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DISCOVERY OF FOG AT THE SOUTH POLE OF TITAN

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ABSTRACT

While Saturn's moon Titan appears to support an active methane hydrological cycle, no direct evidence for surface–atmosphere exchange has yet appeared. The indirect evidence, while compelling, could be misleading. It is possible, for example, that the identified lake features could be filled with ethane, an involatile long-term residue of atmospheric photolysis; the apparent stream and channel features could be ancient remnants of a previous climate; and the tropospheric methane clouds, while frequent, could cause no rain to reach the surface. We report here the detection of fog at the south pole of Titan during late summer using observations from the VIMS instrument on board the Cassini spacecraft. While terrestrial fog can form from a variety of causes, most of these processes are inoperable on Titan. Fog on Titan can only be caused by evaporation of nearly pure liquid methane; the detection of fog provides the first direct link between surface and atmospheric methane. Based on the detections presented here, liquid methane appears widespread at the south pole of Titan in late southern summer, and the hydrological cycle on Titan is currently active.

Key words: infrared: solar system – planets and satellites: individual (Titan)

1. INTRODUCTION

Saturn's moon Titan appears to support an active methane hydrological cycle, with evidence for tropospheric clouds (Griffith et al. 1998; Brown et al. 2002; Roe et al. 2005), polar lakes (Stofan et al. 2007), surface changes (Turtle et al. 2009), and liquid carved channels (Tomasko et al. 2005; Soderblom et al. 2007; Lorentz et al. 2008). Circulation models suggest that liquid methane could be predominantly confined to high latitudes and that methane should be seasonally transported from summer pole to summer pole (Mitchell 2008). Yet little concrete evidence for the surface–atmosphere interactions required for this cycle has been seen. The clouds may produce no rain (Schaller et al. 2006), the large polar lakes could be filled with non-evaporating ethane, rather than methane (Brown et al. 2008), the cause of surface albedo changes is totally unknown (Turtle et al. 2009), and the channels could be a record of an ancient climate (Griffith et al. 2008).

One signature of a currently active hydrological cycle on Titan would be the detection of localized evaporation of liquid methane from the surface. Though evaporation itself is not directly visible, its effects could possibly be detected. While air on Titan has a methane relative humidity of ∼50% (Niemann et al. 2005), near-surface air in direct contact with evaporating methane could locally acquire humidities surface near 100%, allowing the methane to condense into surface-level fog. While methane condensation is clearly seen by the presence of clouds high in the troposphere (where air with 50% humidity can become saturated through lifting), no surface-level fog has yet been reported.

Here we describe a search for surface fog on Titan, discuss the details of possible formation mechanisms for fog, and consider the implications for Titan's hydrological cycle.

2. OBSERVATIONS

To search for fog on Titan we examined all data publicly available through the NASA Planetary Data System database from the VIMS (Brown et al. 2004) instrument on the Cassini spacecraft. VIMS is a hyperspectral imager, obtaining near-simultaneous images in up to 256 channels between 1 μm and 5 μm. This capability, coupled with several strong methane absorption features in Titan's atmosphere throughout this spectral region, allows us to sum multiple wavelength images to construct synthetic filters which probe to different depths in Titan's atmosphere. In Brown et al. (2009a, 2009b), we created three synthetic filters which allowed us to probe to the surface, to the troposphere, and to the stratosphere separately. Using the three filters, we could quickly discern which features were surface features, tropospheric clouds, or stratospheric hazes. Here, we use the same three synthetic filters, and we also create an additional filter from the sum of all channels from 4.95 to 5.12 μm. This region of the spectrum is transparent all the way to the surface and is sensitive to scattering from cloud particles.

Fog, if present, would appear as a bright feature visible in the synthetic filter that probes to the surface, but it would not appear in the filters that probe only to the troposphere and stratosphere. (The many tropospheric clouds, in contrast, appear bright in both the surface *and* tropospheric filters.) Fog (and clouds) would also appear bright in the 5 μm filter where the surface is generally dark but cloud particles are bright. Fog would be indistinguishable from a bright albedo mark on the surface of Titan except that fog could be highly variable. Our strategy to search for fog on Titan was thus to search for features which appear bright in the surface and 5 μm filters, which do not appear in the troposphere and stratosphere filters, and which are temporally variable.

For each of the ∼9000 VIMS hyperspectral observation of Titan available to date, we created the four synthetic filter images and redisplayed them in a south polar projection. We then visually inspected each set of images to search for features which had the expected characteristics of fog. While examining these images, we found that multiple images of a single location viewed at different solar and spacecraft geometries appear subtly different; we thus only considered a detection to be significant when the surface filter and 5 μm filter simultaneously showed a feature as bright as any feature ever observed at the south pole. Four such features, which we will temporarily call "fog-like," were identified. The best examples are shown in

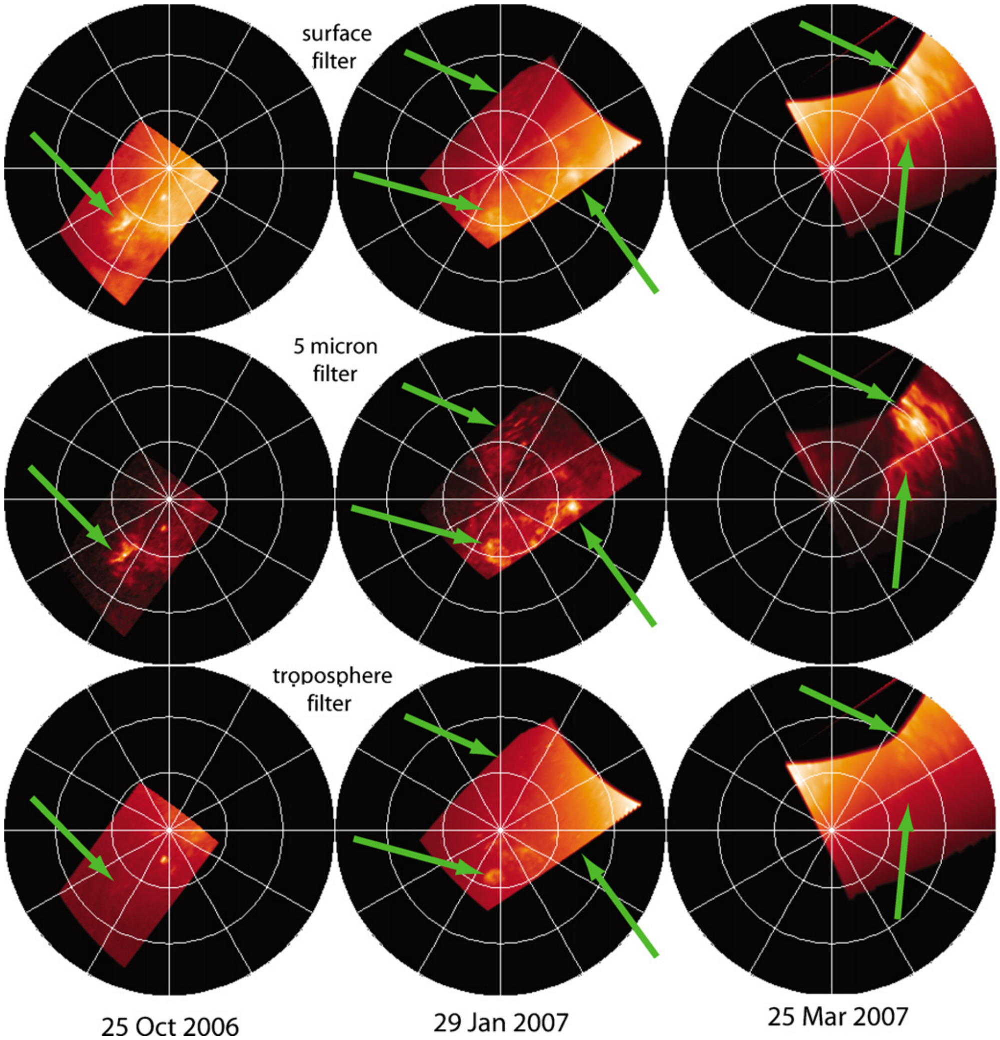

Figure 1. Views of the south pole of Titan on four separate dates. Fog-like features, marked with green arrows, can be seen in the synthetic filter which probes to Titan's surface, and in the 5 μm filter, which is particularly sensitive to large cloud particles. These variable surface features do not appear in the synthetic troposphere filter, which is insensitive to scattering below ~10 km. The images are all shown as identical polar projections with lines of latitude between −60 and −90 shown every 10 degrees and with 0 degree longitude at the top.

Figure 1. These images reveal the typical wispy appearance of these features when seen at moderate spatial resolution. Indeed, the morphological appearance of the 2007 March 25 image is particularly suggestive: features which appear in the troposphere-probing filter appear related to those which appear only in the surface filter, suggesting, perhaps, surface fog which is also rising into the troposphere in places.

A more detailed examination of the full 1–5 μm spectra of these features can provide more clues to their origin. Figure 2 shows an example of comparisons between the spectra of the surface, a tropospheric cloud, and a fog-like feature. The fog-like features appear spectrally unlike any surface unit at the south pole. In spectral regions that are transparent all the way to the surface, the fog-like feature appears identical to the tropospheric cloud, including, most dramatically, the high reflectivity near 5 μm when compared to the surface. Tropospheric clouds are bright at these wavelengths because they are composed of bright single scattering particles with sizes larger than 5 μm (Barnes et al. 2005; Griffith et al. 2005), as expected for condensation of an abundant species like methane. Higher elevation ethane clouds, in contrast, are dark at 5 μm because they are made from smaller particles, as expected for condensation from a minor constituent (Griffith et al. 2006). The spectral similarity of the fog-like feature to tropospheric methane clouds suggests a similar particle size and thus similar high atmospheric abundance. Methane is the only condensible with such a high abundance in Titan's atmosphere. In spectral regions where transmission to the surface is significantly attenuated, but where transmission to the troposphere is high (the 2.1 μm region, for example), tropospheric clouds appear bright while the surface and fog-like features are dark, suggesting again that the fog-like features originate from close to the surface.

3. ANALYSIS

To determine the altitude of the fog-like feature, we perform full calculations of the radiative transfer through Titan's atmosphere using the method of Ádámkovics et al. (2009; see also Ádámkovics et al. 2007) which takes Huygens measurements of temperature, pressure, composition, and haze profiles as initial starting points and solves the radiative transfer equation for 16 pseudo-plane-parallel layers from 0–200 km altitude. While accurate radiative transfer calculations through the poorly known

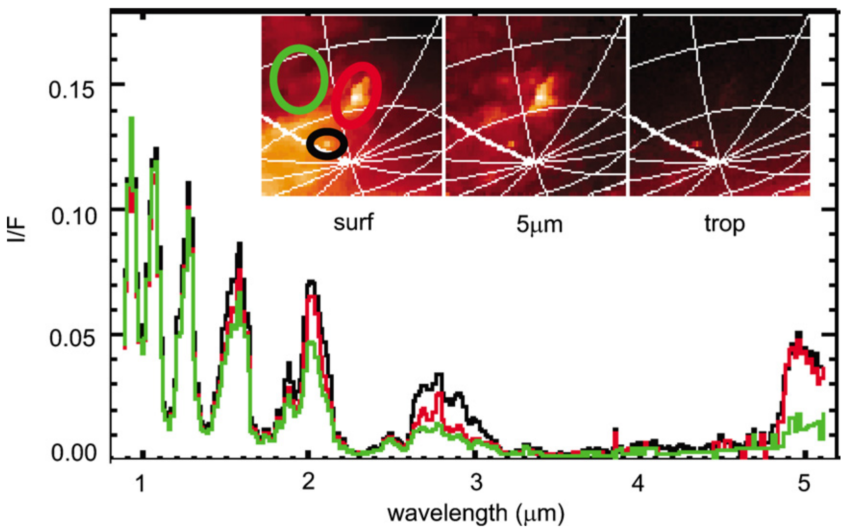

Figure 2. VIMS images of the 2006 October 25 fog. The surface, 5 μm, and troposphere images use the same synthetic filters as in Figure 1. Areas of surface, fog, and tropospheric cloud are shown by green, red, and black ovals, respectively. The full spectra of each of these selected regions are shown in the same colors. The surface, fog, and cloud spectra clearly differ. Both the fog and the cloud are bright at 5 μm, while the fog appears intermediate between the surface and troposphere in the 2.5–3 μm region.

south polar atmosphere on Titan are fraught with uncertainty, we side-step many of these difficulties by instead performing simple comparisons of adjacent areas of the image with and without fog-like features. Assuming that the large-scale atmospheric scattering and opacity do not change significantly between these regions, which are only 400 km apart, we can accurately model the relative effect of adding fog at varying heights to the spectrum.

First, we attempt to reproduce the spectrum of the surface immediately adjacent to the fog-like feature. We model the upper atmosphere haze profile by scaling the Ádámkovics et al. (2009) Huygens-derived aerosol opacity profile until the spectrum beyond 2.15 μm (which is only sensitive to regions above the tropopause) is reproduced. Next we model the spectrum below 2.15 μm by first scaling the modeled surface reflectivity until the modeled spectrum matches the observations in the peak of the 2 μm window and determining the apparent reflectivity of the remainder of the spectral region. At this point, remaining discrepancies between the model and measured spectrum are assumed to be due to the wavelength dependence of the surface reflectivity. This modeling of the spectrum of the surface as seen through Titan's atmosphere is not unique, but provides a basis for comparing the spectra at adjacent locations.

After matching the surface spectrum, we calculate the spectral effect of clouds and fog by adding a series of scattering layers of varying elevations and opacities to the model. In these models, cloud particles are assumed to be large and thus uniformly scattering at all wavelengths, with albedos of 0.99 and Henyey–Greenstein scattering parameters of 0.85 (varying these parameters over wide ranges had little impact on the final spectrum). Figure 3 shows modeled spectrum for a series of optically thin clouds ($\tau = 0.25$) of varying altitudes overlying a surface of reflectivity 0.10. The spectrum of the fog-like feature is best fit by a cloud with an altitude of 750 m. Models with cloud heights of 3 km or higher differ significantly from the data in the 1.98 μm and the 2.09–2.14 μm regions which are particularly sensitive to the lower troposphere. We thus conclude that the fog-like feature is indeed best described as surface fog or perhaps near-surface fog on Titan. No cloud or fog at such a low elevation has ever before been identified on Titan.

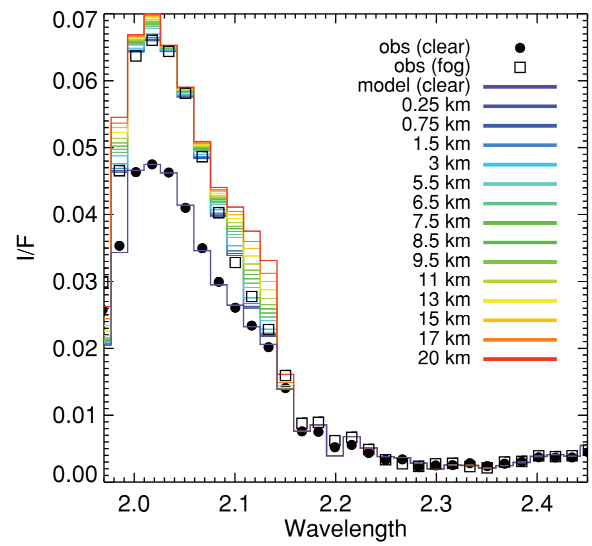

Figure 3. Spectra of the surface (filled circles) and fog (black open squares) in the 2 μm spectral window where altitude is best constrained. The purple line shows the best-fit radiative transfer model which matches the surface. Colored lines show fits to the fog spectra that include an increased surface reflectivity and a scattering cloud layer at altitudes between 0.25 km and 20 km. Cloud altitudes near 750 m most closely match the observations, whereas models with cloud tops above 3 km altitude are inconsistent with the observed spectra.

4. DISCUSSION

Fog forms when the vapor in ground-level air saturates with some species which then condenses. On the Earth, this saturation commonly occurs when air radiatively cools overnight until it reaches the water dew point. On Titan, such a formation mechanism is impossible. Titan's lower atmosphere has a radiative time constant of ~100 yr (Hunten et al. 1984) and 94 K air that has a relative methane humidity of ~50% must be cooled ~7 K before methane condensation will initiate (mixing ratios of any other condensible species are negligible). Similarly, advection of typical Titan air over even the coldest locations on Titan provides insufficient cooling for any composition fog to form. Fog on Titan instead requires elevating the mixing

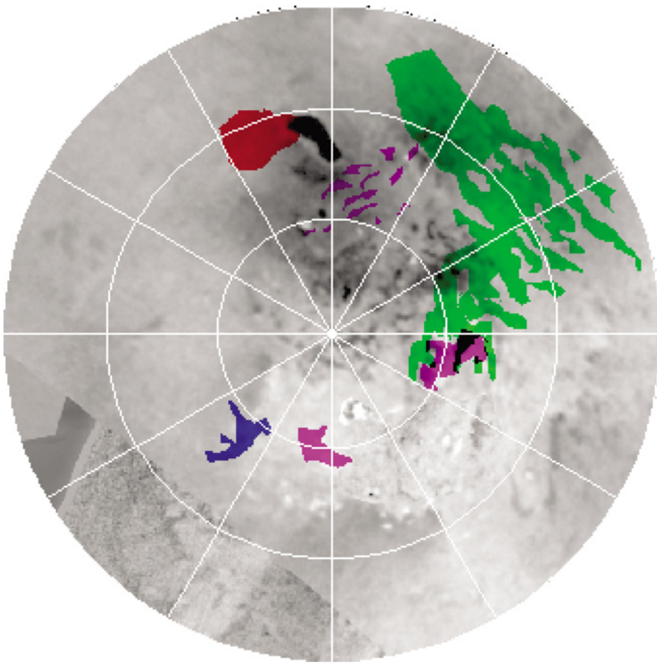

Figure 4. Locations of all identified clouds features. Blue, purple, red, and green are from 2006 October 25, 2007 January 29, 2007 March 9, and 2007 March 25, respectively. The background shows a south polar base map of Titan as derived from the visible imager on the ISS instrument.

ratio of the fog-forming condensible species rather than simply decreasing temperature. If the fog is near ground level, the surface relative humidity of the condensible species must be nearly 100%.

There are few ways to produce such a locally elevated relative humidity of a condensible species on Titan, short of some unphysically motivated mechanical injection mechanism. Indeed, we find no physically plausible explanation other than to hypothesize that saturation occurs where surface air is in direct contact with nearly pure evaporating liquid methane. Liquid methane appears clearly implicated: the fog is composed of large particles, like those of the higher level tropospheric methane clouds, suggesting condensation of an abundant species, and methane is the only major surface constituent with a non-negligible vapor pressure. Methane evaporation alone can lead to significant condensible concentrations. The liquid methane must be nearly pure because evaporation into overlying air can only elevate the humidity of the near-surface air to a value as high as the mixing ratio of the methane in the liquid, thus, to raise the humidity to nearly 100% requires nearly pure liquid methane.

While fog requires saturated near-surface air, methane saturated near-surface air on Titan is unstable to moist convection for a typical Titan thermal profile (Griffith et al. 2008). Rather than forming fog, such air will simply rise through the troposphere. Fog can only persist at the surface if the surface air is both saturated in methane and colder (and thus more stable) than the typical thermal profile. Pools of evaporating liquid methane could indeed be cooler than their surroundings (Mitri et al. 2007) and, under the right meteorological conditions, will add humidity to and drain heat from overlying air parcels. No other formation explanation can naturally explain both the increased humidity and decreased temperature required. This formation mechanism also naturally explains the occasional correlation between fog and overlying tropospheric clouds. If surface humidity is raised without a sufficient decrease in temperature, saturated air parcels will convect into the upper troposphere (Griffith et al. 2000). Much of the continued south polar cloudiness (Brown et al. 2009b) may be tied directly to surface liquid methane evaporating and rising unstably.

The locations of the identified fog features and a comparison to the ISS base map[3] are shown in Figure 4. All identified fog features are southward of 65 S. No correlation is seen between the locations of fog and the location of the one suspected large lake, Ontario Lacus—which perhaps is a reservoir of ethane only or mixed ethane–methane (Brown et al. 2008)—the locations of dark albedo features, or the location of the large observed albedo change (Turtle et al. 2009). No temporal association with known south polar tropospheric cloud outburst appears (Schaller et al. 2006, 2009).

Fog is likely a more common occurrence than shown here; it is difficult to identify in the typical low-resolution images obtained by VIMS, but seen in nearly all high-resolution south polar images. Liquid methane and evaporation are likely distributed even more widely than the observed fog; all evaporation need not cause fog: special meteorological conditions such as low winds are also likely required. Liquid methane appears widespread at the south pole of Titan in the late southern summer.

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