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DISCOVERY OF TEMPERATE LATITUDE CLOUDS ON TITAN[1,2]

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ABSTRACT

Until now, all the clouds imaged in Titan's troposphere have been found at far southern latitudes (60°–90° south). The occurrence and location of these clouds is thought to be the result of convection driven by the maximum annual solar heating of Titan's surface, which occurs at summer solstice (2002 October) in this south polar region. We report the first observations of a new recurring type of tropospheric cloud feature, confined narrowly to ∼40° south latitude, which cannot be explained by this simple insolation hypothesis. We propose two classes of formation scenario, one linked to surface geography and the other to seasonally evolving circulation, which will be easily distinguished with continued observations over the next few years.

Subject headings: infrared: solar system — planets and satellites: individual (Titan)

Online material: color figure

1. INTRODUCTION

The first detection of meteorological activity on Titan was reported by Griffith et al. (1998), who attributed global brightening in several spectral windows to a large cloud covering ∼5%–7% at unknown latitude. This was followed by Griffith et al. (2000), who inferred daily clouds covering ∼0.1%–0.5% of Titan's disk, again at unknown latitude. The first spatially resolved detections of Titan's tropospheric clouds were reported by Brown et al. (2002) and Roe et al. (2002), who used high spatial resolution spectroscopy and narrowband filter imaging to observe clouds near Titan's south pole. Since that time, clouds have regularly been observed in the south polar region (Bouchez 2003; Bouchez & Brown 2005), and the formation hypothesis of Brown et al. (2002) remains the most plausible scenario, in which maximum surface heating occurs on Titan at the south pole near the summer solstice (2002 October), driving atmospheric convection that leads to the formation of moist convective clouds. Until now, no clouds have been observed north of ∼60° south latitude, and the vast majority of clouds have been found south of 70° south latitude.

We report a distinct new type of cloud feature on Titan, discovered recently at temperate southern latitudes. These clouds are unlikely to form via the same surface heating hypothesis that is suggested for the south polar clouds, and we discuss possible formation mechanisms for these new clouds.

[1] Some of the data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

[2] Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (US), the Particle Physics and Astronomy Research Council (UK), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil), and CONICET (Argentina).

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2. OBSERVATIONS

Data presented here were taken at the Gemini North 8 m telescope using the Altair adaptive optics system and the facility near-infrared camera (Herriot et al. 2000; Hodapp et al. 2003) and the W. M. Keck 10 m telescope using the facility adaptive optics system and the NIRC2 near-infrared camera (Wizinowich et al. 2000). Variations in methane and hydrogen opacity with wavelength allow us to discriminate surface, tropospheric, and stratospheric features. The K' filter (2.03–2.36 μm) probes down to Titan's surface, while the H_2 (1–0) filter (2.111–2.137 μm) is sensitive to ∼10 km altitude, and the Brγ filter (2.154–2.183 μm) probes to approximately the tropopause (50 km; Roe et al. 2002). Thus, with these three filters we can determine if a feature is on the surface, in the troposphere, or in the stratosphere. Data reduction was limited to correction for pixel-to-pixel sensitivity ("flat-fielding"), shifting and adding two to four images from each filter and night, and rotating the final image to align Titan's north pole with the vertical axis.

Figure 1 shows data from 13 nights in 2003–2004. Observations in 2003 December and 2004 September are from Keck, while all other data are from Gemini. On nearly every night, a cloud is apparent near the south pole. The Brγ images show no night-to-night changes, except variation that is attributable to variable seeing, instrument performance, and phase angle. The new temperate latitude clouds are most apparent in the troposphere probing images on 2004 April 8 and 9, 2004 May 4, and 2004 September 2, although they appear with lower contrast near the limb on 2003 December 18 and 2004 May 5.

The locations of the clouds in our data, as well as earlier clouds (Brown et al. 2002; Roe et al. 2002; Bouchez & Brown 2005), are shown in Figure 2, showing the south polar clouds clustered south of ∼70° south and the new clouds at a latitude of ∼40° south. We have not yet observed enough of these new clouds to say whether any clustering in longitude is statistically significant.

3. DISCUSSION

The sudden appearance of temperate clouds on Titan cannot be explained easily by the same surface heating hypothesis suggested for the south polar clouds; even 2 yr after southern summer solstice, the pole is still the point of maximum insolation (see Fig. 3). Any successful hypothesis for the appear-

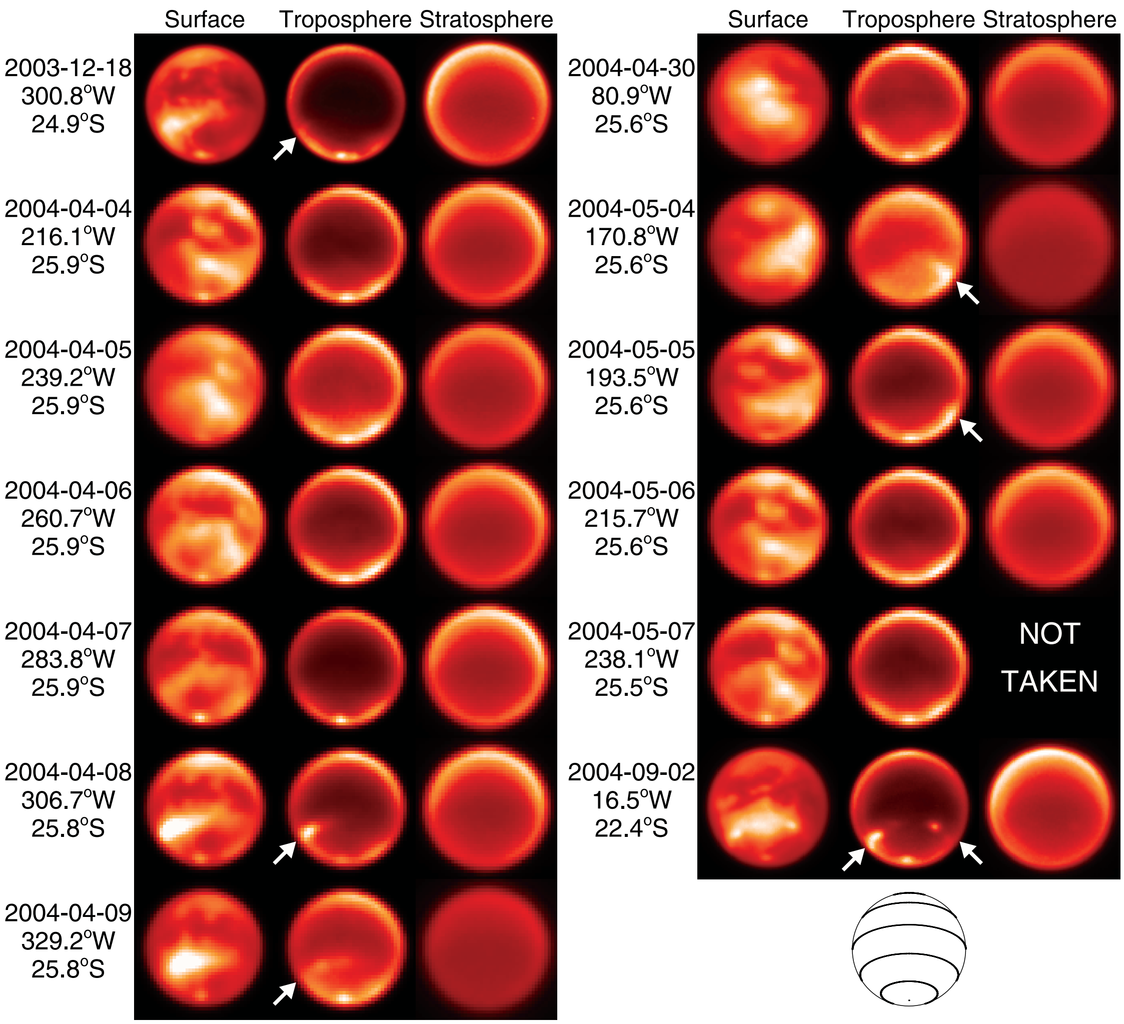

FIG. 1.—Observations of Titan in the three filters. Subobserver longitude and latitude are given. From left to right are images in K' (surface probing), H_2 (1–0) (troposphere probing), and Brγ (stratosphere probing). The wire frame at the lower right is for a subobserver latitude of 25°.6 south. All images are scaled to show Titan at the same size, although its angular diameter ranged over 0″.73–0″.88. In the stratospheric probing images, we see only the limb-brightened stratospheric haze, with a seasonal north-south asymmetry. In the tropospheric probing images, we see the stratospheric hazes limb-brightened, a general brightening in the south due to the tropopause cirrus, the distinct south polar clouds (see especially April 9, although a cloud is near the south pole in every one of these images), and the new ~40° south clouds, which are especially apparent on April 8–9, May 4, and September 2. The new temperate latitude clouds are indicated with white arrows. In the surface probing images, Titan's 22°.5 day^{-1} rotation rate is apparent and the tropospheric clouds also appear.

ance of these new clouds will need to explain several distinct characteristics: (1) The clouds are clustered in latitude (37°–44° south), although they are not at identical latitudes. For example, the point-source cloud of September 2 is at 38° ± 2° south, while the extended cloud of the same date is at 44° ± 2° south. (2) We first observed the new clouds in 2003 December and have seen them regularly, although not constantly, since that time. In spite of numerous earlier observations that would have resolved these clouds, they were not observed earlier, suggesting they are a new or irregularly occurring phenomenon. (3) Like the south polar clouds, these clouds are tropospheric and do not extend into the stratosphere. (4) Most of the clouds extend in longitude for several hundred to several thousand kilometers.

After considering many conceivable methods for forming clouds on Titan, we find two plausible classes of cloud formation models that satisfy all of the constraints above and that could possibly explain these new recurring clouds. The first class of model for spatially confined recurring cloud formation attempts to tie the location of clouds directly to geographic features on the surface of Titan. On the Earth, examples of such spatially confined clouds include orographic, marine, and volcanic clouds. On Titan, the recent sudden onset of temperate latitude cloud activity argues against a permanent surface characteristic—such as the presence of mountain or an ocean—being the sole cloud instigator. We are led to examine instead potential transient events that might be occurring on Titan's surface as a possible source of the recurring but transient clouds. Some conceivable sporadic events tied to Titan's surface involve hypothetical geyser or cryovolcanic activity. Geysers on Titan could not rise high enough to directly form tropospheric clouds (Lorenz 2002), but injection of methane even at the base of the troposphere could cause enough condensation and latent heat release to drive runaway convection and subsequent cloud formation. Cryovolcanism on Titan would likewise not be expected to inject material high into the troposphere (Lorenz 1996) but could release methane and again drive convection and cloud formation. An interesting possibility with no Earth analog is that a small amount of geothermal heating in one location could raise the surface temperature of Titan by enough to drive south polar–style convection and cloud formation. As is hypothesized for the south pole, a surface tem-

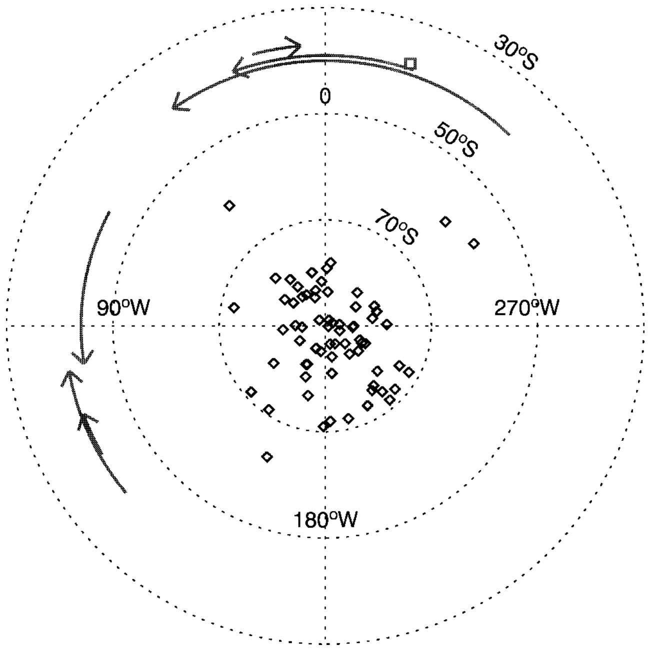

FIG. 2.—Locations of the previously observed south polar clouds (*diamonds*). Extended temperate latitude clouds are represented by solid lines, with an arrow indicating where the cloud may have extended beyond the visible limb of Titan. One spatially unresolved temperate latitude cloud was observed on 2004 September 2 (*square*). The uncertainty in location is 1°–3°. [*See the electronic edition of the Journal for a color version of this figure*.]

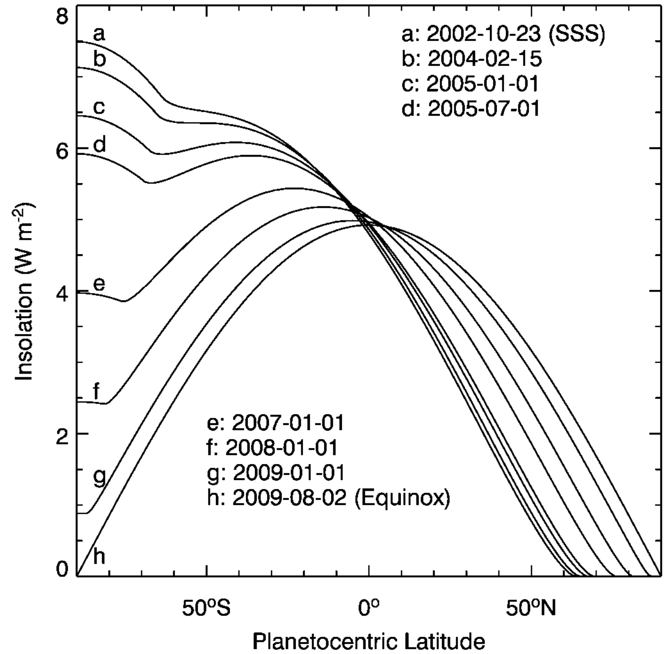

FIG. 3.—Daily mean insolation at the top of Titan's atmosphere. The maximum seasonal insolation occurs at the south pole at the time of southern summer solstice (SSS). In early 2004, a local maximum emerges at ~50° south and then moves northward and becomes the global maximum in 2005 July.

perature increase of only a few degrees kelvin is thought to be sufficient to drive cloud formation.

A second class of model for latitudinally confined cloud formation suggests that, like the south polar clouds, the temperate clouds are tied to Titan's seasonally varying patterns of insolation and global circulation. As Titan moves from southern summer solstice to the spring equinox, the latitude of maximum insolation moves from the pole to the equator, as shown in Figure 3. By equinox (which next occurs in 2009), the global circulation will shift from the pole-to-pole flow thought to occur currently to a two-cell system rising at the equator and sinking at the poles (Tokano et al. 2001). As on the Earth, cloud formation should occur at the location of the rising branch of the circulation system, so by equinox the clouds should shift from the pole to the equator. Between the solstice and equinox, the cloud position has been predicted to follow the location of maximum average insolation (Brown et al. 2002). Yet the south pole remains the point of maximum average insolation until 2005 July, and we expect cooling of the south pole to take even longer, so this initial prediction from the global circulation hypothesis cannot explain the appearance of these temperate clouds. Nonetheless, we note that a secondary local maximum in the average insolation began to occur in 2004 February at ~52° south. This secondary maximum moves northward quickly, passing 40° south in 2005 January. While the presence of a local maximum in insolation does not lead to convection in any simple way, the shift from a single-cell to a two-cell circulation is complicated, so we do not immediately rule out this secondary insolation peak as perhaps beginning to drive this large-scale circulation shift and thus temperate cloud formation. Such complex behavior is best explored in global circulation models (GCMs). Current Titan GCMs (see, e.g., Tokano et al. 2001 and references therein) hold surface temperature temporally fixed and so cannot capture these types of behaviors (including the south polar clouds). New Titan GCMs that allow surface temperature to seasonally vary are needed to test the viability of this hypothesis.

While both of these classes of models fit the constraints of the current observations, both suffer severe limitations. The geological explanation relies on hypothetical cryovolcanic activity that has never been seen and is perhaps unlikely. The meteorological explanation relies on the fact that the circulation is complicated, to dismiss the initial prediction that cloud formation should still occur exclusively at the south pole for several more years. Nonetheless, these two classes of models do the best job of meeting the constraints of the current observations.

Determining which one of the classes of models best explains these new clouds is a straightforward observational problem. In the geological models, the clouds are tied to surface features that move only on geological timescales. These temperate clouds will permanently remain at the locations we see them today, even as the large-scale circulation shifts. In contrast, the meteorological hypothesis predicts that the clouds will move northward as the secondary maximum (and eventually the maximum) in solar insolation moves northward. The beginning of the movement from 40° south to the equator in only 7 yr will be easily seen in remote observations of these clouds over the next few years.

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Note added in proof.—The *Cassini* spacecraft confirmed the frequent presence of these midlatitude clouds with observations starting 2004 May 29 (C. C. Porco et al. 2005, in preparation).