

MARS ATMOSPHERIC NEON PROBES MANTLE VOLATILE CONTENT AND EARLY SURFACE ENVIRONMENT H. Kurokawa¹, S. Sugita², T. Yoshida³, Y. N. Miura⁴, Y. Cho², H. Kumagai⁵, F. Leblanc⁶, N. Terada³, H. Nakagawa³, S. Kasahara², K. Yoshioka², N. Iwata⁷, Y. Saito⁸. ¹ELSI, Tokyo Tech, ²Univ. Tokyo, ³Tohoku Univ., ⁴ERI, Univ. Tokyo, ⁵JAMSTEC, ⁶LATMOS/CNRS, Sorbonne Univ., UVSQ, ⁷Yamagata Univ., ⁸ISAS, JAXA.

Introduction: While Mars' surface has been largely altered by exogenous (impacts and atmospheric escape) and endogenous (volcanism) processes, its interior could record formation history. The potentially large volatile content of the mantle is also thought to have controlled the climate evolution of early Mars through volcanic supply of atmospheric gases and water.

Noble gases are chemically inert, and thus useful to study both the origins of planetary volatile elements and atmospheric evolution. Here we show that Mars' atmospheric neon (Ne) is a powerful probe for the volatile content of its interior, accretion, and early evolution (see [1] for details).

Atmospheric Ne probes deep interior: The Martian atmosphere is being continuously lost by atmospheric escape processes. Noble gases including Ne are removed chiefly by a process called sputtering. Based on a model validated with NASA's MAVEN observations [2], we estimated the lifetime of atmospheric Ne to be 60–100 Myrs. The short lifetime is caused by the low mass of Ne, which leads to a high scale height above the homopause and a high sputtering yield.

The lifetime of atmospheric Ne much shorter than Mars' age suggests contentious supply from a source. We estimated the supply from asteroids, comets, interplanetary dust particles, and cosmogenic Ne in crustal rocks, and found that supply fluxes from these sources are smaller than Ne escape flux ($0.7\text{--}10 \times 10^{20}$ atoms s^{-1} , whose uncertainty is derived from those in atmospheric Ne abundance 1–6 ppm constrained with Viking measurements [3] and the homopause-exobase separation) by orders of magnitude. Thus, we concluded that volcanic degassing of mantle Ne is the most promising origin of atmospheric Ne.

Current mantle Ne content: The balance between the volcanic supply and sputtering loss enables us to estimate Ne abundance in the mantle. Given the maximum estimate for the total (extrusive and intrusive) magma production rate during the late Amazonian, $0.045\text{--}0.09 \text{ km}^3 \text{ yr}^{-1}$ [4], Ne abundance in the source magma was estimated to be $> 0.3\text{--}4 \times 10^{-9} \text{ g/g}$.

The melt fraction of the source mantle is estimated to be 0.02–0.1 from the analysis of rare earth elements in Martian basaltic meteorites [5,6]. Multiplying the above estimated Ne abundance in the magma by 0.02 leads to Ne abundance of the current mantle to be $> 0.5\text{--}$

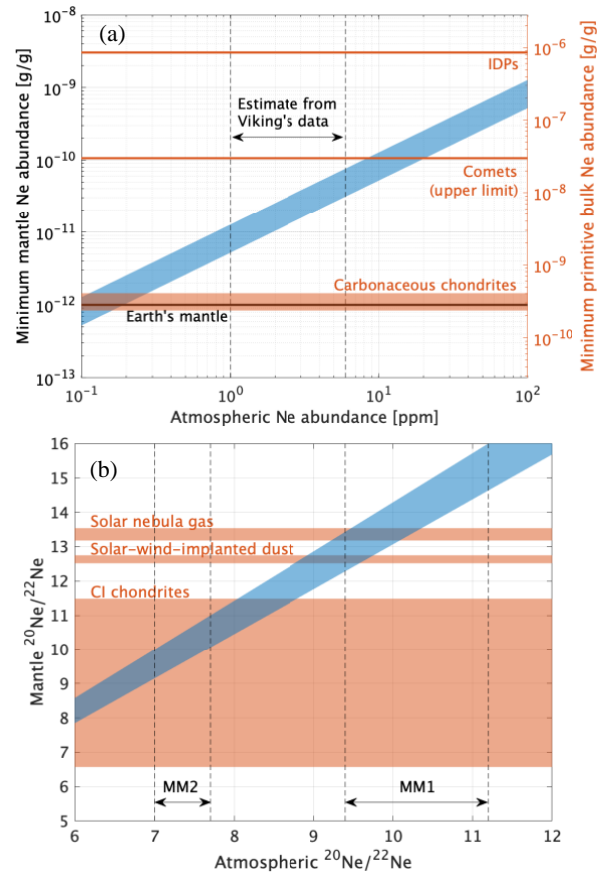


Figure 1. (a) Minimum estimate for mantle (left) and primitive bulk (right) Ne abundances as a function of atmospheric Ne abundance (blue). (b) Mantle Ne isotopic ratio as a function of the atmospheric ratio (blue). Adapted from [1].

$8 \times 10^{-11} \text{ g/g}$ (Figure 1a, left axis). The estimated Ne abundance in Mars' mantle is higher than Earth's, suggesting Mars' volatile-rich interior which could have affected the climate evolution through degassing.

Primordial bulk Ne content: Incorporating the large amount of Ne into the mantle requires an even larger amount of total Ne during the formation stage because of Ne's low solubility in silicate melt and incompatibility. We modeled Ne partitioning between the atmosphere, magma ocean, and solidified mantle in the magma ocean stage and obtained the primordial bulk Ne content to be $> 1\text{--}20 \times 10^{-9} \text{ g/g}$, which is > 300 times larger than that of current bulk Mars (dominated by the mantle; Figure 1a, right axis).

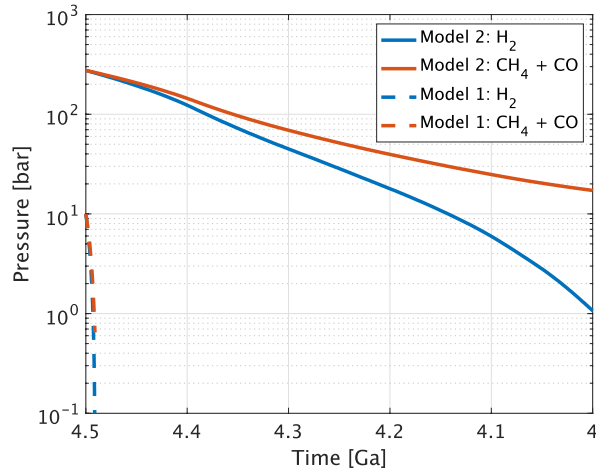


Figure 2. The evolution of the primitive atmosphere via hydrodynamic escape. Models 1 and 2 denote the solar-nebula and chondritic origin cases, respectively.

Origin of abundant Martian Ne: Because different Ne sources have different $^{20}\text{Ne}/^{22}\text{Ne}$ ratios, the origin of abundant mantle Ne can be constrained by its $^{20}\text{Ne}/^{22}\text{Ne}$ ratio. Mantle Ne is not easily accessible, but the balance between the volcanic supply and sputtering loss, latter of which causes isotopic fractionation, again enables us to relate the mantle $^{20}\text{Ne}/^{22}\text{Ne}$ ratio to that of the atmosphere (Figure 1b).

The isotopic ratio of atmospheric Ne ($^{20}\text{Ne}/^{22}\text{Ne}$) has not been measured in situ, and the analysis of trapped gases in Martian meteorites has suggested two possible values: $^{20}\text{Ne}/^{22}\text{Ne} \sim 10$ and ~ 7 [7] (here defined as MM1 and MM2). Figure 1b shows that the former suggests the solar nebula gas or the solar-wind-implanted dust as Ne source, whereas the latter a chondritic source. Different Ne sources imply different accretion histories (e.g., the solar-nebula-gas origin suggests rapid accretion) and, consequently, different primitive bulk volatile compositions.

Primitive bulk volatile content and early atmosphere: Because the primitive bulk volatile content is now anchored by the Ne abundance, identifying the Ne source with the isotopic ratio (and thus the ratio of other volatile elements to Ne) would enable us to estimate primitive bulk contents of other volatiles as well.

If Ne originated from chondritic sources, which are relatively depleted in Ne compared to the solar nebula gas, the derived primitive bulk volatile content is larger. For instance, the H/Ne ratios are 1×10^8 and $>2 \times 10^6$ g/g in CI chondrites and comets, respectively [8,9]. Adapting the latter leads to the primitive bulk H abundance $>2 \times 10^{-3}$.

In contrast, if Ne originated from the captured solar nebula gas, the derived primitive bulk volatile content could be lower. Adapting the protosolar H/Ne ratio ($4 \times$

10^2 g/g), the primitive bulk H abundance supplied from the same source is 4×10^{-6} g/g.

To demonstrate that the two cases suggest quite different evolution scenarios, we computed the evolution of the primitive atmosphere (composed of H_2 , CH_4 , and CO) by using the XUV-driven hydrodynamic-escape rate in Yoshida and Kuramoto [10]. While Model 1 atmosphere (the solar-nebula-origin case) was lost within 1 Myr, Model 2 atmosphere (the chondritic-origin case) remained for a few hundred Myrs to reach geologic ages (< 4.1 Ga). Note that partitioning into surface and interior reservoirs and mantle degassing are not explicitly considered but should have affected the actual evolution.

Future measurements of atmospheric Ne: The above discussion suggests future measurements of Mars' atmospheric Ne isotopic ratio and its abundance as important targets to elucidate Mars' accretion history and volatile content.

The most abundant isotope ^{20}Ne has not been measured so far due to the interference of $^{40}\text{Ar}^{++}$ to $^{20}\text{Ne}^+$ in mass spectrometry. Because of the difficulty, only the abundance of ^{22}Ne has been determined for Ne with in situ analysis [3]. Miura et al. [11] proposed a method to separate Ne from Ar using a permeable membrane. They experimentally investigated preferential permeation of Ne compared to Ar through polyimide and Viton sheets under the terrestrial atmosphere. This method would enable us to measure atmospheric Ne on Mars with future exploration missions.

Mars Sample Return (MSR) is another potential opportunity to measure Mars' atmospheric Ne. The MSR mission will bring back the headspace gas present over the solid samples within the sample tubes. The feasibility to measure Mars' atmospheric component depends on gas exchange with solid samples and potential leakage of gases in transit back to Earth [12].

References: [1] Kurokawa, H. et al. (2021) *Icarus*, 370, 114685. [2] Leblanc, F. et al. *Geophys. Res. Lett.*, 46 (8), 4144–4150. [3] Owen, T. et al. (1977) *J. Geophys. Res.*, 82 (28), 4635–4639. [4] Greeley, R. and Schneid, B.D. (1991) *Science*, 254 (5034), 996–998. [5] Norman, M.D. (1999) *Meteorit. Planet. Sci.*, 34 (3), 439–449. [6] Borg, L.E. et al. (2003) *Meteorit. Planet. Sci.*, 38 (12), 1713–1731. [7] Smith, T. et al. (2020) *Geosciences*, 10 (11), 439. [8] Lodders, K. et al. (2009) In *Landolt-Börnstein, New Series*, VI/4B, 560–630. [9] Rubin, M. et al. (2018) *Sci. Adv.*, 4(7). eaar6297. [10] Yoshida, T. and Kuramoto, K. (2020) *Icarus*, 345, 113740. [11] Miura, Y.N. et al. (2020) *Planet. Space Sci.*, 193, 105046. [12] Swindle, T. D. et al. (2021) *Astrobiology*, accepted.