Low-Latitude Ethane Rain on Titan

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ABSTRACT

Cassini ISS observed multiple widespread changes in surface brightness in Titan's equatorial regions over the past three years. These brightness variations are attributed to rainfall from cloud systems that appear to form seasonally. Determining the composition of this rainfall is an important step in understanding the "methanological" cycle on Titan. I use data from Cassini VIMS to complete a spectroscopic investigation of multiple rain-wetted areas. I compute "before-and-after" spectral ratios of any areas that show either deposition or evaporation of rain. By comparing these spectral ratios to a model of liquid ethane, I find that the rain is most likely composed of liquid ethane. The spectrum of liquid ethane contains multiple absorption features that fall within the 2-micron and 5-micron spectral windows in Titan's atmosphere. I show that these features are visible in the spectra taken of Titan's surface and that they are characteristically different than those in the spectrum of liquid methane. Furthermore, just as ISS saw the surface brightness reverting to its original state after a period of time, I show that VIMS observations of later flybys show the surface composition in different stages of returning to its initial form.

1. Introduction

Many recent studies have investigated the fascinating processes that occur in the atmosphere and on the surface of Titan, the largest of Saturn's satellites. One study[1] from 2008 located stable lakes composed primarily of liquid ethane in Titan's polar regions. At lower-latitudes, lakes are not present but there is still evidence for liquid. The Imaging Science Subsystem (ISS) aboard the *Cassini Spacecraft* witnessed surface changes in areas near clouds systems in 2010[2]. Since then, surface brightening and darkening have been observed on Titan in areas such as Yalaing Terra, Hetpet Regio and central Adiri[3]. These changes are attributed to large-scale surface wetting by rainfall. Due to the large concentration of methane in Titan's atmosphere, this rainfall was thought to be composed of liquid methane. However, it is possible that the rain is composed primarily of liquid ethane. Ethane is produced through photochemical processes in Titan's atmosphere[4] and, as mentioned previously, is found in Titan's polar lakes. Determining the composition of the rainfall would add another link to the "methanological" (or "ethanological") cycle that occurs on Titan, much like the hydrological cycle that occurs on Earth.

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2. Observations

The presence or absence of liquid ethane was determined by comparing the spectral shapes of certain areas on Titan's surface over many sets of flybys. The general areas under observation are shown on a map of Titan in Figure 1. Figure 2 shows these same areas but at higher resolutions. These areas and their adjacent terrain were targeted in this spectroscopic study because of their varying surface brightness, which is described in Barnes et al. (2012)[3]. In Figures 1 and 2, the dark terrain is characteristic of sand dunes and the bright terrain has been aptly named "equatorial bright terrain"[5]. Table 1 provides a summary of the pertinent observations and their properties.

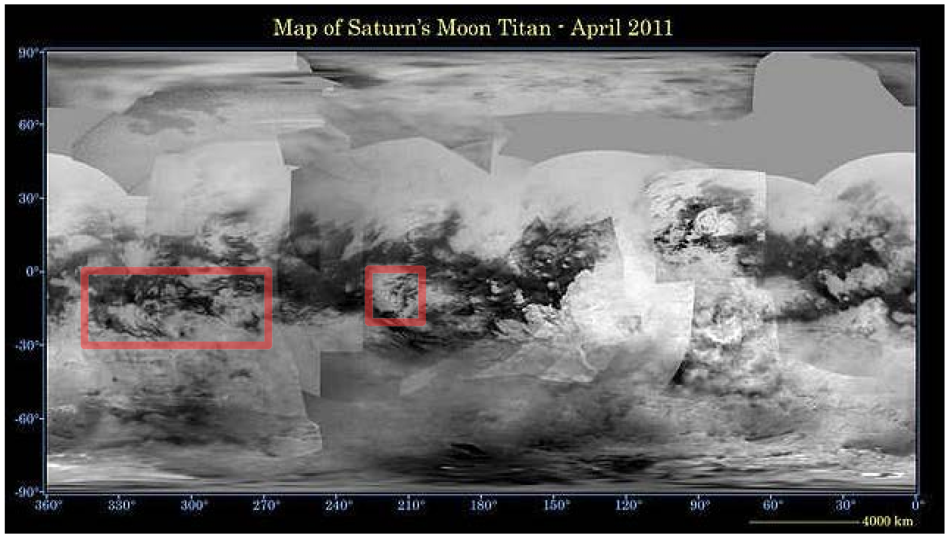

Figure 1* | *This research focuses on the areas within the red boxes. Yalaing Terra and Hetpet Regio lie within the left box and central Adiri lies within the right box.

Table 1 | Properties of VIMS Observations

Location	Flyby	Data Cube ID	Date	Sampling (km/pixel)	Incidence (°)	Int Time (ms)
Adiri	T70	1655782927_1	21 June 2010	14	28	80
----	T77	1687318816_1	20 June 2011	78	40	120
Hetpet Regio	T67	1649198883_1	5 April 2010	58	34	220
----	T76	1683599580_1	8 May 2011	27	33	60
----	T80	1704229716_5	2 January 2012	49	35	280
Yalaing Terra	T56	1623062861_1	6 June 2009	140	52	320
----	T59	1627151462_1	24 July 2009	23	24	280
----	T67	1649188240_1	5 April 2010	30	23	220
----	T76	1683596624_1	8 May 2011	18	40	140
----	T80	1704229716_5	2 January 2012	49	35	280

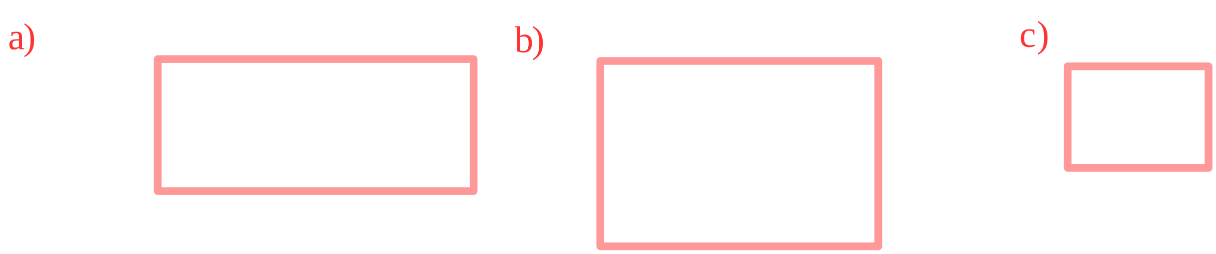

Figure 2* | *High-resolution gray scale images taken at 2.01 μm of a) Yalaing Terra (T76), b) Hetpet Regio (T76) and c) central Adiri (T79). The red boxes surround the specific areas that show spectral evidence of liquid ethane deposition or evaporation.

3. Methods

The primary goal of this study was to use VIMS data to determine if ethane is a major constituent of the rain in Titan's equatorial regions. VIMS data come in the form of “cubes” that are typically 64 pixels by 64 pixels (the spatial dimensions) by 352 channels (the spectral dimension). In this study, we are only concerned with the 256 channels that make up the near-infrared (NIR) to the infrared (IR) region (~0.88 – 5.1 μm).

A spatially-averaged spectrum was computed for each targeted region in each flyby*. “Before-and-after” ratios of these spectra could determine if the *shapes* of the spectra were changing or if the difference was simply caused by changes in surface albedo. However, such a comparison is not valid due to the varying viewing geometries between flybys. Consequently, the spectrum from each targeted region was normalized using the spatially-averaged spectrum of a nearby region that did not change in brightness between flybys. These regions are herein referred to as “standard” regions*. The final normalized spectral ratios were then calculated as follows:

$$\text{Normalized Spectra Ratio} = \frac{(\text{Target Spectrum, Flyby } X \,/\, \text{Standard Spectrum, Flyby } X)}{(\text{Target Spectrum, Flyby } Y \,/\, \text{Standard Spectrum, Flyby } Y)}$$

The error in the VIMS data must be considered when computing these spectral ratios. No formal technique exists for calculating the error in VIMS data. The error is “point-to-point” meaning that certain wavelengths, especially in the 3 – 5 μm range, show greater variations than others. Following the error analysis of Buratti et al. (2010)[6], we assign 1% relative error to the 1 – 3 μm range and 2% relative error to the 3 – 5 μm range in all normalized spectra. Therefore, the normalized spectral ratios (herein referred to as just “spectral ratios”) have relative errors of 1.4% ($[1\%^2 + 1\%^2]^{1/2}$) and 2.8% ($[2\%^2 + 2\%^2]^{1/2}$) in the 1 - 3 μm and 3 - 5 μm micron ranges respectively. This error analysis was applied to all the plots in Figures 3, 4 and 5.

Although the spectral ratios span 0.88 – 5.1 μm, only a fraction of the ratio is useful. This is a result of Titan's thick nitrogen-methane atmosphere. Much of the light from the surface is blocked, leaving only several small spectral “windows” in which VIMS can see through the atmosphere. In the given wavelength range, there are seven windows, but in this case, only three are important. They are centered at 2.03, 2.7 and 5 μm respectively.

To determine if Titan's low-latitude rainfall is composed of liquid ethane, the shapes of the spectral ratios within these windows were compared to a model of liquid ethane that was designed to match the resolution and sampling interval of VIMS[1]. The model is plotted below along with the spectral ratios.

4. Results

4.1 Ethane rain

My investigations of Yalaing Terra, Hetpet Regio and central Adiri yielded exciting results. Variations in the spectral ratios suggest the presence of liquid ethane on Titan's surface and in the equatorial rain storms. In fact, there is evidence of liquid ethane in several areas and at several times

*The spatial consistency of the targeted and standard regions between flybys was maintained with help from the SPICE kernels that accompanied the VIMS data cubes.

suggesting that scattered rain storms on Titan are a frequent occurrence.

While the NIR to IR spectra of many alkanes such as methane and ethane have similar shape, there are certain features that distinguish them from each other. Ethane's spectrum has three clear absorption features that distinguish it from methane's spectrum and each falls within the spectral windows in Titan's atmosphere[†]. In the 2 µm window, there is a feature centered at 2.02 µm and a smaller feature centered at 2.11 µm[1]. In the 5 µm window, the spectrum of liquid ethane has is a very steep absorption line that is not present in the spectrum of liquid methane. The presence of these features in the spectral ratios suggests that liquid ethane exists on the target regions.

4.1.1 Yalaing Terra

The region in Figure 1a appeared to brighten between flybys T67 and T76. This suggests that rain was present on the surface in T67 but had evaporated, or been removed by some process, by T76. The spectral ratio (Figure 3a) between T67 and T76 supports this claim. The three significant absorption features at 2.02 µm, 2.11 µm and 5 µm are clearly present in the data (black). The model (red) was not standardized to fit the data. Instead, it was left offset to allow for clearer viewing. A similar spectral ratio between T80 and T76 did not show signatures of liquid ethane. However, the spectral ratio between T59 and T76 (Figure 3b) did display a broad absorption line in the 2 µm window and a steep decline and increase in reflectance in the 5 µm window. Thus, it is possible that liquid ethane was present in T59 as well as T67. VIMS did observe Yalaing Terra during T61, and the spectral ratio between T61 and T76 did not show strong signs of liquid ethane. This fact suggests that multiple rainstorms dumped liquid ethane in Yalaing Terra between July 2009 and April 2010.

4.1.2 Hetpet Regio

Like Yalaing Terra, Hetpet Regio, seen in Figure 1b, also appeared to brighten between flybys T67 and T76. Once again, the spectral ratio between T67 and T76 (Figure 4a) suggested that ethane was present in T67 but not in T76. The smaller of the two features in the 2 µm window was not present, but the 5 µm feature was very clear. As the model reflectance decreases in the 5µm window, there is a small spike in near 4.96 µm. This same spike also seems to be present in the data as well.

Unlike Yalaing Terra, however, the spectral ratio between T80 and T76 (Figure 4b) did yield evidence of liquid ethane in T80. The 2.02 µm absorption feature and the dramatic drop in reflectance near 5 µm are clearly visible. The fact that the reflectance does not rise sharply after the drop could be attributed to the presence of higher-order alkanes such as butane or propane[7]. VIMS also observed Hetpet Regio in T61, but no signatures of liquid ethane were detected.

4.1.3 Adiri

In central Adiri, VIMS detected an increase in surface brightness between T70 and T77. Five small sections of Adiri were analyzed individually, and one (Figure 1c) appeared to contain liquid ethane in T70. In the spectral ratio (Figure 5) between T70 and T77, the model fits the data very closely. Half of the the large absorption feature is visible in the 2 µm window along with the entire small feature. The fact that the opacity of the atmosphere increases near the edges of the spectral windows could explain why only half of the large feature is present. There is also a sharp fall and rise in reflectance in the 5 µm window, another indicator or liquid ethane.

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†For the spectrum of liquid methane between 1 and 5 µm, see Figure 4a from Clark, Curchin, Hoefen & Swayze (2009)[7].

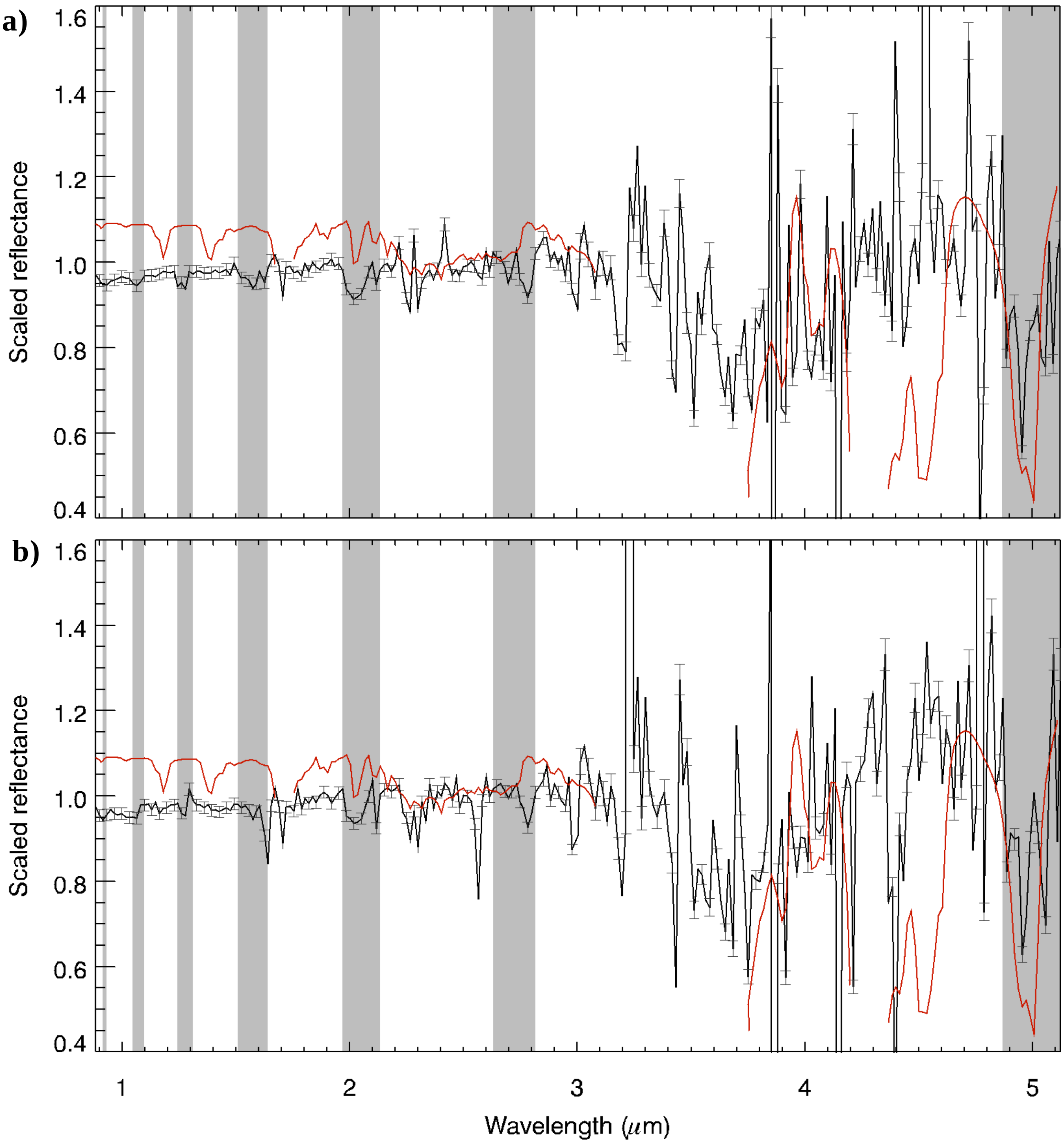

***Figure 3** | Spectral ratios for Yalaing Terra: a) T67 / T76 and b) T59 / T76. The liquid ethane model spectrum (red) has not been normalized to the spectral ratio (black). The model spectrum fits the ratios well in the 2 and 5 µm windows suggesting that liquid ethane was present in T59 and T67. Only signatures within the gray spectral windows are investigated because radiation from the surface does not penetrate the atmosphere at other wavelengths.*

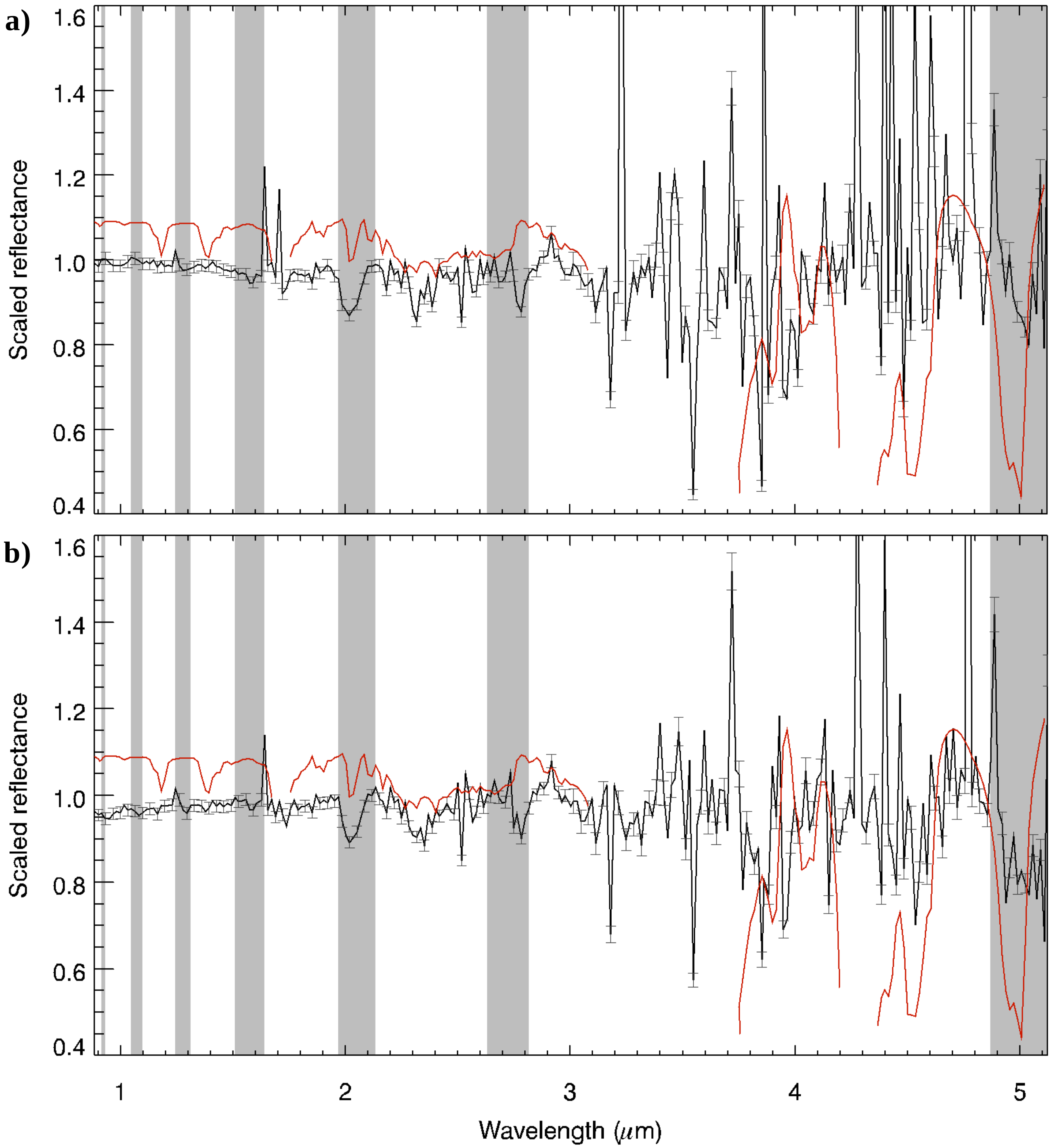

Figure 4 | *Spectral ratios for Hetpet Regio: a) T67 / T76 and b) T80 / T76. The 2 μm absorption feature is very clear in each spectral ratio. Although the 5 μm absorption features in the ratios are not as pronounced as the analogous feature in the model spectrum, the evident drop in reflectance in that region is characteristic of liquid ethane.*

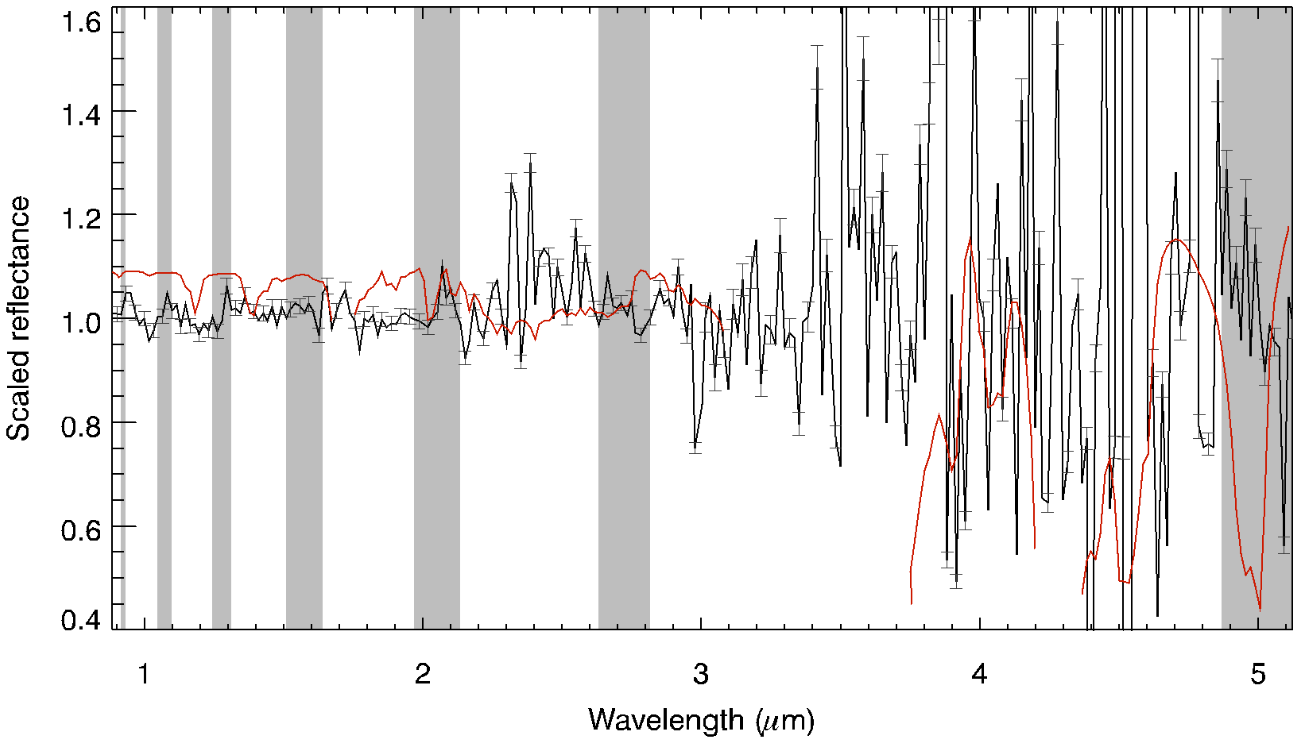

Figure 5 | *Spectral ratio of T70 / T77 for Adiri. Even without normalization the spectral ratio matches the model spectrum in the 2 μm window closely. The 5 μm feature does not match as well but is still present in the spectral ratio.*

4.2 Clouds

Surface spectra suggest that liquid ethane was present in at least one of the targeted regions in T59, T67, T70 and T80. Assuming this ethane was deposited by isolated rainstorms, there must have been clouds near the targeted areas sometime before the liquid ethane was observed. The search for clouds near Yalaing Terra, Hetpet Regio and Adiri was difficult because, in most cases, the correct areas were not observed at the necessary times. In other cases, the VIMS resolution was too low to see small clouds. However, VIMS did catch one cloud system very near to Yalaing Terra in T56 (Figure 6), just 48 days before VIMS saw signs of liquid ethane in T59. The cloud was just north of Yalaing Terra and appeared to stretch at least 1,200 km in the east-west direction. The RGB color scheme (red = 2.01 μm, green = 2.83 μm, blue = 2.13 μm) in Figure 6 is one that clearly displays clouds, which appear brown against the red surface. It is possible that this cloud deposited the liquid ethane that was detected in T59.

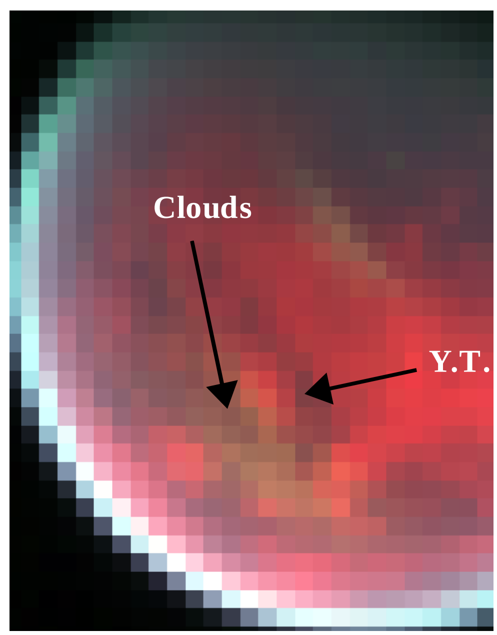

Figure 6*: False-color image of Titan showing clouds (brown) near Yalaing Terra in T56.*

5. Discussion: Titan's Methanological Cycle

Nitrogen and methane gas are the largest constituents in Titan's atmosphere. However, a significant amount of ethane gas is also present due to ultraviolet photolysis of methane[4]. In this process, charged particles from the sun collide with methane gas (CH_4) causing the release of one hydrogen atom. After many years, methyl radicals (CH_3) combine to the form ethane gas (C_2H_6) which then condenses into aerosols around 60–70 km above the surface[8]. According to Griffith et al., (2006)[9], VIMS observed a large cloud composed of ethane located between 51º and 68º north and 10º and 190º west. It is possible that currents in Titan's atmosphere could transport ethane from this cloud, and others like it, to the tropical latitudes where ethane rain is falling. A study investigating the conditions required for rainfall to exist on Titan[10] shows that small (1-4.75mm radii) methane-nitrogen raindrops will completely evaporate before reaching the ground if the relative humidity (RH) of ethane is 0%. The drops can, however, reach the ground if the RH of ethane is 50%. As the drops fall, they begin to reach compositional equilibrium with the atmosphere causing their ethane content to increase. This added ethane, in liquid form, stabilizes the methane-nitrogen drops allowing them to reach the ground with an ethane mole fraction of 0.4 (see Graves, McKay, Griffith, Ferri and Fulchignoni, 2008).

On the surface of Titan, Brown et al. (2008)[1] found strong evidence to suggest that Ontario Lacus, a lake located near the south pole, is composed of primarily liquid ethane. Considering that ethane has been located in the atmosphere, on the surface and now in the rain, perhaps Titan's methanological cycle is actually an *ethanological* cycle. Perhaps ethane is the working fluid in the cycle.

There are no known standing lakes like Ontario Lacus at low latitudes, but there is certainly evidence of liquid. Some equatorial bright terrain have long channels that large form drainage networks[5] suggesting that rain is reaching the ground at low latitudes on Titan. This study proposes that rainfall in the form of scattered, isolated showers is a common occurrence at low latitude. Furthermore, the spectra of the targeted regions no longer resemble liquid ethane after approximately a year meaning that the liquid rain only temporarily remains on the surface. Barnes et al. (2012)[3] confirms this result visually.

Further study is needed to explore the chemical processes occurring on the surface of Titan related to ethane. It is possible that ethane, in gas and liquid phases, plays a much larger role in Titan's chemistry than was once thought. It is also possible that Titan's atmosphere and weather patterns are more dynamic than was once thought. The cocktail of hydrocarbons and other organic compounds in the atmosphere and on the surface could even be driving prebiotic chemistry on Titan. Furthermore, an atmosphere that is more dynamical than once thought could mean that there are sources of energy to power these chemical reactions. By understanding the chemical and mechanical processes that are currently occurring in the atmosphere and on the surface, we can better understand Saturn's distant frigid satellite, Titan.

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