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Formation mechanisms of channels on Titan through dissolution by ammonium sulfate and erosion by liquid ammonia and ethane

Ashley E. Gilliam*, Abraham Lerman

Department of Earth and Planetary Sciences, Northwestern University, 2145 Sheridan Rd – Tech F379, Evanston, IL 60208-3130, United States

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ABSTRACT

Data obtained from the Cassini Visual and Infrared Mapping Spectrometer (VIMS), Imaging Science Subsystem (ISS), and Synthetic Aperture Radar (SAR) instruments have revealed an array of fluvial channels on Titan's surface, often several hundreds of kilometers in length. The paucity of impact craters on Titan's surface suggests a formation by fluvial erosion into the water-ice bedrock. Additionally, at the landing site, the Huygens Probe Descent Imager and Spectral Radiometer (DISR) imaged Earth-like rounded cobbles 0.3–15 cm in diameter composed of water ice, reminiscent of rounded stream clasts on Earth. In this paper we examine different fluvial features on Titan, identified by the Cassini spacecraft, and evaluate the possibilities of channel formation by dissolution of ice by a concentrated solution of ammonium sulfate, and by mechanical erosion by flow of liquid ammonia and liquid ethane. We find that chemical erosion of Titan's channels could be completed in 280 to 1100 years (all units of time in this paper are Terrestrial, not Titanian), much shorter than the period of about 84,000 years that a concentrated $(NH_4)_2SO_4$-H_2O solution could exist as a liquid on the Titan surface. Mechanical erosion of Titan's channels is generally a much slower process, on the order of 10^2 to 10^5 years to completion, and is also slower than mechanical erosion of a model river on Earth, averaging 10^3 to 10^4 years. The erosional sequence of the channels on Titan may have started after the formation of water-ice on the surface by the process of chemical dissolution by $(NH_4)_2SO_4$-H_2O, overlapping, or followed by, a period of mechanical erosion by liquid NH_3. A final stage on the cooling surface of Titan might have been characterized by liquid C_2H_6 as an agent of mechanical erosion.

1. Introduction

Titan, the largest moon of Saturn, is the only satellite in the solar system with a significant atmosphere, harboring a suite of hydrocarbons that display a meteorological cycle similar to the hydrological cycle on Earth. Dendritic networks of sinuous valleys on the surface of Titan were first observed by the Cassini-Huygens mission, where Synthetic Aperture Radar (SAR) images revealed drainage networks with branching morphologies on the order of 100 km in length (Elachi et al., 2005). These observations were supported in greater detail by the Huygens Probe Descent Imager and Spectral Radiometer (DISR) (Tomasko et al., 2005; Soderblom et al., 2007b; Jaumann et al., 2009), and suggested formation by fluvial erosion into the water-ice bedrock. Additional support that the valleys were formed by flowing liquid is the paucity of impact craters on Titan's surface (Porco et al., 2005; Elachi et al., 2005; Jaumann et al., 2009; Wood et al., 2010), indicative of rapid burial or removal of surface topography. Additionally, at the landing site, the DISR imaged Earth-like rounded cobbles 0.3–15 cm in diameter (Tomasko et al., 2005) composed of water ice, indicating that they had undergone abrasion during fluvial transport. Further evidence of widespread fluvial processes on the surface of Titan has been revealed by the Cassini Imaging Science Subsystem (ISS) (Porco et al., 2005) and the Visual and Infrared Mapping Spectrometer (VIMS) (Barnes et al., 2007b; Jaumann et al., 2008).

Unlike on Earth, where liquid H_2O is the major agent of erosion, Titan's liquid erosion likely has multiple contributors. One possible contributor, that arguably garners the most attention, is liquid CH_4. Methane, which forms several percent of Titan's atmosphere, is a likely candidate for liquid erosion due to its stability as a liquid on the surface, its ability to participate in Titan's hydrological cycle, and direct observations of cloud-top altitudes consistent with the condensation altitudes expected for methane (Lorenz et al., 2008). Further support for liquid methane being a primary contributor to Titan's erosion is shown in the works of, for example, Burr et al. (2006, 2009, 2013), Perron et al. (2006), Jaumann et al. (2008), Lorenz et al. (2008), Cartwright et al. (2011), Langhans et al. (2012),

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* Corresponding author.
E-mail address: ashley@earth.northwestern.edu (A.E. Gilliam).

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Black et al. (2012), whose studies suggest that it could plausibly move enough material under conditions present on Titan to account for most of the observed fluvial features, even suggesting that mechanical erosion by liquid methane surface runoff would not require unreasonably high precipitation rates. Works similar to those cited above are numerous, but here we consider other liquids, which are also present on Titan, that could be responsible for the formation of the channels seen on the surface.

In this paper we address two different fluvial erosion processes on Titan. Specifically, we examine the possibilities of channel formation by dissolution of ice by a concentrated solution of ammonium sulfate, and by mechanical erosion by flow of liquid ammonia and liquid ethane. Each of these processes might have functioned over a certain range of temperatures during the cooling history of Titan.

That liquid ethane in Titan's atmosphere is not a pure liquid, but a solution containing CH_4 and N_2, has been shown by Tan et al. (2013, 2015). For surface liquids on Titan, such as in Ontario Lacus, the liquid was given as 15–30% CH_4, 50–80% C_2H_6, and 5–10% N_2 (Luspay-Kuti et al., 2015; Mitri et al., 2007), and a similar composition of liquid C_2H_6 solution on Titan's equator is given by Tan et al. (2015). The physical properties of a C_2H_6-CH_4-N_2 solution are not a weighted mean of the properties of three liquids, each of a very different liquefaction temperature. The properties are likely to be those of a solution of gaseous CH_4 and N_2 in liquid C_2H_6, similar to the properties of a solution of such gases as CO_2, N_2, and O_2 in liquid H_2O. The more soluble gas CO_2 affects the density and viscosity of pure H_2O very little, by less than 3% (Garcia, 2001). The density of ethane solutions on the equator and the poles of Titan, as given by Tan et al. (2015) is 601–547 kg m^{-3}. These values are close to those of pure C_2H_6, 652 kg m^{-3} at 90.4 K and 586 kg m^{-3} at 150 K. We further assume that viscosity, like density, of pure liquid C_2H_6 does not differ much from an ethane solution of methane and nitrogen gases.

2. Observations of streams on Titan

Valley-like features on the surface of Titan are known from the Huygens landing site and by three different imaging instruments onboard the Cassini spacecraft: the Visual and Infrared Mapping Spectrometer (VIMS), operating at 0.35–5.2 μm (Brown et al., 2004), the Imaging Science Subsystem (ISS), operating at 0.2–1.1 μm (Porco et al., 2005), and the Cassini Titan Radar Mapper (RADAR), emitting at 2.2 cm (Elachi et al., 2005). The resolution of VIMS and ISS images, which are hindered by atmospheric scattering and absorption, varies with both the distance of the spacecraft and emission angle. VIMS spatial resolution averages a few km/pixel but for small areas can be as high as 250 m/pixel (Jaumann et al., 2009). ISS resolution ranges from 1 to 10 km, with relatively small areas imaged at 1 km/pixel (Porco et al., 2004, 2005). The synthetic aperture radar (SAR) data from the RADAR are collected in swaths and are of the highest resolution ($\sim$350 m/pixel) available from the Cassini spacecraft (Lopes et al., 2010). Although RADAR coverage of the Titan surface is $\sim$50% to date, compared to near-global coverage by the VIMS and ISS data, the SAR data provide the best resolution for mapping the fluvial networks.

In this study we examine 27 different fluvial features as identified in VIMS, ISS, and RADAR data, chosen based on their geographic diversity and resolution – or our confidence in their classification as a fluvial feature. The locations and dimensions of these features on Titan are indicated in Figs. 1 and 2, and summarized in Table 1. These valleys represent an array of morphologic features and range in size from tens of kilometers to over a thousand kilometers long, and up to ten kilometers wide. The majority of these features are dendritic in nature, forming tree-shaped networks with many contributing branches that converge into larger receiving streams, up to seventh in channel order, indicative of an origin from rainfall (Tomasko et al., 2005; Perron et al., 2006; Lorenz et al., 2008; Jaumann et al., 2009).

In contrast to these complex channels, there are also several fluvial features that seldom exhibit meanders, possess a low channel order, and a large channel width of up to 10 km. These features are inferred to be dry valleys, created as a result of rapid runoff events followed by prolonged droughts (Lorenz et al., 2008).

Another group of fluvial valleys recorded are believed to be the result of erosion by liquid seepage from the subsurface. These sapping channels are classified as being generally shorter and broader than those created by rainfall, and possess a low channel-order (Tomasko et al., 2005; Jaumann et al., 2009). If correct, the presence of sapping channels indicates that Titan has a subsurface aquifer, which will be discussed in a later section.

Also notable are three features inferred as elongated valleys due to their straight course and their relatively small size, two fluvial features that exist within mountain chains and support an origin from rainfall (Langhans et al., 2012), and one system of valleys associated with alluvial fans.

In order to calculate the relative rates of stream incision into the water-ice bedrock on Titan, the channel dimensions used are as shown in Table 1. Measurements of channel slope were made directly from Cassini RADAR SARtopo and altimetry data, and depth from an empirical relationship between channel depth and width as outlined in William (1988). Size-distribution of the channels are shown in Fig. 2.

3. Crustal composition and structure

Previous work (Fortes et al., 2007; and references in Gilliam and Lerman, 2014a, 2014b) has suggested that the interior of Titan is composed of a complex assemblage of silicate minerals, organic matter, liquid water in a subsurface NH_3-H_2O ocean, and ices, overlain by a crust composed primarily of low-pressure water ice, methane clathrate and ammonium sulfate. The exact thickness of the crust is mainly determined by the amount of heat available in the interior as well as the percentage of anti-freezing agents in the subsurface ocean, but is generally thought to be >100 km at present-day (Fortes et al., 2007; Gilliam and Lerman, 2014a).

The formation of the crust is a result of the interaction between Titan's primitive atmosphere and its liquid layer, which were in direct contact immediately after accretion and up until sufficient cooling of the atmosphere resulted in the crystallization of a solid shell composed of ice and methane clathrates (Tobie et al., 2006). After further cooling and thickening, macroporous clathrate grains are thought to have transported pockets of ammonium sulfate solution upwards, incorporating them into the outer shell, where they ultimately solidified to water ice and ammonium sulfate (Fortes et al., 2007). At present-day, a cross-section of the upper part of Titan's interior would reveal a top layer of ice Ih, methane clathrate, and solid ammonium sulfate, of densities 941, 988.5, and 1769 kg m^{-3}, respectively (Fig. 3, Table 2). On Earth, ammonium sulfate occurs as mineral mascagnite in fumaroles and volcanic vents.

4. Channel formation mechanisms

In this section, we consider the characteristics of the valley networks and Titan's surface environment, and several possible mechanisms of channel formation. The four, as shown in Fig. 4 and Table 3, might have operated at different times during Titan's