Hydrodynamic escape of H2O-dominated atmospheres on terrestrial planets in the runaway greenhouse states

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Terrestrial planets exposed to stellar irradiation exceeding the radiation limit are expected to enter runaway greenhouse states and develop H2O-dominated atmospheres provided they possess sufficient surface water (e.g., Kasting, 1988; Nakajima et al., 1992; Kopparapu et al., 2013). Planets orbiting M dwarfs currently in the habitable zone were likely in runaway greenhouse states during the pre-main-sequence phase due to the extremely high stellar irradiation during this stage (e.g., Luger and Barnes, 2015). Early Venus may have also experienced a long-term runaway greenhouse state because of its orbital distance close to the Sun (e.g., Hamano et al., 2013).

Such H2O-dominated atmospheres are estimated to be significantly lost by hydrodynamic escape under the high stellar X-ray and extreme ultraviolet (XUV) irradiation (Watson et al., 1981; Kasting and Pollack, 1983; Kumar et al., 1983; Chassefiere, 1996; Hamano et al., 2013; Luger and Barnes 2015; Tian 2015; Tian and Ida 2015; Bolmont et al. 2017; Bourrier et al. 2017; Guo, 2019; Johnstone 2020). On the other hand, the effects of radiative cooling, which can remove the heating energy obtained by the stellar XUV absorption, have not been fully investigated in H2O-dominated atmospheres. Recently, Johnstone (2020) considered the radiative emission of H2O in rotational bands in the escape outflows of H2O atmospheres and indicated that the radiative cooling may have little effect on the hydrodynamic escape. However, radiative emission by H2O in the wide range of wavelengths and that of radiatively active chemical products can significantly suppress the hydrodynamic escape as in H2-rich atmospheres containing H2O (Yoshida et al., 2022).

This study estimates the escape rate of H2O-dominated atmospheres on terrestrial planets with a 1 Earth mass by applying a 1D hydrodynamic escape model. The model solves the fluid equations considering chemical and radiative processes for a multicomponent gas assuming spherical symmetry to obtain the structure of steady outflow (Yoshida and Kuramoto, 2020; 2021; Yoshida et al., 2022). Radiative cooling is considered through thermal line emission of H2O, OH, H3+, OH+, and H3O+. Radiative heating through X-ray and UV absorption is also considered by adopting the stellar spectrum from 0.1 nm to 280 nm estimated for the young Sun (Claire et al., 2012). The chemical species and reactions considered in this study are the same as those of Yoshida et al. (2022). According to the calculation results, H2O is efficiently photolyzed into various atoms and ions as shown by previous studies. On the other hand, the surviving H2O acts as the vital radiative cooling source in high-temperature conditions due to the heating by XUV absorption. Radiatively active chemical products such as OH also contribute to energy loss by their radiative cooling effects. As a result, the escape rate is approximately one order of magnitude lower than that estimated by Johnstone (2020) under the same XUV flux setting. These findings indicate that the maximum amount of H2O lost by hydrodynamic escape on early Venus was low compared with previous estimates, and terrestrial planets in the habitable zone around M dwarfs are more likely to retain surface water than previously thought.

Keywords: hydrodynamic escape, water vapor atmosphere, runaway greenhouse state, terrestrial exoplanets, early Venus

