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CASSINI VIMS OBSERVATIONS SHOW ETHANE IS PRESENT IN TITAN'S RAINFALL

Paul A. Dalba[1], Bonnie J. Buratti[1], Robert H. Brown[2], Jason W. Barnes[3], Kevin H. Baines[1], Christophe Sotin[1], Roger N. Clark[4], Kenneth J. Lawrence[1], and Philip D. Nicholson[5]
[1] Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, USA; pauldalba@berkeley.edu
[2] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[3] Department of Physics, University of Idaho, Moscow, ID 83844, USA
[4] United States Geological Survey, Denver, CO 80225, USA
[5] Department of Astronomy, Cornell University, Ithaca, NY 14853, USA
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ABSTRACT

Observations obtained over two years by the *Cassini* Imaging Science Subsystem suggest that rain showers fall on the surface. Using measurements obtained by the Visual Infrared Mapping Spectrometer, we identify the main component of the rain to be ethane, with methane as an additional component. We observe five or six probable rainfall events, at least one of which follows a brief equatorial cloud appearance, suggesting that frequent rainstorms occur on Titan. The rainfall evaporates, sublimates, or infiltrates on timescales of months, and in some cases it is associated with fluvial features but not with their creation or alteration. Thus, Titan exhibits frequent "gentle rainfall" instead of, or in addition to, more catastrophic events that cut rivers and lay down large fluvial deposits. Freezing rain may also be present, and the standing liquid may exist as puddles interspersed with patches of frost. The extensive dune deposits found in the equatorial regions of Titan imply multi-season arid conditions there, which are consistent with small, but possibly frequent, amounts of rain, in analogy to terrestrial deserts.

Key words: planets and satellites: individual (Titan) – planets and satellites: surfaces

1. INTRODUCTION

The eight-year exploration of the Saturnian moon Titan by the *Cassini* spacecraft has revealed a world shaped by earth-like processes. Widespread eolian and fluvial erosion has sculpted riverbeds and deltas, laid vast dunes, and covered much of the moon's surface with sand plains. Titan is the only body in the solar system other than Earth to sustain standing liquid—most likely ethane and other hydrocarbons—on its surface. Understanding the "methanological" cycle, the interplay of frost, liquid, and vapor phases of hydrocarbons that coexist near the surface, holds the key to presenting a global view of the evolution of Titan.

Surface erosion on the Earth is driven largely by water existing in either its gaseous, liquid, or solid form. Similarly, on Titan, methane has a triple point near the pressure and temperature conditions of the surface and provides the basis of a "methanological" cycle (Lunine & Atreya 2008). Radar images show large lakes in the polar regions (Stofan et al. 2007; Stephan et al. 2010), which appear to be composed primarily of liquid ethane possibly mixed with other hydrocarbons (Brown et al. 2008). Large polar ethane cloud systems are associated with the lakes (Griffith et al. 2006), and as southern summer gives way to northern spring and summer, these clouds are breaking up (Le Mouélic et al. 2012). Extensive fluvial channels cover large areas of the surface, speaking to catastrophic storms and running liquid on the surface (Lorenz et al. 2008; Jaumann et al. 2008). Modeling of mid-latitude clouds suggests that they dissipate through rain to provide the erosional fluid that carves these channels (Griffith et al. 2005). The surface of Titan contains hydrocarbons, including benzene, methane, and ethane (Clark et al. 2010).

As the *Cassini* observational period approaches nearly a third of the Saturnian year, seasonal changes in cloud patterns are evident, with southern temperate cloud patterns moving into the equatorial and northern temperate regions as predicted and subsequently observed (Rannou et al. 2006; Brown et al. 2010; Rodriguez et al. 2011). The southern Lacus Ontario appears to be receding as the subsolar point moves northward (Turtle et al. 2011a; Hayes et al. 2011). Finally, likely rainstorms have been identified by both *Cassini's* Imaging Science Subsystem (Turtle et al. 2011b) and Visual Infrared Mapping Spectrometer (VIMS; Barnes et al. 2012).

The composition, frequency, and timescales of rainstorms, their connection with both atmospheric cloud patterns and fluvial features on the ground, and the rainstorms' long-term behavior and connection to modeled seasonal changes and volatile transport are all missing observables that would provide the basis for understanding Titan's methanological cycle (for a review, see Lunine & Lorenz 2009). In this Letter, we analyze images obtained over three years from VIMS to derive the composition of rain on Titan, to measure the persistence of liquid on the surface after a rainstorm, and to understand the connection of rain with equatorial and mid-latitude clouds. VIMS is a medium resolution imaging spectrometer with a wavelength range of 0.35–5.1 μm that has been in orbit around Saturn since 2004 (Brown et al. 2004). Although the high opacity of Titan's nitrogen–methane atmosphere renders the surface all but invisible at optical wavelengths, there are several windows of clarity in the mid-IR region, particularly those at 2.0, 2.7, and 5.0 μm. These windows are several VIMS channels wide, and by mapping spectral reflectance, we have derived the composition and compositional changes on the surface as a result of rain and its subsequent evaporation.

2. DATA ANALYSIS

We sought equatorial and temperate regions of Titan that had been observed at resolutions of at least 80 km pixel^{-1} by VIMS during more than one targeted flyby and that showed previous evidence (regional darkening or cloud activity) of rainfall (Turtle et al. 2011b; Barnes et al. 2012). Figure 1 shows the areas targeted for study: Adiri, Hetpet Regio, and Yalaing Terra.

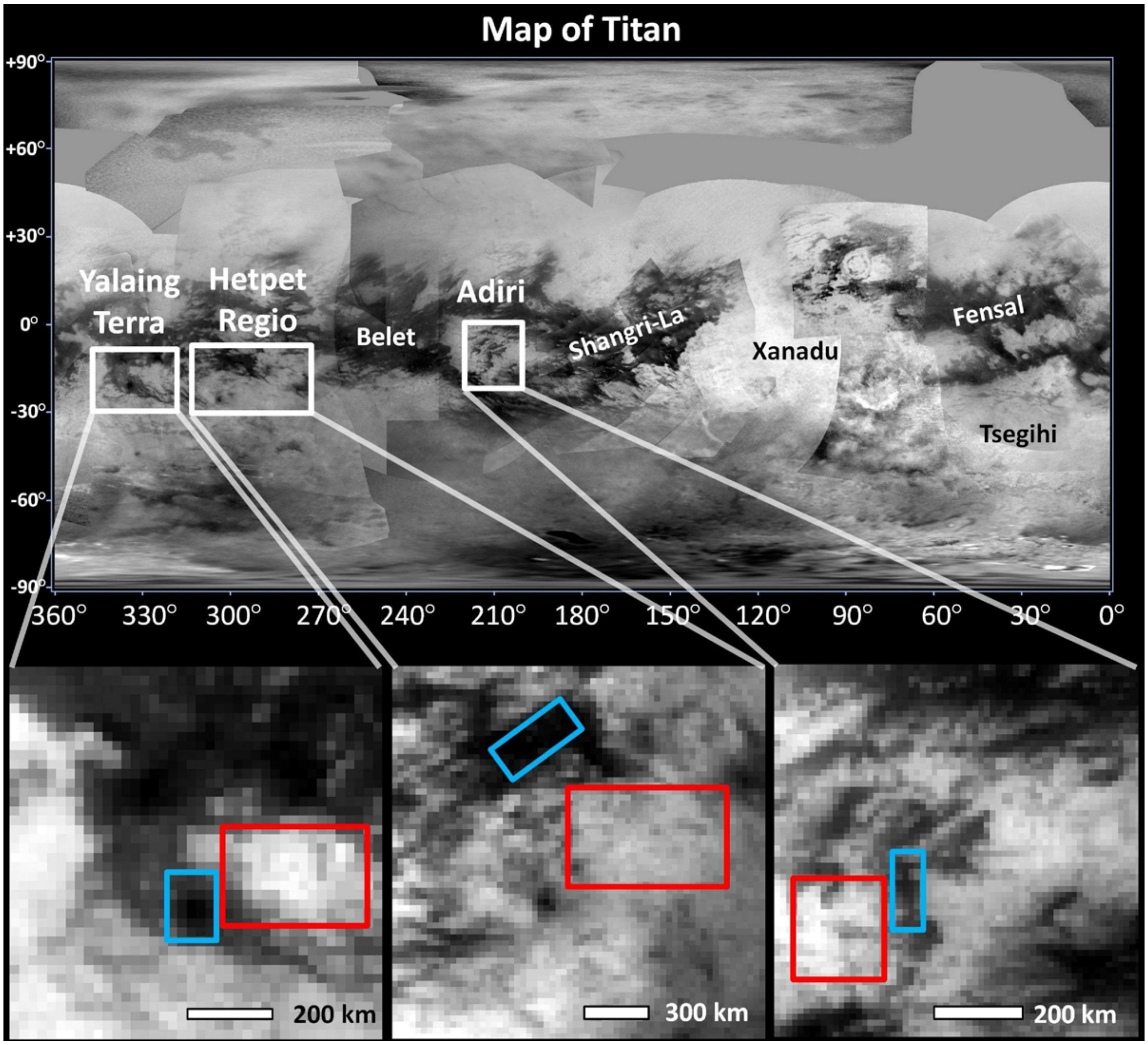

Figure 1. Map of Titan with zoom of target areas. The three areas targeted in this spectroscopic study are Yalaing Terra, Hetpet Regio, and Adiri. The red boxes in each of the three panels below the map surround the specific surface area where brightness changes, indicating possible rain, were observed by *Cassini's* Visual Infrared Mapping Spectrometer (VIMS). The blue boxes surround reference areas, which do not show albedo variations in time, with viewing geometries similar to those in the red boxes. Each panel is an image obtained by VIMS showing the surface at 2.01 μm. The basemap was constructed from Imaging Science Subsystem (ISS) images obtained through the clear filter with an effective wavelength of 0.938 μm. Credit: NASA/JPL-Caltech/Space Science Institute.

These regions of "bright equatorial terrain" (Barnes et al. 2007) are embedded in darker terrain that can be further classified into dune-rich and dune-poor regions (Soderblom et al. 2007). Table 1 summarizes the location, resolution, and viewing geometry of the data studied for these three regions. For this study, we make use of the three spectral windows of atmospheric clarity at 1.98–2.12 μm, 2.62–2.81 μm, and 4.98–5.1 μm to map the composition of Titan's surface before and after a possible rainstorm, and later. There is sufficient spectral range and resolution in these three windows to determine the composition of any wetting agent on Titan's surface by comparing the spectrum to laboratory spectra of liquid methane, ethane, and other relevant hydrocarbons (Clark et al. 2009). The band at 1.5 μm is not used in this study because the spectra of the candidate liquids, ethane and methane, have no absorption features in this area (Brown et al. 2008; Clark et al. 2009).

For each area of interest (Figure 1, red boxes), a spatially averaged spectrum was computed for each targeted flyby and ratioed to the spectrum from 2011 May (T76) or 2011 June (T77) for which no rain was present (see Figure 2). The resulting spectrum within each of the three atmospheric windows was then compared both to laboratory spectra (to determine its composition) and to itself through time to determine if the composition of the region changed. Because the atmospheric path length changed between some of the images, the spectrum from each targeted region was normalized to the spatially averaged spectrum of a nearby "standard" region (Figure 1, blue boxes) that did not change in albedo between flybys and had similar path lengths to the target areas. The final normalized spectral ratios (NSRs) are given by Equation (1):

$$\mathrm{NSR} = \frac{(\text{Target Spectrum,Flyby } X/\text{Standard Spectrum,Flyby } X)}{(\text{Target Spectrum,T76 or T77}/\text{Standard Spectrum,T76 or T77})}. \tag{1}$$

This normalization procedure eliminates possible effects due to different optical depths of the haze. The only remaining concern with haze is time variability. A series of eight stellar occultations by Titan's atmosphere that occurred over the last six years were studied to investigate this concern. Preliminary results from these events suggest that the optical depth of the haze was fairly stable over this period (Sotin et al. 2012). In any case, the effect of the haze changes slowly with wavelength,

Table 1
Summary of VIMS Observations

Location	LAT	W. LONG	Flyby	Date	Image Size (pixels)	Spatial Res. (km pixel^{-1})	Solar Phase Angle
Adiri	−11°	215°	T70	2010 Jun 21	64 × 64	14	32°
			T77	2011 Jun 20	64 × 32	78	22°
			T79	2011 Dec 13	64 × 64	13	24°
Hetpet Regio	−24°	291°	T61	2009 Aug 25	64 × 64	22	12°
			T67	2010 Apr 5	40 × 40	58	15°
			T76	2011 May 8	60 × 52	27	45°
			T80	2012 Jan 2	64 × 64	49	57°
			T82	2012 Feb 19	64 × 36	52	63°
Yalaing Terra	−17°	325°	T56	2009 Jun 6	48 × 48	140	44°
			T59	2009 Jul 24	64 × 64	23	23°
			T67	2010 Apr 5	40 × 40	30	10°
			T76	2011 May 8	64 × 64	18	42°
			T80	2012 Jan 2	64 × 64	49	57°

while we are attempting to detect sharp absorption bands of ethane and methane liquid. Furthermore, the key atmospheric window at 5 μm is nearly devoid of the effects of haze, having an optical depth of less than 0.05 (Sotin et al. 2012).

The power of obtaining ratioed spectra as described by Equation (1) is that instrumental effects are eliminated and that differences among spectra can be easily extracted. The key to the strategy is that the geographical region to which the rain-wetted areas are compared must be dry. Our comparison (dry) regions of T76 and T77 are all high in albedo relative to regions where rain has occurred (Barnes et al. 2012). Furthermore, these regions are all similar in composition to each other and different from rain-wetted areas in Yalaing Terra (T59 and T67), Hetpet Regio (T67 and T80), and Adiri (T70). Figure 2 (panels (a) and (b)) shows both the extracted spectra of T76 and T77 and their ratios. If the two regions differ only in albedo but not composition, there would be a simple step function in the spectral bands. This is the case for the atmospheric window at 2.01 μm (the slopes of the lines going into and out of the band are due to the dependence of the opacity of methane on albedo). The window at 2.7 μm has an absorption band that is more prominent in the low-albedo terrain of T76. This band appears in all our spectra as well as the spectra of Titan's lakes, including Ontario Lacus (Brown et al. 2008). From 2.6 μm to 2.7 μm, the NSR is consistent with liquid ethane, but the absorption band near 2.78 μm conflicts with the increase in reflectivity seen in the liquid ethane model spectrum. It is possible that other hydrocarbons create the features seen in this window. There is a shallow absorption band in the 5 μm region (see Figure 2, panel (a)) that is most likely caused by ethane frost, the spectrum of which is shown in Figure 2, panel (c). In any case, there is no evidence for liquid methane or ethane in any of these regions.

While the spectra between 2 and 5 μm of many alkanes such as methane and ethane have similar shapes, liquid ethane's spectrum has characteristic absorption features within the atmospheric windows that distinguish it from liquid methane (see Figure 2, panels (c)–(e), and Clark et al. 2009). In the 2 μm window, liquid ethane exhibits absorption bands centered at 2.02 μm and at 2.11 μm, and in the 5 μm window, liquid ethane has an absorption band that is twice as deep as that of liquid methane (Figure 2, panel (c)). In the complex 2.7 μm region, liquid ethane is more featureless than methane.

3. RESULTS

3.1. Yalaing Terra

Barnes et al. (2012) showed that the region in Figure 1 (lower left) appeared to brighten between flybys T67 (2010 April 5) and T76 (2011 May 8). The spectral ratio (Figure 2, panel (c)) between T67 (with rain) and T76 (without rain) clearly shows that liquid ethane's characteristic absorption features at 2.02 μm, 2.11 μm, and 5 μm were present during T67. Together, the absorption features and the surface brightening suggest rain was present on the surface in T67 but had evaporated, or had been removed by some process, by T76. The spectral ratio between T80 (2012 January 2) and T76 does not show signatures of liquid ethane. However, the spectral ratio between T59 (2009 July 24) and T76 does display a broad absorption line in the 2 μm window and a steep decline and increase in reflectance in the 5 μm window: liquid ethane is most likely present in T59 as well as T67 (see Figure 2, panel (c)). The feature at 2.8 μm appears in the methane frost spectrum (Figure 2, panel (e)), but other features characteristic of methane are missing. Liquid methane is not a very good match, particularly at 2.15 μm and in the 2.7 μm regions. VIMS spectral observations of Yalaing Terra obtained during T61 (2009 August 25) show weak evidence for liquid ethane, possibly signifying late rain evaporation. Thus, at least two rainstorms occurred in Yalaing Terra between 2009 July and 2010 April.

3.2. Hetpet Regio

As in Yalaing Terra, Hetpet Regio (Figure 1, lower center) also appeared to brighten between flybys T67 and T76 (Barnes et al. 2012). Once again, the spectral ratio between T67 and T76 (Figure 2, panel (d)) suggests that ethane was present in T67 but not in T76. The smaller of the two features in the 2 μm window is not present, but the 5 μm feature is very clear, including the characteristic bump near 4.96 μm. Unlike Yalaing Terra, however, the spectral ratio between T80 and T76 does yield evidence of liquid ethane in T80, with a clear absorption feature at 2.02 μm and a dramatic drop in reflectance near 5 μm. The presence of higher-order alkanes such as butane or propane could explain why the reflectance does not rise sharply after this drop (Clark et al. 2009). At least two rainstorms occurred in this

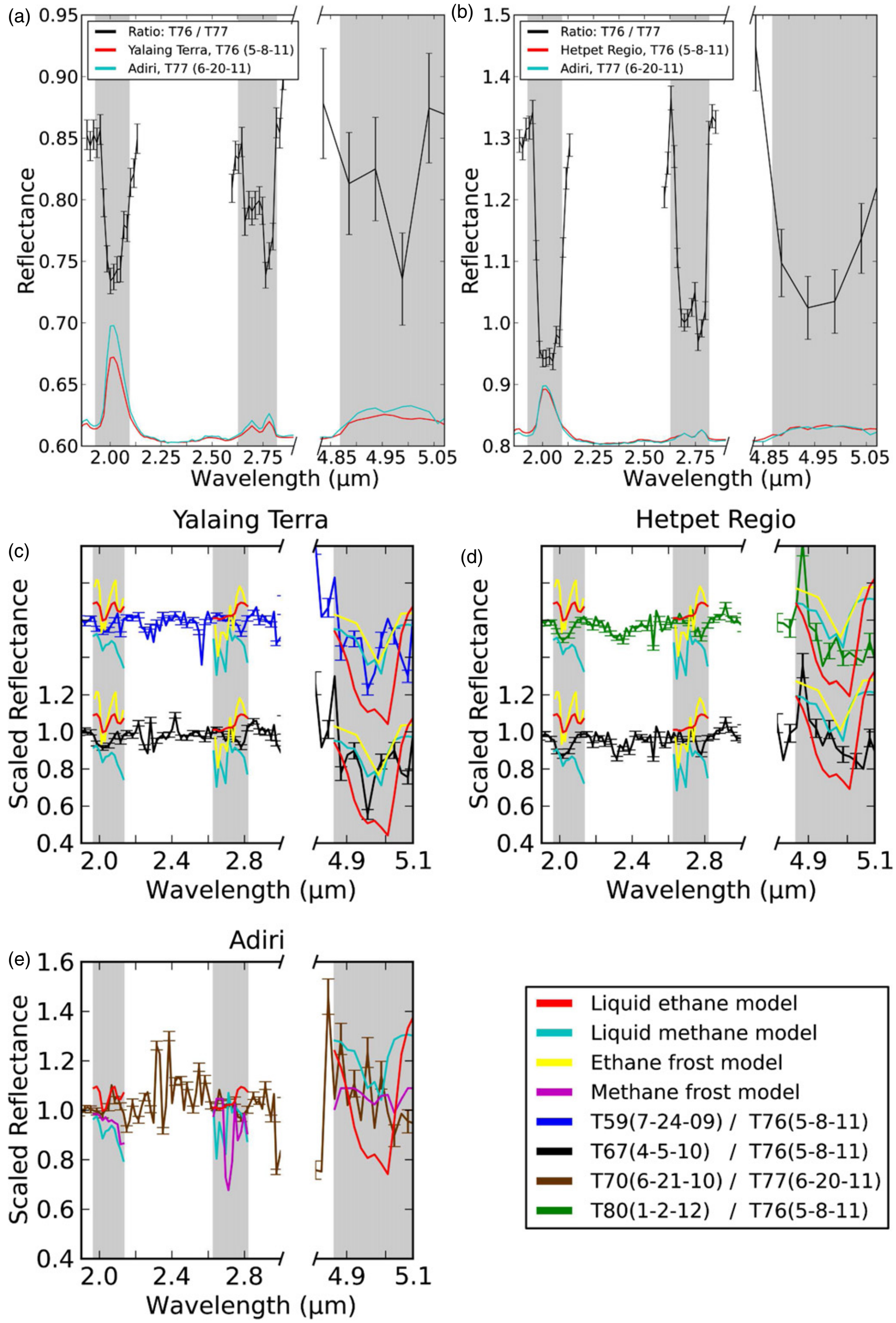

Figure 2. All spectral ratios used to identify the presence and composition of rain on the surface of Titan. Windows of atmospheric clarity containing clues on the surface composition of Titan are shown as gray bars. Because the surface is not visible outside these windows, the spectra have been truncated to only show the three windows centered at 2 μm, 2.7 μm, and 5 μm. Panels (a) and (b) show the extracted comparison spectra and their ratios. Within the error bars, the dips in reflectance in the 2 μm windows of (a) and (b) and the 5 μm window of (b) resemble step functions and are therefore caused by albedo differences and not by the presence of liquid ethane. In (a), the shallow dip in reflectance near 5 μm is most likely due to ethane frost. These comparison regions (T76 for Yalaing Terra and Hetpet Regio, and T77 for Adiri) are devoid of liquid methane and ethane and are appropriate to be used to compute the ratio described by Equation (1). Panels (c)–(e) show the spectral ratios computed with Equation (1) and compared to models of liquid ethane and methane. The presence of absorption features in the 2 and 5 μm bands, as in the Yalaing Terra and Hetpet Regio spectra, shows that the surface most resembles liquid ethane. Near the right edge of the 2 μm window, the spectrum of methane falls off steeply while that of ethane recovers and has another small feature. (In panel (a), the extracted spectra are shifted up 0.6 for viewing clarity. In panels (b), (c), and (d), these shifts are 0.8, 0.6, and 0.6, respectively. The ratios in the 5 μm regions in panels (a) and (b) are coadded spectrally using a bin size of three bands to reduce the noise. In panels (c)–(e), the model spectra have been shifted up or down slightly for viewing clarity. Also for clarity, not every model spectrum is shown with each data set, and every other error bar is shown in panels (c)–(e).)

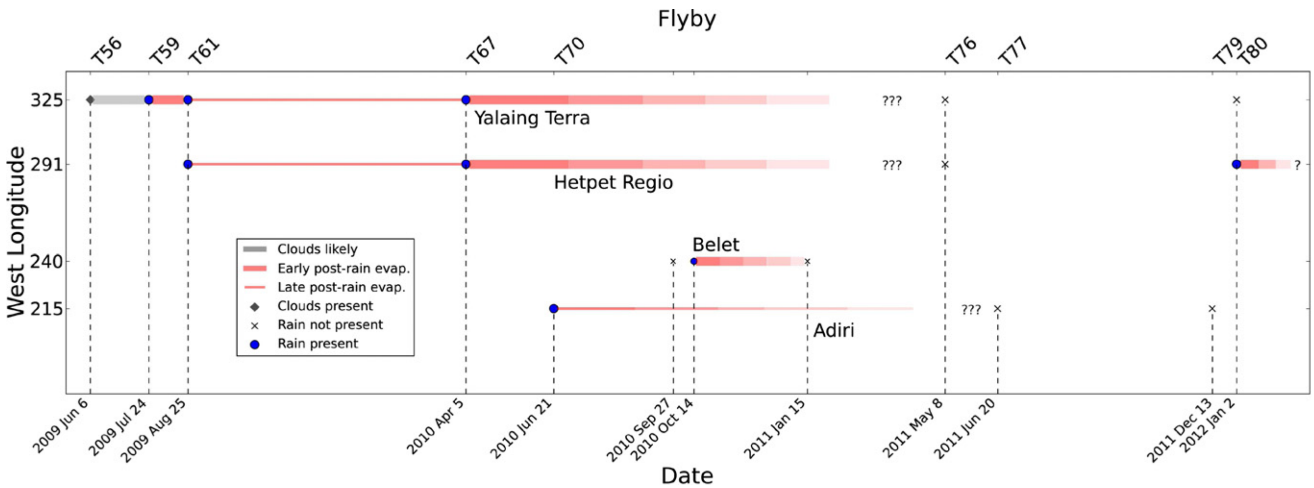

Figure 3. Frequency of rainfall and the extent of subsequent evaporation in the targeted areas. A blue dot indicates times when rain appears to be present on the surface and a black "×" indicates rain was not present. The one gray diamond represents the clouds that were observed near Yalaing Terra on 2009 June 6 (Figure 4). The lengths of the horizontal pink bars represent the length of time liquid apparently existed on the surface. The thickness is a rough indication of the extent of the evaporation and is based on the strength of the absorption features seen in the spectrum of the previous flyby. We estimate that there were at least five scattered storms in the targeted areas between 2009 June and 2012 February. The first occurred in Yalaing Terra around 2009 July 24. The second occurred in both Yalaing Terra and Hetpet Regio around 2010 April 5, although this event could have been two separate storms. The third occurred in Adiri sometime before 2010 June 21. The fourth occurred near Belet sometime around 2010 September (Turtle et al. 2011b). The fifth occurred in Hetpet Regio around 2012 January 2.

region between 2010 April and 2012 January; these are shown in a timeline in Figure 3. It is also possible that the Yalaing Terra and Hetpet Regio rainstorms occurring before 2010 April were one large event.

3.3. Adiri

In central Adiri, VIMS detected an increase in surface brightness between T70 (2010 June 21) and T77 (2011 June 20; Barnes et al. 2012). One small area (Figure 1, lower right) contains liquid ethane in T70. Figure 2, panel (e) shows the ethane absorption bands very clearly at 2 and 5 μm. However, the match is poorer: the shoulder at 2.0 μm is depressed and signatures of methane frost or liquid are evident in all the bands, possibly indicating patches of wet methane or ethane existing on a substrate of methane ice. Recent observations suggest that methane lakes may exist near the equator (Griffith et al. 2012).

4. DISCUSSION

Surface spectra suggest that liquid ethane was present in at least one of the targeted regions in T59, T67, T70, and T80. If this ethane was deposited by isolated rainstorms, clouds must have been present sometime before the liquid ethane was observed. Limited high-resolution coverage of the required areas precludes detection of clouds in most cases. However, VIMS observed a cloud system very near to Yalaing Terra in T56 on 2009 June 6 (Figure 4), 48 days before the detection of liquid ethane. The cloud was just north of Yalaing Terra and appeared to stretch at least 1200 km in the east–west direction. This cloud was likely the source of the rain in T59.

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 (Lunine & Atreya 2008). Although an early study suggested that rain would evaporate before reaching Titan's surface (Lorenz 1993), a more recent study shows that even small (1–4.75 mm radii) methane–nitrogen raindrops will persist if the relative humidity of ethane is at least 50% (Graves et al. 2008). As the drops fall, they begin to reach compositional equilibrium with the atmosphere causing their ethane content to increase. After

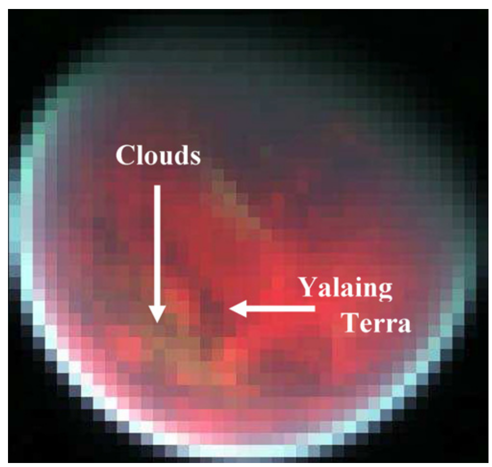

Figure 4. Clouds seen near Yalaing Terra in T56. This composite RGB ($R = 2.01\,\mu$m, $G = 2.83\,\mu$m, $B = 2.13\,\mu$m) exposes clouds (brown) near Yalaing Terra approximately 48 days before rain was detected on the surface.

hitting the ground, the ethane mole fraction further increases as it is more stable at surface conditions than methane, which evaporates more rapidly. With ethane in the atmosphere, on the surface and now in the rain, perhaps Titan's methanological cycle is more correctly an *ethanological* cycle, with ethane being the working fluid. The presence of liquid methane and both methane and ethane frost suggest that the rain contains some amount of methane and that it may freeze upon hitting the ground, much as freezing rain does on the Earth. Regions in the later stages of evaporation such as Adiri may consist of puddles interspersed with a substrate of methane and ethane frost.

Although there are no known standing ethane lakes in the regions we studied, some equatorial bright terrains have long channels that form large drainage networks (Jaumann et al. 2008), including Adiri,[6] suggesting that rain is reaching the ground at low latitudes on Titan. Our three-year survey observed only about 2%–3% of the equatorial regions ($\pm 30°$) of Titan at sufficient resolution to determine surface composition, and the

[6] http://pirlwww.lpl.arizona.edu/~perry/RADAR

surface was observed for only a total of ∼26 hr at this resolution. Many more rain showers could have thus occurred (although the persistence of wet surfaces for months provides evidence for rain outside the times of the flybys). This study proposes that rainfall in the form of scattered, isolated showers is a common occurrence at low latitudes. Furthermore, the spectra of the targeted regions no longer resemble liquid ethane on timescales of months to a year, meaning that the liquid rain remains only temporarily on the surface. The presence of massive dune-covered dark terrain in the equatorial regions (Radebaugh et al. 2008) implies that persistently dry regions could coexist with rain showers, much as in the Earth's arid regions.

Given the complexity of Titan's surface with multiple components coexisting in both liquid and solid forms, and with few observations and limited spatial resolution, it is difficult to reconstruct exactly what happens on Titan's surface. It is clear that despite ethane's low concentration in the atmosphere, it plays a significant role in the methanological cycle and is present on the surface, in the rain, and in the lakes.

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