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Meridional variation in tropospheric methane on Titan observed with AO spectroscopy at Keck and VLT

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ABSTRACT

The spatial distribution of the tropospheric methane on Titan was measured using near-infrared spectroscopy. Ground-based observations at 1.5 μm (H-band) were performed during the same night using instruments with adaptive optics at both the W.M. Keck Observatory and at the Paranal Observatory on 17 July 2014 UT. The integral field observations with SINFONI on the VLT covered the entire H-band at moderate resolving power, $R = \lambda/\Delta\lambda \approx 1500$, while the Keck observations were performed with NIRSPAO near 1.5525 μm at higher resolution, $R \approx 25,000$. The moderate resolution observations are used for flux calibration and for the determination of model parameters that can be degenerate in the interpretation of high resolution spectra. Line-by-line calculations of CH_4 and CH_3D correlated k distributions from the HITRAN 2012 database were used, which incorporate revised line assignments near 1.5 μm. We fit the surface albedo and aerosol distributions in the VLT SINFONI observations that cover the entire H-band window and used these quantities to constrain the models of the high-resolution Keck NIRSPAO spectra when retrieving the methane abundances. *Cassini* VIMS images of the polar regions, acquired on 20 July 2014 UT, are used to validate the assumption that the opacity of tropospheric aerosol is relatively uniform below 10 km. We retrieved methane abundances at latitudes between 42°S and 80°N. The tropospheric methane in the Southern mid-latitudes was enhanced by a factor of ~10–40% over the nominal profile that was measured using the GCMS on *Huygens*. The northern hemisphere had ~90% of the nominal methane abundance up to polar latitudes (80°N). These measurements suggest that a source of saturated polar air is equilibrating with dryer conditions at lower latitudes.

1. Introduction

Methane (CH_4) is the most abundant condensible species on Titan, dominates the energy transport through the atmosphere (Mitchell, 2012), and is part of a complex hydrological cycle (Atreya et al., 2006; Roe, 2012). Clouds of methane can indicate regions of convection (e.g., Griffith et al., 2005), polar subsidence (Anderson et al., 2014), or evaporation from lakes (e.g., Brown et al., 2009; Turtle et al., 2009), while the formation of large scale methane cloud systems are diagnostic of atmospheric dynamics via their morphology (Mitchell et al., 2011) and how they evolve with time (Ádámkovics et al., 2010; Turtle et al., 2011a). The

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amount of methane near the surface is an important factor in triggering convective cloud formation (Barth and Rafkin, 2007) and in determining the strength of storms (Hueso and Sánchez-Lavega, 2006). Precipitation can return methane to the surface (Turtle et al., 2009, 2011a) where fluid transport has some role in closing the hydrological cycle. Seasonal variations in the general circulation (Mitchell et al., 2009) as well as predictions of the locations and frequency of clouds (Schneider et al., 2012) depend on the distribution of methane near the surface, both in the regolith and the lower atmosphere.

Lakes and seas of liquid hydrocarbons (Stofan et al., 2007) provide both sinks and sources of methane on the surface. The north pole contains by far the greatest extent of open liquids on Titan (Hayes et al., 2008; Lorenz et al., 2008; Sotin et al., 2012; Lorenz et al., 2014). The largest sea, Kraken Mare, extends down to 55°N at its southernmost point. A few low-latitude lake candidates have been suggested, one near the equator (Griffith et al., 2012b), and one at 40°S latitude (Vixie et al., in preparation). The sole large lake in Titan's south polar region is Ontario Lacus (Turtle et al., 2009), although there are several basins that have been identified as potential "paleo-seas" that encompass a similar areal fraction to the northern seas (Hayes et al., 2011).

Liquids presumably concentrate at the poles because they are the coldest points on the surface and therefore cold-traps for volatiles. However, the polar clustering might also be related to higher precipitation at the poles (Rodriguez et al., 2009; Brown et al., 2010; Rodriguez et al., 2011) relative to the dune-filled equatorial desert (Lorenz et al., 2006; Radebaugh et al., 2008; Le Gall et al., 2011; Rodriguez et al., 2014), which may be caused by circulation (Rannou et al., 2006; Friedson et al., 2009). The lower elevations of the poles relative to equatorial regions may also play a role (Iess et al., 2010; Lorenz et al., 2013). The reason for the pronounced North to South asymmetry in lake coverage is unknown. Aharonson et al. (2009) cited Milankovic-like cycles in Titan's orbital parameters as a possible explanation, which is supported by simulations of Titan's paleoclimate (Lora et al., 2014).

The physical properties of lakes are complicated by the fact that they are likely mixtures of hydrocarbons. Though methane composes Titan's raindrops, the seas may build up significant fractions of less-volatile ethane. Spectroscopic observations of Ontario Lacus suggest the presence of ethane (Brown et al., 2008), although the abundance is not constrained by these measurements. Recent observations of Ligeia Mare, conducted by the Cassini RADAR instrument, have demonstrated that it is primarily composed of methane (Mastrogiuseppe et al., 2014). Evaporation rates from a lake that is mostly methane will be much greater than from a lake that is mostly ethane (Mitri et al., 2007; Tokano, 2009). Lorenz (2014) points out that the ratio of methane to ethane may vary across lakes due to the concentration of solutes by heterogeneous evaporation and dilution by heterogeneous rainfall.

While shoreline recession at Ontario Lacus was reported over the timescale of the *Cassini* mission (Turtle et al., 2011b; Hayes et al., 2011), the shoreline detection algorithms have been disputed (Cornet et al., 2012), leaving the contemporary evaporation rate over lakes uncertain. *Cassini* has observed albedo variations with both the Imaging Science Subsystem (ISS) and RADAR that depict smaller southern lakes disappearing between adjacent observations (Turtle et al., 2009; Hayes et al., 2011), which was attributed to either infiltration or evaporation, although the rates could not be quantified. Changes in lake and sea volumes over geologic timescales have also likely occurred, as evidenced by the geomorphology of empty lakebeds in some polar terrains and the presence of drowned river valleys in the northern seas, which indicate that the liquid level is rising faster than fluvial sediment is being deposited (Hayes et al., 2008). Some of the lakebeds show a bright reflection near 5 μm, which is interpreted as a compositional signature that is attributed to the formation of organic evaporite (Barnes et al., 2011). The largest outcrop of evaporites are in the tropics, implying that these areas may have been seas during the geological past, perhaps under a different climatic regime (Moore and Howard, 2010; MacKenzie et al., 2014).

The evaporation of methane from surface lakes may have an observational impact on the atmosphere. Tokano (2014) recently revisited the *Cassini* radio occultation data (recorded from 2005 to 2009) and points out that retrievals assuming a uniform tropospheric methane distribution lead to surface pressure distributions that are inconsistent with the predictions of circulation models. Instead, Tokano (2014) argues for a substantially higher methane abundance in the Summer hemisphere. Penteado and Griffith (2010) searched for spatial variation in the methane abundance with high resolution Keck observations. The unsaturated lines of the resolved $3\nu_2$ band of CH_3D are sensitive to possible changes in the tropospheric methane abundance. Their measurements from December 2006 indicated that methane below 10 km altitude is constant to within 20% in the tropical atmosphere, sampled between the range of 32°S–18° N. High resolution analysis with new methane lines lists (de Bergh et al., 2012) illustrates that significant improvements can be made in spectral fitting with recent laboratory data.

Here we present ground-based observations of the methane distribution on Titan using a methodology that improve upon the observing protocol and integration times of Penteado and Griffith (2010), and which are supported by both integral field observations from the same night, as well as a *Cassini* flyby from four days later. Our radiative transfer models include revised methane line lists from the most recent HITRAN database. The observations, data reduction, and calibrations are described in Section 2, while the radiative transfer model is detailed in Section 3. Results are presented in Section 4 and discussed in Section 5.

2. Observations

Observations were performed on 17 July 2014 UT at both the Paranal Observatory and the W.M. Keck Observatory. Instrumentation with complementary observing modes, resolutions, and bandpasses provided flux calibration and characterization of the physical properties of the atmosphere and surface. Fig. 1 illustrates the viewing geometry of the observations that are described below.

2.1. VLT observations

The Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) on the Very Large Telescope (VLT) at Paranal Observatory was used as part of a campaign to monitor clouds on Titan. The spectrometer is fed by an adaptive optics module and uses two sets of stacked mirrors to optically divide and rearrange the field of view (FOV) into a single synthetic long slit that is spectrally dispersed by a grating onto the detector. We used the 0.8" $\times$ 0.8" FOV, corresponding to a spatial pixel scale of 0.0125" $\times$ 0.0250", with the grating that covers 1.45–2.45 μm at a spectral resolution of $\Delta\lambda \approx 1$ nm, corresponding to a resolving power, $R = \lambda/\Delta\lambda \approx 1500$ (Eisenhauer et al., 2003). Four overlapping exposures with 2 $\times$ 15 s coadds, offset by ±0.1" from the disk center in both the X and Y directions of the FOV, are mosaicked to cover the entire disk.

Observations were reduced using version 2.5.2 of the SINFONI pipeline. The standard processing of the raw exposures includes correction of bad pixels, flat fielding, and correction of geometric distortions. The pipeline performs wavelength calibration and then