ESCAPE OF EARLY MARTIAN ATMOSPHERE AND HYDROSPHERE: CONSTRAINTS FROM ISOTOPIC COMPOSITIONS Hiroyuki Kurokawa[1], Kosuke Kurosawa[2], and Tomohiro Usui[3], [1]Dept. of Phys. Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan (kurokawa@nagoya-u.jp), [2]Planet. Explor. Res. Ctr., Chiba Institute of Technology, [3] Dept. of Earth & Planet. Sci., Tokyo Institute of Technology.

Introduction Mars currently has a cold and dry surface environment with a small amount of water-ice observed at the polar caps [1]. On the contrary, increasing evidence suggests that the early Mars sustained a warm climate with a large amount of liquid water [e.g., 2], though it is controversial whether the warm climate was episodic or permanent [3, 4]. Impact erosion and thermal/nonthermal escape have possibly contributed to the loss of the early atmosphere and hydrosphere [5]. However, the timing of the escape and the relative importance of each process are poorly constrained.

The thermal/nonthermal escape induce isotopic fractionation that leaves behind heavier isotopes in the atmosphere and hydrosphere, whereas the impact erosion removes a fraction of atmosphere without the isotopic fractionation. The early evolution of the atmosphere and hydrosphere is constrained by the isotopic data of the martian meteorite Allan Hills 84001 (ALH 84001), which has a crystallization age of 4.1 Ga [6]. A high hydrogen isotope ratio (D/H = 2-4 times the Martian primordial water) at 4.1 Ga [7, 8] suggests that a larger amount of water was lost during the first 0.4 billion years than the later periods by the thermal/nonthermal escape [9]. On the other hand, isotope ratios of nitrogen and noble gases at 4.1 Ga show unfractionated values, implying that the atmosphere was lost after 4.1 Ga [10, 11].

We study the evolution of the martian atmosphere and hydrosphere considering their isotopic ratios. Comparing our results with isotopic data at 4.1 Ga recorded in the martian meteorite ALH 84001, we propose a scenario that the loss of atmosphere and hydrosphere had proceeded before 4.1 Ga. An efficient isotopic fractionation of nitrogen and noble gases due to the thermal/nonthermal escape started after the impact erosion of the thick early atmosphere during the heavy bombardment period.

Model We calculate the evolution of the total amounts of the atmosphere and hydrosphere and their isotopic compositions individually, considering the impact erosion and thermal/nonthermal escape (Fig. 1).

First, we calculate the evolution of the total atmospheric pressure due to the impact erosion using a stochastic bombardment model [12]. We calculate the surface age using the cumulative number of impacts and an empirical curve obtained from the lunar craters [13]. The total pressure of 6 mbar or 100 mbar (corresponds

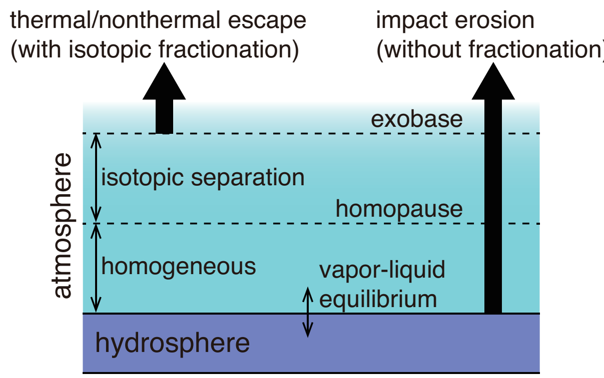

Figure 1: Schematic illustration of our model. Evolution of atmosphere and hydrosphere is calculated considering impact erosion and thermal/nonthermal escape.

to the possible amount of CO_2 in the polar regions and regoliths [14]) at present was assumed. The evolution is calculated backward from present to 4.5 Ga assuming a CO_2-dominated atmosphere. The erosion efficiency at each impact is calculated using a modified sector blow-off model [15]. The momentum of an expanding silicate vapor is calculated using the entropy method [e.g., 16, 17] and thermodynamic data for forsterite [18].

Second, we calculate the evolution of the isotope ratios of the minor volatile elements (D/H, $^{15}N/^{14}N$, and $^{38}Ar/^{36}Ar$) due to the thermal/nonthermal escape. The initial surfacial water of 100 m GEL, which is almost equivalent to the minimum estimate of the paleo-ocean [26], is assumed. We assume the escape rates of the ion pick-up, sputtering, and photochemical escape given by [19, 20]. Hydrogen is lost by the Jeans escape whose escape rate is regulated by the loss of oxygen [21]. Oxygen is assumed to be lost by the ion pick-up [22]. Nitrogen is lost by the sputtering [19] and photochemical escape [23] and argon by the sputtering. The fractionation factor of hydrogen is assumed to be 0.016 [24, 25]. We adapt the fractionation factors of other species tabulated in [19].

Results The evolution of the total atmospheric pressure due to the impact erosion is shown in Fig 2a. The total pressure decreases in several orders of magnitude during the first several hundred million years which corresponds to the heavy bombardment period, whereas the change is relatively insignificant after this period. For both cases (6 mbar and 100 mbar), the total pressure ex-

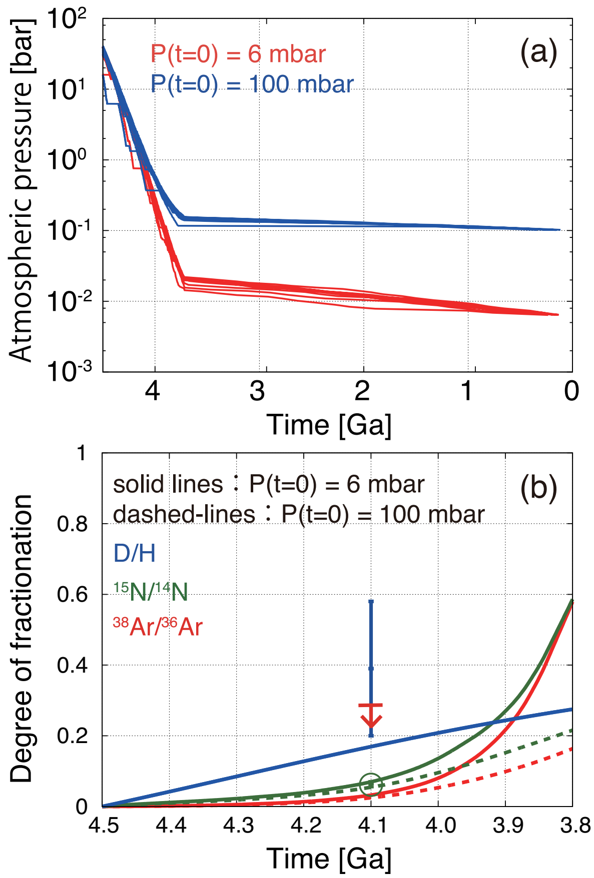

Figure 2: (a) Evolution of total atmospheric pressure due to impact erosion. The results of 10 Monte Carlo simulations are plotted for each case. (b) Evolution of isotopic compositions due to thermal/nonthermal escape. Degree of fractionation, defined as $(I_t - I_{4.5\mathrm{Ga}})/(I_{\mathrm{present}} - I_{4.5\mathrm{Ga}})$ where I_t is the isotopic ratio at the time t, is plotted. Isotopic compositions at 4.1 Ga recorded in martian meteorite ALH 84001 is shown [7, 8, 10, 20, 27, 28, 29].

ceeds one bar before 4.1 Ga. Because the early atmosphere is much thicker than that of the current Mars, the difference in the current total pressure does not affect the total pressure during the early period (> 4 Ga).

The evolution of the isotope ratios due to the thermal/nonthermal escape is shown in Fig. 2b. The nitrogen and argon isotope ratios start to increase as the total pressure decreases. On the contrary, the D/H ratio increases independently because the major reservoir of hydrogen is the hydrosphere. The obtained nitrogen and argon isotope ratios agree with the isotopic data of ALH 84001 at 4.1 Ga, whereas the D/H ratio is lower than the data.

Discussion The discrepancy in the hydrogen isotope ratios can be explained by some additional mechanisms of the oxygen loss because the escape rate of hydrogen is determined by the escape rate of oxygen in our model. Cold ion flow can be a dominant mechanism of oxygen loss in the early Mars [30]. Also, the oxidation of surface material would act as another oxygen sink [9].

Estimates of atmospheric nitrogen isotope composition of ALH 84001 vary significantly ($\sim$ 7 per mil [10] to $>$ 200 per mil [31, 32]). Identification of the actual nitrogen isotope ratio at 4.1 Ga would help to constrain the early evolution of the martian surface environment.

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