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Hydrodynamic escape of a reduced proto-atmosphere on early Mars

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Abstract

A one-dimensional hydrodynamic escape model which includes radiative cooling processes and photochemical processes for a multi-component atmosphere is developed and applied to estimate the duration of early Martian atmosphere with H_2-rich reduced chemical compositions in which the degassed component and solar nebula component are mixed. The mass escape rate decreases with increasing the mixing fraction of CH_4 and CO mainly because of the energy loss by radiative cooling by these infrared active species. Our result suggests that a reduced environment on early Mars may have continued more than 100 Myr, possibly up to $\sim$ 1 Gyr, and played an important role in warming climate and serving organic matters on the martian surface.

1. Introduction

The short growth time of proto-Mars inferred from analyses of Martian meteorites implies that the proto-Mars likely gravitationally maintained both the solar nebula component and the impact degassed component as a proto-atmosphere [1]. Planetary building blocks containing metallic iron should induce production of reduced volatiles such as H_2, CH_4 and CO because metallic iron acts as a reductant for the degassed component [2]. If a reduced proto-atmosphere was formed and maintained on early Mars, it may have played an important role in warming climate and serving organic matters on the martian surface.

However, a reduced proto-atmosphere once formed on a rocky planet has been considered to be rapidly lost by hydrodynamic escape. Previous studies estimating the atmospheric escape rate of an oxidized Martian proto-atmosphere suggest that the proto-atmosphere with the amount equivalent to 100 bar could have been lost per 10 Myr under the EUV flux 100 times the present [3,4]. But, their result likely depends on the assumption that molecules are fully dissociated into atoms. If infrared active molecules such as CH_4 and CO exist in the atmosphere, they may reduce the atmospheric escape rate by radiative cooling. If the atmospheric escape rate had been kept small, the reduced environment would continue for a long time. Here, we develop a one-dimensional hydrodynamic escape model which include radiative cooling processes and photochemical processes for a multi-component atmosphere. We calculate the escape rate of a reduced Martian proto-atmosphere and estimate the duration of the reduced environment on early Mars.

2. Model

We solved the fluid equations for multi-component atmosphere assuming spherical symmetry considering radiative processes and photochemical processes. These equations are solved by numerical integration about time until the physical quantities settle into steady profiles. We use the UV spectrum 100 Myr after the birth of the Sun estimated by the observations of solar-type G stars [5]. CH_4 and CO are considered as radiative coolant from their energy transitions with high emissivity. We calculate the radiative cooling rate by using the photon escape probability. 19 photodissociation reactions including photoionization are considered for 18 atmospheric components. H_2, CH_4 and CO are given as primary constituents of the proto-atmosphere.

3. Results and Discussion

As the basal mixing ratios of CH_4 and CO increase, the escape mass flux decreases: the total escape mass flux when $CH_4/H_2 \sim 0.07$ is one order of magnitude smaller than that of the pure hydrogen atmosphere (figure 1). Concurrently, the mass fractionation between H_2 and other heavier species occurs more remarkably. This result indicates that more fraction of CH_4 and CO tend to be left behind as the degassed component becomes more dominant in the proto-atmosphere.

Figure 2 and 3 represent the surface pressure of initial atmosphere and the timescale for all H_2 loss

from initial atmosphere assuming that CH_4-CO atmosphere whose total number of C is equivalent to 0.1 - 10 bar of CO_2 was left behind after hydrodynamic H_2 loss. The timescale for H_2 loss may exceed 100 Myr when Mars had massive solar nebula component. Moreover, the reduced atmosphere may further continue until reduced carbon species are almost fully oxidized through photolysis and hydrogen escape. Accordingly, a reduced environment may have continued more than 100 Myr, possibly up to 1 Gyr, depending on the chemical composition and the amount of initial atmosphere.

Acknowledgements

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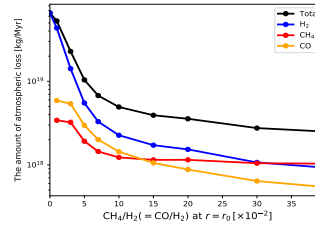

Figure 1: Escape mass fluxes of main gas species per 1 Myr as a function of the lower boundary mixing ratio $CH_4/H_2(=CO/H_2)$. The black line represents the total mass flux, the blue line represents that of H_2, the red line represents that of CH_4 and the orange line represents that of CO.
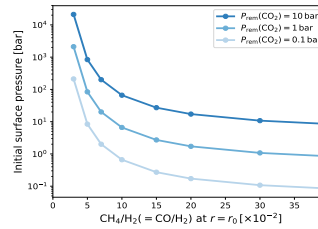

Figure 2: Surface pressure of initial atmosphere as a function of the mixing fraction $CH_4/H_2(=CO/H_2)$ of initial atmosphere. $P_{\mathrm{rem}}(CO_2)$ is the surface pressure of CO_2 after hydrodynamic H_2 loss.
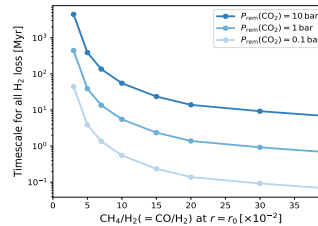

Figure 3: Timescale for all H_2 loss as a function of the mixing fraction $CH_4/H_2(=CO/H_2)$ of initial atmosphere.