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ON THE RELATIONSHIP BETWEEN SECULAR BRIGHTNESS CHANGES OF TITAN AND SOLAR VARIABILITY

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Abstract. Titan's geometric albedo varied noticeably from 1972 to 1978, in phase with variations in solar activity [Lockwood and Thompson, 1979]. We carry out a series of radiative transfer and aerosol formation calculations in order to demonstrate the feasibility of the following scenario for these secular brightness changes: solar activity changes, especially in the UV output of the Sun, result in alterations to the mass production rate of aerosols in Titan's atmosphere, which lead to modifications of their microphysical properties. The latter, in turn, cause the albedo to vary. Current estimates of the change in the solar UV radiation below the dissociation limit of methane imply alterations to the mean radius of the aerosols over an 11-yr solar cycle that are consistent in sign and magnitude with those required to explain the observed secular brightness changes.

Introduction

Titan, Saturn's largest satellite, has an atmosphere more massive than that of Mars, with methane being a major constituent and lower hydrocarbons being minor components [Hunten, 1977]. Titan's atmosphere also contains an optically thick haze of submicron-sized aerosols that are thought to be generated in situ by photochemical or high-energy particle processes [Hunten, 1977; Rages and Pollack, 1978 and 1980, henceforth Papers I and II; and Chang et al., 1979]. The microphysical characteristics of the aerosols chiefly determine the brightness of Titan at visible wavelengths removed from methane absorption features [Papers I and II].

Lockwood [1977] and Lockwood and Thompson [1979] have presented evidence for significant secular variations in the brightness of Titan, Neptune, and Uranus from 1972 to 1978 in blue and yellow light (effective wavelengths = 0.472 and 0.551 μm). From 1972 to 1976, Titan's brightness, corrected to a fixed distance from the Sun and a fixed phase angle, increased by about 10% and 5% in the b and y filters, respectively, whereas from 1976 to 1978, the brightness decreased to about the level of the brightness in 1974. These data for Titan are in good agreement with independent observations made by Noland et al. [1974], Andersson [1977], and Franklin and Cook [1974] over part of this time interval. Neptune behaved in a similar fashion to Titan, but the magnitude of its brightening was much less. Uranus' brightness steadily increased over the entire time period.

Based on the temporal characteristics of these results and the difference in amplitude between Titan and Neptune, Lockwood and Thompson [1979] concluded that the brightness variations of Titan and Neptune were not related to changes in orbital position, aspect angle of observation, or the solar constant, but rather to solar-induced changes of albedo. However, they considered the Uranus results to be attributable to variations in the orientation of its highly inclined axis of rotation. In this paper, we investigate the direct and indirect causes of the secular brightness changes of Titan: We first determine the alterations to the properties of its atmospheric aerosols needed to account for the observations of Lockwood and Thompson [1979]. We then discuss the connection between these required changes and solar variability.

Changes in Aerosol Properties

To simulate the secular brightness variations of Titan, we have carried out a series of radiative transfer calculations in the same manner as in Papers I and II. The single-scattering characteristics of the aerosols were calculated with a Mie scattering program that included the modifications for nonsphericity proposed by Pollack and Cuzzi [1980]. However, according to Papers I and II, the aerosols are sufficiently small so that nonspherical effects are negligible. An accurate numerical scheme based on the doubling-adding method was used to solve the multiple-scattering problem with allowance made for vertical inhomogeneity in the aerosol-to-gas mixing ratio and scattering from the satellite's surface.

From an analysis of measurements of Titan's continuum albedo and the variation of its brightness with solar phase angle, estimates were obtained in Papers I and II of a number of aerosol properties. It was found that $1.5 \leqslant n_r \leqslant 2.0$, $0.20 \leqslant \bar{r} \leqslant 0.35$ μm, and $\tau \geqslant 4$, where n_r, $\bar{r}$, and τ are the real part of the aerosols' refractive index, their cross section weighted-mean radius, and optical depth, respectively. For a given choice of n_r, it was possible to determine $\bar{r}$ to within a few percent. This analysis also yielded values for the aerosols' imaginary index of refraction, n_i, as a function of wavelength, and placed bounds on a shape-related parameter. The above results refer to aerosol properties appropriate for the latter part of 1972. For the nominal model of this paper, we use the values of $\bar{r}$, n_r, n_i, and τ for epoch 1972.88, which are given in Table 1.

There are three properties of the aerosols which might plausibly vary and thus produce noticeable changes in Titan's brightness: $\bar{r}$, τ, and n_i. Although, quite conceivably, several of these may change synchronously, it is useful to examine the effect of varying each parameter separately. For each parameter, we investigate the magnitude of the change needed to reproduce the observed secular brightness variation from 1972 to 1976, and the degree to which the predicted variations follow the track of the observed ones in a two-color diagram. In modeling the modification in n_i, we assumed that the fractional changes in n_i were the same for the b and y wavelengths. Such an assumption is appropriate if the aerosols are made of a nonabsorbing and an absorbing material and the proportion of these two materials in each particle varies with time.

Figures 1a, b, and c compare predicted and observed (rectangles) brightness variations in the b and y filters for models with changing $\bar{r}$, τ, and n_i, respectively. In Figure 1a, several curves are shown corresponding to alternative choices of n_r, while the separate curves in Figure 1b correspond to alternative choices of surface (or cloud) albedo, A_s. The numbers marked at the ends of the theoretical curves indicate the values of the varied parameter at these locations and not at the extremes of the rectangles. Table 1 summarizes the parameter changes needed to match the observed brightness variations from 1972 to 1976. Note that the observed brightness changes from 1976 to 1978 simply retrace part of the 1972 to 1976 track.

According to Figures 1a, b, c, variations in any of the aerosol parameters can lead to a predicted slope in the two-color diagram that is

TABLE 1: Changes in Aerosol Properties Required to Produce the Observed Secular Brightness Changes of Titan

Parameter	Nominal value for Epoch 1972.88*	Ratio of value for a given epoch to the nominal value	
		Epoch: 1972.05	1976.15
Average radius	0.25 μm	0.97	1.15
Imaginary index of refraction	0.033 and 0.017†	1.015	0.92
Optical depth	10	$\gtrsim 2$	0.5

*The refractive index and surface albedo have nominal values of 1.7 and 0.5, respectively.
†The values pertain to wavelengths of 0.4718 and 0.5508 μm, respectively.

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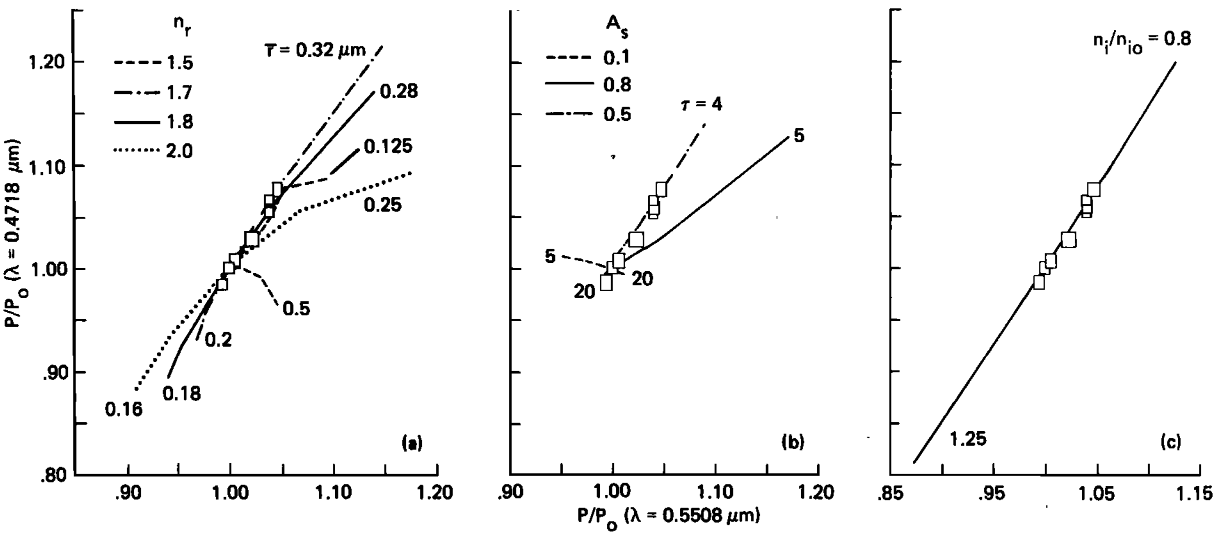

Fig. 1. Comparison between the observed and predicted changes of Titan's geometric albedo p at effective wavelengths of 0.4718 and 0.5508 μm. The observed values from 1972 to 1976 are shown by the rectangles, with the length of their vertical and horizontal sides indicating the estimated uncertainty in the measurements [Lockwood, 1977]. The albedos increase monotonically from 1972 to 1976. The geometric albedos are normalized by their value at epoch 1972.88, the time to which the nominal aerosol properties of Papers I and II pertain. (a) The theoretical curves show the predicted behavior of models in which the cross section weighted mean radius $\bar{r}$ varies for several choices of refractive index n_r. (b) The theoretical curves refer to models in which the optical depth τ is changed for several choices of surface albedo A_s. (c) The theoretical curve refers to a model in which the imaginary index of refraction n_i is varied by constant fractional amounts at both wavelengths.

consistent with the observations. In the case of varying $\bar{r}$, n_r values of 1.7 and 1.8 result in acceptable predictions, while values of 1.5 and 2.0 do not. In the case of varying τ, an A_s of about 0.5 is required, and τ needs to decrease to a value of about 5 near maximum brightness. It might seem odd that increasing the mean particle size causes Titan's geometric albedo to increase. However, this result is due to the fact that the enhancement of the phase function in the backscattering direction with increasing $\bar{r}$ is more important than the decrease in the single-scattering albedo.

According to Table 1, only very modest changes in $\bar{r}$ or n_i are needed to reproduce the magnitude of the secular brightening from 1972 to 1976, while somewhat more substantial changes in τ are required. Some evidence against the latter change can be obtained by examining the variations in the strength of the near-infrared methane features engendered by varying τ. As illustrated in Figure 2, quite sizeable variations would be expected, contrary to the great similarity in the strength of the methane bands found in the spectra of Younkin [1974] and Nelson and Hapke [1978], which were obtained during January 1972, and December 1975 to February 1977, respectively.

Changes in Solar Output

In order to assess the impact of changes of solar output on Titan's brightness, we consider two questions: How do the aerosol properties change as the mass production rate of aerosol material changes? By how much does the component of the solar output responsible for aerosol generation change over a solar cycle? In the previous section, we saw that changes in particle size, composition, or optical depth could account for the observed brightening, but that the optical depth mechanism could be ruled out on other grounds. Since the composition of the aerosols is presently unknown, we cannot simulate the compositional model for the brightening. However, it is possible to relate changes in particle size to changes in aerosol mass creation rates using the Titan cloud model of Toon et al. [1980].

In order to model Titan's aerosol layer, Toon et al. [1980] adapted a model designed by Turco et al. [1979] to simulate the Earth's stratospheric aerosol layer, which is also produced by gas-to-particle transformation processes. The latter correctly duplicates the observed size distribution of stratospheric aerosols [Toon et al., 1979].

In order to simulate Titan's aerosol layer, Toon et al. [1980] assumed that mass is created by unspecified chemical reactions at a prescribed rate above the 0.01 km – atm CH_4 level, where the visible optical depth is about 2. They also assumed that the aerosols are involatile. With these assumptions, the processes controlling the aerosol properties are: particle removal by sedimentation and atmospheric transport (modeled in one dimension by eddy diffusion); and particle growth by coagulation. Toon et al. [1980] found several combinations of model parameters that resulted in an aerosol layer which approximately matched the aerosol properties deduced in Papers I and II. These models were characterized by aerosol mass creation rates of about 3×10^{-13} g/cm^2/s or 1×10^{10} molecules/cm^2/s.

In two widely divergent model atmospheres, Toon et al. [1980] found a similar relation between mass creation rate and particle size.

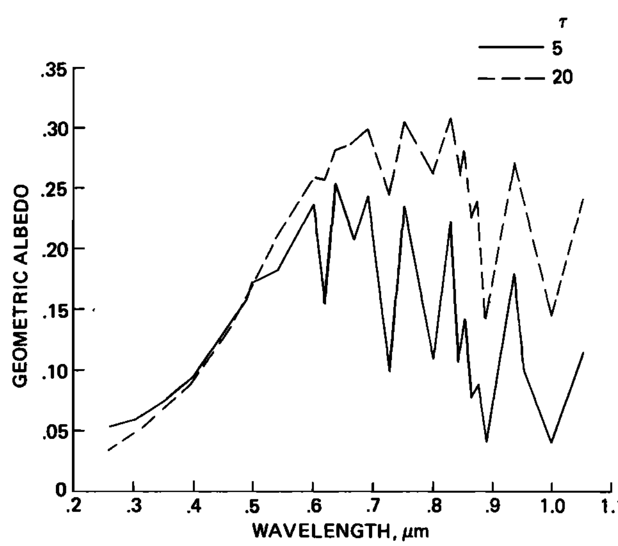

Fig. 2. Geometric albedo as a function of wavelength for models in which the optical depth of the aerosol layer τ is half and twice its nominal value of 10.

As the mass creation rate increased by a factor of 1.5 and 2.0, the cross section weighted average particle size at a wavelength of 0.6 μm decreased by about 10% and 16% at optical depth unity, respectively. At optical depth 2, the corresponding changes were 17% and 30%, respectively. Since the fractional increase in mean radius required to explain the secular brightening between 1972 and 1976 is between 15% and 20%, it appears that a mass input decrease of a factor of 1.5 to 2.0 is required.

The reduction in mean size that accompanies an increase in mass production rate can be understood as follows: When the mass supply increases, a given optical depth level occurs at a lower pressure. Since the particle fall speed is a strong function of particle size and pressure, the mean particle size is smaller for a fixed optical depth.

There are two types of energy inputs to Titan's atmosphere that may, jointly, be responsible for gas-to-particle conversion: solar UV radiation and high-energy magnetospheric particles. It seems likely that the dissociation of methane serves as a starting point for aerosol production [Danielson et al., 1973; Hunten, 1977; Podolak and Bar-Nun, 1979; and Allen et al., 1980]. In this case, the relevant region of the solar spectrum is that at wavelengths smaller than about 0.165 μm. Estimates of the rate at which these short wavelength photons convert methane to aerosols range from about 2×10^{-14} to 4×10^{-13} g/cm^2/s [Podolak and Bar-Nun, 1979; and Allen et al., 1980]. Using the flux of energetic electrons with energies in excess of 40 keV measured by Van Allen et al. [1980] at Titan's distance from Saturn and a conversion rate of 44 eV/CH_4 [Chang et al., 1979], we obtain a mass production rate of about 2×10^{-15} g/cm^2/s due to energetic electrons. Electrons with energies below 40 keV have too small a gyroradius ($\lesssim$ 300 km) to penetrate far into Titan's atmosphere. Thus, it seems likely that solar UV radiation is the chief source of particle production.

Observations from satellite and rocket platforms indicate that the Sun's Ly α radiation decreases by about a factor of 2 from sunspot maximum to minimum [Vidal-Madjar, 1977]. Over the same portion of a solar cycle, an empirical model in combination with more limited observations suggests that the Sun's irradiance at wavelengths between the dissociation limit of methane and Ly α decreases by almost a factor of 2 [Cook et al., 1980]. Allowing for a somewhat smaller amplitude of these variations between 1972 and 1976, we estimate that aerosol-producing UV radiation decreased by about a factor of 1.5 to 2.0 over this interval. The magnitude of this change is in crude agreement with the estimate given above for the alteration in aerosol mass creation rate needed to explain Titan's brightness variations by $\bar{r}$ modulation. Furthermore, the sign of the change is correct. Due to a decline in solar activity from 1972 to 1976, the aerosol mass creation rate should have decreased, which implies an increase in $\bar{r}$ and, hence, a brightening over this interval.

Discussion

Using the change in parameter values between 1972 and 1976 given in Table 1 and the relationship between aerosol optical depth and methane column abundance given in Paper II, we have estimated the change in the Bond albedo in the visible and near-infrared and the change in the bolometric albedo over this time interval. Bond albedo refers to the monochromatic reflectivity integrated over all angles of incidence and reflection, while bolometric albedo is the Bond albedo integrated over all wavelengths and weighted by the solar spectrum. By evaluating these albedos, we investigate the impact of the change in aerosol properties on Titan's heat balance. For the model involving changes in particle size, we find that the Bond albedo in the 0.25–0.7 μm spectral domain decreased from 1972 to 1976, although the geometric albedo increased. This paradoxical behavior is due to the dominating influence of the single-scattering albedo on the Bond albedo; the single-scattering albedo decreased as the particle size increased. However, at longer wavelengths, which are dominated by methane absorption bands, the Bond albedo increased from 1972 to 1976, due to the modulation of the phase function. Averaging these results over the solar spectrum we find that the bolometric albedo decreased by about 2% from 1972 to 1976. For the model involving decreases of the imaginary index of refraction, the Bond albedo increased at all wavelengths, and the bolometric albedo increased by about 4% from 1972 to 1976. Thus, the secular brightness changes over this time interval resulted in an alteration of about a percent in the amount of solar energy absorbed by Titan.

Conclusions

Variations in the size, absorption coefficient, and optical depth of the aerosols in Titan's atmosphere are, each separately, capable of producing secular brightness variations in the blue and yellow that are compatible with the observed secular brightness changes (cf. Figure 1). However, the model involving changes in optical depth predicts a much larger change in the strength of the near-infrared methane bands than appears to be allowed by available measurements. The model involving variations in particle size seems to be very promising, since the magnitude and sign of the required changes are in approximate agreement with those expected from variations in the solar UV output at wavelengths below the dissociation limit of methane. The smaller secular brightness changes of Neptune can be attributed to the photochemically produced aerosol layer in its atmosphere being optically thin [Macy et al., 1978] in contrast to the situation for Titan.

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