Transient clouds in Titan’s lower atmosphere

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The 1980 encounter by the Voyager 1 spacecraft with Titan, Saturn’s largest moon, revealed1,2 the presence of a thick atmosphere containing nitrogen and methane (1.4 and ~0.05 bar, respectively). Methane was found to be nearly saturated at Titan’s tropopause, which, with other considerations, led to the hypothesis that Titan might experience a methane analogue of Earth’s vigorous hydrological cycle, with clouds, rain and seas3–7. Yet recent analyses of Voyager data indicate large areas of super-saturated methane, more indicative of dry and stagnant conditions8,9. A resolution to this apparent contradiction requires observations of Titan’s lower atmosphere, which was hidden from the Voyager cameras by the photochemical haze (or smog) in Titan’s stratosphere. Here we report near-infrared spectroscopic observations of Titan within four narrow spectral windows where the moon’s atmosphere is ostensibly transparent. We detect pronounced flux enhancements that indicate the presence of reflective methane condensation clouds in the troposphere. These clouds occur at a relatively low altitude (15 ± 10 km), at low latitudes, and appear to cover ~9 per cent of Titan’s disk.

Following the Voyager missions, ground-based observations established the visibility of Titan’s lower atmosphere and surface at wavelengths of 0.9, 1.1, 1.3, 1.6, 2.0 and 5.0 μm10–13. During the past 10 years, spectra and images through these ‘windows’, and radar measurements, have revealed a heterogeneous surface underlying a uniform atmosphere devoid of thick variable clouds14–18.

Our observations, covering four spectral windows, were recorded over several years (1993–1997) with the United Kingdom Infrared Telescope (UKIRT), equipped with its spectrometer, CGS4. The 18 spectra, sampling many orientations of Titan’s disk, replicate earlier measurements with two exceptions. On 5 September 1995, Titan’s albedos exceeded those previously measured (at the same Titan longitude) by 14%, 17%, 30% and 200% at 1.3, 1.6, 2.0 and 2.9 μm, respectively. Observations taken a day earlier show a 14% increase in reflectivity at 2 μm, the most transparent of the two windows (1.6 μm observation uncertainty).
and 2 μm) recorded on that date (Figs 1 and 2). These exceptional observations are the focus of this report.

We present the 4 and 5 September 1995 observations in Fig. 1 along with examples of typical spectra of Titan’s leading and trailing hemispheres. Like all previous measurements, they resemble a transmission spectrum of CH4, and demonstrate how the large abundance of this gas controls the opacity of Titan’s atmosphere. Low-albedo regions coincide with strong methane bands. Here, incident solar radiation is absorbed before reaching the troposphere; the non-zero albedo results from sunlight scattered by the stratospheric haze. In contrast, the satellite’s surface is seen through the haze at regions of weak CH4 absorption, corresponding to observed high albedos. Weak methane features within these windows exhibit constant depths and profiles, indicating that there is no appreciable variation in the methane abundance. Yet the average fluxes within these windows vary in a periodic fashion as a result of the heterogeneous reflectivity of Titan’s surface (Fig. 2).

The morphology of the enhanced fluxes on 4 and 5 September 1995—marked in Titan’s windows but absent between windows—excludes instrumental effects. Furthermore, spectra from standard stars obtained throughout every run agree with one another to within 2% at wavelength regions of good atmospheric transmission. The high quality of the UKIRT spectra indicates that the observed flux enhancements accurately document an unusual event in Titan’s lower atmosphere.

The cause of the abnormal window reflectivities of 4 and 5 September 1995 is addressed with radiative transfer calculations (described in ref. 10) that simulate absorption and scattering of incident solar radiation in Titan’s atmosphere. Resultant synthetic spectra are compared with observations to derive properties of the atmosphere and surface. Titan’s near-infrared spectrum results primarily from the absorption of sunlight by CH4, the scattering of sunlight by haze, and the surface albedo. These effects can be isolated by studying separate segments of the spectrum. Applying this approach, we first analyse spectra of the undisturbed Titan to determine the optical depths of haze and CH4, and derive surface reflectivities. After establishing a standard model, we address the peculiar 5 September 1995 spectrum, searching for a solution to explain the different magnitudes of enhancement in each window, their spectral ranges, and the small enhancement at 2.0 μm on the previous day.

Spectral regions within the strong CH4 bands sample altitudes of 30–90 km. At these wavelengths, CH4 lines are saturated and Titan’s non-zero reflectivity, insensitive to uncertainties in the CH4 abundance, directly measures sunlight scattered off Titan’s haze. We assume spherical particles with the reflectivity properties of ‘tholins’, laboratory analogues of Titan’s haze. Because CH4 parameters are known at 1.64 and 2.17 μm, we focused on these spectral regions, and derived haze optical depths of 0.5 ± 0.1 and 0.20 ± 0.04, respectively. These values indicate an effective particle size of 0.4 ± 0.2 μm, which is consistent with earlier studies and provide estimates of the haze optical depth within the spectral windows (Table 1).

Laboratory spectra indicate low CH4 optical depths (τ < 0.05) within the clearest regions of the 1.3, 1.6 and 2.0 μm windows. The higher value at 2.915 μm (τ = 0.4) is transparent enough to allow visibility to the surface, confirming that 2.8 μm is indeed a window.

UKIRT spectra reveal surface albedos for Titan’s leading hemisphere resembling those of Jupiter’s moon Callisto (Table 1). The surface albedo derived at 2.9 μm was dark, as expected. However, unexpectedly it did not change from the leading to the trailing hemisphere. This contrasts with observations at radar and shorter infrared wavelengths, which show an irregular continent-sized surface feature. Our data thus suggest that this feature consists of material that is dark at 2.9 μm: potentially water ice, an ingredient of Titan’s bulk composition, or haze precipitate.

The haze optical depths possess errors of 10% from uncertainties in the derived particle size and distribution. An uncertainty of 20% in the absolute albedo for Titan implies an additional error of 20% in the haze optical depth. The latter error affects the optical depth at different wavelengths similarly. We show the cloud coverages at 15 km altitude needed to enhance the window albedos to those observed on 5 September 1995. The value inferred from the 1.3 μm window derives from the average of the 1.262–1.290 μm flux ratioed to that at 1.277–1.386 μm. This ratio was observed to be 111 ± 0.5 on 5 September 1995. The 1.28 μm surface albedo for Titan’s leading hemisphere was derived from data in ref. 17 and from NASA’s Infrared Space Telescope Facility measurements taken on 25 July 1993. Other leading-hemisphere albedos come from UKIRT observations taken on 14 and 30 September 1993 and 26 October 1997. Trailing-hemisphere albedos at 1.59, 2.0 and 2.9 μm were derived from data from 7 October 1993 (dotted line) and 5 September 1995 (top solid line) and 26 October 1997. Trailing-hemisphere albedos at 1.59, 2.0 and 2.9 μm are nominal spectra of Titan taken at central longitudes of 76, 6 and 18, respectively. Spectra taken on 4 September 1995 (dotted line) and 5 September 1995 (top solid line) deviate from nominal observations at longer wavelengths (for example at 2.15 μm), where the troposphere is probed, and CH4 absorption prevents visibility of the surface. Bottom inset: 5 September 1995 spectrum (solid line) is compared with the leading and trailing hemisphere data at 1.6 μm. Top inset: the transmissivity (e−m) as a function of altitude in Titan’s atmosphere for three wavelengths, convolved with a gaussian filter with a full-width at half-maximum of 3.8 cm−1. At 2.15 μm, solar radiation is absorbed before reaching the surface. The main source of atmospheric opacity, CH4, was modelled with a vertical distribution in which the humidity is specified at the surface and a constant mixing ratio is assumed from the surface up to altitudes at which the mixing ratio exceeds the saturated value. Here a saturation profile is assumed up to the tropopause. A constant mixing ratio (the saturated value) is assumed for the stratosphere. Although a range of humidities is considered, our nominal CH4 profile assumes 50% humidity at the surface, and a stratospheric mixing ratio of 0.02. The supersaturated profiles of ref. 8 are also consistent with our observations. CH4 line intensities and energies were derived by using line-by-line models from the raw laboratory data kindly provided by Strong et al. This technique allowed us to ascertain uncertainties in the continuum of the laboratory measurements (for example resulting from water ice absorption) that particularly affect regions of weak methane absorption characteristic of the windows of Titan’s atmosphere.
Having established a standard model, we address the anomalous 4 and 5 September 1995 spectra. The confinement of enhanced fluxes to Titan's windows indicates a perturbation of the lower atmosphere. Because the enhancements extend into spectral regions insensitive to Titan's surface, for example at 2.14–2.15 and 1.62–1.625 μm (Fig. 3), Titan's surface is not the cause. Weak CH₄ signatures at 2.9 μm also eliminate the possibility that surface variations produced the elevated fluxes; the calculated strengths of the 2.9 μm features exceeded those observed when interpreted with an increase in the surface albedo (Fig. 4a).

To investigate the effects of condensation, we add highly reflective (ω = 0.98) and optically thick clouds to our standard model of Titan. We assume a uniform cloud optical depth throughout the 1.3–3.1 μm region, a behaviour expected for CH₄ particles exceeding 5 μm in size. Large particle sizes and rapid particle growth are predicted in the event of CH₄ condensation on Titan, because condensation nuclei are thought to be scarce. A consistent explanation for all the observations emerges from this analysis. The spectral characteristics of the flux enhancements in each window independently point to the same cause: a thick cloud deck located at 15 km altitude and covering 7–9% of Titan's disk.

Several lines of evidence support this interpretation. Clouds at 15 km altitude enhance Titan's flux at precisely the spectral ranges observed (Fig. 3). Deeper clouds affect a narrower spectral range for each window; higher clouds would be observed over greater spectral ranges (Fig. 4b). Second, the same ~7–9% coverage of clouds located at 15 km reproduces the observed flux enhancements at all windows (Fig. 4). In contrast, low clouds (for example, at 5 km altitude) require 9% covering at 1.28, 1.59 and 2.0 μm, and 15% at 2.9 μm. This is a consequence of the increased CH₄ absorption at 2.9 μm. Last, a cloud deck at 15 km altitude with 9% coverage interprets the 2.9 μm spectral well; deeper (higher) clouds indicate features stronger (weaker) than observed.

On 4 September 1995, observations show a 14% enhancement in the reflectivity at 2.0 μm (Fig. 2). No enhancement occurred at 1.6 μm. On 5 September, the 17% enhancement at 1.6 μm was dwarfed by the 30% change at 2 μm. These observations can be naturally interpreted with the presence of low-latitude clouds on Titan's limb on 4 September (i.e. centred near the equator having an airmass of 2) that rotated into better view the following day. Unfortunately, no observations were scheduled on the day after 9 May 1995 to allow further investigation. When follow-up observations were recorded in 1997, all was normal.

At present it is too early to address the cause for a sudden appearance of clouds on Titan. Cooler and more massive, Titan's atmosphere is not expected to be as turbulent as Earth's. Yet some vertical motion must accompany the meridional motions that equalize the surface temperatures. In addition, clouds from Titan have been hypothesized to be brief events and therefore difficult to detect. Titan's haze, the only seed nuclei identified so far, has a low number density. Thus, in comparison with Earth, particle growth in clouds might be rapid, and closely followed by precipitation and cloud dissipation.

Whether clouds and rain are occasional, although quick, occurrences that punctuate otherwise dry conditions can be addressed by future observations. If caused by convection, cloud formation will be revealed with additional near-infrared data indicating the mass, altitude and duration of the clouds. If volcanic or orographic, the clouds will correlate with Titan's longitude. Titan presents us with a unique opportunity to understand processes native to our biosphere, yet in a cooler atmosphere tens of times more massive than Earth's.

![Figure 4](image-url)
Mesoscopic behaviour of the neutral Fermi gas $^3$He confined in quantum wires

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The behaviour of electron gases in restricted geometries provides a means to explore the fundamental quantum-mechanical properties of fermion gases at mesoscopic length scales. The existence of Coulomb repulsion between electrons unavoidably complicates the physics. Quantum gases of neutral fermions—such as $^3$He quasiparticles in a dilute solution of $^3$He in $^4$He, cooled to millikelvin temperatures—therefore offer a means of probing regimes completely inaccessible to electronic systems. Here we demonstrate the quantum exclusion of a $^3$He fermion gas from a network of narrow channels, connected to a reservoir of $^3$He solution. The effect is expected from simple quantum-mechanical arguments, which predict that the $^3$He atoms cannot enter the channels when their wavelength exceeds $\sqrt{2}/2 \times$ the channel width. By adjusting the temperature of the solution, the energy of the particles and thus their average wavelength can be controlled. In this way, we observe temperature-dependent changes in the penetration of the $^3$He quasiparticles into the channels. Our results demonstrate the macroscopic response of an atomic gas to basic quantum-mechanical restrictions at the mesoscopic level.

Although the $^3$He gas in dilute $^3$He-$^4$He solutions might be expected to show broadly similar behaviour to that of an electron when similarly confined, this Fermi–Dirac quantum fluid has a number of advantages over the usual metallic or semiconducting systems. The medium can be readily decanted into a container shaped to provide the requisite restricted geometry and therefore various solutions can be studied under identical conditions. The $^3$He solutions are absolutely clean at millikelvin temperatures and thus there are no impurity effects. The Fermi parameters of the $^3$He—Fermi energy $E_F$, Fermi temperature $T_F$ and Fermi wavelength $\lambda_F$—can be varied over a wide range by adjustment of the $^3$He concentration. Finally, unlike in the charged electron gas, the potential energy determining the bottom of the excitation band is only a very weak function of the local particle density and there are no problems of Coulomb repulsion.

The Fermi temperature of a dilute $^3$He-$^4$He solution of fractional $^3$He concentration $\chi$ varies as $\chi^2$. A 0.1% $^3$He solution yields a Fermi energy of around 26 mK with an associated Fermi wavelength of 8 nm. This is much smaller than would be practicable in electronic systems, but with helium solutions we can make use of confined geometries on this scale over the temperature range 5–100 mK which is readily accessible with a dilution refrigerator.

The experiment reported here, the detection of the quantum exclusion of the $^3$He gas from a system of narrow channels as the temperature is reduced, was chosen for two reasons. First, it is conceptually simple, and second, it has no direct analogue in an electronic system, as quantum exclusion of an electron gas leads to a change in the local potential which largely cancels the effect. Furthermore, a metallic system cannot be probed over a temperature range spanning $T_F$.

The principle of the ideal experiment is illustrated in Fig. 1. A bulk $^3$He-$^4$He solution is placed in contact with a network of narrow cavities with a scale dimension of $a$. The $^3$He concentration is adjusted such that the Fermi wavelength is longer than $\sqrt{2}a$, or in other words, the confinement energy ($E_0$ of the order of $h^2/(2m^*a^2)$, where $m^*$ is the $^3$He effective mass) is greater than $kT_F$. Therefore, at temperatures well below $T_F$, $^3$He atoms cannot penetrate into the cavities. However, as the temperature is increased, at some point the most energetic atoms begin to penetrate. This starts to occur significantly when $(E_0 + 2kT)$ exceeds the confinement energy $E_0$. Therefore, if over the temperature range used the quantity $(E_0 + 2kT)$ can be made to span the confinement energy, then at the low-temperature end $^3$He is totally excluded from the pores but will be able to penetrate into them at the higher temperatures. We should therefore see an increase in the concentration of $^3$He in the pores with increasing temperature.

The confined geometry is provided by the channels in porous Vycor glass which have a characteristic dimension $a$ of around 7 nm. Given the accepted value for the effective mass $m^*$ for $^3$He quasiparticles as 2.25 times the bare $^3$He atomic mass, the expected confinement energy $E_0$ is 15 mK in temperature units. This is a little low to implement the ideal experiment, as the lowest reliable temperature to which we can cool the cell is around 8 mK, meaning that $kT$ is rather large even at our base temperature. However, calculations show that even with a 0.1% $^3$He solution there should be a significant change of the pore penetration with temperature, and this concentration was chosen. For more dilute solutions much of the variation would occur below 8 mK, and also the measurable effect would be smaller.

We infer the extent of the penetration of $^3$He into the pores from the concentration of $^3$He in the external bulk solution; the bulk concentration is monitored by a capacitative measurement of the dielectric constant of the solution. As the changes in dielectric constant with changes in $^3$He concentration are small, we must ensure that the volume of bulk solution in our experimental cell is as small as possible in comparison with the pore volume. The bulk volume must accommodate both the capacitor for measuring the $^3$He concentration and pads of silver sinter necessary to make thermal contact to the solution. (The sinter pore size is ~100 nm