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FINAL TECHNICAL REPORT

INFRARED SPECTROSCOPY OF JUPITER AND SATURN

NAGW #2796

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Strategy

Infrared spectroscopy provides unique insights into the chemistry and dynamics of the atmospheres of Jupiter and Saturn -- and of Titan, the enigmatic satellite of Saturn. The 5 micron spectral region of these objects is transparent to deep levels, and is therefore particularly useful for the identification of molecules in the deep atmosphere at very low (parts per billion) concentrations. In Titan, 5 micron observations probe atmospheric layers at or near the surface. The observations support and complement VOYAGER and CASSINI measurements. Ground-based spectroscopy is sensitive to lower mixing ratios for selected molecules, while the spacecraft mass and infrared spectrometers probe molecules that are inaccessible from the ground. The ground-based observations also provide time-based data for preparation for the CASSINI mission.

Accomplishments

In 1991 we obtained data at J, H, K, and M and made repeated observations of Titan's albedo as the satellite orbited Saturn. The J albedo is 12+-3% greater than the albedo measured in 1979; the H and K albedos are the same. There was no evidence for variations at any wavelength over the eastern half of Titan's orbit. We also obtained low resolution (R = 50) spectra of Titan between 3.1 and 5.1 microns. The spectra contain evidence for CO and CH_3D absorptions. Spectra of Callisto and Ganymede in the 4.5 micron spectral region are featureless and give albedos of 0.08 and 0.04 respectively. If Titan's atmosphere is transparent near 5 microns, its surface albedo there is similar to Callisto's. These results were summarized in two papers by Noll and Knacke (1992, 1993; Appendix).

In 1992 and 1993 we obtained further spectroscopic data of Titan with the UKIRT CGS4 spectrometer. We discovered two unexpected and unexplained spectral features in the 3-4 micron spectrum of Titan. An apparent emission feature near the 3 micron (nu_3) band of methane indicates temperatures higher than known to be present in Titan's upper stratosphere and may be caused by unexpected non-LTE emission. An absorption feature near 3.47 microns may be caused by absorption in solid grains or aerosol's in Titan's clouds. The feature is similar, but not identical to organics in the interstellar matter and in comets.

Anticipated Work Beyond the Termination of the Grant

We are currently preparing the latest Titan results for publication. The new results will be followed up with further observations at the UKIRT and the IRTF telescopes. During the course of the present grant we also prepared a plan for new observation of CO and other rare constituents in Jupiter and Saturn. The work will initially consist of spatially resolved observations of the disk of Jupiter with the IRTF's CSHELL spectrometer. We expect to get spectra of at least 50 regions across Jupiter's disk. This unparalled spatial (and frequency) resolution should allow us to make significant progress in understanding the origins of trace

compounds and their chemistry in Jupiter. If the Jovian observations are successful, we plan to follow with observations of Saturn.

At the time that this observing program was defined, we learned of the impending Shoemaker - Levy comet impact on Jupiter. We will participate in the campaign to observe this event, concentrating on spectroscopy of Jupiter before, during and after the collisions.

These planned observations are funded under a separate grant through NASA's Solar System Exploration Division, Office of Space Science and applications.

Inventions

There were no inventions completed under this grant.

Publications

A   Noll, K.S. and Knacke, R.F., 1992, "Titans Mid-IR Albedo: New Observations from 3 to 5 microns," in Proceedings Symposium on Titan, ESA SP-338.

A   --- 1993, "Titan: 1-5 micron Photometry and Spectrophotometry and a Search for Variability," Icarus, 101, 272.

TITAN'S MID-IR ALBEDO:
NEW OBSERVATIONS FROM 3 TO 5 MICRONS

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ABSTRACT

New photometric and spectrophotometric observations of Titan in the wavelength interval from 3 to 5 μm were made in June 1990 and June 1991. The broad band flux measured at 4.8 μm in both years and on two different telescopes is more than a factor of three lower than measurements made by two independent groups in 1971 and 1973. No other measurements were made in the 17 intervening years. We conclude that either the original measurements were contaminated by long wavelength leaks or that Titan's albedo at 4.8 μm has decreased. The low resolution spectrum we obtained near 4.8 μm is crudely consistent with the presence of CO at 60 ppm in the lower troposphere and a reflecting layer located between 100 mbar and the surface at 1500 mbar. The spectrum from 3.1 to 4.0 μm is relatively featureless at low spectral resolution but has some hints of structure that may yield information at higher resolution and signal to noise.

Keywords: Titan, infrared photometry, infrared spectroscopy, planetary atmospheres.

1. OBSERVATIONS AND ANALYSIS

1.1 *Background.* Relatively little work in the infrared has been completed since the *Voyager* encounters. Notable are the detection of CO and the determination of the CH_3D abundance (Lutz *et al.* 1983, Marten *et al.* 1988, de Bergh *et al.* 1988). The middle infrared part of the spectrum between 3 and 5 μm was last observed from the ground in 1971 and 1973 (Low and Rieke 1974, Knacke *et al.* 1975); it was not observable at all at these wavelengths with the *Voyager* spacecraft. In this report we describe a new set of observations from 3 to 5 μm including both photometric observations with standard filters and spectrophotometry carried out with a continuously variable filter (CVF). Because mid-infrared wavelengths are likely to penetrate the clouds and hazes, this spectral region may yield information related to Titan's unseen surface.

1.2 *Photometry.* In June 1990 we attempted to obtain a spectrum of Titan near 4.8 μm with the cooled-grating array spectrometer (CGAS) at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea. To our surprise, Titan was much fainter than we had expected based on photometric measurements made in 1971-3 (Low and Rieke 1974, Knacke *et al.* 1975). Unable to detect Titan with CGAS we measured the infrared flux with the RC2 photometer using both the standard broad band M filter (4.40 - 4.96 μm) and a continuously variable filter (CVF) on the nights of 7 and 8 June 1990 (UT).

In order to obtain an independent confirmation of our results we requested service observing time on the United Kingdom Infrared Telescope (UKIRT). T. Geballe observed Titan with the UKIRT UKT9 photometer on 29 August 1990 using the broad band M filter.

For all nights the primary standard star was ν^2 Sgr. It is bright enough at 4.8 μm to allow accurate peaking and was less than 1 hour West and 2° South of Titan on 7-8 June. Orton and Kaminski (1989) found an M filter flux of 23.96 Jy (2.08 mag) for ν^2 Sgr in good agreement with earlier measurements (Tokunaga 1986). We adopted Orton and Kaminski's value for all fluxes reported in this work.

We repeated and extended these observations on 20-26 June 1991 using RC2 at the IRTF to obtain standard filter measurements from J (1.25 μm) through M (4.8 μm) as well as expanded CVF observations. We again used ν^2 Sgr as a standard at 4.8 μm and extended our network of standards to include several other measured stars. In addition we used the A3 star FK4 1548 as a nearby standard to avoid the sometimes serious problems associated with pointing.

At wavelengths beyond 3 μm we were careful to adopt observing procedures designed to minimize problems from RC2's degraded beam profile. This is apparently caused by the inability of the sapphire field lens in RC2 to focus 3-5 μm radiation on the detector (Orton and Kaminski 1989). Likewise problematic is the procedure of peaking at shorter wavelengths, for example with the K filter (2.2 μm), and then switching back to M. The imaging deteriorates in such a way as to cause the position of the peak at longer wavelengths to be shifted relative to the center of the shorter wavelength beam. Therefore, it was important to peak on a bright source or standard that was close to Titan in right ascension and declination for independently for each filter. The good internal agreement we acheived, particulary during the 1991 observations, indicates that we able to overcome the limitations of RC2.

Table 1: 4.8 μm Photometry Results

Date	λ-$\Delta\lambda$ (μm)	F_ν (mJy)	T_b (K)	albedo
Titan				
Jan 71[2]	5.0 - 1.0	110± 20	165	0.064
8 Dec 73[1]	4.9 - 0.8	128± 24	168	0.066
7-8 Jun 90	4.8 - 0.6	29± 6	160	0.023
29 Aug 90	4.8 - 0.6	31± 5	161	0.026
20-6 Jun 91	4.8 - 0.6	24± 2	158	0.019

[1] Knacke *et al.* 1975, observing date from unpublished logs
[2] Low and Rieke 1974, observing date not given, assumed R = 9.4 AU, Δ = 8.4 AU

Titan's fluxes at 4.8 μm as measured by us in 1990 and 1991, along with the earlier work of Low and Rieke (1974) and Knacke *et al.* (1975) are listed in Table 1. The large difference between the new and old data naturally raises the question of how accurate the earlier observations might have been. Unfortunately the difficulty of making such an evaluation so long after the observations took place is formidable. One could take the excellent agreement found by two independent groups working

with separate instruments at different facilities as evidence of accuracy. However, there are potential problems that must be considered.

Low and Rieke made their observations on Mt. Lemmon with the NASA 61 inch telescope and a bolometer system. Knacke *et al.* used the Kitt Peak National Observatory 1.3 and 2.1 m telescopes with the facility infrared photometer, which was also a bolometer, and a set of custom filters. Bolometer systems are known to be susceptible to filter leaks, i.e. non-zero transmission, at long wavelengths. Because Titan's flux density rises rapidly at longer wavelengths this is a particularly troublesome possibility. F_λ is 20 to 40 times higher at 10 μm than at 5 μm as measured by Low and Rieke (1974). A leak as small a 1% in their M filter over a 1 μm bandwidth near 10 μm could then account for as much as 40% of their measured flux. However, the problem of long wavelength leaks would certainly have been familiar to these investigators and it is possible that the bolometer would have been used with a monochromator to check for possible leaks.

Rieke (1991, *private communication*) believes that such a leak could not be ruled out at this point. Joyce (1991, *private communication*) has measured a filter that he believes to be the one used in the 1973 observations he made with Knacke *et al.* and has found what appears to be a small, 0.5-1% leak near 20 μm. It is impossible to know if the filter has retained its physical integrity over the 18 years since it was used to measure Titan, but it seems possible that the Knacke *et al.* results have also been contaminated. There is no record of whether a barium fluoride blocking filter, which has a cutoff at 14 μm, was used. In what might be a perverse coincidence it appears that if leaks are responsible for the difference from 1971-3 to 1990-1 they were very nearly identical in the amount of long wavelength radiation they allowed to leak through.

It should be noted here that the current observations were made with an InSb detector system which is not sensitive to radiation beyond 5.4 μm. Therefore the issue of long wavelength leaks is moot for our new measurements.

An additional complication exists when attempting to compare current results to the older data. The early measurements were made with filters having effective wavelengths and bandpasses that did not exactly coincide with the IRTF M-band filter (Table 1). The large uncertainty in the spectrophotometry described in the next section precludes a definitive assessment, but estimates indicate that as much as 25% of the difference between the 1971-3 and 1990-1 results might be due to differences in filter properties.

Despite the above caveats, the possibility of a change in Titan itself cannot be ruled out. Such a change would not be the first, as we discuss below, and therefore deserves some attention.

One final issue that must be resolved is the physical source of the radiation we have detected. The raw fluxes have been reduced to both geometric albedo and brightness temperature in Table 1. A Titan radius of 2575 km was used for all tabulated values (Hunten *et al.* 1984). Geometric albedo is the appropriate quantity if the observed flux is reflected solar radiation. As discussed below we believe that this *is* the source of Titan's 5 μm flux. We also list brightness temperature for comparison, but for reasons discussed below, we do not think the observed radiation is thermal emission from an optically thick atmosphere or cloud layer.

1.3 *Variability at Visible and Near-IR Wavelengths.* Variability in Titan is not unprecedented. Titan's visible flux changes slowly with an amplitude of about 10%, and the changes appear to be roughly correlated with a seasonal cycle (Lockwood and Thompson 1979, Lockwood *et al.* 1986, Sromovsky *et al.* 1981). Such a model requires that the hemispheric asymmetry in cloud albedo observed by *Voyager*, (Northern hemisphere about 80% of Southern, Sromovsky *et al.* 1981) vary in step, although not necessarily in phase, with the seasonal cycle. Recently, Caldwell *et al.* (1991, private communication) obtained images of Titan with the Hubble Space Telescope that show evidence of a reversal of the hemispheric albedo asymmetry (Southern hemisphere darker) compared to the situation encountered by Voyager 1 in November 1980 (Sromovsky *et al.* 1981). This behavior agrees qualitatively with predictions based on a seasonal model.

A possible near infrared variability with a period of approximately 32 days has also been observed (Cruikshank and Morgan 1980). The

variability at K (2.2 μm) was as much as 60% . Unfortunately, no information is available on possible long term trends in the near-IR An interesting direction for future work will be to determine if variability at 2.2 μm persists and if it is correlated with observable changes at 4.8 μm.

1.4 *Spectrophotometry.* Low resolution (R=50) spectra of Titan in the 3-5 μm window were obtained with the IRTF CVF. The spectrum was sampled at 0.1 μm intervals, about equal to the FWHM of the CVF instrument profile. Incomplete sampling was necessary because of the weak Titan flux and consequent long integration times. From 3.3 to 4.0 μm we interleaved observations from two nights to create an effectively fully sampled spectrum. Signal levels were converted to fluxes using calibrations from Orton and Kaminski (1989). Combined data from 23, 24, and 26 June 1991 are plotted in Figure 1. There is good agreement between the points measured in 1991 and the shorter scan from 4.63-5.13 μm obtained in June 1990.
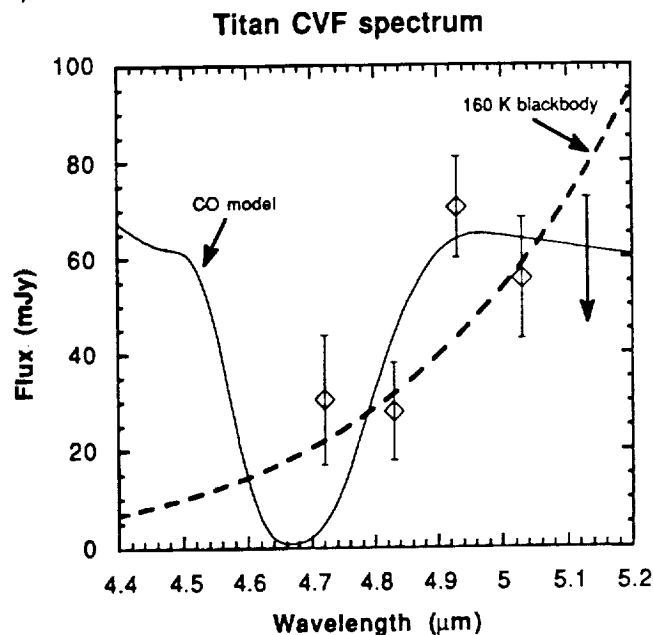
Titan CVF spectrum

Figure 1.
Combined CVF observations of Titan from 23, 24, and 26 June 1991.

In Figure 2 we show the spectrophotometric points obtained in 1990 along with two candidate models. The two models are examples of the two physical mechanisms that are potentially responsible for the 4.8 μm radiation, namely reflected sunlight or thermal emission. It is not possible to discriminate between the two on the basis of the models alone.

A strong argument against thermal emission from an optically thick layer can be raised on theoretical grounds. The pressure of the lowest level in Titan's stratosphere where the temperature is 160 K or greater is less than 5 mbar (Lellouch *et al.* 1989). It is unlikely that the hazes present at these low pressures could be optically thick at 4.8 μm. Indeed, even visible radiation is expected to penetrate to at least P ~ 100 mbar, T ~ 71 K, where a methane condensation cloud may exist, and some fraction of the visible flux may reach the surface (McKay *et al.* 1989). If the haze particles are organic solids resembling the "tholens" measured by Khare *et al.* (1984) with average particle sizes less than 1 μm, infrared radiation near 5 μm will penetrate much deeper, possibly down to Titan's surface.

The 'CO' model was computed with a multi-layer radiative transfer program that included opacity from the gases CO and CH_3D. CO is known to be present in Titan's atmosphere although the altitude distribution is uncertain (Lutz *et al.* 1983). In the model, the CO mole fraction ($qCO \equiv P_{CO} / P_{total}$) was fixed so that $qCO = 6 \times 10^{-5}$ for layers with P $\geq$ 54.5 mbar and $qCO = 2 \times 10^{-6}$ for layers at P $\leq$ 34.9 mbar. This distribution qualitatively agrees with both the infrared and

the microwave measurements of CO (Lutz *et al.* 1983, Marten *et al.* 1988). CO line parameters were taken from the GEISA compilation (Chedin *et al.* 1986). CH_3D is present in Titan with a mole fraction $qCH_3D = 1.1 \times 10^{-5}$ (de Bergh *et al.* 1988). Line strengths and positions for the ν_2 band were adopted from Chackerian and Guelachvili (1983) and lower state energy levels were computed from formulae for symmetric top molecules (Herzberg 1945).
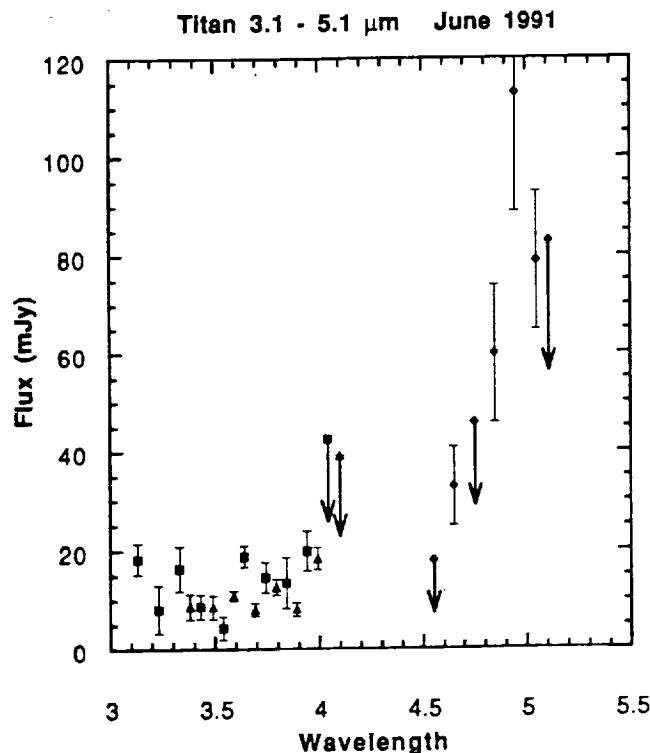
Titan 3.1 - 5.1 μm   June 1991

Figure 2.
Comparison of CVF observations from 7 and 8 June 1990 with two representative models. The curve labelled 'blackbody' represents emission from a 160 K blackbody of radius 2575 km at Titan's distance from the Earth. The 'CO' model is a simple reflecting layer model including absorption from CO and CH_3D and a reflecting layer with a normal relfectivity of 0.055 at 100 mbar.

The model intensity was computed every 0.1 cm^{-1} and was convolved with a triangular function with a FWHM equal to the instrumental resolution. The calculations show that CO dominates the absorptions at 4.67 μm while CH_3D plays only a minor role in this part of the infrared spectrum of Titan. A simple reflecting layer model was used to get an approximate idea of the depth to which the radiation penetrates. The model shown has a reflecting layer with a normal reflectivity of 0.055 located at 100 mbar. Locating the reflecting layer at pressures much less than 100 mbar results in a mismatch to the depth of the apparent CO absorption band at 4.67 μm in the spectrum. However, penetration to greater depths cannot be ruled out with the present data. Because the band becomes saturated, the absorption feature at low resolution broadens relatively slowly. At 4.9-5.1 μm the opacity is from line wings and the optical depth remains less than one even when the reflecting layer is placed at the surface pressure of 1500 mbar.

More realistic models that account for scattering will eventually be required to define the depth to which the radiation reaches. Detailed models at shorter infrared wavelengths suggest that a significant fraction of the reflected light at 2.04 μm is reflected from the surface (Griffith *et al.* 1991). As mentioned above, optical depth due to organic haze particles is expected to be even lower at 4.8 μm than in the visible or at 2 μm. Because absorption cross-sections for small particles scale as $1/\lambda$ we can expect an even greater proportion of 4.8 μm radiation reaches the surface. In that case, the geometric albedo we derive is, at least in part, a property of Titan's surface. Should future work confirm this, a means of directly studying the surface of Titan would be open.

2. DISCUSSION

The possibility of probing Titan's surface through a new spectral window is tantalizing. Titan's albedo as measured with the CVF ranges from 0.02 to 0.09, uncorrected for the unknown effects of gaseous absorption. This can be compared with the albedos of other icy bodies such as Ganymede and Callisto which were also measured by us in 1991. Their albedos at 4.8 μm were determined to be approximately 0.03 and 0.08 respectively. Superficially, the rough agreement between Titan and the Galilean satellites leaves open the possibility that these bodies may have similar surfaces as has already been suggested by Griffith *et al.* (1991). However, it would be prudent to suspend any judgement until a full analysis of 5 μm models has been completed.

The possibility of real variation in Titan's 4.8 μm albedo should not be ruled out either and speculation about what might drive changes on Titan may be a useful exercise. Possible physical drivers of periodic change include seasonal changes (14.8 yr), solar cycle (11 yr), changes related to permanent surface or near-surface properties (29.5 yr), and the periodic change in solar flux from Titan/Saturn's orbital eccentricity (29.5 yr). It is also possible that change could be initiated by a random, non-periodic event. Of these, a seasonal effect seems to be ruled out because Titan was at nearly the same seasonal phase, near solstice, in both sets of observations.

An atmospheric change forced by the sun's 11 year cycle would fit the observations if albedo were anticorrelated with solar UV output (as indicated by solar flux at 2800 MHz). Observed solar 2800 MHz flux at Earth in the last 6 months of 1973 averaged 877 kJy while for the first 6 months of 1990 the average was 1856 kJy, more than twice as high (National Research Council Canada 1991). UV is known to initiate CH_4-N_2 based chemistry in the atmosphere that result in the formation of hydrocarbon and nitrile polymers that might make up Titan's aerosols (Hunten *et al.* 1984). However, one would expect that any atmospheric changes induced by UV (such as enhanced production of hazes) would also have a strong signal in the visible. In fact, the observations made by Lockwood *et al.* (1986) from 1972 through 1984 do not show a correlation between visible albedo and solar activity.

Changes synchronous with the Titan/Saturn's 29.5 year orbital period could explain the observations. For example, it is possible that the production of reflective hazes responds to the 20% variation in solar energy caused by the eccentricity of Saturn's orbit (Fig. 2). Again, one would expect to see this response in the visible albedo as well. Instead, the visible albedo varies with a 12-13 year period not in agreement with our observations.

Instrinsic differences between Titan's Northern and Southern hemispheres might account for the change in flux and would vary with a period equal to Titan/Saturn's 29.5 year orbit. Between the two observations, Titan went from Southern Hemisphere summer (1971-3) to Northern Hemisphere summer (1990). If deposits of absorbing organic material were greater in one hemisphere than the other, perhaps similar to the apparent current state of Neptune's large satellite, Triton (Smith *et al.* 1989), one might observe a regular variation in Titan's infrared albedo. Polar deposits might occur because temperatures at the poles near the surface were estimated to be 3 K colder than at the equator as determined from *Voyager* measurements of 530 cm^{-1} radiation (Flasar *et al.* 1981). If Titan's surface is covered by a global ethane ocean, then polar winter build-ups of N_2 and CH_4-rich surface layers (Stevenson and Potter 1986) may be more pronounced in one hemisphere.

Yet another possibility is that the postulated liquid ethane oceans or lakes may not be global, but may be more widespread in one hemisphere than another. Initial Earth-based radar studies are inconsistent with an ethane ocean covering the entire Titan surface (Muelhmann *et al.* 1990). Indeed the variation by about a factor of three in the radar cross-sections on three different nights appear to favor a real variation in surface properties, although Muhleman *et al.* caution that more observations are required. If we are seeing Titan's surface at 4.8 μm it would be useful to search for a correlation between IR and microwave observations.

Finally, we cannot rule out some kind of dramatic surface event, such as an eruption, that could alter the infrared reflectivity of the at-

mosphere. Currently the source of atmospheric gases N_2 and CO are unknown. The clathrate hydrate model allows for scenarios where gases in a warm interior are constantly evolved and released at the surface (Morrison et al. 1986). Some of this material could be released intermittently in large events. The smooth variation of visible albedo over many years would seem to make this unlikely, but, unlike the visible, the infrared may be sampling well below the tropopause where surface-mediated changes of the atmosphere would be the strongest.

Progress on the issues raised by these observations and their possible explanations can be made by further ground-based observations and eventually - and more definitively - by the Cassini Huygens probe. We plan to continue ground-based infrared photometric and spectroscopic observations.

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Titan: 1–5 μm Photometry and Spectrophotometry and a Search for Variability

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We report photometric and spectroscopic observations of Titan made between 1 and 5 μm in 1990 and 1991. The 4.8-μm albedo we measured is more than a factor of three lower than those found in observations in the early 1970s. Long wavelength filter leaks could have contaminated earlier measurements of Titan's 4.8-μm albedo, although we cannot rule out a change in Titan itself. Titan's 1.25-μm albedo that we measured in 1991 is 14 ± 3% greater than that measured in 1979; the 1.65- and 2.20-μm albedos are the same. There was no evidence for variations with orbital phase at any wavelength over the eastern half of Titan's orbit in 1990 and 1991. We also made new measurements of Uranus and Neptune at 4.8 μm that agree with previous observations.

We acquired low-resolution ($R = 50$) spectra of Titan between 3.1 and 5.1 μm. The spectra contain evidence for CO and CH_3D absorptions. The measured band depths require a reflecting layer located in the troposphere (near 200 mbar) or below. Spectra of Callisto's, Ganymede's and Europa's leading hemispheres in the 4.5–5.1 μm spectral region are featureless and have albedos of 0.094 ± 0.004, 0.044 ± 0.006, and 0.020 ± 0.002, respectively. If Titan's atmosphere is transparent near 5.0 μm, its surface albedo there is similar to Callisto's.   © 1993 Academic Press, Inc.

The cloud-covered surface of Titan is one of the last unexplored places in the Solar System. Little is known about its topography, chemical composition, or even its physical state. The only avenue open so far has been indirect inference based on the observed molecular composition of the atmosphere. The *Voyager* spacecraft and groundbased observations have identified nitrogen, a rich variety of hydrocarbons, nitriles, CO, and CO_2, many of which are predicted to condense and ultimately end up on the surface (cf. Morrison *et al.* 1986). Although the topic has received much attention, the existence and extent of liquids on the surface remain speculative subjects (Lunine *et al.* 1983, Lellouch *et al.* 1989).

Recently, Griffith *et al.* (1991) have suggested that small spectral windows of low opacity in the midinfrared range might allow a direct determination of the surface albedo which in turn would provide information on the physical and chemical state of the surface material. Taking this approach one step further, an observed change in IR albedo in a band containing one or more of these windows might signify some change in Titan's surface or near-surface atmosphere.

One final handle on the nature of Titan's surface is spectroscopic measurement extended to intervals containing bands of molecules that may interact with Titan's surface. The rarely observed spectral interval from 3 to 5 μm could provide an independent measurement of the tropospheric CO abundance. Atmospheric CO might reflect the composition of Titan's near-surface ices.

Relatively little work in the infrared has been completed since the *Voyager* encounters. Notable spectroscopic advances are the detection of CO and the determination of the CH_3D abundance (Lutz *et al.* 1983, Marten *et al.* 1988, de Bergh *et al.* 1988). The middle infrared part of the spectrum between 3 and 5 μm was last observed from the ground in 1973–1974 (Low and Rieke 1974, Knacke *et al.* 1975); Titan was not observable at all at these wavelengths with the *Voyager* spacecraft. Cruikshank and Morgan (1980) completed the most recent photometry known to us at *J*, *H*, and *K* (1.25, 1.65, and 2.20 μm) in 1979.

In this paper, we report the first photometric measure-

[1] Visiting astronomer, Infrared Telescope Facility, operated by the University of Hawaii under contract from NASA.

TABLE I
Titan 4.8-μm Photometry

object/date (UT)	λ (μm)[1]	F_ν (mJy)	albedo ×10³
Titan			
8 Dec 73[2]	4.9	128± 24	70± 13
< Mar 74[3]	5.0	110± 20	74± 14
7 Jun 90	4.8	26.4± 3.0	22.5± 2.6
8 Jun 90	"	26.4± 3.6	22.4± 3.1
29 Aug 90	"	31.5± 4.3	27.2± 3.7
20 Jun 91	"	22.0± 10.3	18.3± 8.3
22 Jun 91	"	20.7± 6.0	17.2± 5.0
23 Jun 91	"	17.7± 2.4	14.6± 2.0
24 Jun 91	"	26.8± 5.7	22.1± 4.7
26 Jun 91	"	27.5± 3.6	22.6± 3.0
23 Aug 91	"	33.4± 5.8	27.2± 4.7

[1] The 4.8 μm IRTF filter is described by Tokunaga (1986).
[2] Knacke et al. (1975), observing date from unpublished logs.
[3] Low and Rieke (1974), observing date not given,
   assumed R = 9.4 AU, Δ = 8.4 AU.

ments of Titan in the mid-IR free of possible contamination from long-wavelength filter leaks. We show a low-resolution spectrum covering the last unobserved gap in Titan's near-IR spectrum from 3.1 to 5.1 μm, and we report a series of photometric measurements that we hope will lay the foundation for long-term searches for variations in the albedos.

Secondary results of this investigation include low-resolution spectra of Ganymede, Callisto, and Europa, marginal detections of Neptune at 4.8 μm on two of five nights, and two 4.8-μm observations of Uranus.

PHOTOMETRY

M band observations of Titan. In June 1990 we attempted to obtain a spectrum of Titan near 4.8 μm with the cooled-grating array spectrometer (CGAS) at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea. To our surprise, Titan was much fainter than we had expected based on photometric measurements made in 1973–1974 (Low and Rieke 1974, Knacke et al. 1975). Unable to detect Titan with CGAS, we measured the infrared flux with the RC2 photometer with the IRTF *M* filter (λ_{eff} = 4.80 μm) and a continuously variable filter (CVF) on the nights of 7 and 8 June 1990 (UT). To confirm our results, T. Geballe observed Titan with the United Kingdom Infrared Telescope (UKIRT) UKT9 photometer on 29 August 1990 using the UKIRT *M* filter. The average *M* band flux from all three nights was 27.6 ± 2.0 mJy (Table I).

The primary standard star was ν^2 Sgr for all 1990 observations. It is bright enough at 4.8 μm to allow accurate peaking and was less than 1 hr west and 2° south of Titan on 7–8 June. We have adopted the Orton and Kaminiski

(1989) *M* filter flux of 23.96 Jy (2.08 mag) for ν^2 Sgr which is 0.06 magnitudes fainter than the IRTF photometry manual value (Tokunaga 1986).

HD161903 is an A star on the IRTF Photometry Manual's Faint Standard Stars list (Elias et al. 1982, Tokunaga 1986) that we used as a secondary faint standard. Based on the *J–L* colors compiled by Tokunaga, we estimate the *M* filter flux of HD 161903 to be 0.263 ± 0.007 Jy (6.98 ± 0.03 mags). The measured values were 0.21 ± 0.01 on 7 June and 0.28 ± 0.01 on 29 August. We attribute the lower value obtained on 7 June to probable pointing errors caused by the inability to peak up on this star and the poor beam profile we were able to obtain with RC2. We find good internal agreement in the data obtained with UKT9 at UKIRT on 29 August. UKT9 uses ZnSe lenses rather than sapphire (Al_2O_3) and does not suffer from the known defocusing problems of RC2.

We repeated the observations at *M* on 20, 22, 23, 24, and 26 June and 23 August 1991, again using the IRTF. The 5-night average of the June observations was 22.9 ± 1.9 mJy, in marginal agreement with the 1990 data. The 23 August measurement is the least reliable because the high airmass and large separation of the standard star from Titan on that night exacerbate the known systematic problems of differential refraction and camera misalignment when the telescope is pointed far from the zenith.

For the 1991 observations we used the star BS 8018 as the primary standard for Titan. Since BS 8018 is not an IRTF standard star, we measured several other standards to determine the spectrum of BS 8018. At *J* through *L'* we used GL 811, HD 161903, and GL 748 from the IRTF standard star list and the solar analog star HD 159222 (Campins et al. 1985). At *M* we used ν^2 Sgr, α Leo, σ Cyg, HD 161903, and HD 159222. Derived BS 8018 fluxes are listed in Table II.

For most observations we observed the standard star, the source, and then the standard star again. We were careful to peak up in each filter. For the *M* band observations, both the target and the standard were too faint for peak up, so we centered first on a late-type star near to Titan and the standard. We repeaked periodically during long integrations.

TABLE II
BS 8018 Flux

Filter	λ (μm)	Flux (mags)	F_ν (mJy)
J	1.25	5.519± 0.018	9920± 164
H	1.65	5.513± 0.021	6359± 123
K	2.20	5.495± 0.026	4165± 100
L	3.50	5.482± 0.014	1860± 24
L'	3.80	5.484± 0.034	1614± 51
M	4.80	5.498± 0.030	1030± 29

The photometric data from both years are summarized in Table I. In Table I we also include the photometric measurements of 1973–1974 reported by Low and Rieke (1974) and by Knacke *et al.* (1975) recalculated to a common Titan radius (r_T) of 2575 km. Geometric albedos, $g = F/S_0 (R_T/R_E)^2 (\Delta_T/r_T)^2$, were calculated using the solar flux (S_0) from Labs and Neckel (1968) with the distance of Titan from the Sun (R_T) and the Earth (Δ_T) for the date of observation. We did not correct for the small phase angle $(\leq 4.2°)$ in our calculation.

All other observations used standard nodding and chopping techniques. Errors for individual integrations are computed from the standard deviation in millivolts/second recorded for each A–B pair. Typically, we recorded 10 to 20 A–B pairs per integration. The coadded integrations of a single night were the unweighted means of the individual integrations taken during the night. An unweighted mean is appropriate when the signal to noise ratio in individual scans is low to prevent the heavy weighting that might be placed on integrations with accidentally low errors. Means of observations obtained on separate nights were weighted by the errors $(1/\sigma^2)$. Whenever weighted or unweighted means were computed, the error of the result was the larger of the calculated error of the mean $(\sqrt{1/\Sigma\ 1/\sigma^2})$ or the standard deviation (σ_{N-1}) of the coadded points. In the majority of the cases we found the former to be larger, indicating that our estimates of the errors are adequate. Standard error propagation was used for all calculations.

Has Titan's 4.8-μm flux varied between 1973–1974 and 1990–1991? The great discrepancies at 4.8 μm evident in Table I naturally raise the question of how accurate the earlier observations of Low and Rieke (1974) and Knacke *et al.* (1975) were. Unfortunately making such an evaluation so long after the observations took place is very difficult. The best indication of accuracy would normally be that two independent groups with separate instruments at different facilities obtained concordant results. Low and Rieke made their observations on Mt. Lemmon with the NASA 61-in. telescope and their own spectrometer. Knacke *et al.* used the Kitt Peak National Observatory 1.3- and 2.1-m telescopes with the facility infrared photometer and a set of custom filters.

The IRTF and UKIRT *M* band filters are identical [see the IRTF photometry manual (Tokunaga 1986) for a detailed description of the filters], but do not exactly coincide with the filters used by Knacke *et al.* and Low and Rieke. Using the near-infrared filter transmission curve for the filter used by Knacke *et al.*, an atmospheric transmission function and filter transmission curves from the IRTF photometry manual, and the spectrum of Titan discussed below, we estimate that the Knacke *et al.* filter recorded a flux as much as 1.18 times higher than the IRTF *M* filter. Sensitivity tests with model spectra indicate that

this factor is very sensitive to the actual flux in the most poorly measured portion of the spectrum from 4.55 to 4.85 μm. The most extreme model we tested, reflection from the surface with no scattering from higher levels, differed by a factor of 2.5. However, the spectrophotometry that we discuss later indicates that there must be some scattering (albeit with large uncertainties) even at wavelengths where the flux is lowest and even this small amount of flux is sufficient to bring the ratio down to 1.2 or less. We conclude that it is unlikely that the differences in the filters can account for the factor of four discrepancy in fluxes measured in 1973–1974 and 1990–1991.

The most worrisome problem for a cool object like Titan, when observed with a bolometer, is the possibility of long wavelength leaks. The Titan fluxes at 10 and 20 μm are at least 40–400 times greater than that at 5 μm (Low and Rieke 1974), so a leak as small as a fraction of 1% could contribute substantially. Our measurements in 1990 and 1991 were made with an InSb detector which is insensitive to photons with wavelengths longer than 5.4 μm, so the problem of filter leaks does not affect our new data. Unfortunately, this is not true for the older observations.

Knacke *et al.* used a gallium-doped germanium bolometer which *is* sensitive to long-wavelength infrared radiation. If a blocking filter was used it would have been barium fluoride which cuts off at 14 μm, but there is no record of this. R. Joyce (private communication 1991) recently measured the long-wavelength transmission of a filter that he believes to be the one used in the 1973 observations and found a 1.5% leak between 17.8 and 20.8 μm. It is not possible to determine if this same leak was present 17.5 years earlier when the observations were made. If it was, and if a barium fluoride filter was not in place, a leak of this size could have contributed 60% of the flux attributed to Titan at 4.9 μm.

Low and Rieke also used a bolometer. We have not been able to obtain information about their filters. Rieke (private communication 1991) believes that a small leak cannot be ruled out, although the problem of long-wavelength leaks was not ignored and it is possible that the bolometer would have been used with a monochromator to check for possible leaks.

We are left in a difficult position regarding the historical data. An unfortunate coincidence of errors could have caused the results of two independent groups to agree spuriously. On the other hand, we do not want to dismiss summarily the possibility of an interesting and significant change in Titan over this period. Therefore, it is unfortunately impossible to make definitive conclusions based on these data, although they do supply motivation enough to remeasure Titan over a number of years.

J through L' band observations of Titan. In June and August of 1991 we also observed Titan with broadband

TABLE III
Titan J through L' Photometry

date (UT)	λ (μm)[1]	F_ν (mJy)	albedo ×10³
20 Jun	1.25	789 ± 8	94.9 ± 1.0
22 Jun		837 ± 14	100.2 ± 1.7
23 Jun		819 ± 27	97.9 ± 3.2
24 Jun		872 ± 15	104.0 ± 1.8
26 Jun		828 ± 15	98.3 ± 1.8
23 Aug		879 ± 15	103.4 ± 1.8
22 Jun	1.65	398.7 ± 7.8	53.8 ± 1.1
23 Jun		410.7 ± 12.2	55.3 ± 1.6
24 Jun		412.1 ± 8.1	55.4 ± 1.1
26 Jun		399.6 ± 8.5	53.5 ± 1.1
23 Aug		404.5 ± 7.8	53.6 ± 1.0
20 Jun	2.20	175.4 ± 1.2	37.0 ± 0.3
22 Jun		175.6 ± 4.5	36.9 ± 0.9
23 Jun		187.6 ± 4.7	39.3 ± 1.0
24 Jun		181.9 ± 4.4	38.0 ± 0.9
23 Aug		173.6 ± 4.2	35.8 ± 0.9
24 Jun	3.45	15.5 ± 0.8	7.0 ± 0.4
22 Jun	3.80	9.4 ± 1.0	5.1 ± 0.5
23 Jun		12.4 ± 0.9	6.7 ± 0.5
24 Jun		13.1 ± 1.0	7.0 ± 0.5
26 Jun		11.7 ± 1.8	6.3 ± 1.0

[1] Filter data are given in Tokunaga (1986)

filters centered at 1.25, 1.65, 2.20, 3.50, and 3.80 μm [*J, H, K, L,* and *L'*, respectively, as described by Tokunaga (1986)]. The results are summarized in Table III.

The aperture was set at 8 or 10 arcsec diameter for all observations. At *J, H,* and *K* we found the centered images to be in the same location for all three filters. With the *L* and *L'* filters we observed degraded beam profiles with peaks not centered relative to one another nor to the *J, H,* and *K* filters. We took extreme care to peak the signal for each measurement.

One question that we hoped to address with these observations is whether Titan is variable at infrared wavelengths both over a time span of years and/or in the course of its 16-day orbit around Saturn. An extensive set of observations of Titan at *J, H,* and *K* was carried out by Cruikshank and Morgan (1980, hereafter CM) in 1979. We have calculated albedos from their flux measurements using the same radius and solar flux. At several orbital phases we averaged multiple measurements that were within 3.7° of one another in orbital longitude.

We assume that Titan rotates synchronously with its orbital period around Saturn and plot both our data and the data of CM as a function of orbital position in Fig. 1. We find no evidence for any variation with orbital position over the eastern half of Titan's orbit in our new 1991 data as we might expect from CM's data. Unfortunately, we did not obtain any data from the western half of Titan's orbit which could have tested the apparent tendency to lower albedo near western elongation.

There is one difference in our data compared to those of CM evident in Fig. 1. The albedo we measure at *J* is consistently higher than that of the 1979 measurements. At *H* and *K* there is no significant difference. We compare the average value of the 1991 albedos to the averages of all CM albedos and to averages of CM albedos corresponding to the same orbital phase in Table IV. The 1991 *J* band average is 1.14 ± 0.03 times greater than the 1979 values at the same phase. The *K* filter average in 1991 shows a very marginal enhancement over 1979 measurements at the same phases, 1.08 ± 0.06, but we judge this to be insufficient evidence for variation. The ratios at both *J* and *K* are larger when all 1979 data are included in the average, but this is due to the lower albedos that appear in the western half of Titan's orbit, a property that may be intrinsic to Titan. Finally, the *H* filter ratio of the 1991 data to the few points from 1979 that were observed at the same orbital phases is 0.95 ± 0.04, again a result that we find consistent with no change.

Uranus and Neptune. We also observed Uranus and Neptune on several nights. The observations are summarized in Table V and Table VI and compared to previous observations. The Uranus flux we measured agrees with earlier measurements within our fairly large uncertainty. Observations of Neptune at this wavelength have often determined only upper limits. There is no evidence for variability, however, because of the large uncertainties in the detections.

SPECTROPHOTOMETRY

Titan. A low resolution ($R = 50$) spectrum of Titan in the 3.1–5.1-μm windows was obtained with the IRTF CVF. We show these data converted to albedo in Fig. 2 where we compare them to albedos at shorter wavelengths measured by Fink and Larson (1979) and references therein as well as to our broadband measurements.

The spectrum was sampled at 0.1-μm intervals, about equal to the FWHM of the CVF instrument profile. Incomplete sampling was necessary because of the weak Titan flux and consequent long integration times. However, the two observations of the 3–4 μm spectrum were offset by 0.05 μm in order to completely sample that interval. Data acquired on 7 and 8 June 1990 were averaged.

In Fig. 3 the 4.5–5.1 μm portion of the spectrum is expanded and compared with two model spectra. The solid line represents a simple reflecting layer model containing gas absorption from CO and CH_3D that we discuss in greater detail below. The dashed curve is a 170 K blackbody with an optical depth of $\tau = 0.6$. Given the large uncertainties in the data, both curves could be considered possible fits to the data.

However, we argue against thermal emission from an optically thick layer. The pressure of the lowest level in
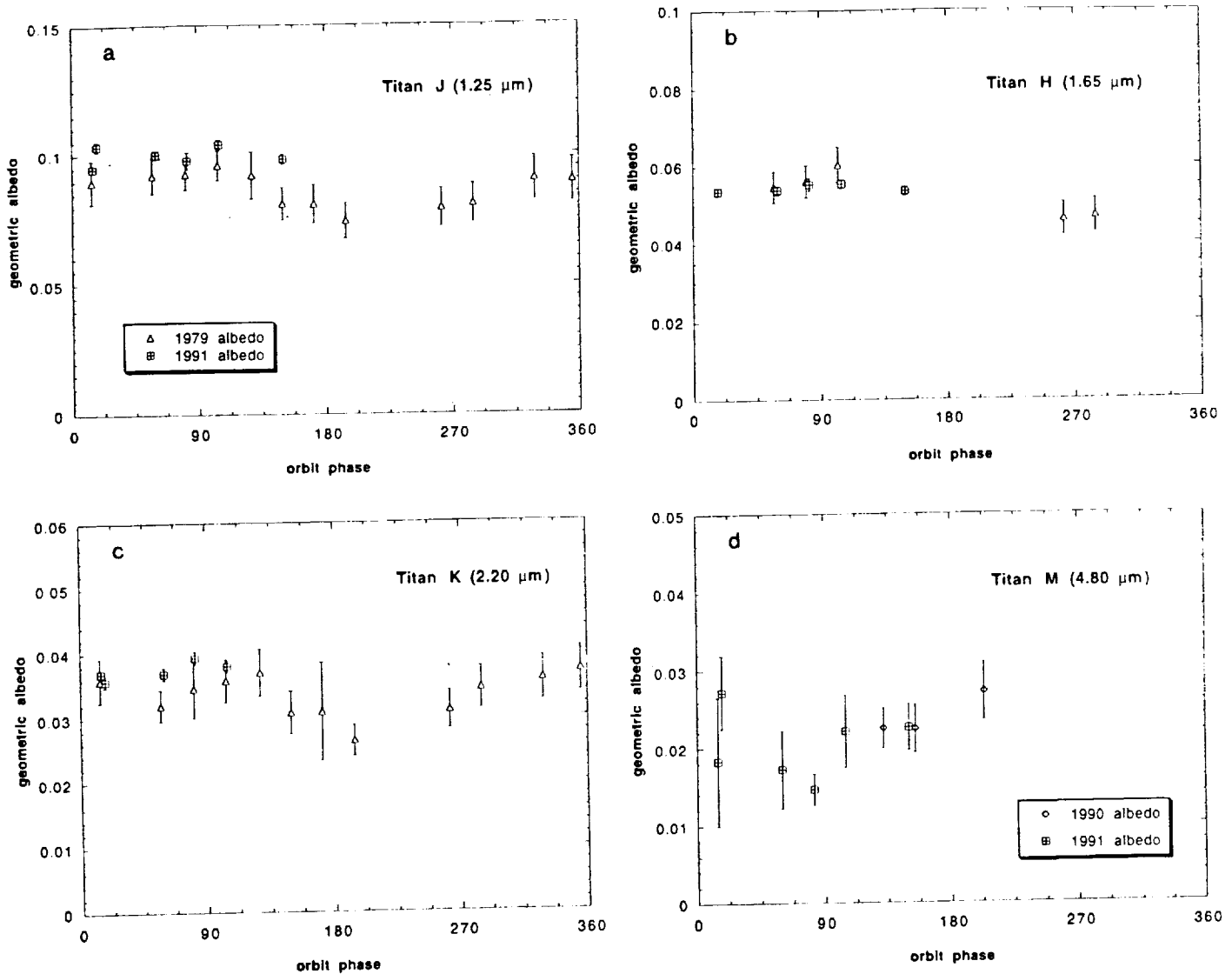
FIG. 1. (a–d) Plots of Titan's geometric albedo as a function of orbital position for the broad band filters *J*, *H*, *K*, and *M*. Data measured by us are shown by the open boxes, data from Cruikshank and Morgan (1980) rescaled to a Titan radius of 2575 km are shown by the filled symbols. Error bars are 1σ the error bars for the 1991 data are often comparable to the size of the symbol. Several of the 1979 points represent averages of albedos measured on different nights, but within no more than 3.7° of one another.

Titan's stratosphere where the temperature is 170 K or greater is less than 2 mbar (Lellouch *et al.* 1989). It is unlikely that the hazes present at these low pressures would reach optical depth 0.6 at 4.8 μm. Haze models consistent with longer wavelength data have optical depths more than an order of magnitude lower than this. Some visible radiation is expected to penetrate to at least $P \sim 100$ mbar, $T \sim 71$ K, where a methane condensation cloud may exist, and some fraction of the visible flux may even reach the surface (McKay *et al.* 1989). If the haze particles are organic solids resembling the "tholins" measured by Khare *et al.* (1984) with average particle sizes less than 1 μm, infrared radiation in windows of low gas

opacity will penetrate much deeper, probably down to Titan's surface.

Of possible gaseous absorbers, only CO, CH_3D, and possibly C_2H_4 of the molecules listed in Table VII are potentially observable in the 4.5–5.3 μm spectrum and then only at pressures of 100 mbar or higher. Based on this we conclude that the spectrum is unlikely to be thermal emission either from hazes or from molecular gas, but rather, is a reflected solar spectrum with gaseous absorption. We consider the location of the absorption in Titan's atmosphere at a position coincident with the CO 1–0 band to be strong evidence that CO is the principal absorber in this spectral window. The low point in the spectrum at

TABLE IV
Comparison of 1979 and 1991 Titan Mean Albedos

data set	λ (μm)	mean albedo ×10³
1991	1.25	98.5 ± 1.4
1979 all		86.2 ± 1.8
1979 same phases	.	86.5 ± 2.0
1991	1.65	54.2 ± 0.6
1979 all		52.8 ± 2.7
1979 same phases		56.8 ± 2.4
1991	2.20	37.1 ± 0.6
1979 all		33.0 ± 1.2
1979 same phases		34.5 ± 1.8

4.55 μm is evidence that CH_3D is also optically thick at this wavelength and implies that the location of the reflecting layer must be at a pressure of 500 mbar or greater, well within the troposphere.

Galilean satellites. There is limited published spectral information on the Galilean satellites from 4.5 to 5.2 μm. Roush *et al.* (1990) present four points for Callisto's trailing hemisphere and two points for the leading hemisphere. Because of their similar size and density, one can infer that in bulk composition Ganymede and Callisto must resemble Titan. If that resemblance extends to the surface, the albedos of the Galilean satellites would be reasonable comparisons for the albedo of Titan's surface, if that surface is in fact probed at any wavelength. Griffith *et al.* (1991) have found that in the near IR (1.3–2.0 μm) the albedos of Ganymede and Callisto do indeed provide a good match to the albedo of Titan in the windows between strong methane bands. Therefore, in order to provide a basis for comparison, we obtained CVF spectra of Callisto, Ganymede, and Europa from 4.6 to 5.2 μm which we display in Fig. 4.

TABLE V
Uranus 4.8-μm Photometry

date (UT)	λ (μm)	F_ν (mJy)	T_b (K)	albedo ×10³
May 76[1]	5.0	38± 26	133± 4	4.1± 2.8
Jun 79[2]	4.8	14± 8	132± 3	1.5± 0.8
8 Aug 80[3]	4.8	16± 4	133.2± 1.5	1.9± 0.4
9-12 Jun 87[4]	4.8	24.6± 3.8	135.8± 0.9	3.0± 0.5
7 Jun 90	4.8	15± 8	133± 3	1.9± 0.9

[1] Gillett and Rieke 1977, observing date not given
[2] Macy *et al.* 1980, observing date not given
[3] Brown *et al.* 1981
[4] Orton and Kaminski 1989

TABLE VI
Neptune 4.8-μm Photometry

date (UT)	λ (μm)	F_ν (mJy)	T_b (K)	albedo ×10³
Apr 76[1]	5.0	< 28[†]	< 138	< 26
Jun 79[2]	4.8	< 13	≤ 138	< 11
8 Aug 80[3]	4.8	14.4± 3.3	138.6± 1.5	12± 3
9 Aug 80[3]	4.8	<7.1	<134.2	<6.1
19 Aug 80[3]	4.8	11.5± 2.6	137.2± $^{1.3}_{1.6}$	10.0± 2.3
21 Jun 91	4.8	<13.5	<138	<11.2
23 Jun 91	4.8	5.3± 3.3	132.3± $^{2.9}_{5.5}$	4.4± 2.7
24 Jun 91	4.8	9.6± 5.9	135.8± $^{3.0}_{5.6}$	8.0± 4.9
26 Jun 91	4.8	<21.4	<140.9	<17.8

[1] Gillett and Rieke 1977, observing date not given.
[2] Macy *et al.* 1980, precise dates not given.
[3] Brown *et al.* 1981.
[†] All upper limits are 2-σ.

The spectra we obtained show no evidence for spectral structure that is meaningful given the relatively low signal-to-noise of the observations. The average albedo over the entire band is 0.094 ± 0.004 for Callisto, 0.044 ± 0.006 for Ganymede, and 0.020 ± 0.002 for Europa. It is interesting to note that this trend is opposite to the trend in visible albedo because the mineral component of these icy sur-
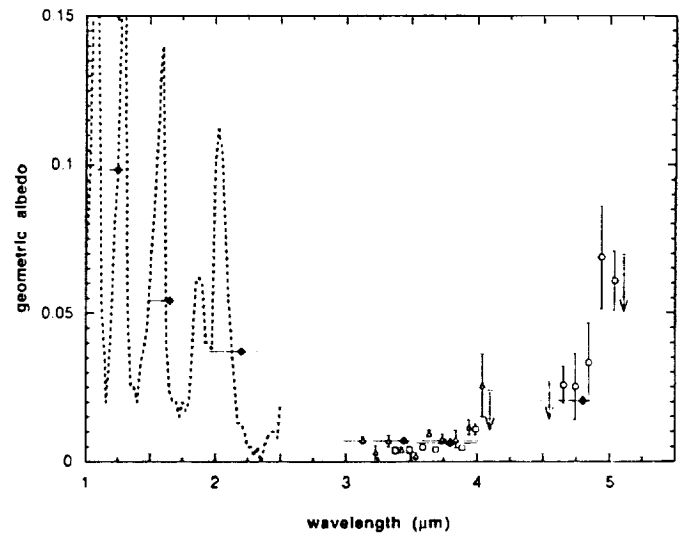

FIG. 2. The new spectrophotometric data obtained by us are reduced to geometric albedo and plotted by open symbols in this figure. Our broad band-filter data are plotted by filled symbols. The data from 4.5 to 5.1 μm are an average of 1990 and 1991 points where they overlapped. For illustration, we compare our new albedos to albedos from 1.0 to 2.5 μm taken from Fig. 2b of Fink and Larson (1979) shown by the dashed line. We note that the Fink and Larson data were not flux calibrated. Albedos were derived by normalizing their data to calibrated observations at λ < 1 μm.
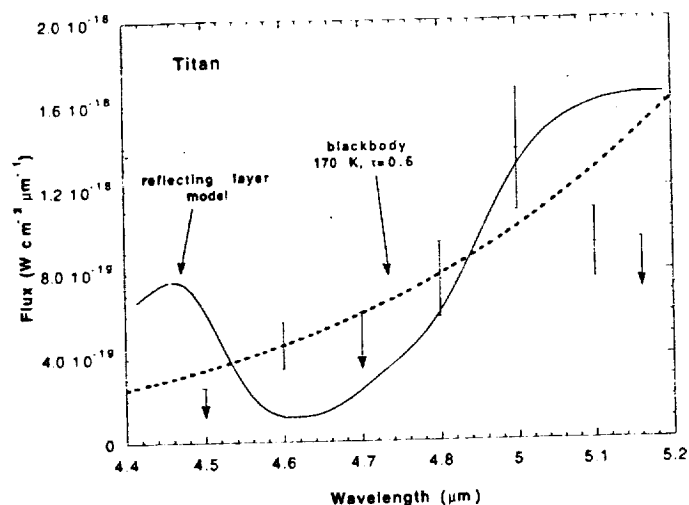
FIG. 3. Titan flux from 4.55 to 5.10 μm compared to two models of very different physical characteristics. The dashed curve is the flux expected from Titan if the source were emission from a high-altitude haze at 170 K with an optical depth of 0.6. The solid line is a model of solar radiation reflected from two layers at different depths in the atmosphere, the deepest being at the surface.
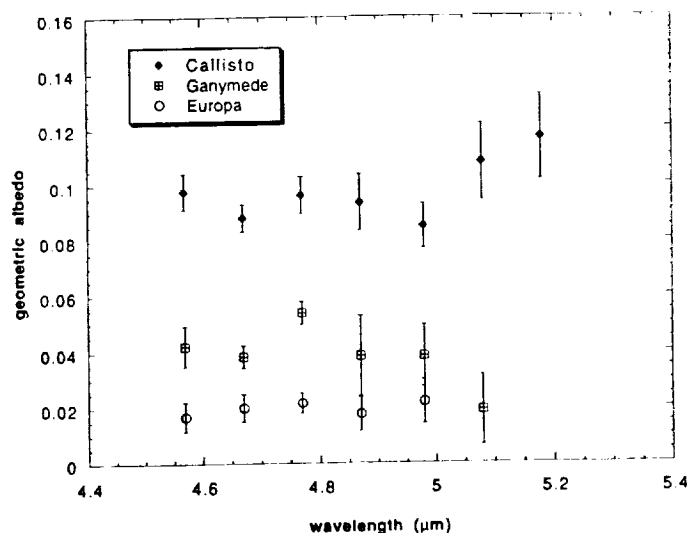

FIG. 4. CVF spectra of Callisto, Ganymede, and Europa are plotted here. We observed the leading hemispheres of all three satellites.

faces is dark in the visible but accounts for most of the reflected light beyond 3 μm (Roush et al. 1990).

Titan's two highest albedo points at 4.95 and 5.05 μm from 1991 have a mean albedo of 0.085 ± 0.014. If this average is characteristic of Titan's surface, then one pos-

sible analog for the surface of Titan is a mineral–ice mixture similar to Callisto's.

Synthetic spectrum. The comparison spectrum in Fig. 3 was calculated with a multilayer radiative transfer program. Two opacity sources, the gases CO and CH_3D, were included in the model. The altitude distribution of CO is uncertain (Lutz et al. 1983, Marten et al. 1988).

Three different CO–altitude distributions were tested. In a "microwave" distribution designed to match the results of Marten et al., the CO mole fraction ($qCO \equiv P_{CO}/P_{total}$) was fixed at $qCO = 2 \times 10^{-6}$ at all altitudes. In an "IR" distribution consistent with the results of Lutz et al., CO was set at $qCO = 6 \times 10^{-5}$ at all altitudes. A modeled spectrum using a compromise distribution consistent with both radio and IR results is shown in Fig. 3. In this distribution $qCO = 6 \times 10^{-5}$ for layers with $P \geq 54.5$ mbar and $qCO = 2 \times 10^{-6}$ for layers at $P \leq 34.9$ mbar. CO line parameters were taken from the GEISA compilation (Chedin et al. 1986).

CH_3D is present in Titan with a mole fraction $qCH_3D = 1.1 \times 10^{-5}$ (de Bergh et al. 1988). Line strengths and positions for the ν_2 band at 4.54 μm were adopted from Chackerian and Guelachvili (1983) and lower state energy levels were computed from formulae for symmetric top molecules (Herzberg 1945). Molecular data for the $2\nu_6$ band were extracted from the GEISA list.

Individual model spectra were computed using a step size of 0.05 cm^{-1} and then convolved to the instrumental resolution with a triangular function having a FWHM of 40 cm^{-1}. The three models shown in Fig. 5 demonstrate

TABLE VII
Candidate Absorbers at 4.5–5.3 μm

molecule	band center (μm)	detectable at 5 μm	observed[1]
CH_4	no bands		
CH_3D	4.55	10^{-6}	1×10^{-5}
C_2H_2	no bands		
C_2H_4	4.8,5.2	10^{-6}	$0.1 - 3 \times 10^{-6}$
C_2H_6	no bands		
CH_3CH	4.7	10^{-5}	$0.4 - 6 \times 10^{-8}$
C_3H_4	5.1	5×10^{-8}	$< 5 \times 10^{-9}$
C_3H_5	no bands		
C_3H_6	4.8,5.3	10^{-6}	–
C_3H_8	no bands		
HCN	4.8	10^{-5}	$0.16-2.3 \times 10^{-6}$
C_2N_2	4.7	5×10^{-7}	–
CH_3NH_2	4.8	10^{-6}	–
CH_2H_2	4.8	10^{-8}	–
CH_3N_3	4.6,4.8	10^{-5}	–
CO	4.7	10^{-6}	6×10^{-5}
CO_2	4.3	10^{-7}	$0.7-1.4 \times 10^{-8}$

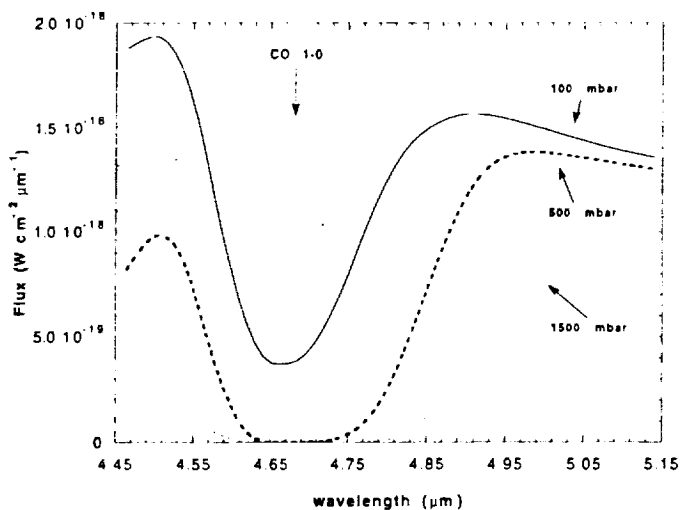[1]Observed abundances at 8-50 μm (Coustenis et al. 1989a, 1989b, 1991)

FIG. 5. The effect of moving a single reflecting layer deeper in the atmosphere is shown with three different model curves. The CO 1–0 fundamental is the strongest feature at 4.65 μm. At longer wavelengths the increase in absorption with increasing depth is from isotopic bands of CO. At shorter wavelengths the increase is due to two bands of CH_3D.

the effect of moving the reflecting layer to greater pressure levels deeper in the atmosphere. The 1500-mbar model corresponds to Titan's surface. The lower J lines of the CO 1–0 band at 4.7 μm are saturated even at relatively low pressures. The additional absorption seen at higher pressures on the long-wavelength wing is due to high J lines of the 1–0 band and to lines from the isotopic bands of ^{13}CO, $C^{18}O$, and $C^{17}O$. We have assumed terrestrial isotope ratios in all cases. On the short wavelength side of the band the increase in absorption comes mainly from the CH_3D ν_2 band.

Only models produced with the compromise distribution are shown in Figs. 3 and 5, but there is little difference in the models produced by the compromise CO distribution and the IR distribution. This is because the models are insensitive to the CO abundance at pressures less than 50 mbar where the two distributions differ. The "microwave" distribution produces a weaker CO band as would be expected. Models with the microwave distribution and the reflection layer at the surface have a CO band comparable in strength to the compromise or IR models with the reflecting layer at 500 mbar. Considering the overall marginal fits of the models, the most that we can conclude from this exercise is that if the spectrum is reflected radiation, then the depth of the CO band requires that a substantial fraction of the radiation penetrate well into the troposphere, quite possibly to the surface. Both current CO abundances can reproduce a band of sufficient depth as can a compromise distribution.

More realistic models that account for scattering might better define the depth to which the radiation reaches. The model shown in Fig. 3 attempts to take this into account by including equal contributions from a reflecting layer at the surface and a second component at 100 mbar. We are able to improve the fit in hybrid models of this kind better than any single reflecting layer model. However, given the limited quality of the data we feel it would be a mistake to continue beyond a demonstration of feasibility at this time. What *is* significant is that like models at shorter infrared wavelengths (Griffith *et al.* 1991), our results suggest that a significant fraction of the reflected light at 4.95 μm may be reflected from the surface. This certainly seems plausible since the optical depth due to organic haze particles should be significantly lower at 4.8 μm than in the visible or at 2 μm because absorption cross-sections for small particles scale as $1/\lambda$. Therefore, we expect that an even greater proportion of 4.8-μm radiation reaches the surface, implying that the geometric albedo we derive is, at least in part, a property of Titan's surface. Should future work confirm this, a means of directly studying the surface of Titan would be open.

DISCUSSION AND CONCLUSIONS

Both the photometric and spectroscopic results in this paper constitute a reconnaissance of Titan's midinfrared properties. In our observations, infrared photometric evidence for variability is rather limited. Whether the intensity at 4.8 μm decreased by a large factor between 1973–1974 and 1990–1991 appears to be impossible to corroborate from the old data. Only future observations seem likely to show whether Titan varies at 4.8 μm. The purpose of communicating the results so far is to point out the possibility of a problem with the old data and to report the new.

The albedos at J and possibly K may have increased modestly between 1979 and 1991, while the H albedo is the same in the 2 years. We did not find albedo variations over the eastern half of Titan's orbit in June 1991. The large variations (up to 60% at K) with a possible 32-day period observed by Cruikshank and Morgan (1980) are neither confirmed nor refuted by our observations. We still need to measure the albedo in the western half of the orbit and over several complete revolutions.

Titan's visible flux does change slowly, and the changes appear to be correlated with seasonal cycle (Lockwood and Thompson 1979, Lockwood *et al.* 1986, Sromovsky *et al.* 1981). These variations reflect changes in Titan's clouds and aerosols. The seasonal phase in 1979 was similar to that in 1991 so the explanation that seems to work well for changes in visible albedo would seem not to fit the

change in albedo we observed at J (unless the amplitude of the seasonal change at J were very large). A fixed-contrast variation (29.5-year period, see Fig. 4 of Sromovsky *et al.* 1981) could account for the observed variation, but it is difficult to explain the absence of variation at H and K and at the same time explain the observed changes at J.

Depending on what the cloud thicknesses turn out to be, infrared variations could reveal either cloud or surface properties. Indeed, variability itself may, in the future, prove to be an indicator of whether midinfrared observations penetrate to the surface. A clear-cut indication of this exciting possibility has so far eluded us. As we have come to appreciate in this work, observations of Titan infrared variability will be difficult and require considerable effort.

A salient result of the spectroscopy in this program has been the probable detection of the CO fundamental band at 4.6 μm in Titan's spectrum. With the present low-resolution data, we cannot resolve the discrepancies between abundance determinations based on the CO 3–0 overtone at 1.6 μm (Lutz *et al.* 1983) and the radio CO measurements (Marten *et al.* 1988). It should be possible to do this with higher resolution spectroscopy using the new array spectrometers that are just becoming operational. We plan such spectroscopic observations, as well as a long-term program to monitor possible infrared variability of Titan.

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