The influence of carbon escape on the evolution of the Martian atmosphere

Ryosuke Yagi[1], *Naoki Terada[1], Shungo Koyama[1], Takeshi Kuroda[1], Hiromu Nakagawa[1], Isao Murata[1], Yasumasa Kasaba[1]

1. Graduate School of Science, Tohoku University

The purpose of this study is to investigate the evolution of atmospheric composition in the early Martian atmosphere. Not only hydrogen and oxygen escapes but also carbon escape to space is considered in this study for two reasons. The first reason is that thermal escape of atomic carbon could be stronger than atomic oxygen on early Mars. The early Martian atmosphere was exposed to stronger Sun’s EUV and FUV radiations than today. The escape parameter, defined as the ratio of the gravitational potential to kinetic energy at the exobase level, could have been small enough to allow massive escapes of these species under such strong radiations. For example, the escape parameter of atomic carbon in the Martian atmosphere was estimated 0.75 times smaller than that of atomic oxygen, and because of an efficient dissociation of CO_2 the densities of these species at the exobase level were comparable at 4.1 billion years ago [Tian et al., 2009]. Hence, we consider that on early Mars, thermal escape of atomic carbon could have been stronger than atomic oxygen. The second reason is the discovery of the concentration of Mn in Gale Crater by Curiosity, which suggests that the early Martian atmosphere could have several mbar or more of O_2 partial pressure in the Hesperian [Noda et al., 2019]. Previous 1-dimensional photochemical models that considered hydrogen and oxygen escapes on current Mars suggested that the O_2 partial pressure could increase only up to 10^{-5} bar [e.g., Chaffin et al., 2017]. This is because the atmosphere self-regulates the loss of hydrogen and oxygen to 2:1 [McElroy and Donahue, 1972], which limits the imbalance between the hydrogen and oxygen escapes and hence prevents a massive oxygen buildup in the atmosphere. In this study, we consider atomic carbon escape as an agent to accumulate O_2 in the atmosphere.

We investigated the effect of carbon escape on the accumulation of O_2 in the atmosphere using two models. The first is a 1-box model that considers only the supply and loss of atmosphere from the atmospheric boundaries. This model was used to get an overview of the atmospheric evolution. The second is a 1-dimensional photochemical model. This model investigated the evolution of atmospheric composition taking into account atmospheric photochemistry in addition to the supply and loss from the atmospheric boundaries. This model was applied during periods when the atmosphere was expected to regenerate to be an O_2-dominated atmosphere after a massive loss of the atmosphere. The results of our 1-box model suggested that an O_2-dominated atmosphere was formed during times when oxygen thermal escape was diminished and carbon thermal escape was still strong. Applying the 1-dimensional photochemical model in the same period, i.e., early in Noachian, ~1 mbar of O_2-dominated atmosphere was formed in about 10^4 years. However, the period of the O_2-dominated atmosphere formation is inconsistent with the Curiosity measurement.

Therefore, we invoked the uncertainly in the evolution of stellar EUV flux due to the difference in the initial rotational speed of the star. When the star's initial rotation speed is fast, the period when the stellar EUV is strong lasts longer. Hence, the period during which the atmosphere cannot be maintained due to massive escape would be longer. This effect shifts the period when the O_2-dominated atmosphere is formed, so that it is in the Hesperian period. Our study suggests that ~1 mbar O_2-dominated atmosphere may be formed during the Hesperian period by taking into account carbon escape, if the stellar evolution is the type of the fast rotator. This is consistent with the results of the Curiosity measurement.

Keywords: Mars, Atmospheric escape, Atmospheric evolution