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STATISTICS OF TITAN'S SOUTH POLAR TROPOSPHERIC CLOUDS

Antonin H. Bouchez[1] and Michael E. Brown
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125
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ABSTRACT

We present the first long-term study of the behavior of the sporadically observed tropospheric clouds recently discovered near Titan's south pole. We find that one or more small individual cloud systems is present in the 70°–80° south region during every night of observation. These clouds account for 0.5%–1% of Titan's 2.0 μm flux, consistent with a global cloud cover fraction of 0.2%–0.6%. Clouds observed over multiple-night observing periods remained nearly fixed in brightness and position with respect to Titan's surface. The continual presence of south polar clouds is consistent with the hypothesis that surface heating during the long period of continuous polar sunlight at the time of Titan's southern summer solstice drives seasonal convection and cloud formation at the pole.

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

1. INTRODUCTION

The discovery of transient clouds in Titan's troposphere (Griffith et al. 1998) was unexpected. While high-resolution imaging studies of Titan's surface in the visible (Smith et al. 1996; Richardson et al. 2001) and near-infrared (Combes et al. 1997; Gibbard et al. 1999; Meier et al. 2000; Coustenis et al. 2001) gradually uncovered Titan's fixed surface albedo features, careful searches failed to conclusively detect any transient cloud features. Instead, the existence of tropospheric clouds on Titan was first confirmed indirectly by disk-integrated infrared spectra that showed that Titan had brightened dramatically in spectral regions sensitive to scattering in the lower atmosphere while remaining unchanged in spectral regions sensitive only to scattering at higher altitudes in the atmosphere (Griffith et al. 1998). Increasingly precise disk-integrated spectra soon after demonstrated that smaller clouds, covering ~1% of Titan's disk, come and go on a daily basis (Griffith et al. 2000), yet the location of both the small daily-varying and the occasional larger clouds remained unknown.

Adaptive optics (AO) observations with the Keck and Gemini telescopes in 2001 December clearly located small transient clouds near the south pole (Brown et al. 2002; Roe et al. 2002). Individual clouds were observed to persist at least 24 hr in one case (Brown et al. 2002) and vary in flux by 50% over 3 hr in another (Roe et al. 2002), but little other information on their lifetimes, formation frequency, and size spectrum can be gleaned from these few observations.

Based on these limited observations, Brown et al. (2002) hypothesized that the presence of clouds forming near the south pole of Titan was a result of local surface heating, which drives atmospheric convection. In the time period around Titan's summer solstice (which occurred in 2002 October), the south polar regions remain in continuous sunlight and receive more daily average insolation than any other spot on the globe. Titan's lower atmosphere is sufficiently close to being convectively unstable that even a small amount of additional heat input at the bottom of the atmosphere is sufficient to cause convection, which in turn can lead to runaway condensation and cloud formation. This hypothesis predicts that clouds will follow the point of maximum average daily insolation, which will remain at the south pole until 2005.

Frequent resolved imaging over many rotations provides the most promising means of constraining basic properties of Titan's tropospheric clouds. Here we present the results of an intensive imaging campaign performed with the Palomar Hale 5 m telescope in the fall and winter of 2002–2003. These observations shed light on the typical locations, lifetimes, formation frequency, and size spectrum of Titan's south polar clouds and constrain the wind speed in the region of Titan's troposphere in which the clouds appear.

2. OBSERVATIONS

Images of Titan were acquired on 16 nights between 2001 December 20 and 2003 January 14, using the JPL AO system and the Cornell-built PHARO camera/spectrograph at the Cassegrain focus of the Palomar Hale telescope (Table 1). All images were taken through a K_s filter (1.990–2.300 μm) and recorded at a plate scale of $0\farcs02517$ pixel^{-1}, with an integration time of 9.085 s. A minimum of 16 images were taken each night, with the telescope offset by 5″ between each set of four to minimize the effect of bad pixels and uncertain flat-field calibration. Observing conditions ranged from photometric to thin high clouds.

Images were processed using standard near-infrared data image reduction techniques (sky frame subtraction, division by a flat-field map, and correction for bad pixels). Each night's images were then sorted by quality of the AO performance, and only the best 8–16 frames were retained. These images were then shifted to a common center and averaged to produce a single mean image of Titan for each night of observation (Fig. 1) and an associated uncertainty map given by the variance of each pixel across the stack of shifted frames.

3. ANALYSIS

In the initial cloud imaging observations of Brown et al. (2002) and Roe et al. (2002), the identification of transient features near the south pole as tropospheric clouds was confirmed by multiwavelength measurement of the height of the features in the atmosphere. The current observations consist of images at only a single wavelength, so the clouds can be neither located nor confirmed by their height in the atmosphere. In-

[1] Current address: W. M. Keck Observatory, 65-1120 Mamalahoa Highway, Kamuela, HI 96743.

TABLE 1
OBSERVATIONS

Date	UT	CML[a] (deg)	Observers[b]
2001 Dec 20	06:31–06:43	92.5	1
2002 Sep 23	11:42–11:45	210.5	1
2002 Sep 24	12:08–12:15	233.5	1
2002 Sep 25	11:29–11:36	255.4	1
2002 Sep 26	12:08–12:24	278.6	2
2002 Sep 27	11:50–12:05	300.9	2
2002 Nov 14	10:21–10:38	305.2	3
2002 Nov 15	10:30–10:54	327.0	4
2002 Nov 16	09:01–09:16	348.2	5
2002 Nov 17	09:59–10:06	11.7	5
2002 Nov 18	09:35–09:42	33.9	5
2002 Dec 24	08:36–09:07	129.1	6
2002 Dec 27	08:03–08:10	196.4	7
2002 Dec 28	07:52–07:59	218.9	7
2003 Jan 12	07:00–07:14	198.0	5
2003 Jan 14	05:31–05:38	241.9	5

[a] West longitude of Titan's central meridian.
[b] Observers: (1) A. Bouchez, M. Brown, M. Troy, R. Dekany. (2) C. Dumas. (3) M. Konacki. (4) C. Trujillo, A. Bouchez. (5) S. Metchev, C. Bian, J. Eisner. (6) J. Carson, E. Furlan, W. Forrest, K. Uchida. (7) E. Furlan, L. Keller, K. Uchida, D. Watson.

stead, south polar clouds were located in these images by their transient appearance on an otherwise time-invariant rotating surface.

In almost all images, one or more distinct sources is visible near Titan's south pole. Comparison with high-resolution maps of Titan's surface now available (Roe et al. 2004; Bouchez et al. 2004) confirm that these brightenings' sources are indeed transient. We have identified 19 unresolved transient bright features in the images, corresponding to 12 distinct transient features visible on 15 of the 16 nights (Table 2). On 2002 November 15—the single night when no obvious south polar transient is visible—the AO correction is poor, and we observe a transient feature both the day before and the day after this night. We conclude that this feature was also present on November 15 but was not detected because of the poor correction. While the height in the atmosphere of these transient features cannot be measured from these data, the near-continuous appearance of transient features near Titan's south pole in these observations strongly suggests that we are viewing the same phenomenon earlier identified as tropospheric clouds.

Cloud identification is aided by the relatively dark and bland appearance of Titan's south polar surface regions; all bright spots near the south pole have been subsequently identified as clouds. The remainder of Titan, however, has complex and bright albedo variations on the surface. The variable performance of AO on different nights of observation makes confident identification of transient features in these regions difficult. The midlatitude clouds recently reported by Roe et al. (2005), for example, would likely not have been detectable in these observations.

In order to measure the flux and location of the transient clouds that were identified, we first attempt to isolate the cloud emission in each image by subtracting the contribution to the images from the haze and surface of Titan. The contribution of sunlight scattered off of Titan's relatively invariant strato-

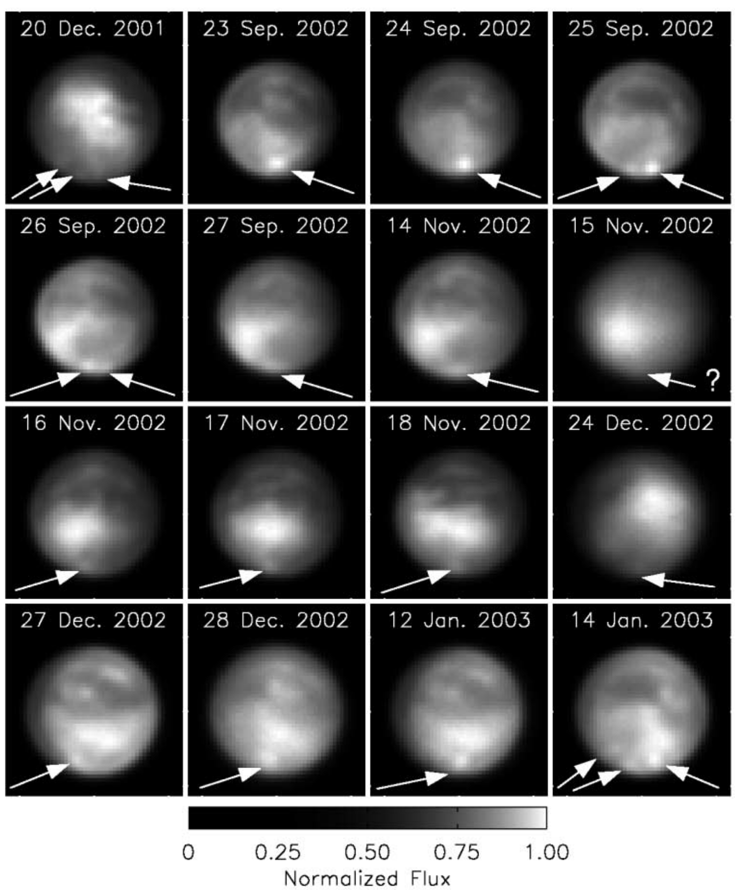

FIG. 1.—Palomar Hale telescope images of Titan in 2001–2003. Transient clouds can be identified near Titan's south pole (*white arrows*) on all but one night (2003 November 15, when the AO correction is poor). Each image is 1″.2 across.

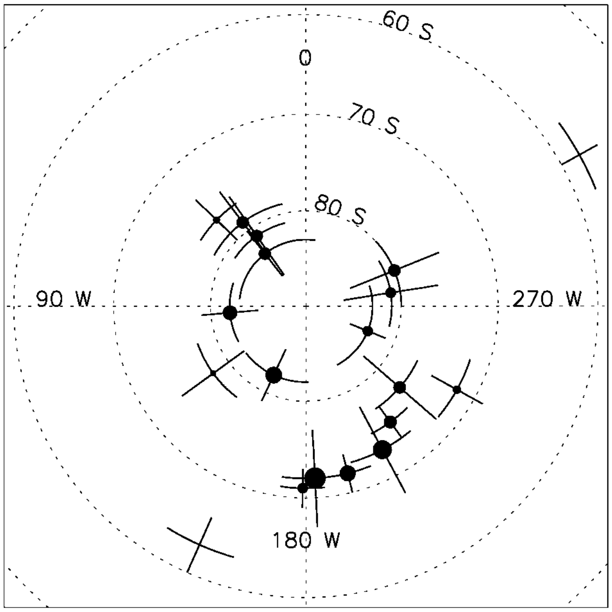

FIG. 2.—Polar stereographic projection of the locations of the transient clouds detected. Relative flux is indicated by the area of the filled circles, and 1 σ uncertainties in the positions are shown with error bars.

spheric haze is removed in an ad hoc fashion by subtracting a scaled Brackett-γ (Brγ, 2.16–2.18 μm) image, obtained on 2002 September 23, from each. The difference images record only sunlight scattered below the altitude at which $\tau_{CH_4} \approx 1$ for the Brγ filter, which corresponds to approximately 50 km (Roe et al. 2002).

Next, we attempt to model and remove the contribution from Titan's surface. The surface contribution is represented by the convolution of a uniform sphere and a variable point-spread function (PSF). We model the PSF as the sum of a diffraction-limited Airy pattern and two Gaussian functions. Such a model PSF is a reasonable approximation of the diffraction-limited core plus seeing-limited halo PSF of an AO system. The width and strength of the Gaussian contributions to each night's PSF are iteratively adjusted until the residuals in the subtraction of the data and the model image are minimized. The halo of emission around Titan's sharp limb provides an excellent measure of the non–diffraction-limited component of the PSF in each image. While it is clear that a uniform disk little resembles the complex surface features seen on Titan, the surface near the south polar regions where the clouds have been identified is indeed one of the more uniform regions of the disk, so locally the subtraction remains good (Roe et al. 2004; Bouchez et al. 2004). Finally, the model PSF-convolved surface image is subtracted from the haze-subtracted image, leaving the south polar clouds isolated from surface and haze contributions.

The location and flux of the unresolved clouds are determined by fitting scaled PSFs to the residual images, and uncertainties in these measurements are determined by adding 20 different realizations of the background and photon noise to the images and repeating the entire forward-modeling process. The flux of each cloud is then normalized to Titan's total flux at an orbital longitude of 253°, using the relative disk-averaged surface brightness found in the high-resolution maps of Bouchez et al. (2004). The clouds of September 27 and November 14 do not appear to be single point sources, so their fluxes and positions are not well measured, but in both cases the same clouds are observed on previous or subsequent nights.

4. DISCUSSION

Transient clouds were detected on 15 of 16 nights in Palomar images of Titan taken between 2001 December 20 and 2003 January 14. The one night on which no clouds were apparent suffered from poor AO correction, and the presence of clouds both the previous and subsequent nights suggests that clouds were present but not resolved even on that night. It therefore appears likely that the clouds were continually present poleward of 70° south during the period of 2001 December to 2003 January. Occasional clouds were also detected at lower latitudes, the furthest north being located at 58° ± 2° south on 2003 January 14 (Fig. 2).

Individual unresolved clouds observed with the Palomar AO system contribute between 0.1% and 1.1% of Titan's flux at 2.0 μm. This flux corresponds to the brightness expected for optically thick, foreshortened clouds with diameters between

TABLE 2
OBSERVED POINT-LINK TROPOSPHERIC CLOUDS

Date	Flux[a] (%)	West Longitude (deg)	Latitude (deg)	Identification[b]
2001 Dec 20	0.38 ± 0.06	46 ± 12	−77 ± 3	1
	0.32 ± 0.06	126 ± 17	−78 ± 4	2
	0.09 ± 0.05	156 ± 8	−63 ± 3	3
2002 Sep 23	1.05 ± 0.08	183 ± 11	−72 ± 5	4
2002 Sep 24	0.89 ± 0.08	208 ± 12	−73 ± 5	4
2002 Sep 25	0.77 ± 0.08	194 ± 8	−72 ± 2	4
	0.52 ± 0.08	279 ± 23	−81 ± 5	5
2002 Sep 26	0.60 ± 0.07	216 ± 9	−75 ± 2	4
	0.62 ± 0.07	292 ± 21	−80 ± 5	5
2002 Nov 16	0.67 ± 0.11	38 ± 46	−83 ± 3	6
2002 Nov 17	0.67 ± 0.11	37 ± 24	−79 ± 4	6
2002 Nov 18	0.67 ± 0.11	35 ± 21	−81 ± 5	6
2002 Dec 24	0.80 ± 0.23	95 ± 23	−82 ± 3	7
2002 Dec 27	0.39 ± 0.10	241 ± 11	−72 ± 3	8
2002 Dec 28	0.58 ± 0.10	229 ± 15	−77 ± 5	8
2003 Jan 12	0.88 ± 0.11	155 ± 27	−82 ± 3	9
2003 Jan 14	0.52 ± 0.10	179 ± 7	−71 ± 2	10
	0.49 ± 0.10	248 ± 40	−83 ± 2	11
	0.18 ± 0.06	299 ± 7	−58 ± 2	12

[a] Flux of cloud, compared to total disk flux at orbital longitude 253° west.
[b] Identification number of individual clouds viewed on multiple occasions.

100 and 400 km (Brown et al. 2002), somewhat smaller than the projected diffraction limit of 500 × 1000 km. Thus, the brightness of the unresolved clouds is consistent with filling factors of 5%–20%.

When we integrate the light of all clouds identified each night, the corresponding areal coverage of optically thick clouds over Titan's visible disk varied from 0.2% on 2002 December 27 to 0.6% on 2002 September 23. These figures are similar to those derived by Griffith et al. (2000) for the areal coverage of the clouds responsible for Titan's daily spectral variations at 2.12–2.16 μm. However, no clouds were detected that rival the 7% coverage event observed spectroscopically on 1995 September 5 (Griffith et al. 1998).

No day-to-day variation in the flux of individual clouds was detected that could not be attributed to their fading due to their reduced projected area and increased methane absorption as they approach Titan's limb. Such geometric fading is clearly seen in the cloud that persisted for four nights from 2002 September 23 to 2002 September 26 (cloud identification number 4), gradually decreasing in flux by 40%. We see no evidence of the rapid cloud formation or dissipation as observed in more sensitive Keck AO observations (Roe et al. 2002).

Tracking the motion of tropospheric clouds is one of the few available methods for measuring the tropospheric wind speeds on Titan. The longevity of the clouds that we have detected (two persist for at least three nights, four for at least two nights) suggests that this measurement might be possible. No cloud shows any significant motion. From these lack of motions, we place 3 σ upper limits of 4.0 m s^{-1} westward and 2.0 m s^{-1} eastward on the wind speeds at 72°–83° south, the location of the four multiple-night clouds. This upper limit applies to altitudes of 10–20 km above the surface, the region in which spectra have placed the cloud tops (Griffith et al. 2000; Brown et al. 2002), and is consistent with the low tropospheric winds predicted by general circulation models of Titan's atmosphere (Hourdin et al. 1995; Tokano et al. 2001).

5. CONCLUSIONS

The 16-night study presented here provides the first long-term look at the tropospheric clouds recently discovered near Titan's south pole. The images show that tropospheric clouds are continually present in the 70°–80° south region and occasionally as far north as 58° south. The constant presence of southern clouds during the current season is consistent with the hypothesis that surface heating during the long period of continuous polar sunlight at the time of Titan's southern summer solstice drives seasonal convection and cloud formation near the pole (Brown et al. 2002). As summer solstice passes, the peak of mean daily insolation will eventually jump from the pole and begin moving northward with the subsolar point. The surface-heating hypothesis predicts that as the polar regions cool, cloud activity there will cease and that new cloud systems will emerge following the subsolar point northward. Observations of Titan and its clouds over the coming years will test this long-term prediction and continue to improve our understanding of Titan's dynamic cloud systems.

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