2.4 PHOTOMETRY AND POLARIMETRY

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Introduction

This paper is a review of currently available information on the photometry, polarimetry, and narrow-band spectrophotometry of Titan. It is convenient to divide the discussion into five major categories:

(1) Brightness and color as a function of orbital position,

(2) Brightness and color as a function of solar phase angle,

(3) Geometric and Bond albedo,

(4) Reflectance as a function of wavelength,

(5) Polarization as a function of solar phase angle.

These topics are dealt with in turn in the next five sections. The final section contains conclusions and a summary of the best, currently available data.

Brightness and Color: Orbital Position Dependence

Titan revolves about Saturn once every 16 days. Originally Pickering (1913) announced a variation in brightness of 0.24 magnitude with this period. Harris (1961), however, conclusively showed that this reported variation is spurious and is due to errors in the magnitudes assigned to comparison stars. His own measurements at McDonald showed no definite variations within ±0.08 magnitude in the V. Nevertheless, visual observers occasionally report semi-permanent markings on Titan (for example, Lyot, 1953) suggesting that brightness variations may occur.

Accordingly, UBV observations of Titan were carried out on 14 nights during the 1968-69 opposition with the Harvard 16" reflector (Veverka, 1970). At this stage it was assumed that the brightness and colors do not change significantly with solar phase angle. Nine of the observations were obtained during one revolution of Titan about Saturn: from January 9 to January 17, 1969. During this time the solar phase angle changed only from 6°.1 to 6°.0. In the V, no variations in brightness, related to orbital position were found in excess of ±0.04 magnitude. To about the same degree of accuracy no variations in the (B-V) and (V-B) colors were detected.

Similar conclusions are reported by Blanco and Catalano (1971). The scatter in their V measurements is slightly smaller than that quoted above but the scatter in their (B-V) and (U-B) measurements is greater. Again, McCord, Johnson and Elias (1971) found no change in Titan's brightness with orbital phase at 0.56 μm.

A recent joint project between the University of Hawaii and Cornell University yielded high quality photometry of Titan at six wavelengths (Noland et al., 1973). Sufficient observations were obtained to permit a separation of brightness changes due to orbital position from those due to changes in the solar phase angle. No evidence for brightness variations was detected as is apparent from the data presented in Table 2-2. Similarly, these data do not show any color changes related to orbital position.

The conclusion is that if short term changes in the brightness of Titan occur, their amplitude does not exceed ±0.02 magnitude, and they are not related to Titan's orbital position. The possibility of long term (secular) changes is considered in Section 3.

If the atmosphere of Titan is optically thick, we would not expect any variations in brightness with orbital position. If the atmosphere is optically thin, then the distribution of surface brightness must be quite homogeneous, unlike that of other Saturn satellites and of the Galilean satellites of Jupiter. The absence of established color changes sets limits on the extent and contrast of the atmospheric changes reported by some visual observers.

Brightness and Color: Phase Angle Dependence

Important information about Titan can be obtained by measuring the phase coefficients at various wavelengths. At small phase angles a smooth surface or a thick Rayleigh atmosphere will have an imperceptible phase coefficient (perhaps .002 mag/deg). A microscopically rough surface with no overlying atmosphere (like that of the Moon) will have an appreciable phase coefficient (say 0.025 mag/deg).

Since the brightness of Titan is independent of its orbital position, its apparent magnitude, reduced to mean opposition distance (Harris, 1961), can be expressed as:

$$m(\alpha) = m_o + \beta \cdot \alpha$$

where: α = phase angle,

m_o = magnitude at opposition,

β = phase coefficient in units of mag/deg.

The phase coefficients for Titan from the Hawaii-Cornell photometry are listed in Table 2-3 and are shown in Figure 2-16. The only other determination of a phase coefficient is by Blanco and Catalano (1971). Although these authors fit their data to a quadratic expression in α, a linear equation yields an equally good fit with $\beta(V) = 0.006 \pm 0.001$. This value of the phase coefficient is in good agreement with the Hawaii-Cornell data.

Table 2-2. Orbital Brightness and Color Solar Phase Angle Dependence

WAVELENGTH	AMPLITUDE (MAG)*
u (0.35 μm)	≤ .018
v (0.41 μm)	.018
b (0.47 μm)	.006
y (0.55 μm)	.010
R' (0.63 μm)	.015
I' (0.75 μm)	.015

* Upper limits on probable amplitudes.

Table 2-3. Phase Coefficients of Titan (Noland _et_ _al._, 1973)

FILTER	WAVELENGTH	PHASE COEFFICIENT (MAG/DEG)
u	0.35	0.014 ± 0.001
v	0.41	0.010 ± 0.001
b	0.47	0.006 ± 0.001
y	0.55	0.005 ± 0.001
R'	0.63	0.002 ± 0.001
I'	0.75	0.001 ± 0.001

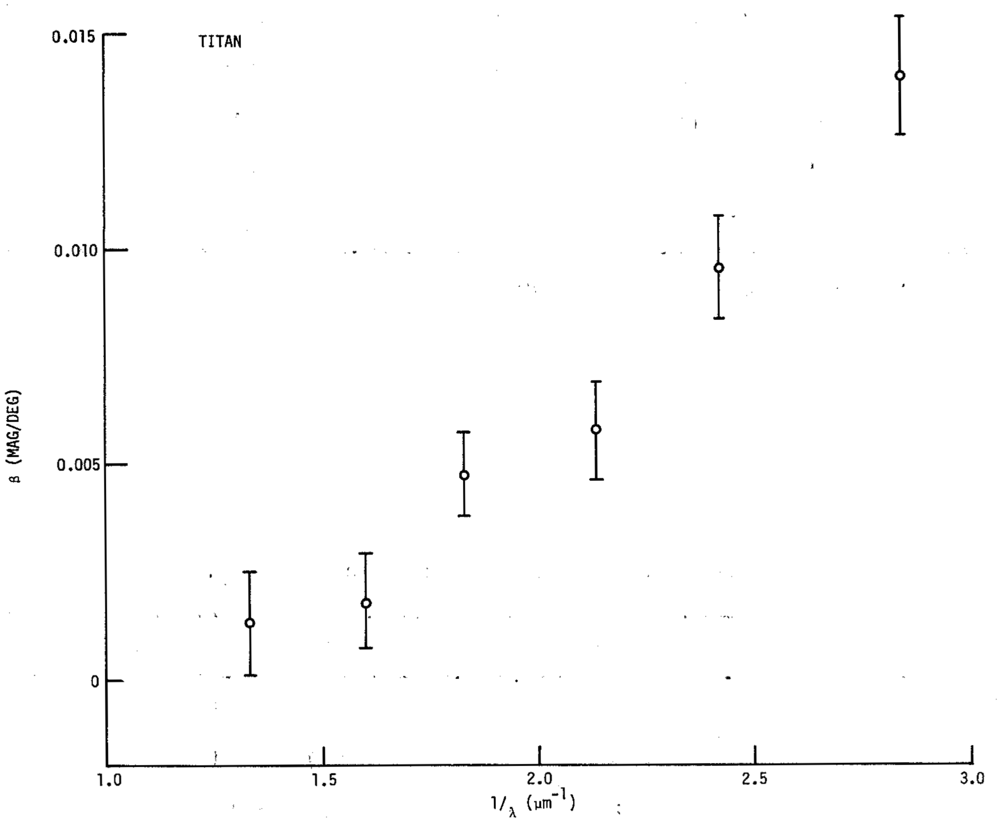

Figure 2-16. The wavelength dependence of Titan's phase coefficient. After Noland et al., 1973.

The information in Figure 2-16 can be used to set limits on possible Titan models. Optically thick Rayleigh scattering atmospheres can immediately be excluded, as can models in which most of the light comes from a solid surface (Noland et al., 1973). Furthermore limits can also be imposed on allowable cloud models (M. Noland, work in progress), using methods similar to those used by Arking and Potter (1968) in the case of Venus.

Geometric and Bond Albedo

Four determinations of the mean opposition magnitude of Titan in the V are listed in Table 2-4. The values agree to ±0.02, but a slight secular brightening between 1961 and 1971 is possible. In what follows we adopt the Harris values of the UBV colors since they agree with other determinations. Thus we have (B-V) = +1.30 and (U-B) = +0.75 reduced to mean opposition.

The corresponding values of the UBV geometric albedos given by Harris (1961) are still viable: $p_U = 0.06$; $p_B = 0.12$; $p_V = 0.21$. The low value of the geometric albedo in the U places a limit of $\tau(0.36\ \mu m) \leq 0.16$ on the optical depth of any pure Rayleigh scattering atmosphere. This upper limit can be lowered considerably using the OAO-2 observations of Caldwell et al. (1973) who report p (0.26 μm) = 0.05. This translates into $\tau(0.36\ \mu m) \leq 0.04$.

Younkin has reported (p. 154) new measurements of Titan's geometric albedo between 0.50 and 1.08 μm. The maximum value is said to be 0.37 at 0.68, 0.75 and 0.83 μm. By assuming an effective phase integral $\bar{q} = 1.3$, consistent with a cloudy atmosphere, he estimates the bolometric Bond albedo to be 0.27.

There is a difficulty with the geometric albedo information beyond 0.6 μm which must be noted. Harris (1961) gives broad-band values of 0.32 in the R (0.69 μm) and 0.27 in the I (0.82 μm), whereas Younkin (1973) quotes narrow-band values of 0.37 near these wavelengths. That the values of Harris are lower is consistent with his use of broad filters in a spectral region of deep absorption bands. McCord et al. (1971) attempt to relate their narrow band measurements to the V measurement of Harris. If their transfer relationship were accepted, their data would imply narrow-band geometric albedos at 0.68 and 0.82 μm of about 0.27 and 0.21, respectively, in disagreement with both Harris and Younkin.

Spectral Reflectance of Titan

McCord et al. (1971) measured the spectral reflectance of Titan from 0.3 to 1.1 μm (Figure 2-17) and found it remarkably similar to the spectrum of Saturn's equatorial belt. Large methane absorption bands are present in both spectra beyond 0.6 μm, and both spectra show steep drop-offs from 0.6 to 0.4 μm. The similarity of the spectra outside the methane bands suggests that the material causing the coloration of the bands of Saturn is present on Titan as well. Below 0.4 μm McCord et al. find that the spectra differ appreciably. The ultraviolet turnup in Saturn's spectrum, probably due to a significant Rayleigh scattering component, is absent in the Titan spectrum. Recent measurements by Caldwell et al. (1973) down to 2600 Å, and by Barker and Trafton (1973) between 3000 and 4350 Å confirm that Titan is dark in the UV. More recent spectral reflectance measurements between 0.5 and 1.08 μm have been reported by Younkin (1973), but have not been published in final form.

Table 2-4. Mean Opposition Magnitudes of Titan

SOURCE	MEAN OPPOSITION MAGNITUDE (V)
Harris (1961)	+ 8.39
Franklin (1969)	+ 8.37
Veverka (1970)	+ 8.37
Blanco and Catalano (1971)	+ 8.35

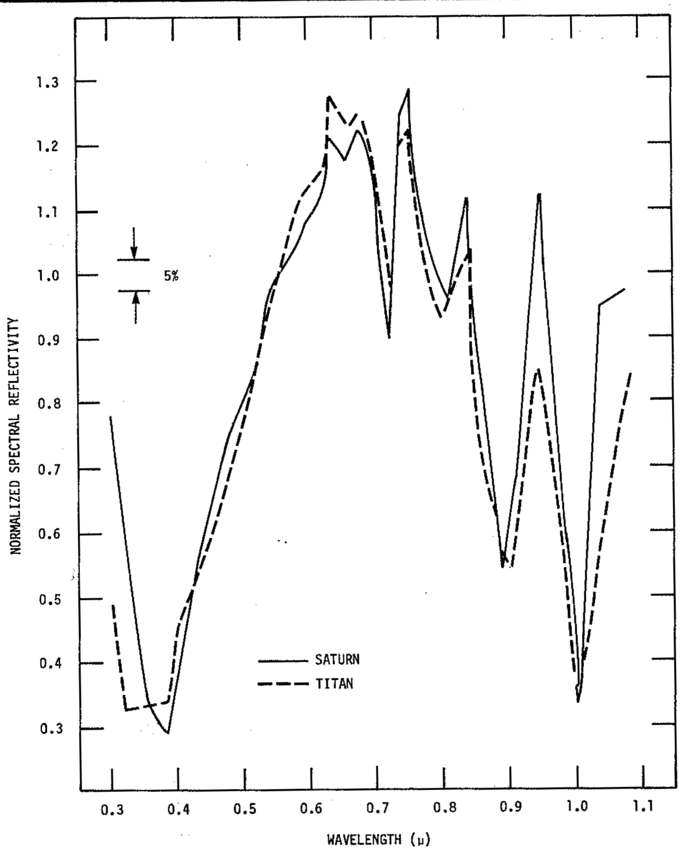

Figure 2-17. The spectral reflectance curve of Titan compared with that of Saturn's equatorial belt, scaled to unity at 0.56 μm. After McCord et al. (1971). Reprinted from The Astrophys. J., 165: 422, with permission of The University of Chicago Press. © 1971. The University of Chicago. All rights reserved. Printed in U.S.A. (The turn-up of the Titan spectrum at 0.3 μm is probably spurious.)

Polarization Phase Angle Dependence

Veverka (1970; 1973) measured the disk-integrated polarization of Titan in white light at phase angles ranging from $0^\circ.4$ to $6^\circ.1$ during the 1968-69 opposition. The observed polarization was small, but positive throughout this interval. By combining this fact with Titan's low geometric albedo in the U, the observations suggest a model in which an optically thin Rayleigh atmosphere overlies an opaque cloud deck.

The observations are shown in Figure 2-18. Note that Titan is intrinsically dark having geometric albedos of 6, 12, and 20% in the U, B, V, respectively (Section 3). Polarization curves of solid surfaces which are this dark tend to have well-defined negative branches at small phase angles, unless those surfaces are unusually smooth -- and there is no reason to expect any planetary surface to be optically smooth. Only for surfaces having very high reflectances (say greater than 50%) does the negative branch disappear and the polarization curves begin to resemble that of Titan. (The disappearance of the negative branch is related to the fact that multiple scattering within the surface achieves a dominant role.)

However such bright materials cannot explain the polarization curve of Titan, since the geometric albedo of Titan is very low: about 20% in the visible, and not 60%!

It is instructive to compare the polarization curve of Titan with those of the Moon, Mars, and Saturn (Figure 2-18). The comparison with Mars is especially interesting since Mars is similar to Titan in both color and albedo. (According to Harris, 1961, the geometric albedos for Mars are 5, 8, and 15% in the U, B, and V, respectively. The corresponding values for Titan are 6, 12, and 21%.) We know that Mars has an optically thin atmosphere, and the polarization that we see in the visible is that of the relatively dark Martian surface. The polarization curve of Titan is quite different, and in fact bears a strong resemblance to that of Saturn, a planet which certainly has an optically thick atmosphere.

Veverka (1973) discussed three a priori possible Titan models shown in Figure 2-19. Model I has an optically thin Rayleigh atmosphere (with possibly an occasional cloud) above the true surface of Titan. Since the geometric albedo of Titan is low, the surface must in this case be dark, and we should, as in the case of Mars, see negative polarization at very small phase angles (unless the surface of Titan is unusually smooth, which seems quite unlikely). Since the observed polarization is on the contrary always positive, Model I can be eliminated.

Either of the two remaining models can explain the observed polarization curve. In Model II, we have an optically thick Rayleigh atmosphere (again, with possibly occasional clouds). Calculations by Whitehill (1971) predict a disk-integrated polarization of about +0.3% at a phase angle of 6° for this case, which is compatible with the observations. However Model II is easily rejected on photometric grounds. Since the geometric albedo of Titan in the U is only 6%, the total optical thickness of any Rayleigh atmosphere cannot exceed $\tau \sim 0.16$ (Evans, 1965). In fact, the value of $p(0.25\ \mu m) = 0.05$ found by Caldwell *et al.* (1973) reduces this upper limit to $\tau(0.36\ \mu m) \leq 0.04$. This certainly is not optically thick and Model II must be rejected.

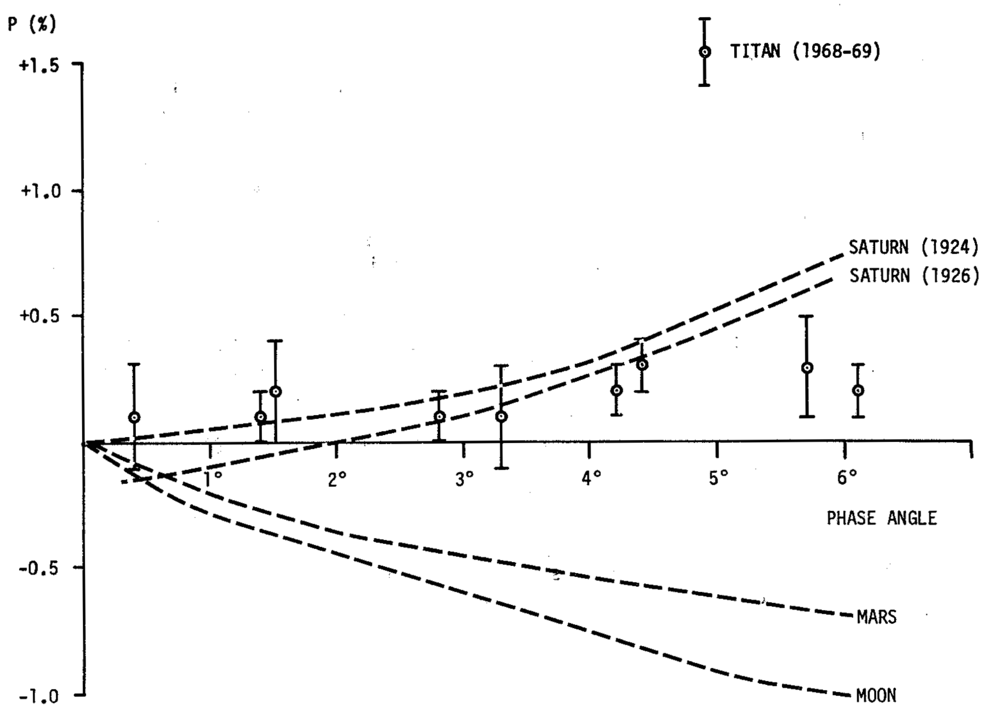

Figure 2-18. Titan measurements compared with polarization curves of the Moon, Mars and Saturn in integrated white light (Veverka, 1973). The Saturn measurements were made at the center of the disk and were found to be slightly variable from year to year. After Veverka (1973). Reprinted from Icarus, 18:659, with permission of Academic Press, Inc.

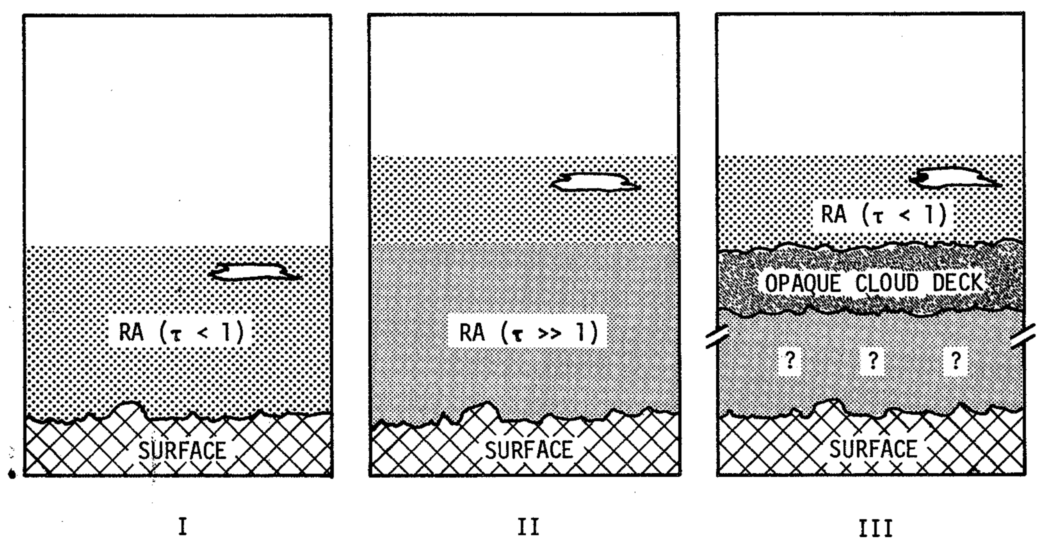

Figure 2-19. Schematic representation of three models of the Titan atmosphere: (I) optically thin Rayleigh atmosphere (RA); (II) optically thick Rayleigh atmosphere; (III) optically thick cloud deck. After Veverka (1973). Reprinted from Icarus, 18:660, with permission of Academic Press, Inc.

In the last model, Model III, we have an opaque cloud top, above which there is a small amount of Rayleigh atmosphere: less than $\tau \sim 0.04$ from the discussion above, a situation similar to that which one might be expected to obtain on Saturn. (Recall that Saturn and Titan have similar polarization curves.) It is also interesting to note in this context that McCord, Johnson, and Elias (1970), found that the spectral reflectance curves of Saturn and Titan are almost identical.

Veverka (1973) concluded that both the photometric and polarimetric properties of Titan can best be explained in terms of a Saturn-like model (Model III), in which there is an opaque cloud deck overlain by an optically thin amount of Rayleigh atmosphere. The unusual red color of Titan would then be due to an absorber of blue and ultraviolet light within the cloud deck. This substance might well be the same as that in the clouds of Saturn.

New polarization measurements of Titan in three colors (0.36, 0.52, and 0.83 μm) were obtained by Zellner (1973) during the 1971-72 opposition (Figure 2-20). They confirm and considerably improve upon the earlier white light measurements by Veverka (1970; 1973). Zellner concluded that his observations "are not consistent with scattering from either an ordinary planetary surface or a pure molecular atmosphere. Apparently an opaque cloud layer with a strong UV - absorbing constituent is needed."

Zellner's conclusions are in part based on model calculations using the Rayleigh-Chandrasekhar theory for the polarization produced by a pure molecular atmosphere above a (non-polarizing) Lambert surface. The observed polarization and geometric albedos cannot be matched simultaneously by such models.

Zellner's three color observations are unique in several respects. The 0.52 μm measurements indicate a steep drop in the polarization from 6° to 4° phase, and the 0.36 μm measurements suggest small negative polarizations near 4° phase. Both characteristics are inconsistent with Rayleigh scattering models.

No cloud model calculations have yet been carried out to match the Titan polarization curves. But Coffeen and Hansen (1973) have analyzed Lyot's white light measurements of the center of the disk of Saturn which resemble the Titan data (cf. Figure 2-18). Thus the conclusions obtained for Saturn can be extended to Titan (Figure 2-21). Cloud models having spherical particles with mean radii of 2-3 μm size distributions $N(r) \propto r^{-2}$ with abrupt cut-offs at $0.75\ r_o$ and $1.25\ r_o$ (where r_o is the mean particle radius), and indices of refraction $n = 1.3$ to 1.5 at 0.55 μm match the observations (Coffeen and Hansen, 1973).

Summary and Conclusions

The available photometric and polarimetric information about Titan can be summarized as follows:

(1) No changes in brightness or color related to orbital position have been detected. This is consistent with the presence of an optically thick atmosphere;

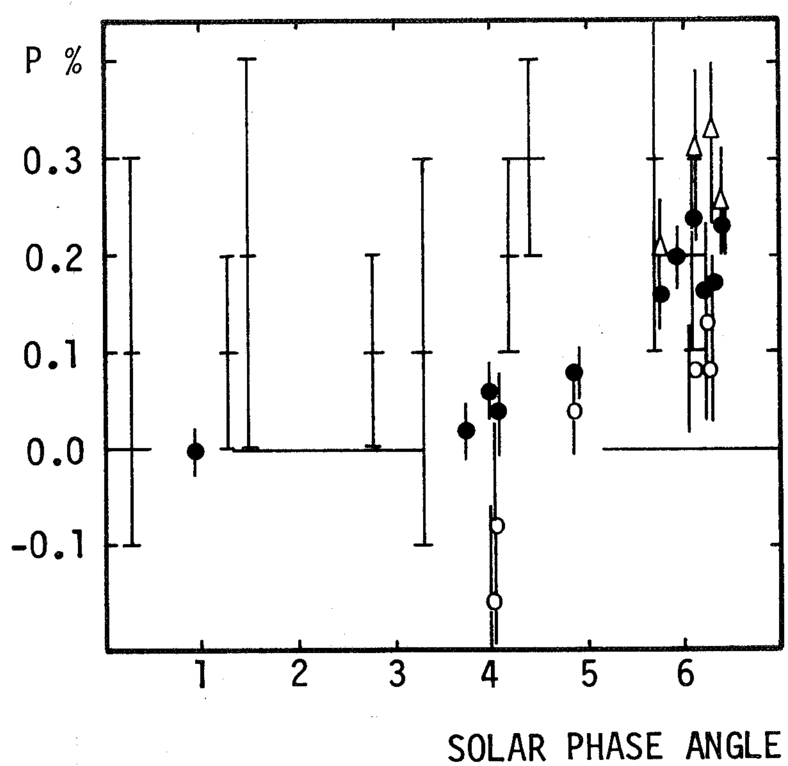

Figure 2-20. Polarization observations of Titan. Open circles indicate observations in ultraviolet light (0.36 µm), filled circles in the green (0.52 µm), and triangles in the near infrared (0.83 µm), all made by Zellner in 1970-71. Crosses represent white-light observations by Veverka (1970) made in 1968-69. After Zellner (1973). Reprinted from Icarus, 18:662, with permission of Academic Press, Inc.

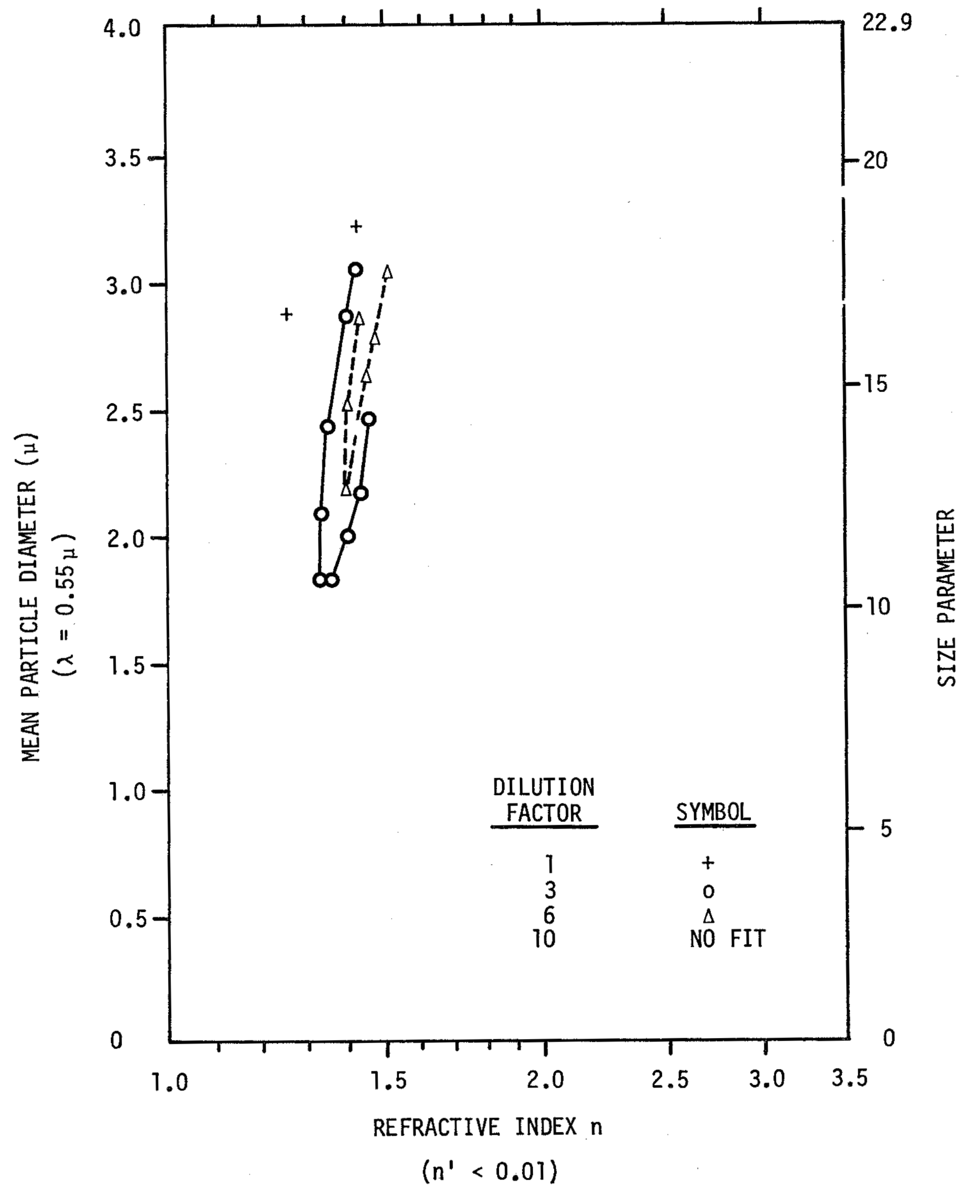

Figure 2-21. Locus of fits of Lyot's observations of the center of the disk of Saturn with Mie calculations for size distributions of spheres, for various multiple scattering dilution factors. After Coffeen and Hansen (1973). Reprinted from Planets, Stars, and Nebulae Studied with Photopolarimetry, copyright © 1974, with permission of University of Arizona Press. All rights reserved.

(2) A phase effect has been detected. The phase coefficients decrease with increasing wavelength from 0.014 ± 0.001 mag/deg at 0.35 μm to 0.001 ± 0.001 at 0.75 μm. The large value of the phase coefficient at 0.35 μm, and its wavelength dependence are inconsistent with an optically thick Rayleigh atmosphere. The low values of the phase coefficients in the red are difficult to explain with optically thin models of the atmosphere. Clouds are required;

(3) The mean opposition magnitude of Titan in the V may have changed from 8.39 in 1961 to 8.35 by 1971, suggesting a possible secular brightening.

(4) The geometric albedo is very low in the UV. Typical values are 0.05 at 0.26 μm and 0.06 at 0.36 μm. This places an upper limit of τ (0.36 μm) $\leq$ 0.04 on the optical depth of any Rayleigh atmosphere above the clouds;

(5) Outside of the methane bands, the geometric albedo may be as high as 0.37, beyond 0.6 μm;

(6) No direct information on the phase integral q exists. Since Titan seems to have an optically thick atmosphere, it is likely that $1 \leq q \leq 1.5$;

(7) Younkin (1973) estimates the bolometric Bond albedo to be 0.27, using q = 1.3. Because of the lack of information about q, an uncertainty of ±10% in the Bond albedo is likely (0.27 ± 0.03);

(8) Detailed narrow-band spectrophotometry shows that the spectral reflectance curve of Titan is very similar to that of Saturn's equatorial belt. This suggests a Saturn-like model for the atmosphere of Titan, including an opaque cloud deck. However, the amount of Rayleigh atmosphere above the cloud top must be much smaller on Titan than on Saturn;

(9) The sharp drop in Titan's spectrum below 0.6 μm indicates a strong UV absorber in the clouds. This material may be the same as that responsible for the orange color of the belts of Saturn and Jupiter;

(10) Polarization measurements of Titan are inconsistent with either an optically thick Rayleigh atmosphere, or with an optically thin atmosphere model in which a significant amount of light is scattered from a solid surface. Optically thick clouds are required;

(11) Titan's white-light polarization curve is similar to that of the equatorial region of Saturn. Cloud models with 2-3 μm spherical particles having indices of refraction between 1.3 to 1.5 (at 0.55 μm), are consistent with the observations;

<u>The single most important conclusion to be drawn from the photometry and polarimetry of Titan is that a Saturn-like cloud model may be required to explain the sum of the observations.</u>

Acknowledgement

The author is grateful to C. Sagan and M. Noland for their helpful discussions. This work was supported in part by Grant NGR-33-010-082.

Sagan: Dollfus has reported from visual observations that he sees a changing pattern on Titan which is different from what he sees on other Jovian and Saturnian satellites. How does this tie in with the constant brightness and color data for Titan presented in Table 2-2.

Veverka: I think that the contrast of the changes has been exaggerated. From Lyot's or Dollfus' drawings of Titan, you might expect brightness fluctuations of many percent, whereas, in fact, to about 1% you don't see anything.

Sagan: One other conclusion from the constancy of the brightness of Titan, which I think is important, is that it sets some limit on the existence of breaks in the clouds, if you believe there are clouds. The question of breaks in the clouds is, of course, a critical question for imaging observations of Titan.

Veverka: You probably don't have any very large breaks, but you can have a lot of little ones ....

Sagan: ....which when time averaged always represent the same fraction?

Veverka: Yes.

Danielson: With regard to model interpretations of the phase coefficient variation presented in Figure 2-16, would the observed coefficients be consistent with a snow-covered surface?

Veverka: It is difficult to explain the low values of the phase coefficient beyond 0.6 μm in this way, unless the surface has a normal reflectance of about 0.6 at these wavelengths. Also the snow would have to change its reflectance rapidly with wavelength, being considerably darker at shorter wavelengths. Even then it would be difficult to understand the absence of a negative branch in the polarization measurements at 0.5 μm, since the geometric albedo there is only about 0.21.

Morrison: Younkin's value of 0.27 for the radiometric Bond albedo is substantially larger than the value normally used in the past. Is there some obvious reason why the old values are wrong?

Veverka: One reason is that according to Younkin the geometric albedo of Titan in the near infrared is higher than formerly believed. Also, unrealistic values of the phase integrals have been assumed in the past.

Trafton: We have made independent measurements of the geometric albedo of Titan in the red and our values agree with those of Younkin.

Hunten: You quoted a value of 1.3 for the effective phase integral used by Younkin in his computation of bolometric Bond albedo. Where does this value come from?

Veverka: It is the value that people tend to use for the outer planets and is a reasonable value for a cloud-covered planet. Of course, we don't know what the actual value is.

Morrison: I also have a question about Figure 2-17. If you allow for the fact that the two curves are normalized together and remove all the gaseous absorption in the atmosphere, would you be left with much of an argument that the two curves are similar, except that they're both red?

Veverka: McCord et al. say specifically that what they attach great importance to is the fact that, outside the methane bands, the spectra are similar.

Morrison: Io is red also, yet there is no reason to think the surface of Io is similar to that of Saturn, although perhaps it is.

Veverka: If you remove all the methane bands, all you are saying is Titan is as red as the equatorial belt of Saturn, and so is Io and so are the rings. That's probably a valid argument. The strong absorber of UV light may be the same in all cases. It may occur in the cloud particles on Titan and Saturn, and in the surface layer on Io and the ring particles.

Sagan: Your polarization measurements of Titan in white light show no evidence of a negative branch at small phase angles. Yet Zellner's ultraviolet data do, at least marginally, indicate the presence of a negative branch. Can you explain this difference?

Veverka: That is a perplexing point. If you are saying that the reason you see some negative polarization at 0.36 μm is because you are looking at a surface, you would expect to see more of the surface at 0.8 μm than at 0.36 μm. I think if there is a negative branch at 0.36 μm, it is telling you something about the clouds.

Danielson: What does dust in the atmosphere do? What kind of polarization does that cause?

Veverka: I don't know the answer to that question. It is very hard for me to guess. All I can say definitely is that a pure Rayleigh atmosphere won't do. You need some large scatterers. But what the properties of the scatterers should be, I can only guess. Judging from Coffeen and Hansen's analysis of Lyot's Saturn measurements, which are similar to the Titan data you could explain the Titan observations with a cloud of spherical particles with indices of refraction between 1.3 and 1.5 (at 0.55 μm) and mean particle sizes of the order of two to three microns.

Morrison: Although the spectral reflectance curves of Titan and Saturn are very similar there are differences in the absolute values of the albedos.

Veverka: Yes, and it is important to establish accurately what these differences are. It is hard to measure the geometric albedo of Saturn minus its Rings.

Caldwell: Such differences could be due to differences in the clouds or possibly in the amounts of atmosphere above the clouds. How hard is it to make an ultraviolet polarization observation of Titan? The signal must be very low.

Veverka: Zellner is presently measuring red polarization values to something like plus or minus 0.05%, whereas the ultraviolet values are hard to measure to better than 0.1%.

Postscript, December 4, 1973: Hunten's suggestion (p. 5) that the surface of Titan is being continuously paved by photochemical 'asphalt' falling out of the atmosphere, provides the best means of reconciling the photometric and polarimetric observations with an optically thin Titan atmosphere. This photochemical 'asphalt' would be produced copiously by the action of ultraviolet light on the hydrogen-methane atmosphere in the manner discussed by Strobel, and can probably be identified with the reddish material responsible for the coloration of Titan.

If the production of such substance is efficient and planetwide the surface of Titan may well be covered with a fairly thick, smooth and uniform layer of this material. Then there would be no albedo markings on Titan, which would explain why Titan shows no brightness fluctuations as it revolves about Saturn. Second, this type of surface could be quite smooth optically, making the absence of a negative branch in the polarization curve understandable. Finally, it is likely that such a surface could match the phase coefficients observed for Titan.

Thus Hunten's suggestion makes it possible to have an optically thin atmosphere, but only at the expense of having the surface continually paved by photochemical 'asphalt'. Note that this requires a modification of Danielson's model, because now the reddish aerosol must not only occur in the atmosphere, as postulated by Danielson, but must also copiously cover the surface.