# Chapter 5

# Direct detection of variable tropospheric clouds near Titan's south pole

## 5.1 Introduction

Atmospheric conditions on Saturn's largest satellite Titan allow the possibility that Titan could possess a methane condensation and precipitation cycle with many similarities to the earth's hydrological cycle, a process which otherwise has no close analog within the solar system. Detailed study of Titan from the Voyager spacecraft and subsequent high resolution earth-based imaging, however, have shown no evidence for any tropospheric condensation clouds (Smith *et al.*, 1996; Combes *et al.*, 1997; Gibbard *et al.*, 1999; Coustenis *et al.*, 2001), even though recent low-resolution studies have provided indirect spectroscopic evidence for their transient existence (Griffith *et al.*, 1998, 2000). Here we present the first resolved images and spectra of Titan clearly showing transient cloud features, all of which are concentrated near the south pole. The discovery of these clouds demonstrates convincingly the existence of condensation and localized moist convection in Titan's atmosphere. Their location at the pole, near the current point of maximum solar heating, suggests that methane cloud formation is seasonally controlled by small variations in surface temperature and will move from the south to the north pole on a 15 year time scale.

Searching for clouds on Titan is best performed with high resolution images and spectra

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[1] This chapter has been published as M.E. Brown, A.H. Bouchez, and C.A. Griffith, **Direct Detection of Variable Tropospheric Clouds Near Titan's South Pole**, *Nature*, 420, 795–797, 2002. It was written by M. Brown, with input from A. Bouchez. A. Bouchez performed the image processing and the radiative transfer modeling of the spectra, thereby calculating the altitude and aerial coverage of the clouds discovered near Titan's south pole.

at wavelengths between about 2.0 and 2.3$\mu$m. At these wavelengths, absorption of photons by Titan's methane ranges from negligible (2.00 to 2.05 $\mu$m) to nearly complete (2.17 to 2.29 $\mu$m), while absorption by Titan's haze is low (Griffith *et al.*, 1998, 2000). The transparent range allows images at these wavelengths to sense to the surface, while the complete range of methane absorption across the wavelength region allows spectra to probe all levels in Titan's atmosphere. High spatial resolution is critical to recognize any small distinct cloud against the surface of Titan.

## 5.2 Observations

Using the adaptive optics (AO) system at the W.M. Keck Observatory (Wizinowich *et al.*, 2000), we have obtained images with both the spatial resolution and spectral coverage critical for searching for clouds. AO achieves high spatial resolution by partially compensating for the smearing effect of turbulence in the earth's atmosphere and delivering a near diffraction- limited image. Images from five nights of observations (Fig. 5.1) demonstrate the remarkable spatial resolution achieved with the AO observations. Surface features which have been consistently imaged since 1995 are seen at their highest resolution ever. The images from 10 and 11 December 2001 and 28 February 2002 all show almost the same face of Titan, and the reproducibility and rotation of surface features is apparent. More remarkable, however, are the transient changes visible near the south pole of Titan. These changes are more apparent in polar projections of the images (Fig. 5.2). The bright unresolved spot on the southern limb in the 10 and 11 December images has disappeared by February. The February image instead shows a much larger brightening extending ~1400 km from 80 to 70 south latitude. Numerous small morphologically similar isolated bright spots occur throughout the images but cannot be verified to be transient because of a lack of duplicate coverage of most longitudes.

## 5.3 Results

To determine the height in the atmosphere where the transient spots occur, we examined spectra from the 10 and 11 December bright southern spot and compared them to spectra obtained at a location 900 km directly east on the satellite, where the line-of-sight samples

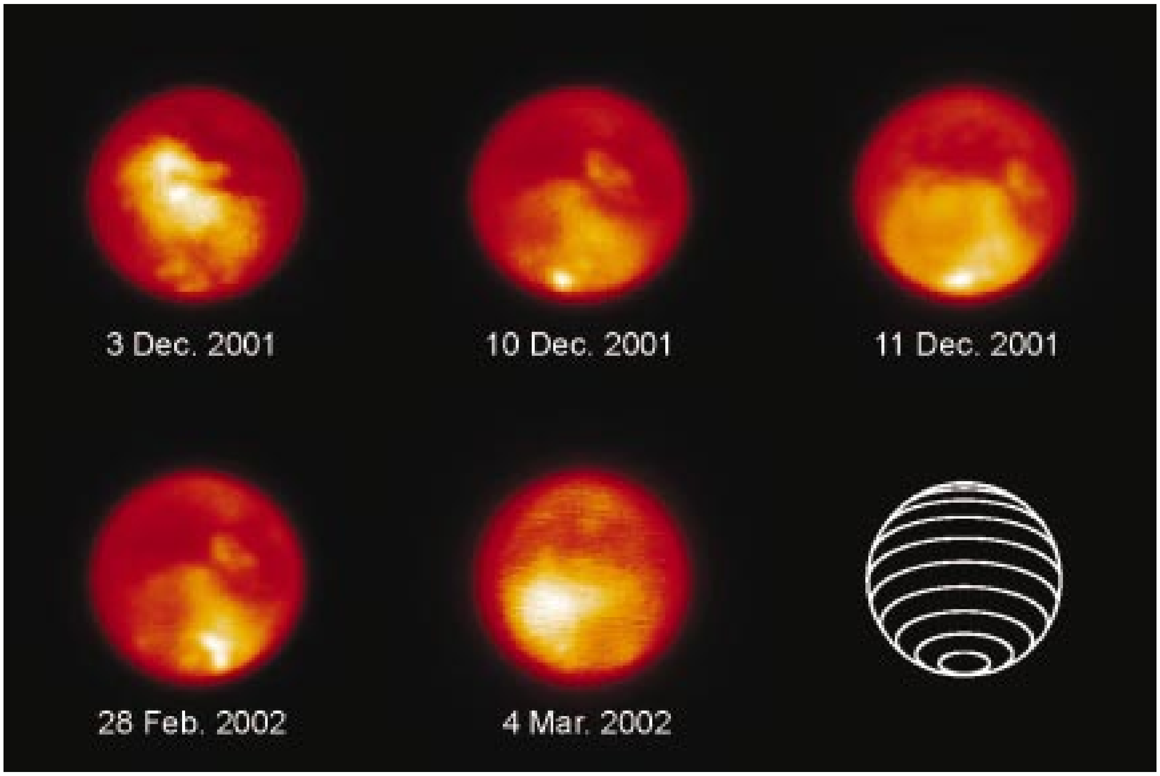

Figure 5.1: Images of Titan show the transient existence of cloud features near the south pole. Images and spectra from 2, 10, and 11 December 2001 were obtained using NIRSPEC, the facility near-infrared spectrograph (McLean *et al.*, 1998), while images (only) from 28 February and 4 March 2002 were obtained using NIRC2, the facility near-infrared AO imager. Images were obtained in the K' wavelength band, which extends from 1.96 to 2.29 $\mu$m, and have an angular resolution of 0.05 arcseconds (a linear resolution of 330 km on 10 December 2001) on the satellite. The images shown are combinations of from 4 to 20 individual images shifted to a common center, summed, and divided by an image of the individual pixel response function ("flat field"). The apparent elongation of the cloud feature on the 11 December 2001 image is a temporary artifact of the AO system. Owing to non-photometric observing conditions during some of the nights, no absolute flux calibration was obtained. The individual images are scaled to best see the polar clouds. The line figure shows every 15 degrees of latitude projected for Titan's subsolar latitude of -25.6 degrees at the time of the observations. Titan's subsolar longitudes at the times of observations were 69, 228, 249, 235, and 325 degrees for the 2, 10, and 11 December, and the 28 February and 3 March observations, respectively.

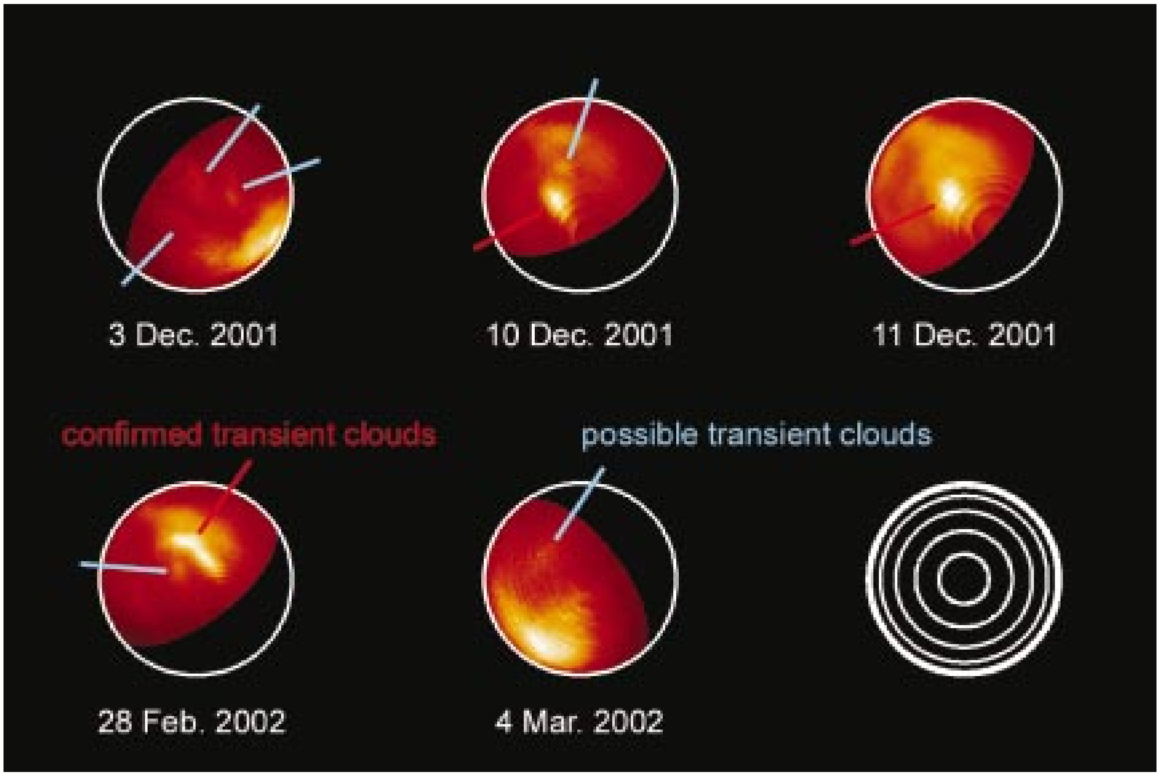

Figure 5.2: The transient polar clouds are best seen in polar projections of the images of Titan. A longitude of zero (facing Saturn) is straight up in these projections and longitude increases counter-clockwise. The line figure shows every 15 degrees of latitude. Confirmed transients (those for which we have multiple images confirming change) are labeled by red lines, while morphologically similar features whose transient nature is unconfirmed are labeled by blue lines. On 10 and 11 December the single brightest spot appears at longitude $150 \pm 30$, latitude $77 \pm 3$ south (the large errors in locating spots near the limb precludes any detection of cloud motion between the two nights). The 28 February images shows small brightenings at $200 \pm 20$, $87 \pm 5$ and $174 \pm 10$, $65 \pm 5$, but none at the precise location of that seen in December. Also visible is a much larger brightening between latitudes 70 and 80 S; nothing similar is seen in the December images. The projections were created by using the circular symmetry of the limb of Titan to define the center of the disk and then projecting the intensity onto a spherical grid. Errors in the position of the center of the disk of $\pm 0.02$ arcseconds give errors in the projected longitude and latitude of features near the south pole of 20 and 5 degrees respectively. No intensity corrections are made for variations in the viewing angle.

the same latitude at an identical zenith angle of 65 degrees but no transient brightening occurs. A comparison between the 2 spectra (Fig. 5.3) shows that they are essentially identical beyond 2.16 $\mu$m. These regions of the spectrum contain strong methane absorption lines which saturate in the stratosphere of the satellite. At shorter wavelengths the methane absorption is progressively weaker so photons penetrate progressively deeper into the atmosphere until at a wavelength of 2.12 $\mu$m photons reach the surface. The two spectra diverge at a wavelength of 2.155 $\mu$m, which clearly requires a reflective layer somewhere between the stratosphere and the surface. Detailed plane-parallel radiative transfer calculations using the models of Griffith *et al.* (1998, 2000) of the difference between the two spectra shows that the bright spot is best modeled as an unresolved highly reflective cloud layer with a filling factor of 25% at an altitude of $16 \pm 5$ km above Titan's surface, in the middle of Titan's troposphere. The errors in this height estimate are dominated by uncertainties in tropospheric methane abundance; deviation from the plane-parallel assumption at this zenith angle is less than 4%. No changes are apparent in the altitude, intensity, or location of the cloud from 10 to 11 December. These images and spectra conclusively demonstrate the existence of transient clouds in the troposphere of Titan and point to the presence of a vigorous and currently active cycle of methane condensation and dissipation.

The December 2001 cloud has a brightness equivalent to ~0.3% of the total brightness of the disk of Titan at these wavelengths, and can be explained by a single (foreshortened) cloud of 200 km diameter or smaller clouds with the same total area. The 28 February 2002 cloud is significantly larger, reflecting a flux equivalent to ~1% of the total flux of Titan, and covering an apparent area of $4.4 \times 10^5$ km$^2$, implying a filling factor of only ~5%.

These transient clouds will cause rapid changes to Titan's full-disk spectrum similar to the ~0.5% variations previously observed shortward of 2.170$\mu$m and interpreted as evidence for such clouds (Griffith *et al.*, 2000). The difference in wavelength of spectral divergence between 2.170 $\mu$m in the full-disk spectra and 2.155 $\mu$m in the current spectra suggests a change in cloud height or latitude since the time of the previous observations.

## 5.4 Discussion

No obvious connection exists between these transient tropospheric clouds and the southern tropopause level scattering layer (Bouchez *et al.*, 2000; Lorenz *et al.*, 2001; Griffith *et al.*,

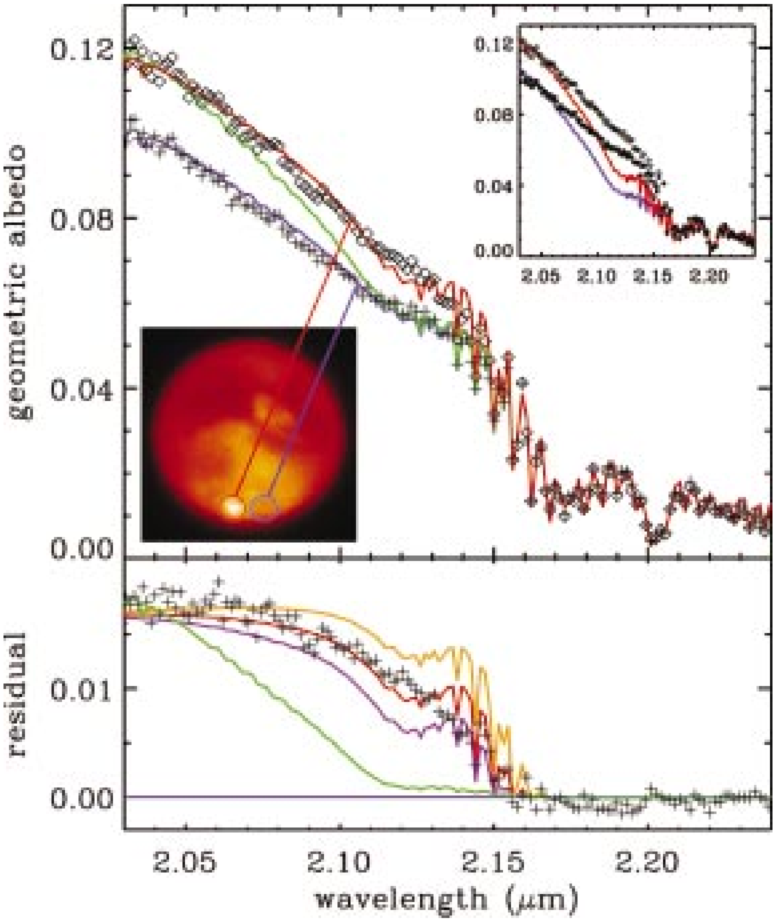

Figure 5.3: Spatially resolved spectra of the disk of Titan showing the height in the atmosphere of the transient features. A comparison of a spectrum of the 10 December 2002 transient brightening and of a location 900 km east on the disk which samples the surface and atmosphere at an identical zenith angle of 65 degrees shows that the transient brightening is caused by tropospheric clouds. The upper panel compares spectra from the regions labeled on the 10 December image with best fit radiative transfer models. The blue line shows the best-fit model to the non-cloud region, while the red line shows the effect of adding a bright scattering layer at 18 km. The green line demonstrates the poor fit obtained if an attempt is made to fit the transient brightening as a surface albedo effect. Neither spectrum can be modeled without the presence of a tropopause cirrus layer of optical depth 0.10±0.02 at 30-40 km (Bouchez *et al.*, 2000; Lorenz *et al.*, 2001; Griffith *et al.*, 2003; Bouchez *et al.*, 2003). The inset shows the best fit models without this tropopause cirrus. The bottom panel shows the difference between the two spectra and between models with clouds at 14 (purple), 18 (red), and 24 km (orange). The green line again shows the poor fit if the spectral difference is modeled purely with a change in surface albedo. The mismatches between the models and data are due to inaccuracies in the methane line strengths; these inaccuracies contribute the greatest uncertainty to the derived cloud height. The spectra were obtained simultaneously using a 0.054 arcsecond wide spectral slit centered on the brightening and placed east-west across the disk. Both spectra have been divided by the spectrum of the G4V star HD 32923 taken at an identical airmass of 1.02 to correct for effects of instrumental sensitivity, telluric absorption, and solar spectrum. The radiative transfer model uses doubling and adding techniques to approximate the equation of radiative transfer, along with line-by-line and Mie scattering calculations to incorporate gas absorption and scattering by particulates. The nominal value of methane humidity is that of Griffith *et al.* (2000); changes of factors of two in methane or allowing methane supersaturation do not significantly change the results.

2003; Bouchez *et al.*, 2003) which occurs at an altitude around 40 km and is visible in the spectra of Fig. 3. This layer has been observed since at least 1994 and has been variously described as a cloud, haze layer, or fog, but the true physical nature, composition, and cause remain unknown. Though this scattering layer is routinely observed, the lack of a consistent name has caused confusion as to its stability and even existence. We use the term "tropopause cirrus" as a morphological name for this distinct layer which describes its approximate altitude, small optical depth, and large areal coverage. At the time of observations, this cirrus layer covered the entire southern hemisphere at latitudes further south than 35 degrees (Bouchez *et al.*, 2003). The southern tropopause cirrus layer is not currently known to vary, though it is likely to change on seasonal time scales with changes in stratospheric haze chemistry and dynamics (Lorenz *et al.*, 2001).

The most striking property of these transient cloud events is their unexpected concentration near the south pole of Titan. While heating at southern summer solstice might be expected to drive polar convection, studies of tropospheric conditions on Titan have suggested an absence of seasonal variation (Hunten *et al.*, 1984; McKay *et al.*, 1997) and predicted that methane clouds, if present, should concentrate at the equator year-round (Tokano *et al.*, 1999). These hypothesized seasonal invariances come from consideration of the long radiative time scale of Titan's lower troposphere which does not allow tropospheric temperatures to appreciably change on seasonal timescales (Hunten *et al.*, 1984).

These predictions of invariance do not consider the effects of small seasonally varying surface temperatures, however, and instead examine only conditions measured during southern spring equinox at the time of the Voyager flyby. Even a very small seasonally and latitudinally varying surface temperature, which is a necessary consequence of Titan's widely varying seasonal insolation, will affect the magnitude of the surface sensible heat flux and change temperatures in the lower troposphere. If the lower tropospheric lapse rate is close to the boundary between stability and instability, as has been measured on Titan (McKay *et al.*, 1997; Lindal *et al.*, 1985; Lellouch *et al.*, 1989), a small additional heat flux can drive the creation of a thermally convective layer, the height of which will depend on the magnitude of the additional heat input and therefore on the surface temperature. Assuming the conditions least favorable to convection that have been inferred from Voyager measurements (McKay *et al.*, 1997), even a surface temperature rise of only 1 K is sufficient to cause a convective layer 7 km in height. If this convective layer reaches the point at which methane saturates, the height of which is highly dependent on the methane humidity but is estimated to be ~4 km in typical models (Griffith *et al.*, 2000; Hunten *et al.*, 1984; Lindal *et al.*, 1985; Lellouch *et al.*, 1989), methane condensation will render the air buoyant and drive clouds to the ~15km levels observed (Awal and Lunine, 1994). In regions with lower surface temperatures, the convective layer will be smaller or even non-existent, and condensation will not occur.

At the time of our observations, Titan was approaching southern summer solstice, and, owing to Titan's obliquity of 27 degrees, the polar regions were in continuous sunlight and receiving more daily averaged insolation than any other spot on the satellite (and 50% more daily averaged insolation than the equator at equinox). We hypothesize that this insolation leads to a maximum surface temperature in these polar regions which drives a convective layer large enough to cause methane condensation and the ensuing moist convection. This hypothesis predicts that the location of these convective clouds will follow the location of maximum insolation (with some lag owing to the thermal inertia of the surface).

## 5.5 Acknowledgements

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