Titan's Physical Nature and Biological Potential

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Abstract

Titan is the largest of Saturn's moons and the second largest in the entire solar system. This planetary body is characterized by a set of unique features, such as a thick atmosphere, surface liquid bodies, and many others that make it a cryogenic version of Earth. By hosting many dynamic physical and chemical processes different yet similar to the blue planet's, Titan is an extremely interesting candidate for extraterrestrial life and the focus of many astrobiology research studies.

1 Titan's Physical Characteristics

Orbiting at about 1.43 billion km from the Sun, Saturn is the planet with the greatest number of moons, whose count has been observed to be at least 274 [1]. At a distance of approximately 1,200,000 km from its apparent surface, the moon Titan orbits the planet with an orbital period of 15 days and 22 hours [2]. It is tidally locked to Saturn which means it always shows it the same face. Its orbit has an eccentricity of 0.0288 [3] and its inclination with respect to Saturn's equator is 0.348 degrees [4].

With its diameter of 5000 km, Titan is the largest among Saturn's moon and the second largest in the entire solar system [5]. For comparison, it is about 50% larger than Earth's Moon and 80% more massive. It is even larger than Mercury, although not as massive [6]. Aside from this collection of interesting enough characteristics, Titan achieves a set of even more relevant records that makes it one truly unique body in the Solar System, mostly related to its composition. It even hosts a methane cycle similar to the Earth's water cycle, with such elements present on the planet in all three physical states and in continuous transformation [7, 8]. This physical and chemical dynamism resembles Earth's in many aspects, making it a sort of cryogenic smaller twin of the blue planet. Research is actively contributing to prove its potential to accommodate a different, yet plausible, methane-based life.

2 Atmosphere and Climate

Titan's atmosphere is one of the most unique in the entire solar system. It is the only moon capable of hosting an atmosphere denser than Earth and is one of the two only moon atmosphere with clouds and weather. It is the most gas-rich moon in the entire solar system [9].

As revealed by Voyager's mission for the first time, Titan's atmosphere has a surface pressure of 1.448 atm and is mostly made of Nitrogen with a stable approximately 5% concentration of methane up to 8 km from the surface [10]. Titan's atmospheric composition also includes other hydrocarbons among which ethane, and other gases like carbon dioxide, carbon monoxide, hydrogen cyanide, helium, and many others. Hydrocarbons are in particular hypothesized to be produced by the UV rays breaking methane [11]. However, according to the estimations, this process should have destroyed all the methane within 50 million years. Evidence of the constant availability of methane in the atmosphere suggests the existence of a source of methane that replenishes it, most probably related to cryovolcanic activity [12].

Titan's exposition to the Sun's sunlight is as low as 1% of Earth's with a further 10% of absorption by its thick atmosphere [13]. However, Titan's is both characterized by a strong greenhouse effect, which traps sunlight and makes it less cold than it would be, and a second anti-greenhouse effect caused by its haze that absorbs part of the sunlight [14]. The consequence is that the temperature at the surface is lower than at high altitudes. However, Titan's surface temperature of -180°C is perfect for the existence of methane in both liquid and gaseous form [15]. Huygens probe's observations confirmed the occurrence of methane rain on Titan.

In summary, Titan's atmosphere enables a methane cycle which is interestingly similar to Earth's water cycle [7, 8]. In particular, at the time of the previous observations, more liquid bodies were found in the north pole, even though seasonal temperature variations are as high as few degrees Celsius on Titan. As Titan's nature provides the moon with one single Hadley cel, one single convective flow of gas has been hypothesized to travel between the two poles [16]. This would imply that the liquid that has been observed to be deposited at the north pole will evaporate and migrate to the south pole to condense again during the southern winter.

3 Methane Seas and Rivers

Titan's temperature makes it possible for it to host liquid bodies at surface level, near the poles. Such characteristics were strictly unique to Earth before the Cassini probe's confirmation. In particular, such bodies of hydrocarbons have mostly been found in the north pole, provided the moon was in its northern winter season. However, the existence of transitory equatorial liquid bodies has been theorized to be possible under heavy rain conditions. In order of size, Kraken Mare, Ligeia Mare, and Punga Mare are the largest seas located near the north pole, surrounded by smaller lakes [15]. At the south pole, instead, four dry depressions have been observed, possible remnants of old dried-up seas. Ontario Lacus is the only relevant liquid methane lake at the South Pole. It should be considered that Titan's seasonality is governed by Saturn's orbit, and thus the moon witnessed a southern summer until 2010, after which liquid hydrocarbons are expected to evaporate at the north pole to condense at the south pole [17], as already mentioned in Section 2. While the proportion in the lakes' composition is variable, it is consistent for all Titan's bodies of hydrocarbons with majority of Methane, followed by Ethane, and a smaller fraction of Nitrogen.

Cassini's RADAR-based bathymetry measured a maximum depth of roughly 180 meters for the Ligeia mare and 110 meters for the Punga mare. Measures from Kraken Mare showed no electromagnetic signal's reflection, possibly implying its seabed is too deep to be measured with such a technique. Ontario Lacus' maximum depth has been measured to be as low as 50 meters [15].

Finally, weather and precipitations, in particular, make it possible for Titan to have liquid rivers flowing on the surface and modeling labyrinthic shapes over the icy crust, which have been largely imaged by previous space missions [18].

4 Surface and Internal Structure

Titan's thick atmosphere is very opaque, making it hard to observe the surface directly in the electro-optic spectrum. However, the probe Cassini was able to collect observations of Titan's surface by means of infrared instruments and synthetic aperture radars. Despite Titan's formation being dated back as far as the origin of the Solar System, evidence like the craters' count shows that its surface is much younger. Furthermore, the estimated rigidity of the icy layer of Titan suggests the moon is not very active geologically speaking. However, the moon's dynamic physical nature is made far more evident by the presence of mountains, ridges, and fractures in the terrain, which are typical signs of tectonic activity [19].

Titan's even includes areas similar to deserts shaped by the wind and even liquid-eroded channels. As a matter of fact, the only available photo of Titan's surface was taken by the probe Hyugens and portraits of rounded-shaped stones [20]. As this shape is essentially addressable to a mix of phenomena including water erosion, Titan is the only planet where such pebbles may be found, except for Mars in a lower measure, due to its past presence of water, and Earth, indeed. The Cassini probe also detected natural extremely low-frequency radio waves, even though Titan's surface has been hypothesized not to be a good reflector for such kind of electromagnetic waves. This calls for the possible existence of a sub-surface ocean, a hypothesis strengthened by the systematical surface shift also measured by Cassini [21]. Basically, the moon's surface shall be decoupled by its internal core and floating on a subsurface ocean as reflected in Titan's tides [22]. Unfortunately, other evidences suggest that this oceanic layer should lay between the surface icy layer, and another internal high-pressure icy layer, meaning it is probably protected by the volcanic activity of the rocky layer. This could have had huge implications for the possible existence of life under the surface.

5 Azotosomes and Exotic Metabolisms

Protobiology has long studied the role of ribonucleic acids in the formation of early terrestrial life. However, recent research has shifted part of its attention toward the role of lipids in such a process. Terrestrial cells' membranes are composed of phospholipids, which are based on chain of polar and non-polar molecules. The non-polar heads of such chains are compatible with water and are chemically attracted in a way that create a protective shall around an inner aqueous life content. As the aggregation of such a molecular structure have been mostly studied to take place in water, which is liquid matter, Titan's liquid seas are extremely interesting to astrobiology. With methane being the only substance available in the form of surface liquid deposits on an extra-terrestrial planetary body, scientists interrogated themselves about the plausibility of spontaneous, and even alternative, lipid formations.

Titan is characterized by physical processes that consume hydrocarbons flowing down from the atmosphere. Stevenson et al. [23] searched for alternative spontaneous cell membranes that could be capable of metabolizing such hydrocarbons. A constraint for their study is is to consider material plausibly generated by the interaction of UV rays in a methane-rich atmosphere. A further attention point concerns the capability of maintaining properties similar to lipids at room temperature but in an extreme cryogenic environment. The result of such a study was the successful simulation of alternative membranes, named "azotosomes" after their prevalently nitrogen-based composition. Such membranes would be different in many aspects, with them being shorter and less responsive to thermal fluctuation, as Titan thermal conditions diverge much from Earth. Also, their polar heads would assemble due to their mutual polarization rather than the interaction with polar water molecules. However, their flexibility has been measured to be surprisingly similar to Earth's liposomes, which is not trivial at such cold temperatures. It is worth noting that those are simulation results and reproducing them in a real environment would be far more challenging. Also, the theoretical proof of the existence of such membranes does not in turn prove the existence of life on Titan. Still, it proves that part of the conditions that are believed to be necessary for the evolution of extra-terrestrial life are satisfied on Titan, which makes it a promising candidate for future studies.

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