# Scatterers in Triton's Atmosphere: Implications for the Seasonal Volatile Cycle

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**Nitrogen and methane ices on the surface of Triton, Neptune's largest satellite, are exchanged between the summer and winter hemispheres on a seasonal time scale. Images of the satellite's sky obtained by the Voyager 2 spacecraft show the presence of several types of scattering materials that provide insights into this seasonal cycle of volatiles. Discrete clouds, probably composed of $N_2$ ice particles, arise in regions of active sublimation. They are found chiefly poleward of 30°S in the southern, summer hemisphere. Haze particles, probably made of hydrocarbon ices, are present above most, but not all places. Recent snowfall may have occurred at low southern latitudes in places where they are absent. The latent heat released in the formation of the discrete clouds may have a major impact on the thermal balance of the lower atmosphere. Triton may have been less red at the time of the Voyager flyby than 12 years earlier due to recent $N_2$ snowfall at a wide range of latitudes.**

THE ATMOSPHERE AND SURFACE OF Triton are strongly coupled by the seasonal exchange of volatile frosts between the summer and winter hemispheres. Much of its surface is covered with nitrogen and methane ices (*1*) at a temperature of about 38 K (*2*) that buffer a $N_2$ vapor–dominated atmosphere having a surface pressure of only about 16 μbar (*3, 4*). Triton's atmosphere also contains minor amounts of the less volatile ice methane, whose gaseous mixing ratio at the surface equals about $4 \times 10^{-5}$ (*5*). According to models developed before and after the Voyager 2 spacecraft's flyby of the Neptune system (*6–9*), some of the sunlight that is absorbed in the summer hemisphere is used to sublimate $N_2$ and $CH_4$ ices. The vaporized gases are carried by atmospheric winds to the winter hemisphere, where they recondense, releasing their latent heat to warm this part of the satellite and forming a winter deposit of frost. The atmospheric pressure of $N_2$ vapor may be large enough to require only very modest pressure gradients to drive the sublimation winds, thereby also insuring that the satellite's surface has almost a constant temperature, at least in the frost covered regions (*6, 7*).

The subsolar point on Triton follows a complicated path owing to the rapid precession of its orbital normal about Neptune's pole, reaching extremes of about ±52° latitude on time scales of one to several centuries (*6*). During the course of the summer season in either hemisphere, several tens of grams of $N_2$ per square centimeter and much smaller amounts of $CH_4$ are expected to be sublimated and transferred to the other (winter) hemisphere (*8*). At the time of the Voyager encounter, the subsolar point was situated at 45°S, close to its most extreme southerly position. Therefore, one might have expected that the low and middle latitudes of the southern hemisphere would have lost most, if not all, of their seasonal layer of ice, with this material residing throughout the northern hemisphere at the time of the flyby. This expectation does not match in an obvious way the occurrence of high albedo regions (≈0.8) throughout much of the southern hemisphere and the presence of a lower albedo surface (≈0.6) at low and middle latitudes of the northern hemisphere (*10, 11*).

We have analyzed Voyager images of Triton's limb that show the presence of scattering materials in the atmosphere to obtain empirical constraints on the nature of the satellite's seasonal cycle of volatiles. As described in detail below, there are two major scatterers: "discrete" clouds that occur in the lowest portion of the atmosphere in some places; and an "extensive haze" that occurs in a more continuous fashion. The discrete clouds are probably made of $N_2$ ice, while the extensive haze is probably composed of hydrocarbon ices that are products of methane photochemistry. Solar and interstellar medium Ly α photons dissociate gaseous $CH_4$ and begin a series of chemical reactions that lead to hydrocarbon gases such as $C_2H_2$, $C_2H_4$, $C_2H_6$, and $C_4H_2$ that condense in the cold, lower atmosphere (*5, 10*).

There are two sets of Voyager images of Triton that we have analyzed to characterize the properties of the scatterers in its atmosphere. First, images of the satellite's limb were obtained with the clear filter of the narrow angle camera at a spatial resolution of 2 to 3 km $lp^{-1}$ (line pair) at latitudes ranging from about 80°S to about 30°N latitude (data set 1). These low phase angle images (sun-satellite-spacecraft angle ≈60°) are useful for defining the spatial distribution of the scatterers. Second, a number of images were taken with the violet, blue, green, and orange filters of the wide angle camera at very high phase angles (141° to 160°) (data set 2). These lower resolution images (10 to 25 km $lp^{-1}$) are useful for measuring the diffraction peak of atmospheric particles, which can be analyzed to determine their mean size (*12, 13*). We obtained geometrically and photometrically corrected images by applying standard data reduction programs that employ ground-based and spacecraft calibration information (*14*). The brightness of each pixel in the image is expressed in *I/F* units, which is the ratio of the measured radiance to that of a normally illuminated, perfectly reflecting Lambert surface.

Figure 1 shows a series of azimuthal scans at constant radial distances from the satellite's limb that were made on one of the high-resolution, low phase angle images of data set 1. The scans having negative altitudes are situated on Triton's disk and display chiefly brightness variations across its surface. The scans having positive altitudes display the brightness of scattering material in Triton's atmosphere. A high level of brightness is seen at altitudes ranging from about 0 to 6 km at longitudes ranging from +30° to +70°E and latitudes ranging from about 74° to 64°S. This feature is representative of "discrete clouds" seen on a number of the images of data set 1. They have high brightness values, comparable to or somewhat less than that of the satellite's surface, are located only in the bottom portion of the atmosphere (at altitudes ranging from 0 to as high as 8 km), and span limited horizontal portions of the limb (their horizontal dimensions are usually several hundred kilometers).

We interpret the discrete clouds as being composed of $N_2$ ice particles, in view of the clouds' high brightnesses and restricted spatial dimensions. $CH_4$ ice is a less likely possibility since the mixing ratio of methane vapor is more than four orders of magnitude lower than that of $N_2$ vapor and the methane relative humidity at the surface appears to be less than 100% (*5*). Also, the spatial properties of the discrete clouds are incompatible with that of a photochemical haze and their brightness properties are inconsistent with those of the material seen in plumes (*5, 10*): Plumes appear dark when projected against the satellite's surface, whereas the discrete clouds appear bright in such a geometry (as in Fig. 1).

We have detected bright clouds chiefly at latitudes poleward of about 30°S in the images of data set 1. In particular, discrete

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clouds cover approximately 37% of the surface poleward of 30°S, but only about 6% of the surface equatorward of this latitude, based on the fraction of the lengths of limbs having discrete clouds. Furthermore, the satellite's atmosphere is much brighter at high phase angles poleward of this location. We interpret this spatial property of the discrete clouds as an indication of where vigorous sublimation of $N_2$ ice was occurring at the time of the Voyager flyby. In particular, active sublimation was occurring in many places poleward of 30°S, but only in restricted portions of the lower latitude, southern polar cap.

The discrete cloud in Fig. 1 has an asymmetric profile: Its 70°E longitude edge is much sharper than its 30°E edge and it has a peak brightness very close to the 70° edge. Thus, it may be originating from a source located underneath this edge. We have examined high-resolution images of Triton's surface near the location of this cloud and find that a large dark albedo region is situated at the latitude and longitude position of this edge of the cloud. The dark region is located within a few hundred kilometers of smaller, dark albedo features that were the apparent source regions for the east plumes seen on the Voyager images (*10*). It seems reasonable that active sublimation would be stronger at places where more sunlight is being absorbed, provided that the visible absorbing material is mixed with $N_2$ ice or is in close contact with it.

We estimated the mean size of the particles constituting the discrete clouds by analyzing the high phase angle images of data set 2 at high southern latitudes. First, we estimated the single scattering phase function (*15*) at a variety of phase angles and wavelengths by simulating radial intensity scans that went from Triton's surface into its lower atmosphere (*12, 13*). In so doing, we allowed for the spherical geometry of the atmosphere near the limb, particulate scattering of both the direct solar beam and light emanating from the surface, sunlight scattered by the surface to space, and the limited resolution of these images (*16*). Then, we fitted these results to the diffraction peaks produced by spherical particles of different sizes to estimate the mean particle radius of the atmospheric scatterers (*17*). The latter procedure is illustrated in Fig. 2, which compares the phase functions derived from a number of high phase angle, blue filtered images at a latitude of 52°S with those calculated for several different sized particles. According to the comparison shown in this figure and our more complete least-squares analysis of all the images of data set 2, the particles of the discrete clouds have a cross section–weighted average particle radius, $r$, of $0.73 \pm 0.25$ μm.

The vertical optical depth, $\tau$, of the discrete cloud shown in Fig. 1 may be estimated from its observed brightness close to the surface, the spherical geometry of the limb, its scale height, and the single scattering albedo, $\varpi_0$, and phase function, $p$, of the cloud particles (*12, 13*). Selecting the scale height to be 5 km, $\varpi_0$ to be 1, and $p$ to be 0.3 (*17*), we find an average value of about $3 \times 10^{-2}$ for $\tau$, with an uncertainty of a factor of several due chiefly to the uncertainty in $p$. Larger values for $\tau$ would be inferred from the observed brightness if the discrete cloud is present over a restricted portion of the line of sight through it. However, this enhancement is at most a factor of several if the cloud's horizontal extent in the direction along the line of sight is comparable to its observed extent along the limb.

Using the above results on typical optical depths, $\tau$, and particle sizes, $r$, for the discrete clouds, we can infer a number of their other properties and relate these results to energy cycles. The mass of material per unit area in these clouds equals approximately $(2/3)r\rho\tau$, where $\rho$ is the particles' density. With $r$, $\rho$, and $\tau$ set equal to 0.7 μm, 1 g cm$^{-3}$, and $3 \times 10^{-2}$, respectively, we find a mass loading of about $1.4 \times 10^{-6}$ g cm$^{-2}$, which is many orders of magnitude smaller than the mass of $N_2$ vapor ($\simeq 0.2$ g cm$^{-2}$).

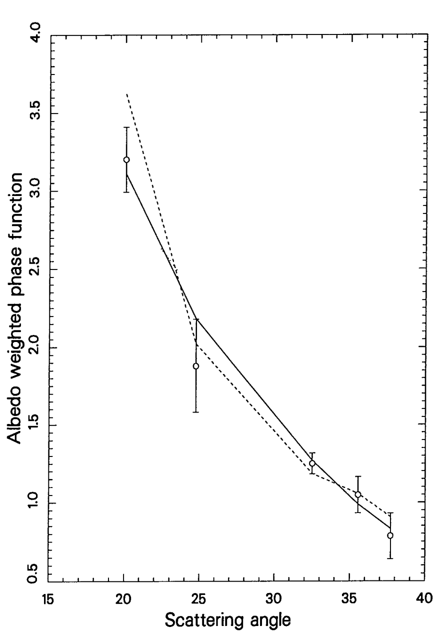


**Fig. 2.** Comparison between the phase functions (with scattering angle in degrees) inferred from various blue filtered, high phase angle images of Triton at a latitude of 52°S (circles with error bars) and the predicted behavior of particles having alternative choices of the cross section–weighted mean particle radius, $r$: $r = 0.2$, 0.73, and 2.0 μm correspond to the dotted, solid, and dashed curves, respectively. The error bars reflect the formal uncertainty in the goodness of fit of a model to radial brightness scans of the high phase angle images.

The average latent heat released per unit area, $dE_l/dt$, during the formation and dissipation of a discrete cloud is given by $mL/t \simeq mLv_s/h$, where $m$, $L$, $t$, $v_s$, and $h$ are the cloud's mass per unit area, latent heat of condensation, lifetime of the cloud, sedimentation velocity of the cloud particles, and average altitude, respectively. Particles having a mean size of 0.7 μm fall to Triton's surface in about $1.6 \times 10^5$ s from a height of 3 km (*18*). Using this value for $t$, the value of $m$ deduced above, and the latent heat of $N_2$ condensation, we find that $dE_l/dt$ equals about $2.3 \times 10^{-2}$ erg cm$^{-2}$ s$^{-1}$, a value that is a factor of 15 times larger than the heat conducted down from the warm ionosphere (*19*). Thus, latent heat release may be an important component of the atmosphere's heat balance close to the surface in regions of active sublimation and can help to generate a troposphere, that is, a region where the temperature decreases with increasing altitude. At higher altitudes, heat conduction may dominate the atmosphere's energy budget, resulting in temperatures that increase with altitude. This change in temperature gradient and hence atmospheric stability

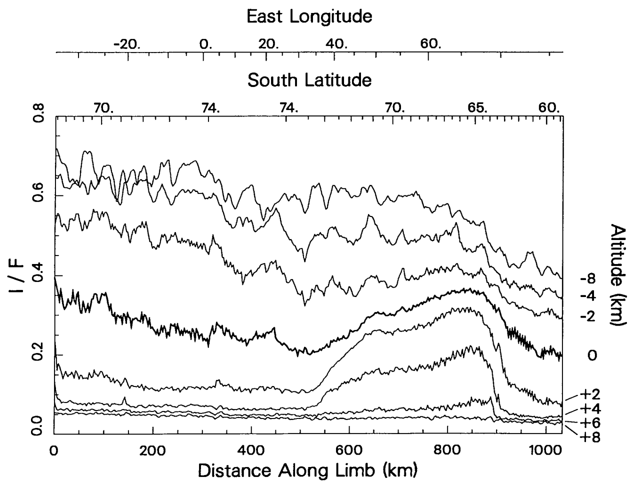


**Fig. 1.** Azimuthal scans of brightness in $I/F$ units at constant altitudes (kilometers) above and below Triton's limb (numbers next to right axis) on a high-resolution Voyager image of Triton (1139401). The bottom horizontal axis shows distance along the limb, while the top horizontal axes show latitude and longitude. Note the discrete cloud that spans 30° to 70°E longitude at positive altitudes above the limb.

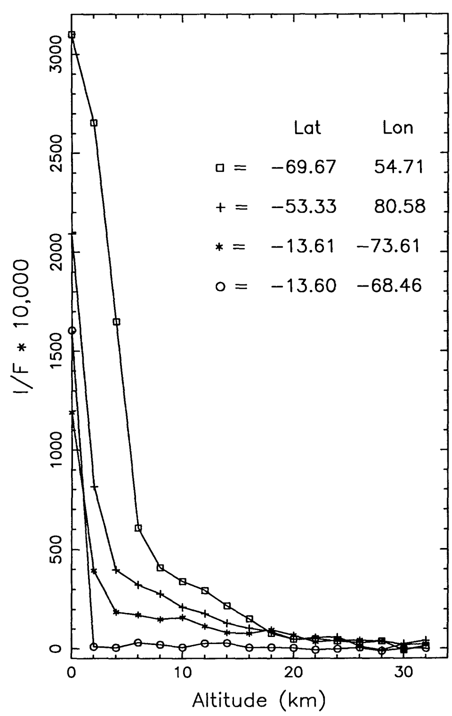


**Fig. 3.** Radial scans perpendicular to Triton's limb at a variety of positions, as derived from high resolution, clear filtered images at low phase angles. This plot shows representative altitude profiles of the extensive haze, including one where it is apparently absent (bottom curve). The numbers in the upper right-hand corner indicate the latitudes (Lat—negative means southern) and eastern longitudes (Lon) of the curve having the indicated symbols to the left of the coordinates.

with altitude may determine the heights attained by plumes (*19*).

Figure 3 shows radial brightness scans perpendicular to Triton's limb at a number of representative locations on the high-resolution, low phase angle images of data set 1. Proceeding from the uppermost curve to the lowest one at low altitudes, these scans go through the discrete cloud of Fig. 1, a cloud-free area at high southern latitude, and two cloud-free areas at low southern latitudes. In the first three of these scans, the atmospheric brightness is comparable to the background noise level at altitudes greater than about 20 to 30 km. But, it gradually increases below this location with decreasing altitude until either the surface is intersected (as in the second curve from bottom) or a low altitude region of much more steeply increasing brightness, namely, a discrete cloud (as in the upper curve), is intersected. The scatterers responsible for this brightness pattern have been called the "extensive haze" particles (*10*).

The extensive haze is present on all limbs viewed at latitudes poleward of about 30°S and is present on most limbs viewed at lower southern and low northern latitudes. However, as illustrated by the lowest curve in Fig. 3, a portion of the limb on one image of data set 1 shows no detectable haze. We will discuss the implications of this scan shortly.

We suggest that the extensive haze is made of hydrocarbon ices formed from the condensation of products of methane photochemistry (*5, 10*). This suggestion is based on the similarity in the brightness level of the extensive haze in many places characterizing the images of data set 1. Also, the extensive haze is present in a continuous fashion throughout the lowest several tens of kilometers of the atmosphere, in accord with model predictions for a photochemical haze (*5*).

To carry out a more quantitative comparison between the properties of the extensive haze and the predictions of photochemical models, we have made a crude estimate of the mass production rate of the haze material. First, we obtained an estimate of the mean particle radius, $r$, of the haze particles by analyzing the high phase angle images of data set 2 in a fashion similar to that employed above for the discrete clouds, but now carried out at low southern latitudes, where discrete clouds are largely absent. We find that $r$ equals 0.1 μm, with an uncertainty of a factor of 3. Next, we estimated the average optical depth of the haze, $\tau$, from its brightness levels on a number of scans analogous to those shown in Fig. 3. We find an average $\tau$ of $3 \times 10^{-3}$ (*20*). Using these two values and a density of 0.7 g $cm^{-3}$ (*13*), we estimate that the mass of haze material per unit area, $m$, equals approximately $1.4 \times 10^{-8}$ g $cm^{-2}$.

The rate at which haze material is being lost to the surface by sedimentation, $dm/dt$, is given approximately by $mv_s/H$, where $v_s$ is the particles' sedimentation velocity and $H$ is their scale height. The parameter $m$ is given above, $v_s$ may be obtained from the particles' mean size, density, and altitude (*18*), and $H$ is found to be about 10 km from the radial scans of data set 1. We, therefore, estimate that $dm/dt$ equals $4.6 \times 10^{-15}$ g $cm^{-2}$ $s^{-1}$, with an uncertainty of about a factor of 10. In steady state, the loss rate of haze particles equals their production rate. Strobel's photochemical (*5*) model predicts that the mass production rate of condensed hydrocarbons equals $4.7 \times 10^{-15}$ g $cm^{-2}$ $s^{-1}$ in the southern hemisphere of Triton at the epoch of the Voyager flyby. This prediction is consistent with the value of $dm/dt$ derived here, lending support to the hypothesis that the haze material is composed of hydrocarbon ices.

As illustrated by the bottom curve of Fig. 3, there are a limited number of places where the sky brightness is not measurable in the images of data set 1. More precisely, there is no detectable haze material between latitudes of approximately 4° and 18°S on image 1139433. However, haze material is clearly present north of 4°S on this image, along the entire extent of image 1139427, which starts 5°S of 1139433 and proceeds to higher southern latitudes, and along the entire limb of image 1139340, which lies about 5°W of 1139433 and overlaps the latitudes covered by 1139433 at their extreme northern and southern ends, respectively (compare the bottom two curves in Fig. 3). Places where haze is absent may be locations of recent condensation and precipitation of $N_2$ ice throughout the lowest several tens of kilometers of the atmosphere. The precipitating snow removes the photochemical haze particles by condensing on them and by scavenging them on their way to the surface.

Our analysis of scattering materials in Triton's atmosphere provides constraints and insights into the behavior of the seasonal cycle of volatiles. In particular, the spatial distribution of discrete clouds may provide markers of places of vigorous sublimation, while the absence or the reduction of the extensive haze in some places may indicate places of recent snowfall. Accepting these premises, we find that vigorous sublimation of $N_2$ ice was occurring at the time of the Voyager encounter at many locations south of 30°S and at a limited number of locations between 30°S and the equator. Also, recent snowfall took place in a narrow corridor northward of 20°S.

The above inferences may be compared with the predictions of several recent models of Triton's seasonal cycle. They are in good agreement with the model of Stansberry *et al.* (*9*), who used the spatial distribution of albedo observed by Voyager (*11*) in an energy balance model to predict the present pattern of sublimation and deposition of volatiles. However, our data contradict Spencer's (*8*) "historical" models, in which he attempted to follow the volatile cycle over a complete set of seasons. Spencer's models place the equatorward edge of the seasonal southern $N_2$ frost layer at about 52°S at the time of the Voyager flyby. We note that Stansberry *et al.* (*9*) encountered difficulties when they tried to run their model over a full set of seasons. In both cases, temporally and spatially constant values for the albedo of $N_2$ frost and the underlying surface were used.

Possible clues to more realistic seasonal models may be provided by a surprising change in Triton's color over a period of 12 years. Triton's globally averaged disk was much redder in 1977 (*21*) than either its globally averaged disk in 1989 or any of the spatially well-resolved positions seen by Voyager in 1989 (*10, 11*). During this time interval, the subsolar point and subearth point moved by only about 12°S. The observed difference cannot be accounted for by simply adding neutral colored frost to the northern, winter hemisphere, but rather also requires a change of much of the southern hemisphere toward a more neutral color over this 12-year period (*11*). We suggest that these color changes may imply that $N_2$ ice clouds and snowfall were far less ubiquitous in the southern hemisphere in 1977 than in 1989 (*22*).

Support for this hypothesis is provided by the albedo pattern seen on full disk image 1138709: the disk is systematically brighter at the locations of the limb clouds seen on later images, due perhaps to the combined effects of the clouds themselves and $N_2$ snow that fell from them onto the surface. These locations are also more neutral in color than much of the rest of the satellite (*11*).

Our analysis also provides a bit of information on the wind regime on Triton. If the discrete cloud of Fig. 1 originates from its 70°E edge, as we have suggested, then the cloud material is being blown chiefly in a westward direction in the 2- to 6-km altitude region of the atmosphere. Winds blowing in a similar direction are implied by the geometry of the two plumes detected by Voyager at an altitude of about 8 km (*10, 23*). Also, image 1138709 shows the presence of a small, bright offshoot to the northeast of the dark spot of the discrete cloud, in addition to a major bright area to the west of the dark spot. These results are consistent with the meteorological model of Ingersoll (*7*), in which much of the northward transport of volatiles from the southern summer hemisphere to the northern winter hemisphere takes place within a 1-km thick boundary layer, with flow taking place to the northeast in the boundary layer and to the west aloft. Wind speeds of 2 to 4 $m\ s^{-1}$ at the altitudes of the discrete cloud of Fig. 1 are implied by the length of the cloud on the limb, the sedimentation velocity of an averaged size cloud particle, and the assumption of a source at the eastern end. These values are in the same ballpark, but a bit lower than Ingersoll's estimate of 5 to 10 $m\ s^{-1}$ for winds at these altitudes (*7*).

Finally, we point out the possible importance of hydrocarbon ices to the energy budget of the surface. $N_2$ and $CH_4$ ice absorb sunlight only in limited portions of the near infrared (*1*). If only these ices were present in the upper layers of Triton's surface, as might occur through the continual operation of the seasonal cycle, the surface temperature would be much colder than its observed value, the atmospheric pressure would be many orders of magnitude smaller, and little transport would occur over a seasonal time scale. Material capable of absorbing visible radiation is chiefly responsible for warming the sunlit portions of Triton's surface (*11*). We suggest that ultraviolet radiation acting on hydrocarbon ices when they are in the atmosphere, at the surface, and even below the surface coverts them into visible absorbing, complex polymers. There is a limited amount of laboratory data supporting such a chemical transformation scheme (*13*). Since hydrocarbon ices are continually generated in the sunlit portion of the atmosphere by methane photolysis, perhaps the visible absorbing, polymeric material is also continually produced in such locations. The continual generation of this visible absorbing material may help to keep the satellite's surface from approaching unit albedo and therefore becoming even colder than it is.

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15. The phase function provides a measure of the fraction of light scattered in different directions. It tends to be large at small scattering (high phase) angles.
16. We calculated the single scattering components exactly and included in an approximate fashion multiply scattered light (*12, 13*). Light scattered from the surface was described by photometric functions based on Hapke's theory that were derived from Voyager images by Hillier *et al.* [B. Hapke, *Icarus* **67**, 264 (1986); J. Hillier *et al.*, *Science* **250**, 419 (1990)].
17. Mie theory was used to calculate the phase functions of polydispersed spheres at high phase (low scattering) angles. As shown by Pollack and Cuzzi, scattering at these angles does not depend sensitively on the particles' shape. These authors also provided estimates of the phase functions of randomly oriented, nonspherical particles at other angles, where there is a much greater variation with shape. [J. B. Pollack and J. N. Cuzzi, *J. Atmos. Sci.* **37**, 868 (1980).]
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22. Given a sedimentation time of about two Earth days and a cloud optical depth of about $3 \times 10^{-2}$, we find that an optically thick snow layer can form quickly from snowfall associated with the discrete clouds at high southern latitudes. Recent snowfall may also have occurred at low southern latitudes, according to our interpretation of the spatial distribution of the extensive haze.
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