the residuals from the fit in b are shown in d. The r.m.s. residual along the full signal is ~0.0022 for a 1-s average, and is the result of photon noise. The remaining residuals that occur when the star is partially occulted are the result of unmodelled structure in Triton’s atmosphere and rarely exceed 0.01. The effect of these on our determination of the 1,400-km pressure can be estimated by differences among the fits in Table 1. The omitted central portion of the light curve (see text) corresponds to radii <1,400 km (altitudes <48 km); the atmosphere below that does not affect the 1,400-km pressure.

The 4 November 1997 occultation of the star Tr180 (also known...
the combined immersion and emersion fit (second to last column in Table 2), and then fit the entire light curve again (last column in Table 2).

Although the agreement is not perfect between all model fits for the atmospheric parameters at a radius of 1,400 km, it is very good. In particular, the close agreement between the immersion and emersion atmospheric parameters for two widely separated locations on Triton supports the idea that the sublimation and condensation of nitrogen maintains the surface frost at the same temperature. The pressure at 1,400 km, 2.3 ± 0.1 μbar, is derived from the fit to the immersion and emersion data (the error bar includes the systematic differences between the fits in Table 1). This is significantly greater than the 1,400-km pressure of 1.4 ± 0.1 μbar measured with stellar occultations in 19959 and the value of 0.8 ± 0.1 μbar extrapolated from a surface pressure of 14 ± 1 μbar measured by Voyager in 198910–11. The pressure at 1,400 km has certainly increased between 1995 and 1997, based on the two sets of stellar occultation data; the temperature at 1,400 km has also increased from 47 ± 1 K (ref. 11) to 50.3 ± 0.5 K. As these temperatures are consistent with the 1,400-km temperature predicted by atmospheric models based on Voyager data12,13, a surface-pressure increase between the 1989 and more recent measurements is the most likely explanation for the difference (rather than using an inappropriate model for extrapolating the pressure from the surface to 1,400 km).

This surface-pressure increase implies a temperature increase of the surface frost, as the principal constituent of the tenuous atmosphere, nitrogen, is presumed to be in vapour-pressure equilibrium with the surface frost. The surface pressures and corresponding equilibrium temperatures for N2 are plotted in Fig. 2, where two cases are shown.

In the first case, we have extrapolated the occultation pressures from a radius of 1,400 km to the surface radius of 1,352 km (an average of published values10,11) using a multiplicative factor of 17.5, which is valid under the assumption that the shape of the thermal profile11 has not significantly changed since the Voyager encounter (filled symbols in Fig. 2). We justify this assumption by the consistency of the atmospheric temperature at 1,400 km (Table 2) with the models12,13. These measurements show a steady increase in pressure and surface-frost temperature. At this rate the atmosphere has tripled in bulk since the time of the Voyager encounter, which would require ~0.9% of the total solar energy incident on Triton during the intervening time to sublime the frost. In the second case, we make a more conservative estimate of the surface pressure derived from the stellar occultation data by assuming an isothermal atmosphere below 1,400 km (open symbols in Fig. 2). Even for this case, the atmosphere has nearly doubled in bulk since the time of Voyager.

Triton’s atmosphere is supported by surface frosts, which at any instant are expected to be at the same temperature everywhere, due to heat from the surface frost, as the principal constituent of the tenuous atmosphere, nitrogen, is presumed to be in vapour-pressure equilibrium with the surface frost. The surface pressures and corresponding equilibrium temperatures for N2 are plotted in Fig. 2, where two cases are shown.
to efficient transfer of latent heat through the atmosphere. This global frost temperature determines atmospheric pressure through vapour-pressure equilibrium; thus a frost temperature increase from 37.5 K (in 1989) to 39.3 K (in 1997) can be inferred from the observed increase in atmospheric pressure (the non-isothermal case in Fig. 2).

The mechanisms that can cause a change in frost temperature (and hence surface pressure) are: (1) non-static (migrating) surface-frost distribution; (2) changes in the optical properties of the surface frost; and (3) changing insolation on a static surface-frost distribution. (Although subsurface heat flow—geothermal or seasonal—can affect the energy balance, it is unlikely to have varied rapidly in the past decade.)

Simple seasonal models of long-term frost migration, with uniform frost albedo and emissivity, show monotonic long-term transfer of most of Triton's nitrogen frost to the poles, which have the minimum seasonally averaged insolation. In most of these models, the remaining seasonal frost migrates between hemispheres in response to the seasonal insolation cycle, and all frosts should be almost exhausted from the southern hemisphere during the current extreme southern summer. This would result in a rapid decrease in atmospheric pressure, the opposite of what our 1995 and 1997 observations indicate has occurred.

A substantial decrease of mean frost albedo or emissivity could account for the pressure change. For instance, model 'F' of Spencer and Moore, which assumes unit emissivity, can account for the atmospheric change if the mean frost Bond albedo dropped by 0.12 between 1989 and 1997. Observational and theoretical work suggests that large changes in frost optical properties may indeed occur on Triton.

The frost's total absorbed insolation may have increased, due to the increase in the southerly subsolar latitude in the past decade. We computed the change in surface pressure that would result solely from the change in subsolar latitude from August 1989 (47.8° south) to November 1997 (51.0° south), under the assumption that no volatile transport had occurred in the intervening 8 years. Five different maps of the 1989 N₂-ice distribution on Triton were generated based on the albedos measured by Voyager. The emissivity of the N₂ ice was taken as a free parameter in each of these frost models, and was adjusted such that the temperature of the N₂ was equal to 37.5 K (corresponding to 14 bar surface pressure) in 1989. The N₂-ice thermal balance was then recomputed using the subsolar latitude appropriate for Triton in late 1997, under the assumption that the distribution of N₂ ice was unchanged (albedos did change slightly, due to the illumination-angle dependence of the bolometric albedo, and the rotation of some N₂-ice-covered portions of the globe into darkness). Several of these models result in pressure increases comparable to the measured increase. Thus, the observed global warming of Triton may be due to increased insolation of a permanent south polar cap.

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Correspondence and requests for materials should be addressed to J.L.E. at the Department of Earth, Atmospheric, and Planetary Sciences, MIT.

**Superconductivity in oxygen**

K. Shimizu, K. Suhara, M. Ikumo, M. I. Eremets and K. Amaya

Department of Material Physics, Faculty of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan

CREST of Japan Science and Technology Corporation, Kawaguchi, Saitama 332-0012, Japan

Advanced Science Research Center, Japan Atomic Energy Research Institute, Ibaraki 319-1195, Japan

Among the simple diatomic molecules, oxygen is of particular interest because it shows magnetism at low temperatures. Moreover, at pressures exceeding 95 GPa (~0.95 Mbar), solid molecular oxygen becomes metallic, accompanied by a structural transition. The metallization process is characterized by an increase in optical reflectivity, and a change in the slope of the resistance—