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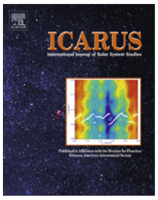

Transient climate effects of large impacts on Titan

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ABSTRACT

Titan's thick atmosphere and volatile-rich surface cause it to respond to big impacts in a somewhat Earth-like manner. Here we construct a simple globally-averaged model that tracks the flow of energy through the environment in the weeks, years, and millenia after a big comet strikes Titan. The model Titan is endowed with 1.4 bars of N_2 and 0.07 bars of CH_4, methane lakes, a water ice crust, and enough methane underground to saturate the regolith to the surface. We find that a nominal Menrva impact is big enough to raise the surface temperature by ~80 K and to double the amount of methane in the atmosphere. The extra methane drizzles out of the atmosphere over hundreds of years. An upper-limit Menrva is just big enough to raise the surface to water's melting point. The putative Hotei impact (a possible 800–1200 km diameter basin, Soderblom et al., 2009) is big enough to raise the surface temperature to 350–400 K. Water rain must fall and global meltwaters might range between 50 m to more than a kilometer deep, depending on the size of the event and how rapidly bedrock ice warms and founders. Global meltwater oceans do not last more than a few decades or centuries at most, but are interesting to consider given Titan's organic wealth. Significant near-surface clathrate formation is possible as Titan cools but faces major kinetic barriers.

1. Introduction

It has long been appreciated that a comet big enough to punch through Titan's atmosphere would generate impact melts of liquid water that could persist for considerable periods of time (Thompson and Sagan, 1992; Artemieva and Lunine, 2003, 2005; O'Brien et al., 2005). Water melts on Titan are interesting for many reasons, foremost the likelihood that interesting chemistry takes place when the nitrogenous organic matter expected to be widespread and abundant on Titan's surface is dissolved in liquid water (Thompson and Sagan, 1992). The chemical picture is somewhat reminiscent of Darwin's warm little ponds, or more closely, Miller and Bada's ponds on ice: liquid pools that concentrate simple products of atmospheric chemistry like HCN and H_2CO as water freezes. This path to the origin of life was featured in Jacob Bronowski's classic television series and companion book, *The Ascent of Man* (Bronowski, 1973).

Previous work has focused on impact-generated crater lakes, sometimes called impact oases. Upper limits on how long lakes last are obtained by balancing the latent heat of fusion (released when water freezes to the bottom of an ice lid) against thermal conduction through the ice lid. Cooling of this kind is slow and crater lakes deeper than 100 m were predicted to endure 10^4–10^6 years (Thompson and Sagan, 1992; Artemieva and Lunine, 2003). O'Brien et al. (2005), using a 2-D numerical heat conduction code, found that the more realistic geometry made the lake freeze some 100 times faster, even in the favorable case of a hypothetical water-ammonia eutectic.

Here we focus on impacts big enough to raise the whole surface of Titan to the melting point. In overview, the work we describe here parallels work we have done for impacts on Earth (Sleep et al., 1989; Zahnle, 1990; Melosh et al., 1990; Zahnle and Sleep, 1997; Zahnle et al., 2007; Nisbet et al., 2007) and Mars (Sleep and Zahnle, 1998; Segura et al., 2002). On Earth, big impacts vaporize water that later rains out. This can also happen on Mars, but because the martian atmosphere is thin, the atmosphere stores little of the impact energy; thus Mars is prone to cool quickly. By contrast, Titan's thick atmosphere provides a huge thermal buffer. It takes a big impact to heat it, but once heated it takes a long time to cool down.

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2. Background assumptions

Titan is likely to have evolved significantly in response to *uv* photolysis, hydrogen escape, and the steady brightening of the Sun Lunine et al. (1989), McKay et al. (1993, 1999), and Lorenz et al. (1997). At the currently observed hydrogen escape flux of 1.4×10^{10} H_2 molecules $cm^{-2}\,s^{-1}$ (referred to the surface, Cui et al., 2008), Titan will consume its apparent methane inventories (Atreya et al., 2006; Lorenz et al., 2008) in 15–60 Myrs, depending on whether the chief product is ethane or H-poor polyaromatic hydrocarbons, respectively.

Another constraint is that the products of billions of years of methane destruction are not visible on the surface (Gall et al., 2011). A representative photochemical model (Wilson and Atreya, 2004) predicts that ethane should accumulate at 40 m/Gyr. Gall et al. (2011) find that Titan's sand dunes today correspond to the equivalent of a global layer 0.6–6 m deep. At current rates, this layer would take 15–150 Myr to accumulate. Modeling of isotopic evolution of methane can be made consistent with an older age of 60–1600 Myr, but uncertainties in the modeling do not preclude an age as young as 10 Myr (Nixon et al., 2012).

Taken together these observations—call them methane's time scale paradox—would seem to place us in a special time in Titan's history when methane is abundant. It is curious to note that crater counts and best estimates of the current impact cratering rate suggest that the surface itself may be older, some 200–1000 Myrs (Neish and Lorenz, 2012). For these reasons and others, Titan's story seems likely to have been complicated by non-uniformitarian tendencies.

Here we set worries aside and treat Titan at the times of big impacts as having an atmosphere and surface like today's and a crust made of water ice and methane. We restrict our consideration to three volatiles: N_2, H_2O, and CH_4. Our reasons for making these conservative assumptions are: (i) A nitrogen atmosphere like today's is a reasonable starting point, because the amount of N_2 outside Titan's interior is not likely to have changed greatly since Titan's formation (Mandt et al., 2009). The important qualification is that much or most of the nitrogen may have been in a condensed state similar to Triton when the Sun was fainter (Lorenz et al., 1997; McKay et al., 1999). (ii) Water ice is the default choice for the crust because water is almost certainly the most abundant ice in bulk Titan as it is generally in icy satellites. The simple morphology of Menrva suggests that Titan had a relatively thick strong crust (Moore and Pappalardo, 2011). The important qualifications are that water ice is not unambiguously seen spectrally at the surface (Soderblom et al., 2010), and the rounded cobbles seen at the Huygens landing site may hint of something softer than water ice. (iii) Methane is currently the volatile that rains, and thus is the default agent of surface erosion. The important qualification is that methane may only be present in the atmosphere at special times. (iv) This is the first detailed study of its subject, and thus should be kept as simple as possible. The important qualification is that CO_2 ice (Wye et al., 2007), ethane (Lunine et al., 1989; Atreya et al., 2006), and several clathrates (Thomas et al., 2007, 2008; Mousis and Schmitt, 2008; Choukroun et al., 2010; Tobie et al., 2012) are all likely to be present or likely to form, and thus neglecting them may leave a system that is fundamentally too simple.

Our specific assumptions are an isothermal 1.4 bar N_2 atmosphere plus 5% CH_4, a water ice crust, and methane lakes that cover 3% of the surface to a depth of 40 m (equaling the 10^5 km^3 volume estimated by Lorenz et al., 2008). There is also methane in the soil. Heat from the Huygens Probe evaporated methane and other volatiles (including C_2H_6 and CO_2) from the surface (Niemann et al., 2005, 2010; Lorenz et al., 2006), which suggests that the methane aquifer extends practically to the surface. We arbitrarily assume that the crust contains 5% methane (g/g), which corresponds to a porosity of 10% (liquid methane's density is about half that of the crust). We assume that porosity extends to a depth $d_s = 1.5$ km. At greater depths the pores are sealed off as bubbles. This estimate is scaled from Earth, where porosity persists in ice to depths of 40–120 m (Bender et al., 1997), to Titan with weaker gravity and cold ice. This may be an underestimate; Nimmo and Manga (2007) estimate that cold ice can support porosity to 4–5 km at Europa's similar gravity. These assumptions correspond to a total crustal methane reservoir of 14×10^6 km^3 ($\sim$1.6 bars), which is big, about 24 times bigger than the atmospheric inventory. On the other hand, this volume of fluid falls short by a factor of 3–10 of what is required to resolve the methane time scale paradox.

3. Big basins

The biggest known obvious impact feature on Titan is Menrva, a well-preserved $\sim$444 km diameter impact basin partially seen by Cassini imaging radar (Wood et al., 2010). The next largest known crater is $\sim$180 km diameter. Menrva is comparable in size to Gilgamesh on Ganymede or Lofn on Callisto, both of which are young in the cosmic sense of post-dating the late bombardment. Menrva's age is indeterminate. At current impact rates one expects on the order of one Menrva in 4 Gyr on Titan (Zahnle et al., 2003; Dones et al., 2009), with an uncertainty that effectively embraces the entire history of the Solar System.

There is some evidence of at least one older and bigger crater on Titan. Hotei Regio is a $\sim$700 km diameter quasi-circular IR albedo feature that appears to lie within a larger basin that in turn appears, at least on the side mapped by radar, to be an arc of a circle named Hotei Arcus (Soderblom et al., 2009). The albedo feature has been a leading candidate for a cryovolcanic flow (Soderblom et al., 2009), but Soderblom et al. (2009) suggest that the basin itself is an ancient impact feature, perhaps as large as 1200 km diameter, that has been severely degraded. We will make much of Hotei-scale impacts here. Bigger, more ancient impacts are plausible (cf., Sekine and Genda, 2012), but Hotei is big enough to illustrate the key points.

3.1. Impact energies from crater scaling

Textbook crater scaling is highly suspect for a basin as big as Menrva, let alone Hotei. Given this caveat, we use formulae for impact craters in the gravity-scaling limit derived from experimental Π-group relations by Schmidt and Housen (1987) as expressed by Zahnle et al. (2008). The cratering efficiency Π_V goes as

$$\Pi_V \equiv \frac{\rho_t V_{ap}}{m_i} = 0.2\,\Pi_2^{-0.65}\cos\theta, \qquad (1)$$

where

$$\Pi_2 \equiv \frac{2g}{v_i^2}\left(\frac{m_i}{\rho_i}\right)^{1/3}. \qquad (2)$$

The apparent volume V_{ap} in Eq. (1) is measured with respect to the original surface. In these expressions ρ_i and ρ_t denote the densities of the projectile and target, m_i, v_i, and d_i denote the mass, impact velocity, and diameter of the projectile, and g is the surface gravity. The dependence on incidence angle θ (measured from the vertical) is that recommended by Melosh (1989). We assume the apparent crater can be described as a paraboloid with a depth/diameter ratio of 0.15, which gives

$$D_{ap} = 1.1\left(\frac{\rho_i}{\rho_t}\right)^{1/3}\left(\frac{v_i^2}{g}\right)^{0.22} d_i^{0.78}\cos^{1/3}\theta. \qquad (3)$$