Assessment of Ammonia as a Biosignature Gas in Exoplanet Atmospheres

Jingcheng Huang[1✉], Sara Seager[1,2,3], Janusz J. Petkowski[1], Sukrit Ranjan[4], Zhuchang Zhan[1]

[1]Department of Earth, Planetary and Atmospheric Sciences, Massachusetts Institute of Technology [2]Department of Physics, MIT [3]Department of Aeronautics and Astronautics, MIT [4]Lunar & Planetary Laboratory/Department of Planetary Sciences, University of Arizona, ✉: **huangjc@mit.edu**

Takeaway

- Ammonia (NH_3) in a terrestrial planet atmosphere is generally **a good biosignature gas**, primarily because terrestrial planets **have no significant known abiotic NH_3 source**. The conditions required for NH_3 to accumulate in the atmosphere are, however, stringent.
- NH_3's high water solubility and high bio-useability likely prevent NH_3 from accumulating in the atmosphere to detectable levels unless **life is a net source of NH_3** and produces **enough NH_3 to saturate the surface sinks**. In this case, NH_3 is only removed by photochemistry.
- To establish NH_3 as a biosignature gas, we must **rule out mini-Neptunes with deep atmospheres**, where temperatures and pressures are high enough for NH_3's atmospheric production.

Intro

I am motivated to study NH_3's biosignature potential because:

- NH_3 plays a significant role in biochemistry
- NH_3 is an ideal N source; some life can use NH_3 as an energy source
- NH_3 has a very high solubility in water
- (Seager et al., 2013) → break the N_2 triple bond → fixing atmospheric H_2 and N_2 into NH_3 ('cold Haber World')

Methods

1. Solubility and Henry's law

- H is Henry's law constant for a species X in mol Pa^{-1} m^{-3}
- C is the dissolved concentration in the solution in mol m^{-3}
- P is the partial pressure in Pa

$$H_{(X)}^{CP} = \frac{C_{(X)}}{P} \qquad \frac{d\ln(H^{CP})}{d(1/T)} = -\frac{\Delta H_{diss}}{R}$$

2. Ocean-NH_3 Interaction Model

- The Henderson–Hasselbalch equation
- pH is the ocean's overall pH
- T_{NH3} is the planet's total NH_3 reserve in mol
- $V_{Ocean-E}$ is the volume of the ocean in L

$$\frac{[NH_3]}{[NH_4^+]} = 10^{(pH-9.25)}$$

$$[NH_3] + [NH_4^+] = \frac{T_{NH_3}}{V_{Ocean-E}}$$

$$[NH_3] = \frac{T_{NH_3} \cdot 10^{pH}}{(1.77828 \times 10^9 + 1 \times 10^{pH}) \cdot V_{Ocean-E}}$$

3. Photochemistry Model

- We use our photochemistry code to calculate the NH_3 mixing ratio as a function of vertical altitude in exoplanet atmospheres.
- Our full photochemistry model encodes more than 800 chemical reactions and UV photolysis of atmospheric molecules. It also includes 111 species.

High solubility

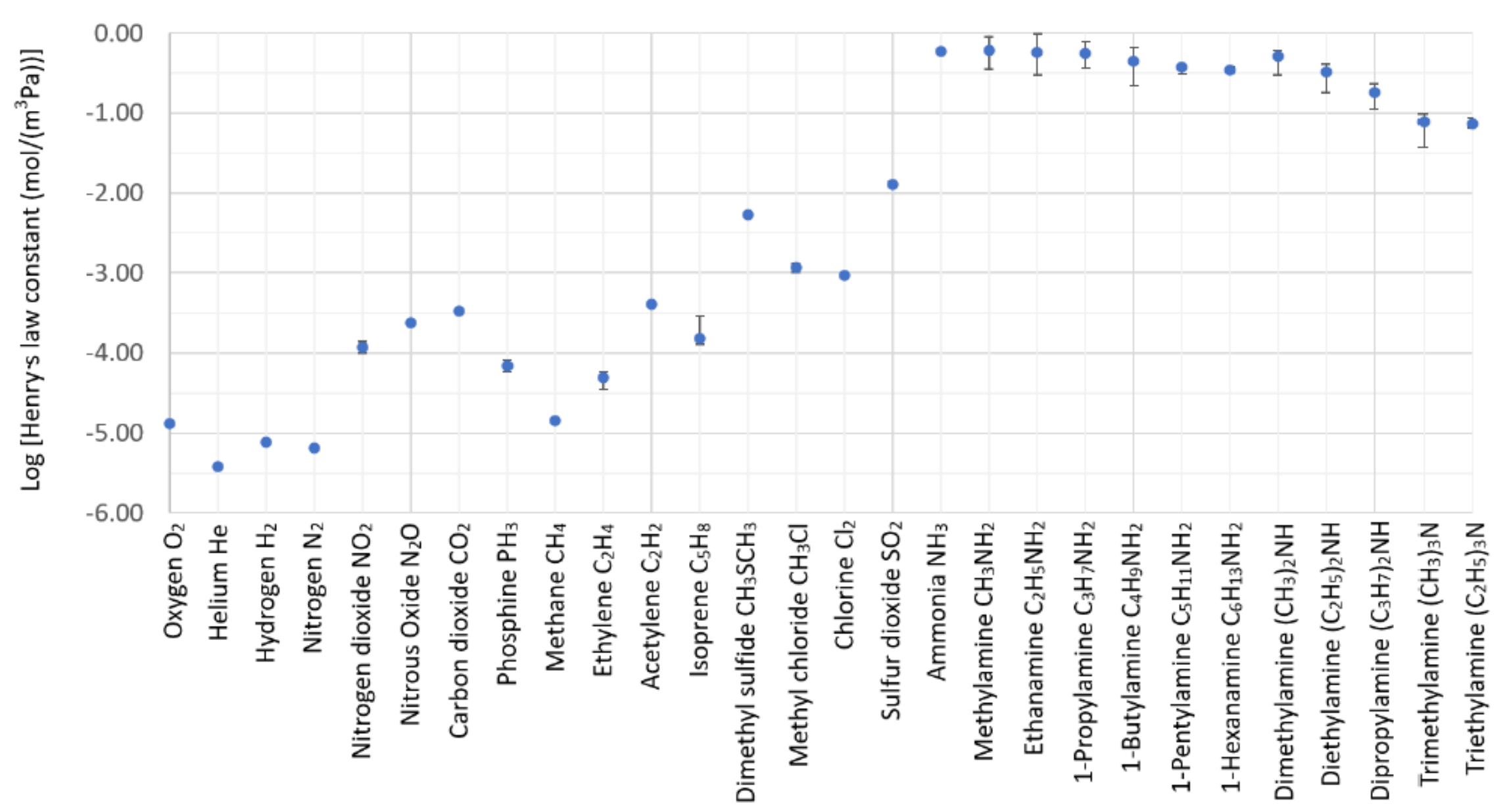

Figure 3-8. The solubility of common molecules on a log scale. The x-axis shows the chemical species' name, and the y-axis shows Henry's law constant on a log scale. Ammonia and other amines are at least two orders of magnitude more soluble than other chemicals in the list, including several biosignature gas candidates that have already been studied.

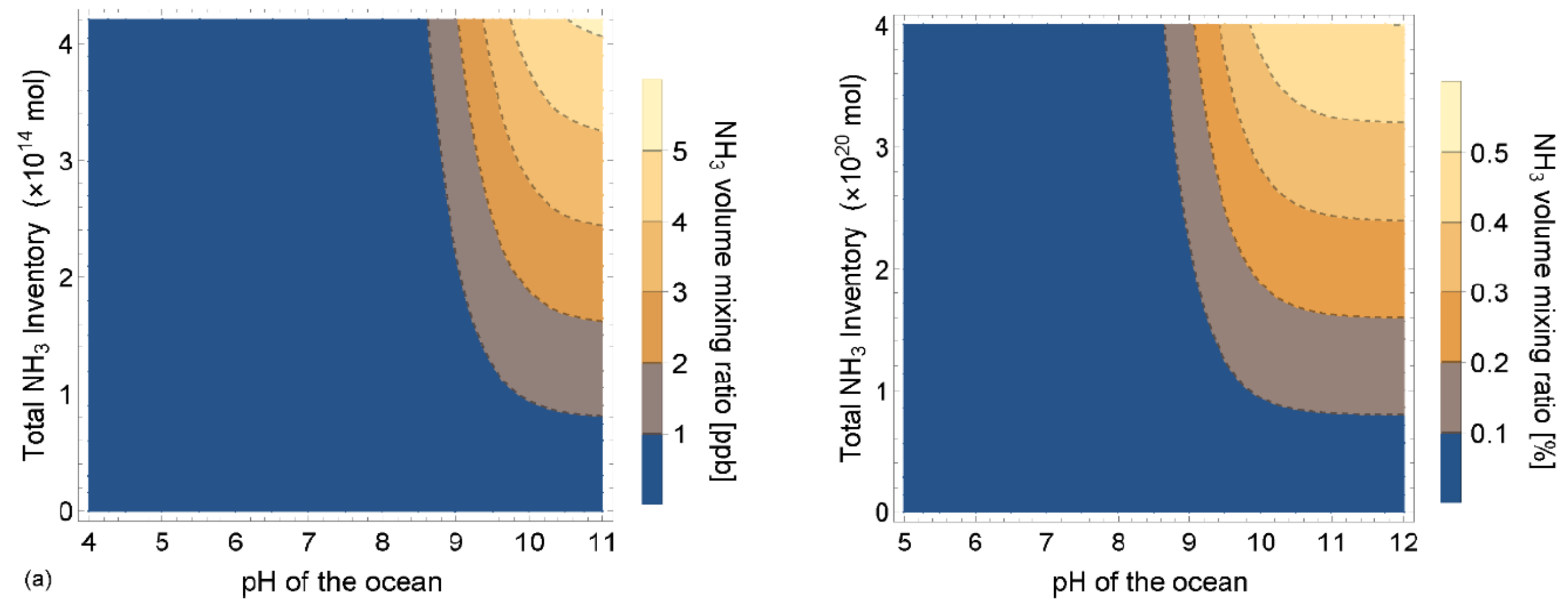

Figure 3. Equilibrium volume mixing ratio of NH_3 as a function of the planet's total NH_3 reserve and ocean pH. The x-axis is the ocean pH, and the y-axis is the planet's total NH_3 reserve in mol. The contours are NH_3 volume mixing ratios. We assume the planet has an Earth-sized total N reservoir (4×10^{20} mol) and an Earth-sized ocean (1.335×10^{21} L). (a): If life cannot produce a substantial amount of NH_3 and only maintain an Earth-like NH_3 inventory (~10^{14} mol), the NH_3 volume mixing ratio is extremely low regardless of the ocean pH level ($4 \leq pH \leq 11$). (b): If life manages to convert almost all of the planetary N reservoir into NH_3 (~10^{20} mol), NH_3 will become one of the major chemical species in the atmosphere.

Two cases

Case I. When the surface is saturated with NH_3: The required biological surface flux to reach 5 ppm is on the order of 10^{10} molecules cm^{-2} s^{-1}, comparable to the terrestrial biological production of CH_4.

Case II. When the surface is unsaturated with NH_3: Due to additional sinks present on the surface, life would have to produce NH_3 at surface flux levels on the order of 10^{15} molecules cm^{-2} s^{-1} (~4.5×10^6 Tg $year^{-1}$). This value is roughly 20,000 times greater than the biological production of NH_3 on Earth and about 10,000 times greater than Earth's CH_4 biological production.

Table 3-8. Simulated mixing ratios and surface fluxes for exoplanets with H_2-dominated, CO_2-dominated, and N_2-dominated atmospheres orbiting M dwarf stars (M5V).

Atmospheric scenarios	NH_3 column-averaged mixing ratio	NH_3 surface flux needed [molecules cm^{-2} s^{-1}]	
		With NH_3 deposition	Without NH_3 deposition
H_2-dominated	5.0×10^{-6} (5 ppm)	6.40×10^{15}	1.44×10^{10}
CO_2-dominated	5.0×10^{-6} (5 ppm)	3.60×10^{14}	8.49×10^{8}
N_2-dominated	5.0×10^{-6} (5 ppm)	7.10×10^{14}	6.77×10^{10}

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