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. It is possible 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 from 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 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 hydrolgical cycle on Titan is current active.

Subject headings: planets and satellites: Titan – infrared: solar system

1. Introduction

Saturn's moon Titan appears to support an active methane hydrological cycle, with evidence for 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 (Cassini Radar Team 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 carved channels could be a record of an ancient climate (Griffith et al. 2008). One signature of active evaporation would be fog on Titan. In Titans atmosphere, fog can only occur when near-surface air saturates through direct contact with liquid methane. The detection of fog would reveal the presence of actively evaporating surface liquid methane and would point to a vigorous surface-atmosphere exchange in a currently active hydrological cycle.

2. Observations

To search for fog on Titan we examined all data publically available through the PDS 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 and 5 μm. This capability, coupled with several strong methane absorption features in Titans atmosphere throughout this spectral region, allows us sum multiple wavelength images to construct synthetic filters which probe to different depths in Titans atmosphere. We use identical synthetic filters already developed and demonstrated in Brown et al. (2009a) and Brown (2009b). We also added an addition synthetic filter from the sum of all channels from 4.95 to 5.12 μm. This region of the spectrum is transparent to the surface and is sensitive to scattering from small particles. Fog, if present, would appear as a bright feature visible in the synthetic filter which probes all the way to the surface, but not visible in the filters which probe only to higher altitudes. It will appear bright in the 5 μm filter where the surface is generally dark but small cloud particles are bright. Such a feature would be indistinguishable from a bright permanent albedo mark on the surface of Titan except that fog could be highly variable.

To search for such bright variable features, we projected all VIMS surface and troposphere images to a common south polar projection and searched for the transient presence of bright surface features which did not appear in the tropospheric synthetic filter. Multiple images of a single location obtained at different solar and spacecraft geometries can appear subtly different; we thus only considered the appearance of unmistakable bright spots. Four such potential fog features were identified. The best examples are shown in Figure 1. These images reveal the typical wispy appearance of these features when seen at moderate spatial

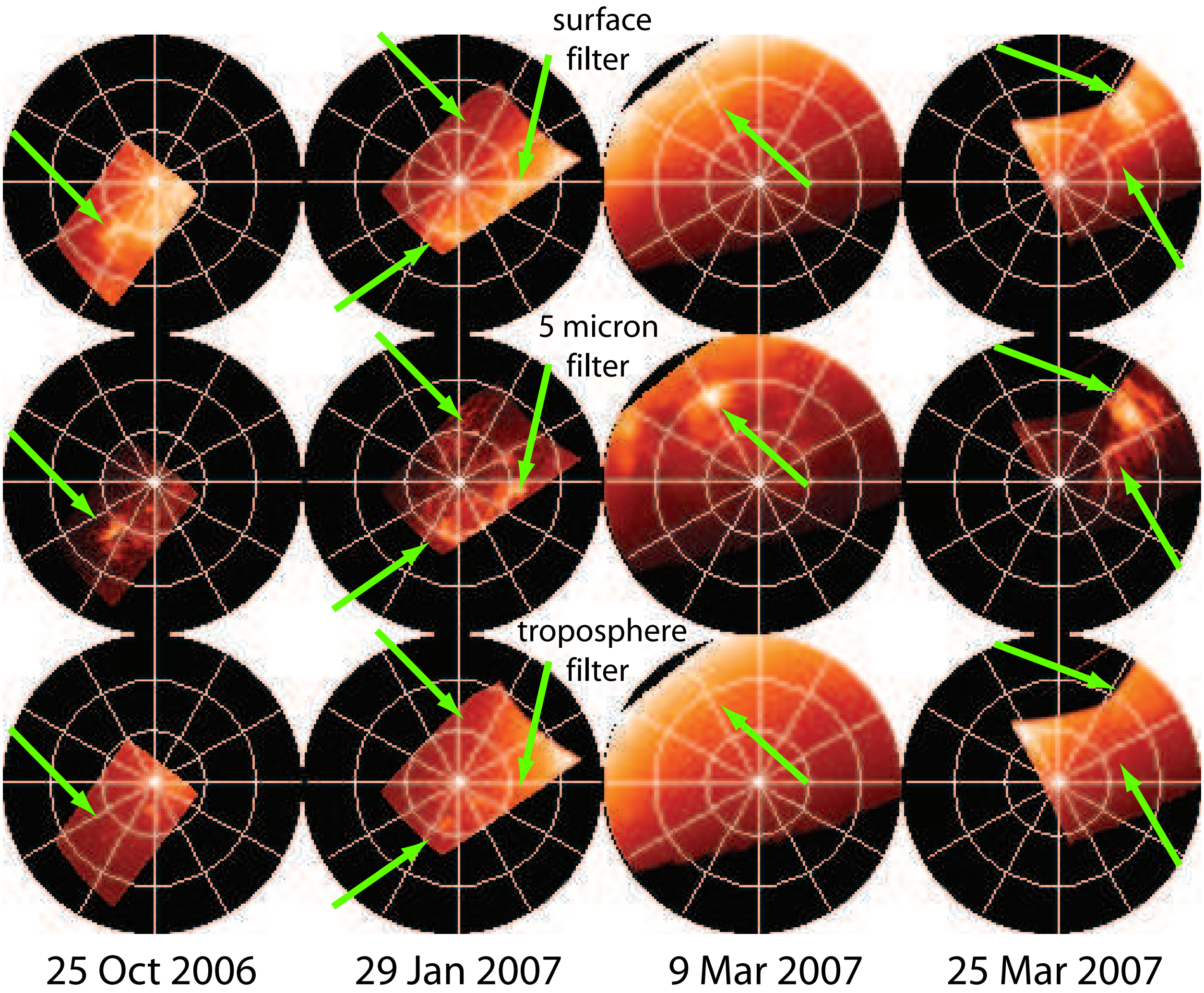

Fig. 1.— Views of the south pole of Titan on four separate dates. Variable features, marked with green arrows, can be seen in the synthetic filter which probes to Titans surface, and in the 5 μm filter, which is particularly sensitive to large cloud particles. These variable surface features do not appear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

resolution. Indeed, the morphological appearance of the 25 March 2007 image is particularly suggestive: features which appear in the troposphere-probing filter appear related to those which appear only in the surface filter.

To further explore the cause of these variable features, we examined the full 1 - 5 μm spectra of regions of the regions ofpotential fog. Figure 2 shows an example of comparisons between the spectra of regions that we identify as unvarying surface, tropospheric cloud, and the variable near-surface feature. The variable surface features appear spectrally unlike any surface unit at the south pole. In spectral regions that are transparent all the way to the surface, the variable -surface feature appears identical to the tropospheric cloud, including, most dramatically, the high reflectivity near 5 μm, when compared to the surface feature. Tropospheric clouds are bright at these wavelengths because they are composed of bright single scattering particles with sizes larger than the wavelength of the light (Barnes et al. 2005; Griffith et al. 2005). In spectral regions where light 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 is dark. The variable feature and the unvarying surface appear spectrally similar, suggesting that the variable feature originates from close to the surface.

3. Analysis

To determine the altitude of the variable near-surface feature, we perform full calculations of the radiative transfer through Titans atmosphere using the method of Ádámkovics et al. (2007). While accurate radiative transfer calcuations through the poorly known 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 features. Assuming that the large-scale atmospheric scattering and opacity does not change significantly between these regions, which are only 400 km apart, we can accurately model the relative effect of adding fog to the spectrum.

First, the aerosol opacity profile through Titan's south polar atmosphere is scaled until the cloud-free spectrum beyond 2.15 μm is reproduced. The cloud-free spectrum is matched below 2.15 μm by setting the surface reflectivity spectrum to match the observations. In the 2 μm window, the base surface reflectivity of 0.096 must be attenuated with 5 arbitrary Gaussian features to produce the agreement between model and spectrum. This parameterization of the surface reflectivity spectrum is not unique, but provides a basis for comparing the spectra at adjacent locations.

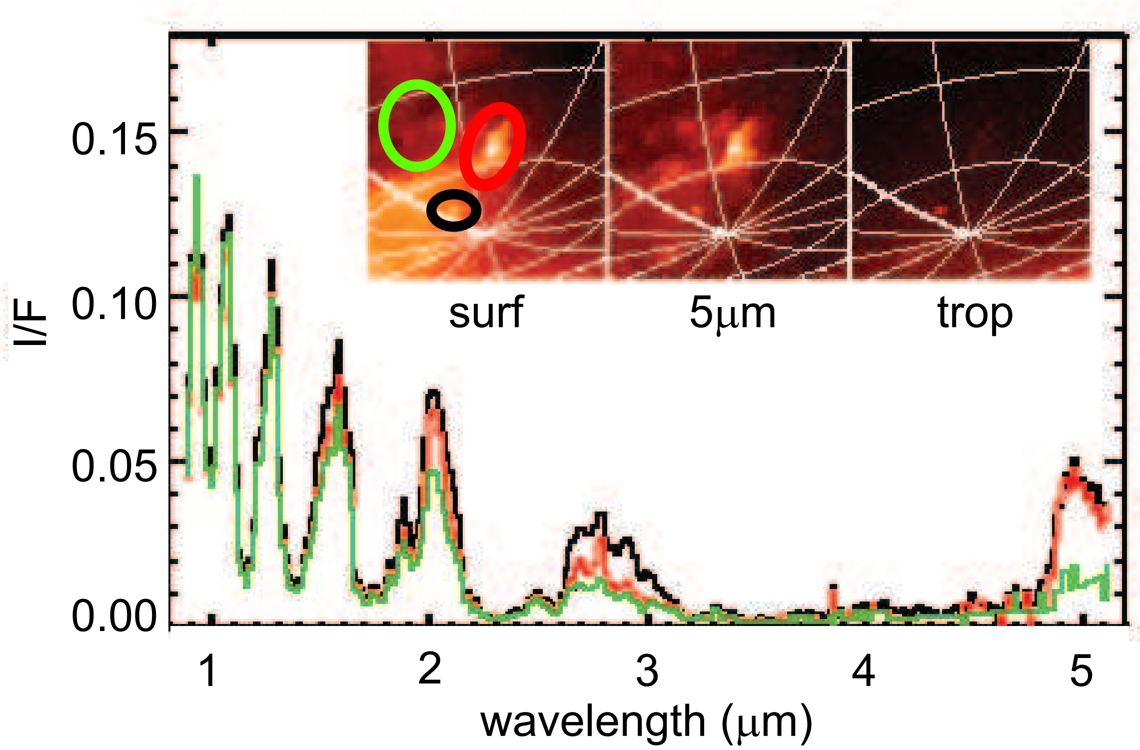

Fig. 2.— VIMS images of the 25 October 2006 fog. The surface, 5 μm, and troposphere images use the same synthetic filters are in Figure 1. Areas of clear sky, fog, and tropospheric cloud are shown by green, red, and black ovals, respectively. The full spectra of each of these select regions are show 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.

After matching the cloud-free spectrum, a series of spectra are calculated with clouds of varying opacity and altitude. Clouds are modeled by splitting the nearest atmospheric layer and inserting a uniformly scattering cloud layer between them. This method maintains the aerosol opacity structure while including a cloud layer with distinct scattering properties. In the limit of very thin clouds, we confirm that the additional layer does not create a change in the calculated spectrum. Cloud particles are assumed to be large and uniformly scattering at all wavelengths with an albedo of 0.99 and a Henyey-Greenstein scattering parameter, 0.85. The best agreement between the models and observations occurs for a cloud layer with a scattering optical depth of 0.25, a scattering altitude near 0.75 km, and an underlying surface reflectivity of 0.10. A series of spectra are calculated with optically thin clouds (optical depth of τ=0.25) in each model layer.

As seen in Figure 3, the spectrum of the variable feature is best fit with a cloud with an altitude of 750m. Models with cloud heights of 3 km or higher differ significantly from the date in the 1.98 μm and the 2.09-2.14 μm regions which are particularly sensitive the lower troposphere. We thus conclude that the variable feature is indeed best described as surface fog on Titan.

4. Discussion

Fog forms when the vapor in ground-level air saturates and condenses. On the earth, this saturation can commonly occur when air radiatively cools overnight until it reaches the dew point. On Titan, such a formation mechanism is impossible. Titans lower atmosphere has a radiative time constant of $\sim$100 yr (Hunten et al. 1984) and 94K air that has a relative humidity of $\sim$50% must be cooled $\sim$7K before condensation will initiate. Similarly, advection of typical Titan air over even the coldest locations on Titan provides insufficient cooling for fog to form.

Fog on Titan instead requires elevated surface humidity. If the fog is at ground level, the surface relative humidity must be nearly 100%. Such an elevated surface humidity occurs if the surface air is in contact with nearly pure evaporating liquid methane. Saturated low-level air on Titan is, however, unstable to moist convection for a typical Titan thermal profile(Griffith et al. 2008). Fog can only persist at the surface if the surface air is both saturated and colder than its surroundings.

Pools of evaporating liquid methane will 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

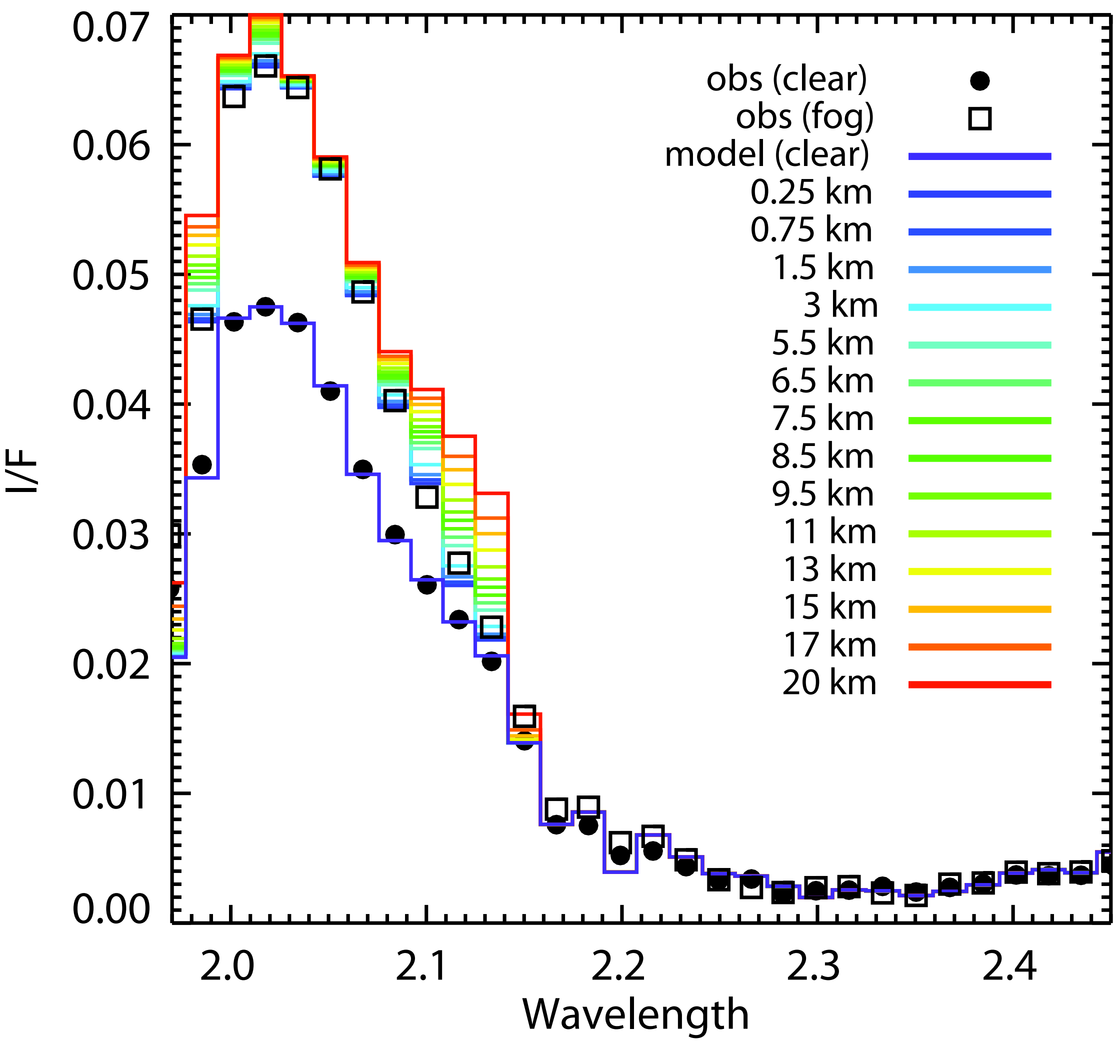

Fig. 3.— Spectra of the surface (filled circles) and fog (black open squares) in the 2 μm spectral window where altitude is best constrained. The purple line shows the best fit radiative transfer model which matches the surface. Colored lines show fits to the fog spectra that include an increased surface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

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 may be tied directly to surface liquid methane.

The locations of the identified fog features are shown in Figure 4. All identified fog features are southward of 65S. No correlation is seen between the locations of fog and the location of the one suspected large lake, Ontario Lacus, 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 even more distributed; 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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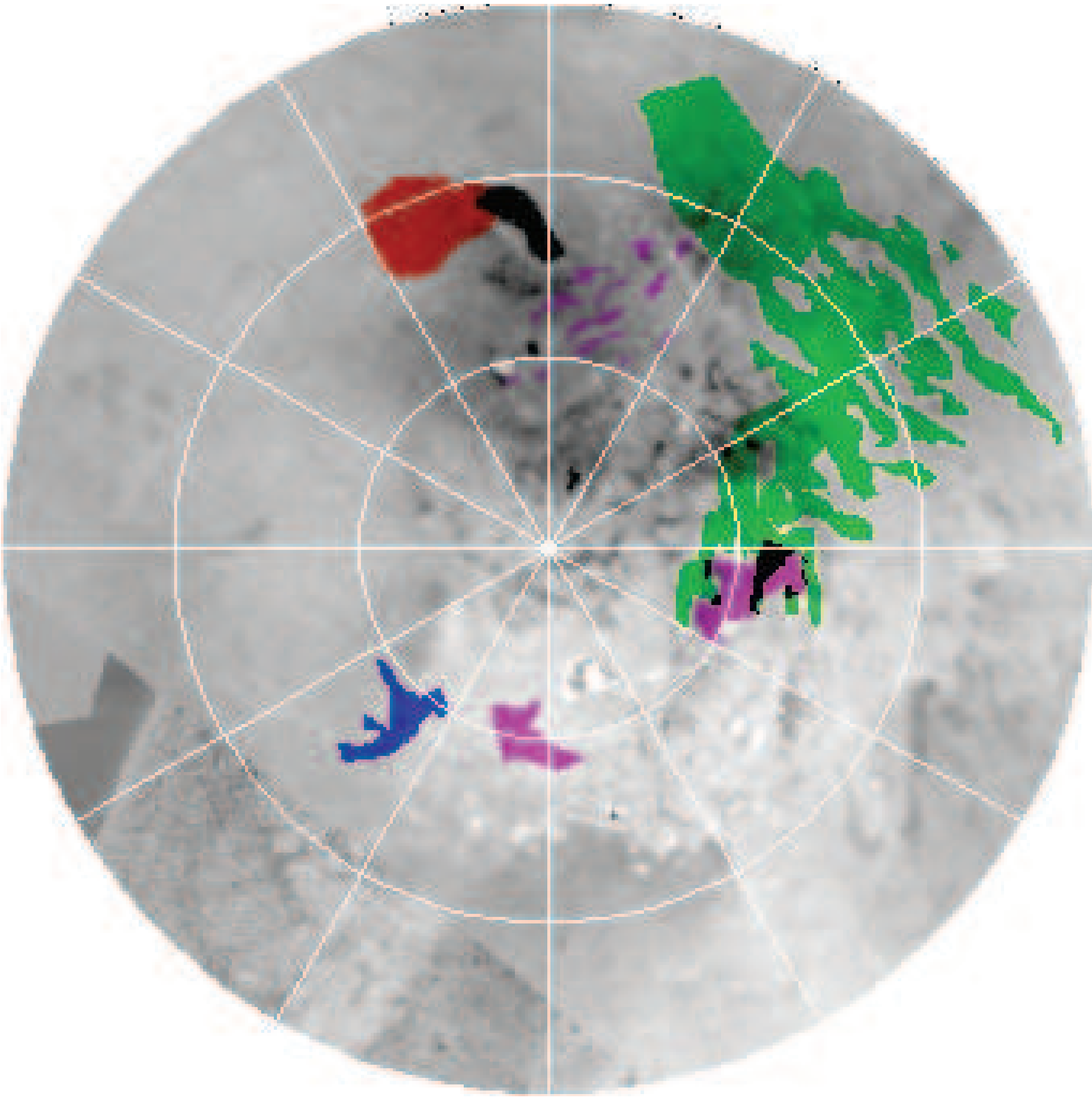

Fig. 4.— Locations of all identified clouds figures. Blue, purple, red, and green are from 25 Oct 2006, 29 Jan 2007, 9 Mar 2007, and 25 Mar 2007, respectively. The background shows a south polar basemap of Titan as derived from the visible imager on the ISS instrument.

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