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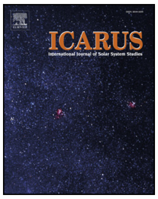

Impact degassing and atmospheric erosion on Venus, Earth, and Mars during the late accretion

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ABSTRACT

The atmospheres of the terrestrial planets are known to have been modified as a consequence of the impact degassing and atmospheric erosion during the late accretion. Despite the commonality of these processes, there are distinct gaps – roughly two orders of magnitude – between the abundances of noble gases and nitrogen in the present-day atmospheres on Venus, Earth, and Mars. The element partitioning on planetary surfaces is thought to be significantly different between the three planets ∼ 4 Ga: the runaway greenhouse on Venus, the carbon-silicate cycle and ocean formation on Earth, and the CO_2-ice and H_2O-ice formation on Mars. Consequences of element partitioning for the atmospheric evolution during the late accretion onto Venus, Earth, and Mars are investigated with a numerical model. We set upper limits to the partial pressures of CO_2 and H_2O on Earth and Mars, which corresponds to the state of phase equilibrium and carbon-silicate cycle. The final N_2 mass shrinks by ∼ 40% and ∼ 15% for Earth and Mars, respectively. The effect of element partitioning is found to be insufficient to reproduce the gaps. For Venus, the survival of the primordial atmosphere through the late accretion may partially account for the present-day atmosphere. Whereas on Mars, the atmospheric escape due to solar extreme UV and wind may have also influenced the atmospheric evolution.

1. Introduction

Atmospheres on terrestrial planets are believed to form as a consequence of volatile delivery and atmospheric erosion by impacts of numerous asteroids and/or comets (e.g., Abe and Matsui, 1985; Melosh and Vickery, 1989; de Niem et al., 2012; Schlichting et al., 2015). The impacts do not only supply volatiles, but also remove part of the pre-existing atmospheres by impact erosion.

During the terrestrial planet formation, several tens of Mars-sized protoplanets were formed through the accretion of planetesimals. Subsequently, several giant impacts between these protoplanets occurred at the late stage of the terrestrial planet formation (e.g., Kokubo and Ida, 1998). If the protoplanets grew in the presence of the nebula, they have captured a primary atmosphere of nebular gas (e.g., Ikoma and Genda, 2006).

According to the record on the Moon, the planets also experienced accretion of numerous impacts after the giant impact stage, which is called late accretion (e.g., Bottke et al., 2010; Chou, 1978). Volatiles in the accretion bodies were vaporized forming a secondary atmosphere from impact degassing and/or volcanic degassing. The late accretion includes the Late Heavy Bombardment (LHB), which is a spike of impact frequency between 4.1 Ga and 3.8 Ga inferred from the craters on the Moon. The excess of highly siderophile elements in Earth's mantle may reflect the additional meteoritic influx after core formation, which is called Late Veneer (e.g., Chou, 1978). The total mass of the late accretion is estimated to range from ∼ 1 to ∼ 2.5% of the planetary masses (e.g., Bottke et al., 2010; Marchi et al., 2018). The period of the late accretion extends from the time of core-mantle differentiation, namely, the magma ocean phase, to that of the LHB. The magma ocean phase would last a few Myrs for Earth and Mars (Elkins-Tanton, 2008; Hamano et al., 2013). The origin of the late accretion impactors is unknown, but geochemical studies (e.g., Fischer-Gödde and Kleine, 2017; Dauphas, 2017) have shown that the isotopic compositions of the late veneer in Earth's mantle is more similar to enstatite chondrites than carbonaceous or ordinary chondrites.

Noble gases and nitrogen (N) contained in the atmosphere provide important clues to the origins of volatiles forming the atmosphere, oceans, and life (H, C, N, O, S, and P). Due to noble gases and to a lesser extent N being chemically inert (e.g., Marty, 2012), they have mainly been partitioned into the atmosphere since ∼ 4 Ga, and so their abundances record the history of atmospheric formation and evolution.

A similarity in the abundances of noble gases and N in the

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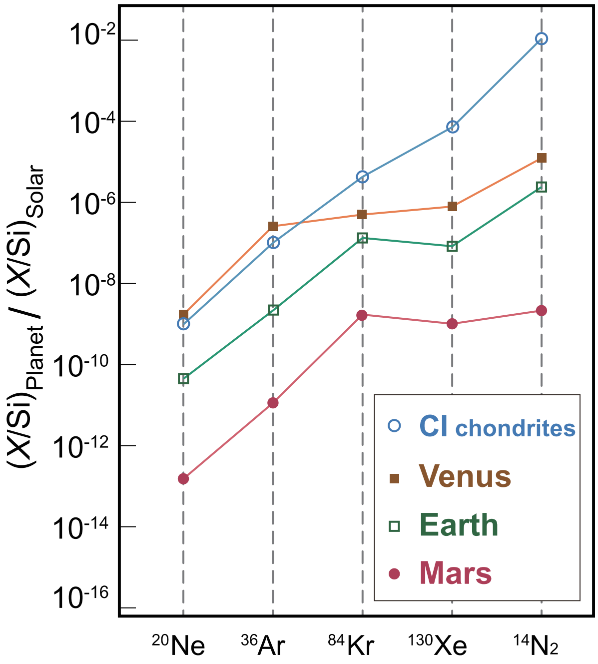

Fig. 1. Abundances of noble gases and N in CI chondrites and terrestrial planet atmospheres and known crustal reservoirs relative to Si with respect to the corresponding solar ratios (data are from Pepin, 1991).

atmospheres of Venus, Earth, and Mars with chondrites may suggest the same origin (e.g., Pepin, 1991; Marty et al., 2016). However, there are distinct gaps in the abundances in the atmospheres on the three planets: compared to Earth, Venus is enriched and Mars is depleted in noble gases by roughly two orders of magnitude, respectively (Fig. 1). The origin of these gaps is poorly understood. Since the noble gases and N are inert molecules, it is possible that these gaps were created during the early stage of atmospheric formation and evolution.

To a first approximation, the depletion pattern of noble gases and N in the planetary atmospheres follows the trend in chondritic values, but some differences between the planetary and chondritic abundances imply secondary effects: for instance, cometary additions to noble gases in the planetary atmospheres (e.g., Marty et al., 2017) and preferential loss of xenon (Pujol et al., 2011). The ratio of N to noble gases differs between three planets, which may be caused by the difference in the partitioning of N into the mantle between them due to N being less inert than noble gases (Mikhail and Sverjensky, 2014; Wordsworth, 2016). Whereas these differences suggest additional complexities of the atmospheric evolution, we aim to explain the most distinct gaps: the orders-of-magnitude gaps in the abundances of noble gases and N between three planets.

We investigate a possible explanation of these gaps involving the direct effect of impacts. Genda and Abe (2005) proposed one possible scenario that explains the differences in the atmospheric contents of argon, krypton, and xenon on Venus and Earth. By using numerical simulations, they demonstrated that the presence of oceans significantly enhances the loss of atmosphere during a giant impact and it can determine its subsequent atmospheric amount and composition. Protoplanets on orbits similar to Earth are expected to have had oceans, whereas those with Venus-like orbits are in the runaway greenhouse state (e.g., Hamano et al., 2013; Hamano et al., 2015). As a result, a noble gas-rich primordial atmosphere survived on Venus, but not on Earth. However, the following late accretion might have influenced their atmospheres.

Even after the giant impact stage, the terrestrial planets have experienced numerous impacts. de Niem et al. (2012) demonstrated that the atmospheric pressure had strongly increased for both Earth and Mars during the LHB. They also found that the initial pressure does not matter much compared to volatiles added by impact delivery. This means that the differences in the atmospheric content on Venus and Earth might have changed after giant impacts. Therefore, it is important to investigate the atmospheric evolution during the late accretion to understand the origin and evolution of planetary atmospheres. In this study, we constructed a numerical model of impact degassing from impactors and atmospheric erosion on Venus, Earth, and Mars during the late accretion. Partitioning of elements in different surface reservoirs might influence the resulting noble gases and N abundances: the runaway greenhouse on Venus (e.g., Kasting, 1988; Hamano et al., 2013), the carbon-silicate cycle on Earth (e.g., Walker et al., 1981), and the CO_2-ice formation on Mars (e.g., Forget et al., 2013; Nakamura and Tajika, 2003). Although noble gases and N are mainly partitioned into the atmosphere, the distinct environments on the three planets may have created the differences in their concentrations in the atmospheres, leading to the various escape rates of noble gases and N due to impact erosion (see Section 2.3 for details).

The purpose of this work is to investigate the atmospheric evolution of Venus, Earth, and Mars during the late accretion considering the effect of element partitioning. We describe our model in Section 2. Numerical results for the noble gases and N abundances in the atmospheres and their dependence on parameters will be shown in Section 3. We discuss the origin and evolution of the atmospheres of the three terrestrial planets in Section 4 and summarize our conclusions in Section 5.

2. Numerical model

2.1. Variables

Table 1 lists the variables and their meanings in our model.

In our model, the atmosphere is assumed to contain three components of volatiles: CO_2, H_2O, and N_2 + non-radiogenic noble gas. The number i represents each atmospheric component (1: CO_2, 2: H_2O, 3: N_2 + noble gases). Since the amount of noble gases is small, we assume that N_2 represents the third component. We note that N can be more easily partitioned into other reservoirs than noble gases (e.g., Pepin, 1991). Because the difference in N partitioning between three planets are poorly constrained and controversial (e.g., Mikhail and Sverjensky, 2014; Wordsworth, 2016), we assume that N is partitioned into the atmosphere. The partitioning may decrease the N abundance in the atmosphere by a factor, but it would hardly change our discussion about the orders-of-magnitude difference in the abundances of noble

Table 1
A list of variables and their meanings in our model.

D	impactor diameter	T	planet surface temperature
V	entry velocity of impactor	H	scale height
M_{imp}	impactor mass	ρ_0	atmospheric density
ρ_{imp}	impactor density	m_{atm}	atmospheric mass
Σ_{imp}	cumulative impactor mass	$m_{atm,\ i}$	mass of volatile species i in the atmosphere
Σ_{imp}^{tot}	total impactor mass	$\overline{m}$	mean molecular mass
x	abundance of volatiles in an impactor	m_i	volatile component molecular mass
x_i	abundances of volatile species i in an impactor	N_i	molecular numbers
X_C	parameter for volatile abundance in an impactor	P	total pressure
R_t	planetary radius	P_i	partial pressure
M_t	planetary mass	P_i^{crit}	upper limit of partial pressure
u_{esc}	planetary escape velocity	ξ	impact energy parameter
ρ_t	planetary mean density	η	atmospheric erosion efficiency
α	impact angle	ζ	impactor's escaping efficiency
V_{ground}	impact speed at ground level	m_a	eroded atmospheric mass
V_∞	expansion speed of vapor plume	m_v	eroded impactor vapor mass