

# Numerical calculations of the longevity of impact oases on Titan

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## Abstract

A promising setting for the formation of interesting prebiotic molecules on Titan is the transient liquid water environment formed by a comet impact, as originally suggested by Thompson and Sagan (1992, in: Symposium on Titan, ESA SP, vol. 338, p. 167). The impact melt (water or a water–ammonia mixture) generated in such an event can react with the abundant photochemical hydrocarbons and nitriles deposited on the surface of Titan to form more complex molecules such as purines and amino acids. We use a finite-difference thermal conduction code to calculate how long it takes for realistic liquid deposits in crater floors to freeze in the Titan environment. Our results suggest that 15 km diameter craters can sustain liquid water or water–ammonia environments for  $\sim 10^2$ – $10^3$  yr and 150 km craters can sustain them for  $\sim 10^3$ – $10^4$  yr. We discuss the implications of these timescales for organic chemistry on Titan.

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## 1. Introduction

Since the discovery of a methane atmosphere around Titan by Kuiper (1944), Titan has attracted much exobiological interest. In the 1970s, before spacecraft reconnaissance established surface conditions with certainty, much of this interest centered around the possibility that the greenhouse effect of a thick atmosphere could permit hospitable surface conditions. The Voyager 1 encounter in 1980, however, showed that while the atmosphere is a familiar one in some respects (1.6 bar, mostly molecular nitrogen), the surface temperature of around 95 K is far too low for liquid water (Tyler et al., 1981).

Many organic compounds were detected in Titan's atmosphere, however. These form as a result of the recombination of molecular fragments produced by methane and nitrogen photolysis. Ultraviolet solar radiation is primarily responsible, although irradiation by electrons in Saturn's magnetosphere is an additional energy source. Around 20 species have been detected in Titan's atmosphere thus far, mostly by

mid- and far-infrared spectroscopy—see Coustenis and Taylor (1999) or Coustenis and Lorenz (1999) for a review.

Carl Sagan and others championed the role of photochemistry in synthesizing organic compounds as a key factor favoring the ubiquity of life in the Universe, and made many laboratory experiments energizing reducing gas mixtures (much like the original Urey–Miller experiments) with spark discharges or UV light (e.g., Khare et al., 1978, 1981, 1984; Sagan and Khare, 1979). The typical product, when the gas mixture is dominated by a Titan-like mixture of methane and nitrogen, is a red tarry deposit, termed by Sagan 'tholin'—a refractory mixture of carbon–nitrogen–hydrogen compounds. In addition to this material, which in spectral color is a good match to the haze observed in Titan's atmosphere by the Voyager cameras, are larger quantities of simple and not-so-simple gases including simple nitriles (HCN, CH<sub>3</sub>CN, C<sub>2</sub>N<sub>2</sub>, etc.). The latter gases condense in Titan's lower atmosphere and would be deposited, along with the tholins, as liquids or solids on the surface.

All of these photochemical products are interesting for modelers of atmospheric chemistry (see, e.g., Strobel, 1974; Yung et al., 1984; Toublanc et al., 1995; Lara et al., 1996; Dire, 2000), but they only go part way to addressing the

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origins of life, a connection that is often used to justify the exploration of Titan. The problem is that Titan's atmosphere is essentially bereft of oxygen or oxygen-containing compounds like water—even the most abundant (CO) is present only at a few tens of ppm (Noll et al., 1996). This is a crucial point for two reasons. First is that the chemistry that sustains life requires liquid water as a solvent. Second, virtually every organic molecule of biochemical interest (such as amino acids, sugars, fatty acids, and nucleic acids) contains some oxygen. Since there is no way to incorporate oxygen into the chemical chain in Titan's atmosphere, the organics in its atmosphere will only occur as astrobiologically less interesting nitriles and hydrocarbons. On the other hand, experiments have shown that tholins and nitriles are readily hydrolyzed by liquid water into amino acids (e.g., Titan tholin yields about 1% amino acids by mass on hydrolysis (Khare et al., 1986)), so if the organics accumulating on Titan's surface are exposed to liquid water, an entirely new step in chemical synthesis—one much more interesting for the origin-of-life question—could be introduced.

On a global-average basis, Titan's surface is far too cold for liquid water. However, the same logic applied to the Earth says that the Earth is too cold for molten silicates (i.e., rock). Generally this is true, but in particular regions at particular times, conditions that are far out of the ordinary can persist. One such circumstance is water-driven or cryo-volcanism, which while quite possible on Titan, is considered separately (Kargel, 1992; Tobie, 2003). Another circumstance that can drive extensive heating, melting, and (potentially) chemistry is that of a planetary impact (Thompson and Sagan, 1992). Using an analytic approximation, Thompson and Sagan (1992) estimate that liquid water can persist for  $\sim 10^4$  yr in a 10 km diameter crater and  $\sim 10^6$  yr in a 100 km crater. In addition, they consider melt in ejecta blankets around craters as a potentially more important source of liquid water, with a shorter duration ( $\sim 200$  yr) but significantly greater surface coverage. However, this timescale is based on the assumption that the melt exists as a layer within the ejecta. In reality, geologic evidence from craters on Earth indicates that the melt and the solid clasts in the ejecta are intimately intermixed and that the melt cools and solidifies quite rapidly, forming a glass or microcrystalline solid (Melosh, 1989; French, 1998). This rapid cooling of the melt is due primarily to its close contact with the colder clasts, and in the case of Earth (and presumably Titan as well), by its passage through the cooler atmosphere.

In this paper, we extend the work of Thompson and Sagan (1992) and treat the cooling and freezing of impact-generated melt within craters using a numerical model that allows for the use of more realistic geometries than did their analytical approximation. In addition, while they only treated pure H<sub>2</sub>O for their calculations of freezing timescales, we treat both H<sub>2</sub>O and ammonia dihydrate (NH<sub>3</sub>·2H<sub>2</sub>O), which is a potential surface constituent on Titan and is expected to increase the duration of impact-

generated melt environments (Lorenz et al., 2001). Ammonia dihydrate is thermodynamically, but not kinetically preferred, so in the case of rapid cooling, a stoichiometric mixture of water and ammonia monohydrate may form in place of the dihydrate. Such a mixture will likely have thermodynamic properties intermediate between pure water and ammonia dihydrate (Croft et al., 1988). Thus our choice of H<sub>2</sub>O and ammonia dihydrate give the upper and lower limits possible with water–ammonia mixtures. We compare our results to the estimates of Thompson and Sagan (1992), and discuss the implications of our results for organic chemistry on Titan.

## 2. Impact melt production and crater morphology

When an asteroid or comet strikes a planet, most of its energy goes into driving an explosion that excavates a crater, and may throw material high into the atmosphere. The size of a crater formed by a given sized projectile depends on a number of factors, such as impact speed and angle, target and projectile composition and density, and the gravitational acceleration of the target body. As several of these parameters are generally unknown, some assumptions are usually made (e.g., the average impact velocity of a stony or iron body on Earth is generally taken to be  $\sim 20$  km/s (Melosh, 1989)). The impactor that formed the  $\sim 1$  km diameter Meteor Crater in Arizona was an iron body  $\sim 30$  m in diameter (Melosh, 1989). The Chicxulub crater on the Yucatan peninsula has a diameter of  $\sim 180$  km (Grieve and Theriault, 2000), and the diameter of the impactor, assuming a rocky composition, is  $\sim 15$  km (Collins et al., 2002).

In addition to excavating a crater, some of the energy from the impactor also goes into heating the target material, some of which may melt. The amount of melt (as a fraction of crater volume) increases the larger the crater. For example, one of the biggest impact structures on the Earth is the 1.85 Gyr old Sudbury structure in Canada. Sudbury's original diameter is estimated at  $\sim 250$  km (Grieve and Theriault, 2000), but it has been heavily eroded and deformed since its formation. The impact generated a huge melt sheet, and metal sulfide blobs quickly precipitated out of the melt and settled in the footwall rocks (breccias and fractured/faulted basement rocks) below the melt sheet (e.g., Naldrett, 1999). Today these blobs, now long-frozen, constitute one of the largest nickel deposits in the world.

Thompson and Sagan (1992) assumed that the volume of melt within craters on Titan would be about 1% of the crater volume, based on terrestrial results. Recent simulations have shown that this is an underestimate of the amount of melt that would actually be produced on Titan. Impact conditions on Titan are significantly different than impacts on Earth. While the Earth's surface and many of the impactors striking it are rocky, Titan's surface and most of the impactors striking it (comets and other outer-Solar-System debris) are icy. In addition, the average impact velocity is lower on Ti-

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