Introduction

Saturn has many satellites orbiting around it, with Titan being its largest. Titan is the only satellite with a dense atmosphere (~1.47 bar)(Charnay et al. 2014; Glein 2015) composed primarily of nitrogen. Besides Earth, it is the only planetary body in the solar system with molecular nitrogen in its atmosphere. The Huygens probe by ESA, aboard NASA's Cassini orbiter, was crucial in gathering bulk of this data. Titan is enveloped in a thick organic haze (Imanaka et al. 2004). Titans is also the only satellite to have free HCN atoms (Vuitton et al. 2006) which are the main constituents for complex organic molecules.

The detection of exoplanets has rapidly increased in the last decade. One of the main questions driving this research has always been the habitability and search for signs of life or the conditions encouraging life’s development. This brings Titan into focus, as it is an ocean world with an Earth-like hydrological cycle and a thick atmosphere of nitrogen and methane (MacKenzie et al. 2021). Titan presents a unique opportunity, given its relatively close distance to us, to search for signs of life or how life may develop in future.

Understanding the source of nitrogen in Titan’s atmosphere is a topic of significant interest. It would shed light on Titan’s formation and evolution and other icy bodies in the solar system or beyond (Scherf et al. 2020). This also broadens the scope of studying processes related to our Solar system. This literature review delves into the studies concerning the source of nitrogen in Titan's atmosphere based on existing body of work in this area. We will explore the wide range of factors and processes that can influence the presence of nitrogen. Finally, we discuss upcoming missions that may enhance our understanding of this topic.

Sources of Nitrogen

Titan’s nitrogen (N_2) could be from the solar nebula during its formation, suggesting that Titan's atmosphere is primordial (Scherf et al. 2020). Comets, which are rich in ammonia ice and other nitrogenous compounds, deposited these building blocks during the Late Heavy Bombardment. Solar winds within the protostar nebula, consisting of a stream of charged particles from the Sun, may have embedded N_2 within ice grains. Jupiter, along with these solar winds, could have contributed to providing Titan with the necessary building blocks. Other potential sources include chondrites, cometary grains, or a combination of these factors (Glein 2015; Krasnopolsky 2016; Scherf et al. 2020)

Once these building blocks were present on Titan, any number of processes would have attributed to N_2 in atmosphere, such as photochemical dissociation from NH_3, impact-induced dissociation of NH_3 to N_2 or outgassing.

Methods to determine the source of nitrogen on Titan

There are two main methods to determine the source of nitrogen on Titan is by using Isotopic evidence and comparative planetology (Scherf et al. 2020) : 1) $^{14}N/^{15}N$ ratio is distinct for various sources in the solar system and many have been determined. By comparing the isotopic composition of nitrogen in Titan's atmosphere with these known ratios, we can confirm its origin and gain crucial insights into its source. 2) Comparing Titan's atmosphere with those of other similar icy bodies, such as Pluto or Triton, provides additional insights. They all occupy the outer Solar system area so we can compare their isotopic signatures. We can identify if they have shared origin or similar evolutionary processes.

Atmospheric Composition

Titan has an atmosphere that is mainly dominate by nitrogen (N_2~98%) while methane (CH_4~2%) makes up most of the remaining percentage (Marounina et al. 2015). Earth 's atmosphere is also dominated by nitrogen mainly. Source of nitrogen on Earth is likely to be chondritic (Scherf et al. 2020). Titan's this somewhat similar composition to Earth is intriguing given that it is located in the outer Solar system where there are other volatiles in abundance like methane and water and nitrogen is quite rare relatively. Scherf et al. (2020) raises a further possibility that the source and evolution of this N_2 atmosphere of the icy bodies may be very different. Geological, biological and anthropogenic processes are also fractionating nitrogen on Earth. On icy bodies such as Titan this fractionating mainly happens by atmospheric escape and photochemical processes.

Formation and Evolution of Titan's Atmosphere

During accretion Titan gathers large amounts of nitrogen as N_2 or ammonia and carbon as methane. This inherited atmosphere went through rapid escape and heavy isotope enrichment (Lunine et al. 2010). When Titan cooled it led to condensation of methane on the surface. N_2 dissociated from NH_3 during this time and ended up in the atmosphere as gas. As Titan grew further it led to more heating occurred which eventually led to the escape of the N_2 from the atmosphere followed by the methane outgassing from interior. Initial inventory of volatiles suggests that N_2 originated from NH_3 and CH_4 from carbon compounds (Owen 2000). It was posited that outgassed NH_3 from Titan would dissociate by photochemical processes and calculations show that it would lead to a thick N_2 atmosphere given Titan's lifetime (Atreya et al. 1978).

Ultraviolet radiation from Sun causes the dissociation of molecular nitrogen mainly in the upper atmosphere. Titan lacks magnetic field which allows the magnetospheric ions from the Saturn to penetrate Titan's atmosphere and sputter atoms and molecules from it (Shematovich et al. 2003). Titan's haze contains various aromatic compounds. These aromatic compounds are efficient absorbers of the ultraviolet radiation and can act as a mediator during charge exchange (Imanaka et al. 2004).

Titan's atmosphere has undergone significant changes due to a combination of internal and external processes(Marounina et al. 2015). There has been many times when it has been depleted of methane and thus became nitrogen rich (Charnay et al. 2014). Impact-induced NH_3–N_2 conversion, outgassing and atmospheric erosion suggests that either the atmosphere was formed after the Late Heavy Bombardment, or the early atmosphere acquired during the accretion was massive to begin with (Marounina et al. 2015).

If the atmosphere of Titan was originated early, the only way it could survive to present day was if the Sun was a slow rotator otherwise the escape of N_2 would have been too great. This suggests that either the outgassing happened at a much later stage or further nitrogen was provided via a different source (Scherf et al. 2020). To better understand this early state of Titan's atmosphere, determining the isotopic ratios of non-radiogenic isotopes of argon (38Ar/36Ar) and neon (22Ne/20Ne) by in situ sampling will help (Lunine et al. 2010).

Atmospheric gases may have originated from deep within the rocky core of Titan via hydrothermal or cryo-volcanic processes as opposed to the photochemical processes. This is supported by the $^{14}N/^{15}N$ ratio between cometary NH_3 and Titan's N_2 (Glein 2015). It is further supported by the similar isotopic composition to the ammonia ice on comets (Krasnopolsky 2016). Another interesting idea for the source of Titan's atmospheric N_2 is of hydrothermal oxidation of NH_3. It could be tested by comparing it to $^{14}N/^{15}N$ of N_2 in Enceladus plume. As Enceladus does not have an atmosphere so the result would be solely geological (Glein et al. 2009).

Isotope measurement may have potential inaccuracies. Isotope measurement is done by using mass spectroscopy. Where the measurement was performed is extremely important. In an atmosphere at what height and in which molecule specifically (Erkaev et al. 2020). For example the $^{14}N/^{15}N$ ratio for N_2 in the atmosphere of Titan was measured to be twice as high as the same ratio for HCN (Glein et al. 2009).

Future Missions and Studies:

NASA's upcoming Dragonfly mission aims to explore Titan's surface and atmosphere (Barnes et al. 2021). It is set to arrive on Titan sometime in mid-2030s (Boulesteix et al. 2024). This mission will specifically look at Titan's prebiotic chemistry, habitability potential or bio-signatures (Madan et al. 2023). Given that Titan's atmosphere has the prebiotic CxHyNz compounds (Hedgepeth et al. 2022). When mixed with water these compounds have been shown to make amino acids. So, Dragonfly mission should be able to find some of these amino acids (Hedgepeth 2022).

Along other instruments Dragonfly also has aboard a mass spectrometer for atmospheric probing, which could help provide more data and help understand more thoroughly the nitrogen processes and origin on Titan. ESA's Comet interceptor (Sánchez et al. 2020) will further the knowledge of subject.

Conclusion

Over the last two decades our understanding of Solar system and the icy bodies, especially at the outer edge has increased immensely. But still there are major gaps in our knowledge. We still do not know the source of atmospheric N_2 on Titan (Scherf et al. 2020). We also do not have enough data from Triton or comets to study and compare this data. We do know that this atmospheric N_2 has come from NH_3 (Scherf et al. 2020). It has come via photodissociation, impact- induced dissociation or from deep inside the rocky core via hydrothermal and cryovolcanic processes. There is some support for the idea that the source of this ammonia is cometary (Atreya et al. 1978; Glein 2015; Krasnopolsky 2016). In future with more in-situ sample acquisition from upcoming missions such as NASA's Dragonfly(Barnes et al. 2021), and ESA's Comet interceptor (Sánchez et al. 2020)will help compiling this isotopic signature database. We also need to understand our Sun's evolution. Sun's history is tied deeply with the evolution of icy bodies and their atmosphere(Scherf et al. 2020).

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