Triton’s Distorted Atmosphere

J. L. Elliot,* J. A. Stansberry, C. B. Olkin, M. A. Agner, M. E. Davies

A stellar-occlusion light curve for Triton shows asymmetry that can be understood if Triton’s middle atmosphere is distorted from spherical symmetry. Although a globally oblate model can explain the data, the inferred atmospheric flattening is so large that it could be caused only by an unrealistic internal mass distribution or highly supersonic zonal winds. Cyclonic winds confined to a jet near Triton’s northern or southern limbs (or both) could also be responsible for the details of the light curve, but such winds are required to be slightly supersonic. Hazes and clouds in the atmosphere are unlikely to have caused the asymmetry in the light curve.

Data from the Voyager 2 encounter with Triton in August 1989 (1) showed that Triton’s atmosphere is dynamic on short time scales. Dark plumes rose from the surface to an altitude of 8 km and were observed to drift downwind for more than 100 km (2). Wind streaks on the surface in the southern hemisphere indicated a near-easternly flow near the ground with wind speeds of 5 to 15 m s⁻¹ (3). Discrete clouds were seen up to 8 km above the surface, and haze was detected up to altitudes of 20 to 30 km (4). Because Triton is predominantly N₂, the atmosphere is in vapor-pressure equilibrium with the surface ice (the heat of vaporization and condensation equalize the surface temperature on Triton), seasonal changes in insolation can produce changes in surface pressure of several orders of magnitude (5). The thermal structure of Triton’s middle atmosphere is probably controlled by a steady-state balance of heat input from the sun and magnetospheric electrons, radiative processes involving CH₄ and CO, and thermal conduction to the surface (6). On the basis of the plumes, the lower 8 km of the atmosphere has been modeled as a troposphere (7).

To test atmospheric models based on Voyager data and to measure the predicted changes in surface pressure with time, we began monitoring Triton’s atmosphere with a series of Earth-based stellar occultation observations in 1993. The results of these observations (8) are not consistent with the temperature and pressure predicted by models (6) at an altitude of 90 km. For the 14 August 1995 occultation discussed here, the Infrared Telescope Facility (IRTF) was situated close enough to the center of Triton’s occultation shadow to record the partial focusing of starlight by Triton’s atmosphere—a phenomenon known as the “central flash” (9). The central-flash ray-paths probe several scale heights deeper into the atmosphere than the main immersion and emersion light curves of the occultation. They also sample large portions of the planetary limb, making the central flash a tool that has been used to investigate the properties of winds and extinction (particulate and molecular) in the atmospheres of Mars, Saturn, Titan, and Neptune (10, 11).

The visible wavelength occultation data (Fig. 1) exhibit two asymmetries in the light curve.

REFERENCES AND NOTES

6. To obtain adequate count rates, the conventional Mössbauer spectra of (Mg,Fe)O were fitted to Lorentzian and Voigt line shapes using the computer programs of B. Harte and S. Kesson.
7. Compositions were determined using a Cameca CAMECA electron microprobe at the University of Edinburgh, Department of Geology and Geophysics, operating at 20 kV with a beam current of 20 nA.
8. The epoxy disks were mounted with cellophane tape behind a 200- to 500-μm-diameter hole drilled in 25-μm-thick Mg foil. The foil acts as a collimator, absorbing more than 99% of the 14.4-eV γ rays. Absorber densities based on the thickness of the samples and chemical compositions were >10 mg of Fe per square centimeter for the (Mg,Fe)O inclinations and approximately 1 mg of Fe per square centimeter for the (Mg,Fe)Al(Si)O₃ and TAP inclinations. Mössbauer spectra were collected for times ranging from 1 day for the (Mg,Fe)O inclinations to more than 20 days for the silicate inclusions. Mössbauer spectra were recorded at room temperature in transmission mode on a constant acceleration Mössbauer spectrometer (CARIB; see reference material no. 1541; line widths of 0.42 mm/s for the outer lines of Fe₂⁺ were measured). The γ rays are collimated to the selected sample diameter using a Pb shield, and the source-sample distance is reduced to <5 mm. The latter results in a solid angle similar to conventional experiments, and hence a similar count rate. Because the signal quality depends on absorber density (measured in milligrams of Fe per square centimeter) and not the total amount of iron in the sample, the reduction in sample size has no effect on the effective thickness of the absorber. When electronic absorption due to heavier elements is low and the point source is relatively new (<1 year old), high-quality Mössbauer spectra (comparable to conventional measurements) can be recorded on samples with diameters as small as 100 μm. For further information see G. A. McCammon, V. Chaskar, and G. G. Richardson, in Planetary Geology, 2: 657 (1998) and C. A. McCammon [Hyper. Int. 92, 1235 (1994)].

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curve. (i) The peak of the central flash occurs about 2 s later than the midpoint between the half-light times, and (ii) the slope of the light curve is shallower before the peak of the central flash than afterward. The infrared (IR) light curve also shows a delayed peak. We consider two classes of models for explaining these features of the visible light curve: (i) distortion of the refractive properties of the atmosphere from a spherical shape, and (ii) extinction within the atmosphere. In the first class of models, we explore the possibilities that the atmospheric shape is distorted by a nonradial component of Triton’s gravitational field and that the shape is oblate because of zonal winds. We also consider the possibility that changes in the refractivity of the atmospheric gas itself (nonuniform composition) could explain the light curve.

To quantify the distortion required to reproduce the measured light curve, we constructed a model atmosphere in which surfaces of constant refractivity were elliptical, with the ellipticity $\epsilon = 1 - R_{e}/R_{p}$, where $R_{e}$ is the equatorial radius and $R_{p}$ is the polar radius. For each position along the IRTF path, the points on the limb that supplied refracted starlight are those whose perpendicular from the tangent to the limb intersects the telescope. For each limb point that was a source of refracted starlight, the flux was calculated from a small planet model (12), modified to use the radius of curvature (instead of the radius) of the elliptical limb to determine the focusing. Fluxes from all perpendicular limb points were added to obtain the light-curve flux. Figure 2 shows the starlight intensity in the vicinity of the central flash predicted from our best elliptical model for the light curve, and it illustrates how the orientation of the ellipse is related to the timing of the central flash and the different light-curve slopes before and after it. At no time does the IRTF chord cross the evolute, a condition that is in agreement with the lack of a sharp peak in the light curve.

The elliptical model was fit to the IRTF visible light curve by least squares (Table 1). Fits for three cases of atmospheric ellipticity were carried out: a circular model ($\epsilon = 0$), a prolate model ($\epsilon < 0$), and an oblate model ($\epsilon > 0$); the implied atmospheric properties (13) were also derived. The orientation of the ellipse was a free parameter. The “minimum radius probed” (Table 1) refers to the deepest level of the atmosphere probed by starlight (from the near limb) for the IRTF data, as calculated for the three models. These can be compared with the surface radius [1352.6 ± 2.4 km (14)]. The best-fitting oblate model is compared with the data in Fig. 3A. Both the oblate and prolate models match the time offset and differing slopes in the central flash (Fig. 3B), whereas the circular model does not. The best fitting elliptical figures are symmetric about Triton’s polar axis [(15) Table 1 and Fig. 2]. Assessing the significance of the three solutions with the F test [(16) Table 1], the oblate solution is the most probable choice of the three. Assuming that the data are telling us that Triton’s atmosphere is oblate, we first examine whether the modeled ellipticity is consistent with an atmospheric circulation. Winds symmetric with Triton’s rotation axis are an attractive explanation, because the orientations of the elliptical models (Table 1) were free parameters and are con-
consistent with the direction of Triton's pole. The (deprojected) ellipticity of 0.042 requires an equatorial wind speed of 290 m s$^{-1}$—about twice the speed of sound in Triton’s atmosphere and 18 times larger than the tangential velocity of Triton’s surface due to its rotation (17). Such high-velocity winds are not realistic, but winds restricted to latitude bands near the northern or southern limbs (or both) can explain the data without being so extreme. By specifying an atmospheric pressure gradient that is consistent with the modeled ellipticity of the atmosphere, we can calculate cyclostrophic wind velocities in the region of the atmosphere probed by the central flash; that is, near 45° north or south (18). We restricted our attention to a 10° latitude band, specified a constant surface pressure and a constant latitudinal temperature gradient within the band, and assumed that the temperature was constant with altitude. Although the isobars are locally oblate (pressure monotonically declines from the equatorward to the poleward side of the band), isopycs are locally prolate below about 13 km altitude and oblate above (19). Based on this simple model, we found that the latitudinal temperature gradient required to achieve a local atmospheric distortion equivalent to an ellipticity of 0.042 was about −0.7 K degree$^{-1}$, with a resulting wind speed at 30 km altitude of 170 m s$^{-1}$ (which is 30 m s$^{-1}$ greater than the sonic velocity). The latitudinal temperature gradient required to give an ellipticity of −0.032 (Table 1) near the surface was −1.5 K degree$^{-1}$, with a corresponding wind speed of 110 m s$^{-1}$ at 5 km altitude (20). It is possible that the isopycs in Triton’s atmosphere that formed the central flash are oblate near the south limb and prolate near the north, giving an effective pear shape to the atmosphere. If so, both limbs could have contributed flux to the central flash, and the required ellipticities and wind speeds would be less. Such complex atmospheric figures are not unknown: Multiple chords probing Titan’s central flash revealed a limb profile more complex than a simple ellipse (11).

In principle, it is possible for refractive asymmetry to be caused by nonuniform atmospheric composition. We consider this unlikely because the detected minor constituents, CO and CH$_4$, have small mixing ratios—less than 1% in the regions probed by Voyager (21). Argon would not have been detected by Voyager. However, the winds (2, 3) that are clearly evident from Voyager imagery should keep the atmosphere well mixed. So even if there were substantial amounts of Ar, large refractivity gradients could not be maintained.

Finally, we consider gravity as the cause of the distorted atmosphere. The deviation of a gravity field from spherical symmetry could be produced by a non-spherical mass distribution and could have contributions from four sources: Triton’s rotation, tidal forces from Neptune, a non-uniform internal mass distribution, or a permanent distortion in Triton’s figure.

The ellipticities caused by Triton’s rotation and the tidal perturbation of Triton’s atmosphere by Neptune, −0.001 (22), are more than 10 times smaller than our modeled ellipticity. Triton’s internal mass distribution, or an intrinsically distorted figure for Triton itself, are also unlikely to be

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Table 1. Models for Triton’s atmospheric figure.

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<thead>
<tr>
<th></th>
<th>Circular</th>
<th>Prolate</th>
<th>Oblate</th>
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<tbody>
<tr>
<td>Background level (ADU s$^{-1}$)</td>
<td>1,029,670 ± 140</td>
<td>1,029,600 ± 150</td>
<td>1,029,500 ± 160</td>
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<tr>
<td>Background slope (ADU s$^{-2}$)</td>
<td>0.25 ± 0.17</td>
<td>0.26 ± 0.17</td>
<td>0.24 ± 0.17</td>
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<tr>
<td>Star signal (ADU s$^{-1}$)</td>
<td>21,110 ± 140</td>
<td>21,170 ± 150</td>
<td>21,270 ± 160</td>
</tr>
<tr>
<td>Midtime (seconds after 07:30:00 UT)</td>
<td>253.00 ± 0.05</td>
<td>253.00 ± 0.05</td>
<td>252.99 ± 0.05</td>
</tr>
<tr>
<td>Equatorial half-light radius (km)$^\dagger$</td>
<td>1,445.3 ± 1.4</td>
<td>1,441.4 ± 2.3</td>
<td>1,450.8 ± 1.9</td>
</tr>
<tr>
<td>Lambda (isothermal) at half-light</td>
<td>85.8 ± 6.9</td>
<td>84.3 ± 2.3</td>
<td>77.7 ± 4.8</td>
</tr>
<tr>
<td>Thermal gradient exponent [b (12)]</td>
<td>15.6 ± 6.6</td>
<td>12.8 ± 3.8</td>
<td>8.8 ± 4.6</td>
</tr>
<tr>
<td>Apparent ellipticity</td>
<td>0.007 ± 0.003</td>
<td>0.018 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>Position angle (PA) of pole (degrees)</td>
<td>0.57 ± 2.5</td>
<td>5.2 ± 5.2</td>
<td></td>
</tr>
<tr>
<td>Minimum center distance (km)</td>
<td>94 ± 11</td>
<td>98 ± 12</td>
<td>115 ± 15</td>
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<thead>
<tr>
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<tr>
<td>degree$^{-1}$</td>
<td>1.382.6 ± 3.7</td>
<td>1.397.8 ± 4.4</td>
<td>1.357.1 ± 7.0</td>
</tr>
<tr>
<td>Nominal winds (m s$^{-1}$)</td>
<td>0.39 ± 2.10</td>
<td>2.17 ± 0.17</td>
<td>2.02 ± 0.28</td>
</tr>
<tr>
<td>Number density [10$^{12}$ cm$^{-3}$]</td>
<td>2.77 ± 0.39</td>
<td>2.10 ± 0.30</td>
<td>3.36 ± 0.57</td>
</tr>
<tr>
<td>Pressure [μbar]</td>
<td>1.65 ± 0.23</td>
<td>1.27 ± 0.17</td>
<td>2.02 ± 0.28</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>34.3 ± 2.3</td>
<td>43.9 ± 2.4</td>
<td>43.5 ± 2.5</td>
</tr>
<tr>
<td>Temperature gradient (f2) (K km$^{-1}$)</td>
<td>0.48 ± 0.20</td>
<td>0.40 ± 0.19</td>
<td>0.27 ± 0.14</td>
</tr>
</tbody>
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<thead>
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<th>Oblate</th>
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<tbody>
<tr>
<td>Degrees of freedom</td>
<td>1,493</td>
<td>1,494</td>
<td>1,494</td>
</tr>
<tr>
<td>Sum of squared residuals</td>
<td>9.52583 × 10$^7$</td>
<td>9.51108 × 10$^7$</td>
<td>9.43371 × 10$^7$</td>
</tr>
<tr>
<td>F test: probability (circular + noise)</td>
<td>9.9 × 10$^{-2}$</td>
<td>5.5 × 10$^{-1}$</td>
<td>5.5 × 10$^{-1}$</td>
</tr>
</tbody>
</table>

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The shadow velocity was fixed at 25.0341 km s$^{-1}$, and the time per data point was 0.300 s. $^\dagger$The equatorial radius corresponds to the semimajor axis for the oblate model and to the semiminor axis for the prolate model. $^\dagger$PA is measured from north through east; the PA of Triton’s pole was 32° and the PA of Neptune (relative to the center of Triton) was $^{-32}$. $^\dagger$For the prolate model, this represents the cyclostrophic wind speed required to give local ellipticity of −0.032 at 5 km altitude; for the oblate model, this is the cyclostrophic wind at 45° S and 1382-km radius for an atmosphere with local (deprojected) ellipticity of 0.042.

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*The shadow velocity was fixed at 25.0341 km s$^{-1}$, and the time per data point was 0.300 s. $^\dagger$The equatorial radius corresponds to the semimajor axis for the oblate model and to the semiminor axis for the prolate model. $^\dagger$PA is measured from north through east; the PA of Triton’s pole was 32° and the PA of Neptune (relative to the center of Triton) was $^{-32}$. $^\dagger$For the prolate model, this represents the cyclostrophic wind speed required to give local ellipticity of −0.032 at 5 km altitude; for the oblate model, this is the cyclostrophic wind at 45° S and 1382-km radius for an atmosphere with local (deprojected) ellipticity of 0.042.

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able to create the necessary distortion. The first-order deviation of Triton's gravity field from spherical symmetry is described by Triton's J₂ coefficient, which was not directly measured during the Voyager flyby. However, a nonuniform mass distribution would reveal itself through distortion of Triton's surface figure. Although only spherical solutions of the surface-feature control network were originally attempted for Triton (16), the distorted atmosphere has prompted us to re-examine the original data in an attempt to obtain triaxial solutions for Triton's surface. Unfortunately, the control network covers only 80° in latitude and 120° in longitude, which is too small a fraction of Triton's globe to distinguish a spherical shape from an elliptical shape. Reanalysis of Triton's limb images shows departures of 0.042 of Triton's limb images shows departures of 0.042, we find that the resulting total number of degrees of freedom for the first fit and for the second fit (with the extra parameters). Then we form the statistic $F = (x_1^2 - x_2^2)/(d - 2)^2$, where $d$ is the number of degrees of freedom for the second fit, and $x_1$ and $x_2$ are the sum of residuals from the first and second fits, respectively. If the noise is assumed to follow a Gaussian distribution, then $F$ follows the $F$ distribution, and one can readily calculate the probability that the noise would cause a given value of $F$, or larger.

17. Hubbard et al. found that their occultation-derived oblateness for Titan's atmosphere, 0.016, implied a supersonic equatorial wind velocity of 240 m s⁻¹ if they assumed a global circulation with a constant angular velocity, which is how we derived the 290 m s⁻¹ value.

18. Winds with speeds exceeding the tangential rotational velocity of the surface have dynamics dictated by the cyclostrophic balance between the force of gravity, the centrifugal force due to the zonal wind circulation, and the pressure gradient force. See J. R. Holton, An Introduction to Dynamic Meteorology (Academic Press, New York, 1979).

19. The altitude of the transition between prolate and oblate isopachs depends somewhat on atmospheric temperature, which varies with depth in the models. The altitude of the transition between prolate and oblate isopachs depends somewhat on atmospheric temperature, which varies with depth in the models.

20. Altitudes are relative to a spherical surface, assumed to be at the base of the model region, where the pressure is constant. This reference surface need not coincide with the physical surface, so the altitudes of the prolate and oblate regions are adjustable, and the altitude of the reference surface could be different in the northern and southern hemispheres.

References and notes


8. C. B. Oskin et al., ibid., in press.


12. J. L. Elliott and L. A. Young, Astron. J. 103, 991 (1992). This model assumes hydrostatic equilibrium and a power-law temperature dependence on radius $r$, $T(r) = T_{\text{ref}} r^{-p}$, where the temperature is $T_{\text{ref}}$ at a reference radius $r_{\text{ref}}$ and $b$ is the power-law exponent.

13. The atmospheric parameters apply to the submerger (longitude 81.9°, latitude –6.0°) and submerger (longitude 270.5°, latitude 13.5°) half-light points on Triton (8). All the fitted global limb shapes give nearly the same temperature (Table 1) for a radius of 1400 km: 43.5 ± 2.5 K for the oblateness solution. This agrees within the error with the 44.5 ± 1.8 K temperature derived from models excluding the central flash (8), which are about 5 K colder than models based on Voyager data (6). The pressure at 1400 km is somewhat dependent on the assumption of limb shape (Table 1), but all pressures are well above the predictions of models based on Voyager data (6). Our higher pressure may be due to an inadequacy of the models or to a change in Triton’s surface temperature between 1989 and 1995 (5).


15. Triton’s atmospheric figure at the half-light level from the occultation chords is $-0.029, PA = 20° + 10°$ (Table 1), minimum center distance $-191 ± 36$ km (8). This figure applies to altitudes of about 145±1 km and applies predominantly to the eastern and western limbs, whereas the light-curve figure is dominated by light from the northern or southern limb that passes through the atmosphere at a smaller radius. Hence the shape of Triton’s atmosphere may be changing with altitude (a property of some of the global circulation models we investigated).

16. The overlying circular model was derived by decreasing the closest approach distance to create a central flash that was everywhere larger than the oblate model. Using this closest approach distance, we fit a circular model to the oblate model with the central 40% removed (8) to match the main drop and recovery of the data. For the IR model, the atmosphere was assumed to be spherically symmetric, with the same atmospheric parameters and closest approach as the overlying circular model. The only source of asymmetry in this model is extinction.


18. We thank W. McKinnon and P. Hubbard for helpful discussions and P. Nicholson and W. Hubbard for comments and criticisms. This work was supported in part by NASA grant NAGW-1494 and by the Friends of Lowell Observatory.

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