Icarus 299 (2018) 443–459

Contents lists available at ScienceDirect

Icarus

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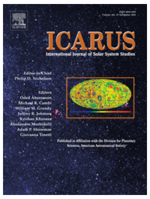

A lower limit of atmospheric pressure on early Mars inferred from nitrogen and argon isotopic compositions

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ARTICLE INFO

Article history:
Received 22 June 2016
Revised 25 April 2017
Accepted 11 August 2017
Available online 24 August 2017

Keywords:
Mars, atmosphere
Atmospheres, evolution
Atmospheres, composition

ABSTRACT

We examine the history of the loss and replenishment of the Martian atmosphere using elemental and isotopic compositions of nitrogen and noble gases. The evolution of the atmosphere is calculated by taking into consideration various processes: impact erosion and replenishment by asteroids and comets, atmospheric escape induced by solar radiation and wind, volcanic degassing, and gas deposition by interplanetary dust particles. Our model reproduces the elemental and isotopic compositions of N and noble gases (except for Xe) in the Martian atmosphere, as inferred from exploration missions and analyses of Martian meteorites. Other processes such as ionization-induced fractionation, which are not included in our model, are likely to make a large contribution in producing the current Xe isotope composition. Since intense impacts during the heavy bombardment period greatly affect the atmospheric mass, the atmospheric pressure evolves stochastically. Whereas a dense atmosphere preserves primitive isotopic compositions, a thin atmosphere on early Mars is severely influenced by stochastic impact events and following escape-induced fractionation. The onset of fractionation following the decrease in atmospheric pressure is explained by shorter timescales of isotopic fractionation under a lower atmospheric pressure. The comparison of our numerical results with the less fractionated N ($^{15}N/^{14}N$) and Ar ($^{38}Ar/^{36}Ar$) isotope compositions of the ancient atmosphere recorded in the Martian meteorite Allan Hills 84001 provides a lower limit of the atmospheric pressure in 4 Ga to preserve the primitive isotopic compositions. We conclude that the atmospheric pressure was higher than approximately 0.5 bar at 4 Ga.

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1. Introduction

Whereas present-day Mars has a thin atmosphere (6 mbar on average), ancient Mars probably had a denser atmosphere. Geomorphological evidence such as valley networks and deltas on Mars requires repeated episodes of liquid water runoff in the Noachian period (e.g., Hynek et al., 2010). A dense atmosphere with a climate warm enough to sustain liquid water on the Martian surface has been proposed to explain the fluvial terrains (e.g., Pollack et al., 1987; Forget and Pierrehumbert, 1997; Ramirez et al., 2014; Ramirez, 2017).

The idea of a permanent warm climate on early Mars was questioned; climate models showed that a pure CO_2 atmosphere on Mars cannot maintain a mean surface temperature higher than the freezing point of water (e.g., Kasting, 1991; Forget et al., 2013), and geochemical evidence suggested that water fluvial activity was mostly limited to the subsurface (Ehlmann et al., 2011). The ancient Mars might have been cold, but global atmospheric circulation under a dense atmosphere is needed to transport water to highlands by atmospheric circulation, and consequently to create fluvial terrains by episodic melting events of the ice on the highlands, even in the cold early Mars scenario (Wordsworth et al., 2013, 2015; Cassanelli and Head, 2015).

The Martian atmosphere would have been lost and replenished by several processes (Fig. 1). Exploration missions and analyses of Martian meteorites have revealed that almost all the volatile elements in the Martian atmosphere and surficial water are enriched in heavier isotopes, which suggests that lighter isotopes were preferentially removed by atmospheric escape induced by solar radiation and wind (Jakosky and Phillips, 2001). In addition, impacts of asteroids and comets erode and replenish the atmosphere (Melosh and Vickery, 1989; Zahnle, 1993; de Niem et al., 2012). Volcanic degassing (Craddock and Greeley, 2009) and gas deposition by interplanetary dust particles (IDPs) (Flynn, 1997) would have contributed to the replenishment of the atmosphere. Although the escape/replenishment processes are not completely understood, the

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http://dx.doi.org/10.1016/j.icarus.2017.08.020
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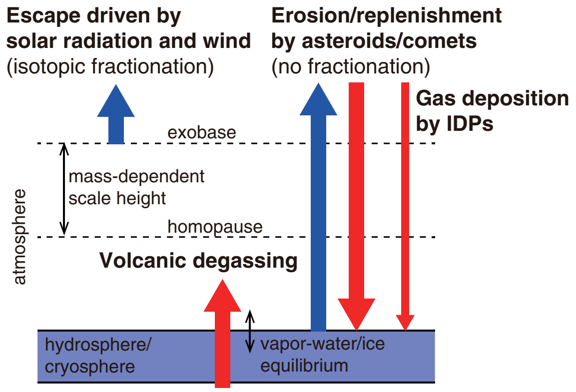

Fig. 1. A schematic view of the model used in this study.

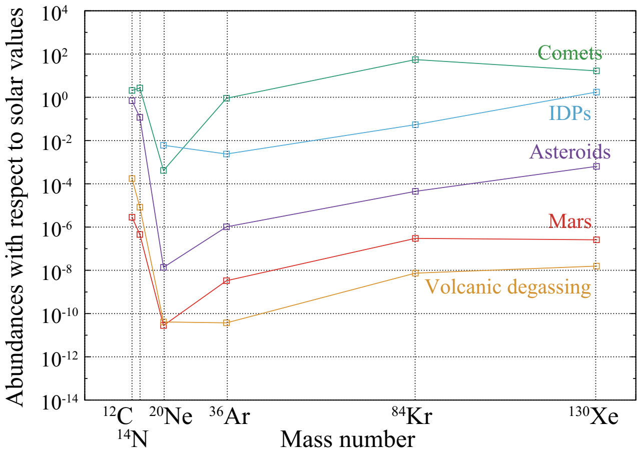

Fig. 2. Elemental abundances in asteroids, comets, IDPs, volcanic gas, and the Martian atmosphere, with respect to the solar values. The abundance in the atmosphere is normalized by the mass of solid Mars. Those of asteroids, comets, and IDPs ($C_{\mathrm{Ne,IDP}} = 1$) are normalized by the masses of these bodies. The abundance in volcanic gas shows the sum of degassed mass during 4.5 billion years in our model ($C_{\mathrm{vol}} = 1$) normalized by the mass of solid Mars. Data are from: solar abundance (Pepin, 1991), asteroids (CI chondrites, Pepin, 1991), comets (Dauphas, 2003), IDPs (Flynn, 1997), and the Martian atmosphere (Pepin, 1991; Mahaffy et al., 2013).

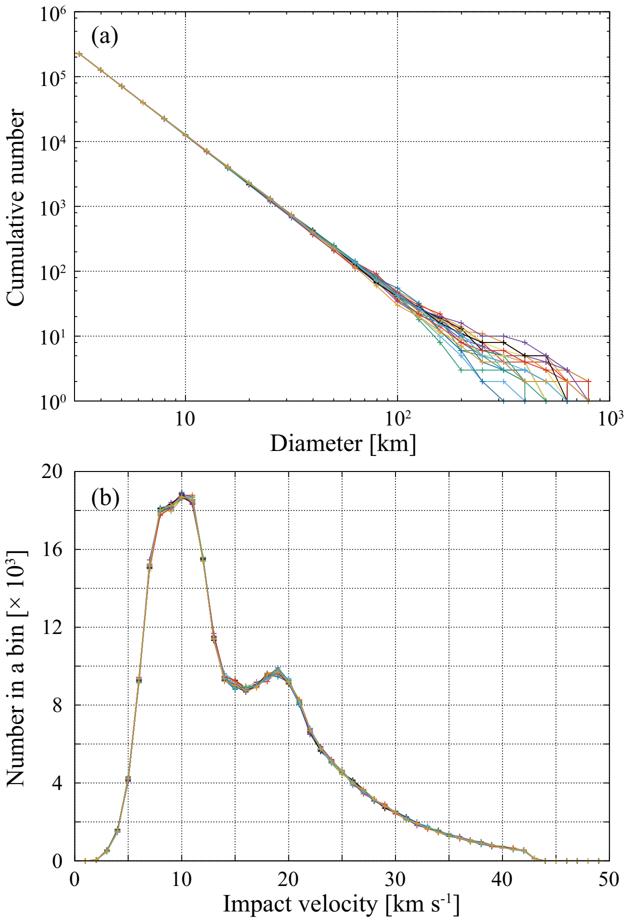

Fig. 3. (a) Size and (b) velocity distributions of impactors (selected 20 examples of the Monte Carlo results).

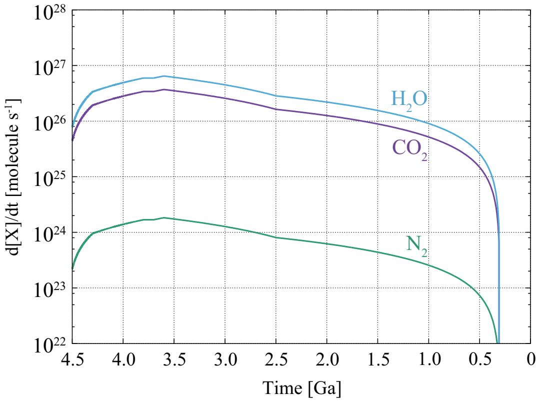

Fig. 4. Volcanic degassing rates of CO_2 (purple), N_2 (green), H_2O (sky blue) as a function of time. The model is based on Craddock and Greeley (2009) ($C_{\mathrm{vol}} = 1$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

geological evidence mentioned above suggests a net decrease in the atmospheric pressure throughout the Martian history.

Elemental and isotopic compositions of the atmosphere have been used to trace the history of the Martian atmosphere in literature (Jakosky, 1991; Jakosky et al., 1994; Pepin, 1991, 1994; Jakosky and Jones, 1997; Zahnle, 1993; Slipski and Jakosky, 2016). Out of these, Jakosky et al. (1994) and Pepin (1994) are the most comprehensive studies that examined the evolution of the Martian atmosphere, taking atmospheric escape induced by solar radiation and wind, impact erosion, and volcanic degassing into account. They concluded that the fractionated isotopic compositions of N, Ne, and Ar in the Martian atmosphere are explained by interplay between the escape and replenishment by volcanic degassing. Contrary to the unfractionated Kr isotopes, the fractionated Xe was suggested to be the remnants of a hydrogen-rich primordial atmosphere lost by hydrodynamic escape at the earliest stage of the Martian evolution (Pepin, 1994).

Whereas these comprehensive studies are suggestive to constrain the evolution of the Martian atmosphere, recent isotopic measurements of the Martian atmosphere by *Curiosity* (Atreya et al., 2013; Wong et al., 2013) and analyses of the Martian meteorites (Mathew and Marti, 2001) provided new data that can be compared with model calculations. In particular, $^{15}N/^{14}N$ and $^{38}Ar/^{36}Ar$ ratios of the early atmosphere recorded in Martian meteorite Allan Hills (ALH) 84001 (Mathew and Marti, 2001) are used to constrain the atmospheric pressure on early Mars at 4.1 Ga (the crystallization age of ALH 84001, Bouvier et al., 2009; Lapen et al., 2010) in this study.

We constrain the atmospheric pressure on early Mars by combining a numerical model and isotopic data recently obtained from exploration missions and from analyses of Martian meteorites. Our numerical model is explained in Section 2. In Section 3, we calibrate input parameters to reproduce the elemental and isotopic

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