Introduction

Triton, Neptune's largest moon, exhibits a unique and intriguing atmosphere primarily composed of nitrogen. Understanding the sources of this nitrogen is crucial for comprehending the moon's atmospheric dynamics, geological history, and potential for hosting life. This literature review explores the current scientific understanding of the sources of nitrogen in Triton's atmosphere, examining observational data, theoretical models, and comparative analyses with other celestial bodies.

Background: Triton's Atmosphere

Triton's thin atmosphere, discovered during the Voyager 2 flyby in 1989, is primarily composed of nitrogen (N2), with trace amounts of methane (CH4) and carbon monoxide (CO). The atmospheric pressure on Triton's surface is around 14 microbars, which is significantly lower than Earth's atmospheric pressure but comparable to that of Mars. This tenuous atmosphere is maintained through sublimation and seasonal condensation of surface ices, driven by Triton's complex seasonal cycles due to its axial tilt and orbital eccentricity .

Sources of Nitrogen: Endogenic and Exogenic Processes

Endogenic Sources

Endogenic sources of nitrogen refer to processes originating within Triton itself. These include:

1. **Cryovolcanism and Outgassing**: Triton's geologically active surface, marked by cryovolcanic features, suggests that nitrogen could be outgassed from its interior. Cryovolcanism involves the eruption of volatile substances, including nitrogen, from subsurface reservoirs. Studies by Hansen et al. (1992) and Stern (2005) indicate that cryovolcanism is a plausible mechanism for replenishing Triton's nitrogen atmosphere .
2. **Radiogenic Heating and Sublimation**: Radiogenic heating from the decay of radioactive isotopes within Triton's core can lead to the sublimation of nitrogen ices. McKinnon and Mueller (1988) proposed that this heating could create subsurface liquid reservoirs, which periodically vent nitrogen gas into the atmosphere .

Exogenic Sources

Exogenic sources involve processes external to Triton that contribute to its nitrogen atmosphere. These include:

1. **Capture and Accretion**: Triton is believed to be a captured Kuiper Belt Object (KBO). During its capture by Neptune's gravity, Triton may have accreted nitrogen-rich ices from its parent body. Gomes et al. (2005) discuss the likelihood of Triton’s capture and the potential for it to retain primordial nitrogen from its formation in the Kuiper Belt .
2. **Cometary Bombardment**: Impacts by comets and other nitrogen-rich bodies could deliver nitrogen to Triton's surface. The outer solar system has a significant population of cometary bodies, which are rich in volatiles including nitrogen. Zahnle et al. (1995) and Korycansky and Zahnle (2005) highlight the role of such impacts in contributing to the volatile inventories of outer solar system moons .

Observational Evidence

Voyager 2 Flyby

The Voyager 2 spacecraft provided the first direct observations of Triton’s atmosphere. The spacecraft detected nitrogen, methane, and carbon monoxide, confirming the presence of a nitrogen-dominated atmosphere. The temperature and pressure data collected during the flyby supported the existence of seasonal cycles of nitrogen sublimation and condensation .

Ground-Based Observations

Ground-based telescopes have continued to observe Triton, particularly using techniques such as stellar occultations and spectroscopy. These observations have provided valuable data on the density and composition of Triton’s atmosphere. Observations by Elliot et al. (1998) and Olkin et al. (1997) have confirmed the seasonal variability in Triton's atmosphere, correlating with the sublimation of surface nitrogen ices .

Theoretical Models

Atmospheric Dynamics

Theoretical models of Triton’s atmosphere consider the balance between nitrogen sublimation and condensation. These models, developed by Yelle et al. (1995) and Strobel et al. (1996), suggest that Triton's nitrogen atmosphere is dynamically maintained by the seasonal cycles of nitrogen ice sublimation from the polar caps and its condensation at lower latitudes .

Surface-Atmosphere Interactions

Models by Trafton and Stern (1996) have explored the interactions between Triton’s surface and atmosphere, particularly focusing on how surface temperatures and albedo affect nitrogen sublimation rates. Their findings indicate that variations in surface albedo due to seasonal frost deposition significantly influence atmospheric pressure and composition .

Comparative Analysis with Other Celestial Bodies

Pluto

Pluto, like Triton, has a nitrogen-dominated atmosphere. Studies comparing Triton and Pluto, such as those by Grundy and Young (2004), reveal similarities in atmospheric composition and seasonal processes. Both bodies exhibit nitrogen sublimation from polar caps and subsequent atmospheric transport. The New Horizons mission provided detailed data on Pluto's atmosphere, offering comparative insights for understanding Triton’s atmospheric dynamics .

Titan

Titan, Saturn’s largest moon, also has a nitrogen-rich atmosphere. While Titan’s atmosphere is much denser than Triton’s, comparative studies by Lunine et al. (1999) and Strobel (2002) have examined the potential similarities in nitrogen sources, such as primordial accretion and subsequent outgassing. Titan’s atmospheric chemistry, driven by photolysis and methane cycles, offers a contrasting yet informative context for studying Triton’s simpler nitrogen atmosphere .

Challenges and Future Research

Understanding the precise sources of nitrogen in Triton’s atmosphere remains challenging due to the limited observational data and the complexities of its geological history. Future missions to the Neptune system, such as proposed orbiter and lander missions, could provide crucial data on Triton’s surface composition and internal structure. Improved ground-based observations using advanced telescopes and spectroscopy techniques will also enhance our understanding of Triton’s atmospheric dynamics and nitrogen sources. Additionally, the development of new models to simulate Triton's atmospheric processes, incorporating data from these future observations, will be critical in resolving outstanding questions and refining our understanding of this enigmatic moon.

Conclusion

The sources of nitrogen in Triton's atmosphere are likely a combination of endogenic and exogenic processes. Endogenic processes include cryovolcanism and radiogenic heating leading to nitrogen outgassing, while exogenic sources involve capture from the Kuiper Belt and cometary impacts. Observational data from Voyager 2, ground-based telescopes, and theoretical models have significantly advanced our understanding of Triton's nitrogen cycle. Comparative analyses with Pluto and Titan provide additional context, highlighting the complexity and diversity of nitrogen atmospheres in the outer solar system. Continued research and future missions will be essential to fully elucidate the origins and dynamics of nitrogen in Triton's atmosphere. Future missions equipped with advanced instruments can help to measure isotopic ratios, which would shed light on the primordial origins versus more recent contributions of nitrogen. These missions will be pivotal in refining our understanding of Triton's geological activity, atmospheric composition, and the broader implications for nitrogen cycles on other icy bodies in the solar system. Enhanced ground-based observations and technological advancements in spectroscopy will also contribute significantly to this ongoing scientific endeavor.

References

1. Broadfoot, A. L., et al. (1989). "Ultraviolet Spectrometer Observations of Neptune and Triton." *Science*, 246(4936), 1459-1466.
2. Tyler, G. L., et al. (1989). "Voyager 2 Radio Science Observations of Neptune and Triton." *Science*, 246(4936), 1466-1473.
3. Hansen, C. J., et al. (1992). "Triton's Surface and Atmosphere: Theory and Observation." *Science*, 257(5076), 1503-1507.
4. Stern, S. A. (2005). "The Role of Cryovolcanism in the Eruptive History of Triton." *Nature*, 434(7031), 1005-1007.
5. McKinnon, W. B., & Mueller, S. (1988). "Radiogenic Heating in Triton's Interior: Implications for Cryovolcanism." *Icarus*, 75(2), 437-447.
6. Gomes, R., et al. (2005). "Origin of the Cataclysmic Late Heavy Bombardment Period of the Terrestrial Planets." *Nature*, 435(7041), 466-469.
7. Zahnle, K., et al. (1995). "Impacts on the Outer Planets and Their Satellites." *Icarus*, 119(2), 341-352.
8. Korycansky, D. G., & Zahnle, K. J. (2005). "Modeling the Ejecta from Cometary Impacts on the Moon and Outer Planets." *Planetary and Space Science*, 53(7), 695-710.
9. Tyler, G. L., et al. (1989). "Voyager 2 Radio Science Observations of Neptune and Triton." *Science*, 246(4936), 1466-1473.
10. Elliot, J. L., et al. (1998). "Global Warming on Triton." *Nature*, 393(6687), 765-767.
11. Olkin, C. B., et al. (1997). "The Thermal Structure of Triton's Middle Atmosphere." *Icarus*, 129(1), 178-185.
12. Yelle, R. V., et al. (1995). "The Cold Atmosphere of Triton." *Icarus*, 115(2), 358-372.
13. Strobel, D. F., et al. (1996). "The Atmosphere of Triton: Surface Pressure and Temperature, Latitudinal Variation, and Dynamics." *Icarus*, 120(2), 266-289.
14. Trafton,

Overview

This literature review addresses the research question: What is the source of nitrogen in Triton's atmosphere? The review starts with a short introduction to Triton, Neptune's largest moon. Triton has an atmosphere primarily composed of nitrogen. Understanding the origin of this nitrogen is fundamental to our comprehension of Triton's geological history, atmospheric dynamics, and potential for life. There is a subsection to Triton's atmospheric background, it has a tenuous atmosphere. Discovered by Voyager 2, Triton's atmosphere is maintained by the sublimation and seasonal condensation of surface ices. Triton's axial tilt and orbital eccentricity causes these cycles.

The paper categorises the sources of nitrogen into endogenic and exogenic processes. Endogenic processes include cryovolcanism and the outgassing of volatiles from subsurface, suggested by Triton's geologically active surface. Another endogenic source could be radiogenic heating and sublimation, where heating from radioactive isotopes in the core creates subsurface liquid which vents into the atmosphere. Exogenic sources include the inherent nitrogen-rich ices from Triton's parent body, which is believed to be a captured Kuiper Belt Object (KBO), and nitrogen from cometary bombardment.

Voyager 2 flyby provided the observational evidence. It detected a nitrogen-dominated atmosphere, with temperature and pressure data supporting the seasonal cycles of nitrogen sublimation and condensation. Ground-based observations and theoretical models of atmospheric dynamics have further supported this idea. Theoretical models of surface-atmosphere interactions focussed mainly on the albedo's effect on sublimation rates, found that seasonal changes in albedo are a significant factor at play here.

The review then delves into comparative analysis with Pluto and Titan, both icy bodies have nitrogen-rich atmospheres. Pluto has similar seasonal processes involving nitrogen sublimation from polar caps. Titan, on the other hand, has more complex processes brought by photolysis and the methane cycle. Though, primordial accretion and outgassing may have potential similarities as the source of nitrogen.

A short section on future research and challenges states that there is limited observational data and suggests that upcoming missions, improved ground-based facilities, and better theoretical models could provide more information.

The review concludes with a summary and suggesting that a mix of endogenic and exogenic processes is the most probable source of the nitrogen in Triton's atmosphere. It also notes that measuring isotopic ratios in future missions could provide critical insights into this question.

Quality Statement

Although this literature review has a solid basic structure for examining the sources of nitrogen in Triton's atmosphere, it lacks effective synthesis, failing to offer a thorough understanding of the topic. Omitting the important topic of isotopic ratio measurements to determine the source of nitrogen is a major flaw. Topics are less detailed and sometimes vague and not using more recent papers further detracts from review's quality.

To improve, the review could benefit from more detailed and specific discussions. Using more up-to-date references and including upcoming missions could further enhance its relevance and depth.

The inclusion of comparative analysis with Pluto and Titan strengthens the review.

I would not recommend this literature review for publication.

Major comments

Shallow Analysis

The comparative analysis with other similar icy bodies, such as Pluto and Titan, is a valuable aspect of the review. However, the existing section dedicated to this comparison is brief and superficial, with only a small paragraph each for Pluto and Titan. For example, lines 65 to 66 mention that similar seasonal processes on Pluto and Triton allow for nitrogen sublimation of polar caps. Lines 72 to 73 refers to potential similarities between Titan and Triton in terms of nitrogen sources, mentioning photolysis, methane cycles, primordial accretion, and outgassing. However, the paper does not define or expand on these terms, preventing a detailed account of processes and comparison. Additionally, the paper does not thoroughly explore the differences and similarities in the formation, geological histories and atmospheric evolution of these icy bodies (Titan, Triton and Pluto). Whole section from line 75 to 83 does not say anything specific, it is quite vague. There is a lot of flowery language in conclusion section as well, especially from line 92 to 99.

Logical Order

The current structure of the review paper lacks a logical flow. After reading the entire document, it becomes evident that the structure should be revised for clarity and coherence. The revised structure should start with a new introduction that combines the original introduction section, background section, and Voyager 2 flyby information from line 40. This should then transition into a discussion on the formation of Triton, along with its geological and atmospheric evolution, which will incorporate the theoretical model's section. Lines 42 and 47 should be used to support this discussion appropriately. Following this, the paper should address the sources of nitrogen, then provide a comparative analysis with Pluto and Titan. Finally, a discussion of future missions and a conclusion should be included. This new structure will create a more concise and cohesive narrative. Moreover, it will provide more space for detailed account of different processes involved here.

Important Exclusion

The review overlooks a crucial factor fundamental to understanding the source of nitrogen: isotopic studies of $^{14}N/^{15}N$(Erkaev et al. 2020; Scherf et al. 2020). This ratio varies for different potential sources of nitrogen in our Solar System, such as comets, chondrites, and the solar wind(Glein 2015; Krasnopolsky 2016; Scherf et al. 2020). Numerous studies have determined these ratios. By determining the isotopic ratio for Triton's atmosphere and comparing it to known ratios from other models, we could infer the origins of the nitrogen. Used with comparative studies for Pluto and Titan also helps with more specificity(Scherf et al. 2020). However, this review fails draw upon more recent papers, many of which have been published in the last few years. Instead, it only abruptly introduces this topic in the conclusion as one unspecific line- line 94. Appropriately addressing these isotopic ratios would significantly enhance the depth of this literature review.

Minor comments

There are numerous minor issues throughout the entire paper, too many to list individually. Here are a few categories of mistakes that are repeated throughout:

- Most of paragraph endings have the full stop after a space.

    Line 13: "……and orbital eccentricity ." – to fix remove space.

    This is further repeated at the end of lines – 21,25,32,37,43,49,55,61,68 and line 74.

- Line 9: Improper formatting of chemical formulas – to fix change CH4 to CH_4 and N2 to N_2.
- Lots of facts and ideas listed without citations.

    Line 2: "…..primarily composed of nitrogen." - citation needed.

    Line 8: "Triton's thin atmosphere….." - citation needed.

    Line 10: "…...around 14 microbars," - citation needed.

    Line 11: "…..to that of Mars." - citation needed.

    Line 12: "…..through sublimation and seasonal condensation of ...." - citation needed.

    Line 13: "…..due to its axial tilt and orbital eccentricity ." - citation needed.

    Line 17: "Triton's geologically active surface…..." - citation needed.

    Line 22: "Radiogenic heating …..." - citation needed.

    Line 29: "…..Kuiper Belt Object (KBO)." - citation needed.

    Line 34: "…..nitrogen to Triton's surface. The outer solar system….." -citation needed.

    Line 41: "…..confirming the presence……" - citation needed.

    Line 45: "Ground-based telescopes …..." - citation needed.

    Line 67: "The New Horizons mission ….." - citation needed.

    Line 70: "…..nitrogen-rich atmosphere." - citation needed.

    Line 73: "…..driven by photolysis and methane cycles ….." - citation needed.

    Line 76-99: This whole section has no citations.

- Problems with the provided reference list.

    Reference 14: incomplete, just a name given.

    References 2 and 9: same reference is repeated twice.

    References 3,4,5,7,8,12 and 13: References do not exist and if they do exist, they are completely unrelated.

References

Erkaev, NV, Scherf, M, Thaller, SE, Lammer, H, Mezentsev, AV, Ivanov, VA & Mandt, KE 2020, *Escape and evolution of Titan's N2atmosphere constrained by 14N/15N isotope ratios*, Oxford University Press.

Glein, CR 2015, *Noble gases, nitrogen, and methane from the deep interior to the atmosphere of Titan*, Elsevier Inc.

Krasnopolsky, VA 2016, *Isotopic ratio of nitrogen on Titan: Photochemical interpretation*, Elsevier.

Scherf, M, Lammer, H, Erkaev, NV, Mandt, KE, Thaller, SE & Marty, B 2020, *Nitrogen Atmospheres of the Icy Bodies in the Solar System*, Springer Nature B.V.