



Physical Constraints on the Survival of Ammonia within Planetary Environments

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Abstract

Ammonia is a promising biosignature species, highly unstable in the presence of UV radiation on a timescale of $\sim 10^3$ years. However, its abundance or presence in the atmosphere is not determined by biological processes only; it highly depends on physical factors that include pressure, temperature, and stellar flux. In this paper, we explore selected physical conditions which affect the survivability and accumulation of ammonia in the atmospheric environment of a planet. We find that, unlike low-pressure rocky planets, stable environments where ammonia can persist through either biological or non-biological processes are feasible with high-pressure mini-Neptunes with hydrogen-rich atmospheres.

1. Introduction

Detection of life beyond the Earth has come to rely on the presence of certain gases within a planet's atmosphere that could indicate life on that planet. Of the various gases that could comprise a biosignature, ammonia (NH_3) has been proposed as a highly reactive and unstable compound that, unless continuously produced, would not be expected to naturally persist on or above a planet's surface or in its atmosphere.

On Earth, NH_3 is produced by life. It is not a molecule that would be expected to occur naturally in high quantities in the atmospheric chemistry of any planet because it is readily destroyed by ultraviolet radiation and chemical interactions.

However, the interpretation of ammonia as a biosignature needs to be done with care. That which might be a sign of life on one planet could be due to physical effects on another. For

example, the presence of ammonia in the atmosphere is a function not only of whether it is biological in origin but also whether the environment is conducive to allowing it to survive in the atmosphere for a long enough period of time.

In this paper, the effects of pressure, temperature, and radiation on whether ammonia can survive within a planet's atmosphere are considered. Unlike other research that may focus more on the pathways of chemical reactions, this research is based more on a physical approach than a chemical one.

2. Physical Properties of Ammonia Relevant to Atmospheric Survival

Ammonia is a light, polar molecule that responds very sensitively to ultraviolet radiation. When ammonia undergoes photodissociation from a high-energy photon, the molecule will essentially break up into simpler components. This gives ammonia a short lifetime in an atmosphere unless the environment provides inadequate protection from radiation.

The stability of ammonia also depends on temperature. On colder environments, ammonia can condense or stay in the lower layers of the atmosphere. On hotter temperatures, ammonia forms but much deeper in the atmosphere and can't reach all the way to the higher altitude.

These properties make the presence of ammonia in an atmosphere dependent not only on its rate of production but also on the physical environment that governs its destruction and transport.

3. Role of Atmospheric Pressure

The atmospheric pressure is crucial for the survival of ammonia because it dictates the extent of shielding against stellar radiation. Low-pressure atmospheres, which are a common feature of rocky planets, provide very little shielding against stellar radiation. In this case, ammonia molecules are directly exposed to UV radiation and are destroyed on relatively short timescales.

High-pressure atmospheres differ in being physically thicker and therefore contain more material in a column that could absorb and scatter incoming radiation. High-pressure

atmospheres can also support ammonia in deeper atmospheric layers where it would be protected from photodissociation, and vertical transport mechanisms can then allow ammonia to move upward into levels where it might be detected.

High atmospheric pressure is, therefore, one of the major reasons that can ensure ammonia would survive long enough to reach observable or detectable concentrations.

4. Effects of Temperature on Stability of Ammonia

Temperature influences both the stability of ammonia and its distribution within an atmosphere. This would mean that on cold planets, the condensation of ammonia or its confinement to the lower atmospheric layers can reduce its observable abundance. Moderate temperatures may favor the survival of gaseous ammonia while throttling quick destruction.

On very hot planets, ammonia can be produced effectively in the deeper layers of the atmosphere, but high temperatures can prevent it from surviving into the higher altitudes where observations are usually obtained.

This implies that ammonia can survive at temperatures that maintain the molecule in a stable gaseous state without its swift destruction.

5. Stellar Radiation Interaction

Stellar radiation, in particular ultraviolet, is one of the most significant factors determining ammonia's survival. UV photons possess enough energy to break the molecular bonds of ammonia into pieces with a high degree of photodissociation.

Planets, therefore, orbiting active or high-UV stars are not likely to retain ammonia in their atmospheres unless they have thick atmospheres that shield their inner layers from radiation. The effectiveness of this shielding depends strongly on atmospheric composition and depth.

This means that a particular atmospheric composition can act very differently given the different radiative output of the host star.

6. Comparative Planetary Environments

They are characterized by strong UV radiation, low atmospheric pressure, and little protection. It would indeed be expected that ammonia in such environments would be destroyed more quickly than it could be produced or accumulate.

In stark contrast, mini-Neptunes are characterized by large hydrogen-dominated atmospheres that are highly pressurized and exhibit strong temperature gradients. This environment favors the preservation of ammonia against its rapid destruction, even in a nonbiological setting.

This makes the type of planet a critical variable to consider in the interpretation of atmospheric ammonia.

7. Discussion



In this respect, the analysis here shows that ammonia's survival is predominantly set by physical conditions and not just by its source production mechanism. The presence of atmospheric ammonia cannot be taken as an indication of life in general if the atmospheric pressure, temperature, and radiation environment conditions are not taken into consideration.

Conclusive interpretation of the ammonia biosignature is only feasible when physical conditions strongly inhibit abiotic formation and survival of this molecule. In hydrogen-rich atmospheres, detection of ammonia could instead indicate a false positive for life.

8. Conclusion This work shows that ammonia is in fact a very constrained phenomenon from a physical perspective. The persistence of ammonia abundance requires high pressure, appropriate temperature conditions, and shielding of stellar radiation to last long enough to be detectable. The implication for the use of ammonia as a biosignature is that it will strongly depend on planetary context. Therefore, missions undertaking exoplanet life searching should include atmospheric physics in biosignature interpretation frameworks. This would suggest that

ammonia is essentially a contextual biosignature whose meaning will change with physical planetary conditions.

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