Chapter 2. Titan as a Laboratory for Prebiotic Chemistry

2.1. Introduction

Titan is the largest moon of Saturn, and in fact, one of the largest moons in the Solar System. Discovered by Christian Huygens in 1655, it is larger in diameter than the planets Mercury and Pluto. This alone would make Titan an intriguing target for exploration, and Titan was visited by the Voyager 1 spacecraft in 1980, and more recently by the Cassini/Huygens mission to Saturn. Additionally, Titan possesses a thick nitrogen/methane atmosphere, shrouded in haze that obscures the surface.

Clearly, the atmosphere has been the primary focus for planetary scientists studying Titan. Early spectroscopic measurements found methane at concentrations of a few percent, and later higher hydrocarbons such as acetylene and propane were observed. Table 2.1 gives the mole fraction of some select species in Titan's atmosphere [Lewis, 2004]. Of course, the concentration of these compounds vary by latitude and altitude [Flasar*, et al.*, 2005]. Nitrogen containing species, such as HCN, were also discovered. These compounds are the result of photochemistry in the upper reaches of the atmosphere. Photochemistry also results in aerosols which form a haze at high altitudes (>300 km) [Imanaka*, et al.*, 2004]. The aerosols eventually fall to the surface, during which condensation of organics onto the aerosol may occur. The temperature at the surface of Titan is about 90 K. The compounds that reach the surface are thus frozen and trapped on the surface.

Table 2.1 Selected components of the atmosphere of Titan

Species	Mole fraction
N_2	~.94
CH_4	0.06
H_2	2×10^{-3}
CO	5×10^{-5}
C_2H_6	2×10^{-5}
C_2H_2	2×10^{-6}
HCN	2×10^{-7}

The chemistry that occurs in the upper atmosphere drives interest in Titan as a laboratory for prebiotic chemistry. The compounds formed in the upper atmosphere eventually fall down to the surface, where impacts and cryovolcanism will mix them with liquid water. The melt pools will freeze, and preserve the products of hydrolysis for later examination. Each frozen pool represents a separate experiment in prebiotic chemistry on a scale that is unavailable on Earth. The direct exploration of the surface of Titan, and of these frozen pools, would contribute greatly to our understanding of prebiotic chemistry, and perhaps ultimately to an understanding of how life arose on Earth.

2.2. Tholins

Any attempt to understand the complexity of the chemical reactions occurring in the atmosphere of Titan will require an experimental approach that can simulate these reactions. The current approach uses an electrical discharge in a gas mixture of nitrogen and methane representative of the atmosphere of Titan, using reactors like that in Figure 2.1. A number of workers have performed these kinds of experiments, utilizing a variety of experimental conditions, varying temperature, pressure, and the form of the discharge, either microwave, DC, or AC.

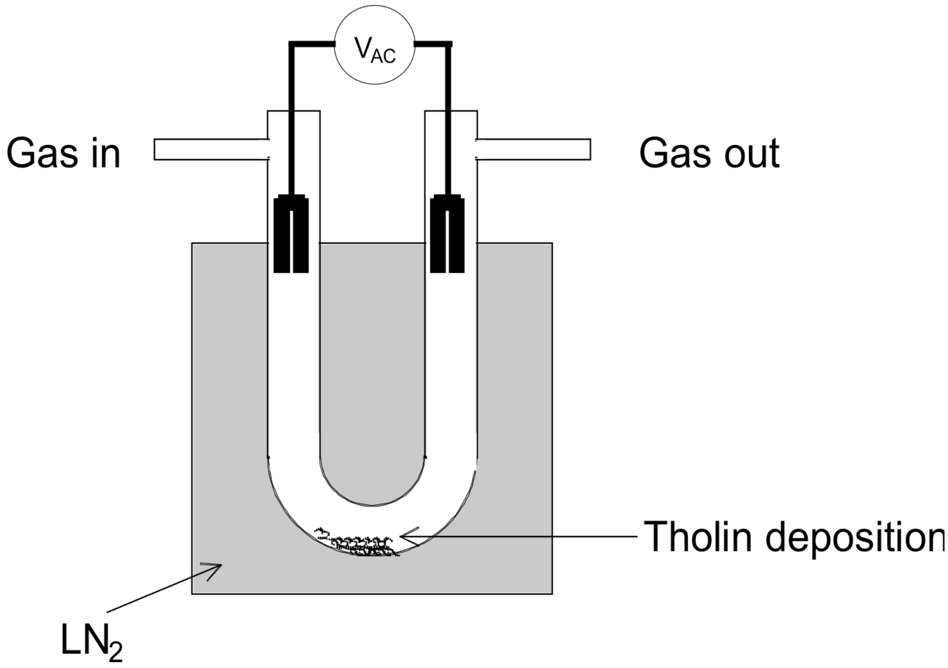

Figure 2.1. Plasma reactor for the production of tholins.

In all cases, however, these experiments yield a reddish brown or orange polymeric material, coined by Carl Sagan as "tholin," from the Greek, meaning "muddy" [Sagan and Khare, 1979]. Figure 2.2 is a diagram of the kind of plasma reactor used to produce the tholins discussed in this thesis. The details of the production of the tholin are described elsewhere [Sarker, *et al.*, 2003]; [Somogyi, *et al.*, 2005].

Chemically, the tholins are composed of CHN compounds, usually with C/N ratios of around 2, and C/H ratios of around 0.75 [Sarker*, et al.*, 2003]. Infrared analysis indicates that the material possesses basically all the functional groups one might expect, such as amines, nitriles, alkenes, and imines. Electrospray mass spectral analysis shows many thousands of compounds. The sheer complexity of the material makes the tholins highly intractable to most analytical methods.

Several workers have performed hydrolysis of the tholins, mainly reporting on the yield of amino acids produced. Hydrolysis in acid produces amino acids in yields between 0.2 and 7 mg/g tholin [Mcdonald*, et al.*, 1994]. Obviously, a large number of other kinds of molecules, including urea [Khare*, et al.*, 1986], are formed during hydrolysis as well. Hydrolysis may also produce carboxylic acids, alcohols, or possibly even purines and pyrimidines.

2.3. Impacts on Titan

Like all planetary bodies, Titan is occasionally hit by an impactor of a size large enough to survive passage through the atmosphere and hit the surface. Artemieva and Lunine have modeled the result of such impacts [Artemieva and Lunine, 2003; [Artemieva and Lunine, 2005]. Restricting their modeling to comets, they find that projectiles smaller than 100-200 m will not reach the surface intact, and that impactors larger than 1 km in diameter are basically unaffected by the atmosphere. This is important since projectiles smaller than this will experience enough atmospheric drag to significantly alter the impact velocity and thus crater size. Assuming the surface is composed of water ice, a 2 km diameter icy projectile impacting at a velocity of 7 km/s or higher, at an angle of impact between 30° and 45°, will generate 2-5% melt by volume within the crater [Artemieva and Lunine, 2003].

Not unexpectedly, much of the surface organics will be heavily shocked and ejected from the crater. However, the impact modeling shows that a significant percentage of the organics are deposited in the melt at the bottom of the crater [Artemieva and Lunine, 2003]. Furthermore, the liquid will ice over quite rapidly, and then proceed to freeze downward. The timescale for complete freezing of the melt pool is surprisingly long. Several hundred or even thousands of years (if there is a significant amount of ammonia, as seems likely) would be required for complete freezing. This is plenty of time for significant aqueous alteration of the organic material.

Modeling of cratering rates shows that there should be hundreds of craters greater than 100 km in diameter on the surface of Titan [Artemieva and Lunine, 2005]. Many will likely be covered and obscured by organic deposits, but the more recent craters should be more visible. In any event, over the entire planet a very large quantity of organics would have been processed by water during the history of the Solar System.

2.4. Recent data from Cassini-Huygens

The Cassini-Huygens mission arrived at Saturn on June 30, 2004. Several close flybys of Titan have already been completed, and many more are planned in the coming years. As well, the Huygens probe successfully penetrated the atmosphere of Titan and landed on the surface in January 2005. While analysis of the data is ongoing, some intriguing results relevant to the question of organic surface chemistry have been obtained.

Two separate features seen on the surface are relevant to this discussion. Data obtained with the radar imager aboard the probe has revealed a large (180 km in diamter) circular feature, possibly a volcanic dome or an old impact scar [Elachi*, et al.*, 2005]. Channels that appear to carry material away from the center radiate from the feature. The radar imager also shows that the surface of Titan is rather young; few impact features are visible in the radar strip obtained [Elachi*, et al.*, 2005]. This could be the result of coverage by organics produced in the atmosphere.

The Visible and Infrared Mapping Spectrometer aboard Cassini has also revealed a feature best interpreted as a cryovolcano [Sotin*, et al.*, 2005]. The putative volcanic dome is 30 km in diameter, and appears to be releasing volatiles. Eruptions of ammonia-water liquids from such a volcano would undoubtedly lead to mixing of the surface organics with the liquid.

2.5. Conclusions

Titan is one of the most intriguing bodies in the Solar System. Possessed of a thick nitrogen-methane atmosphere, photochemistry in the upper atmosphere leads to the production of a wide variety of organic compounds which eventually settle to the surface. Impacts or cryovolcanism would then lead to the mixing of the organics with liquid water, or ammonia-water mixtures. Hydrolysis of the organics produces a range of oxygenated organic compounds, including amino acids. When the melt pools freeze, they preserve the products of hundreds or thousands of years of complex organic chemistry. Each melt pool is an individual experiment in prebiotic chemistry waiting for analysis. Exploration of Titan, with a particular emphasis on the organic chemistry of the surface, would provide a new insight into the origin of life that would be unobtainable on Earth.

2.6. References

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