The effect of radiative cooling on the hydrodynamic escape of a Martian proto-atmosphere

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Due to its large distance from the Sun, Mars was likely formed from volatile-rich building blocks that had been prepared under cold nebular environments. This is supported by the geochemical nature of the Martian mantle that is estimated from the analysis of Martian meteorites (Dreibus and Wanke, 1985). During the rapid accretion of Mars suggested from the chronology of Martian meteorites (Dauphas and Pourmand, 2011; Tang and Dauphas, 2014), a proto-atmosphere was likely formed from both the solar nebula component and the impact degassing component. A recent numerical study of Martian proto-atmosphere formation estimates that the surface pressure and temperature of a Martian proto-atmosphere in the last stage of accretion were possibly greater than several kbars and 2000 K, respectively, with a composition enriched in reduced species such as H_2, CO and CH_4 due to chemical interactions with silicate-metal mixtures (Saito and Kuramoto, 2017).

If the Martian proto-atmosphere was originally so massive, a large fraction of the atmospheric mass should have escaped to space to be consistent with the thin atmosphere on present Mars. One of the candidate mechanisms to induce such massive escape is hydrodynamic escape. Hydrodynamic escape occurs when radiative heating of an atmosphere accelerates a radial outflow of an atmosphere against the planetary gravity. From observations of young solar proxies, the extreme ultraviolet (EUV) flux of the young Sun is estimated to be as strong as ~100 times the present mean flux (Ribas et al., 2005). This would be powerful enough for the initial Martian atmosphere to be largely lost by hydrodynamic escape.

Previous numerical studies (Lammer et al., 2013; Erkaev et al., 2014) estimate that a proto-atmosphere with the amount equivalent to ~100 bar could have been lost from early Mars per 10 Myr under the EUV flux 100 times the present. If such a EUV flux intensity was kept over ~100 Myr after the formation of planes as estimated from the observation of young solar proxies, their result suggests that a proto-atmosphere with an amount equivalent to ~1000 bar could have been eventually lost.

These previous studies assumed that all of molecules were dissociated into atoms in the upper atmosphere supposing that high EUV flux may dissociate molecules such as H_2, H_2O and CO_2. However, it is likely that a significant fraction of molecules stays undissociated at least in the lower part of EUV absorption region. If infrared active molecules were included in the atmosphere, they may reduce the amount of atmospheric loss due to the radiative cooling, but its efficiency remains poorly understood. Here, we develop a 1D radiative hydrocode which includes molecular species and analyze the effect of radiative cooling on the hydrodynamic escape of a proto-Martian atmosphere. First, we apply the model including chemical processes to a pure hydrogen atmosphere. Second, we add CO to a hydrogen atmosphere and consider the effect of radiative cooling on the hydrodynamic escape. The solar EUV flux was given to be 100 times the present mean flux with the time-averaged present solar EUV spectrum.

In the calculation of a pure hydrogen atmosphere, we consider 15 chemical reactions and assume that atmospheric components are H, H_2, H^+, H_2^+, H_3^+. We assume that only H_2 exists at the lower boundary. Model simulations show that molecular H_2 survives and dominate the escaping atmosphere in all calculated altitude. This result suggests that the radiative cooling by molecules may be important.

Next, we consider a H_2-CO atmosphere and the effect of radiative cooling by CO. In the calculation of a H_2-CO calculation, we neglect the chemical processes. As the mixing ratio of CO increases, the escape mass flux decreases due to the radiative cooling by CO. Simultaneously, the crossover mass, i.e. the largest molecular mass of atmospheric constituents that can be dragged up by H_2, decreases. The crossover mass may become smaller than the mass of CO when the mixing ratio of CO becomes greater than ~15%. In such a case, only H_2 may escape leaving behind CO in the proto-atmosphere. Our results indicate that molecular species are likely dominant even in a proto-atmosphere exposed to intense EUV flux, and radiative cooling by molecules may significantly decrease the total amount of atmospheric loss from early Mars.

Keywords: Martian proto-atmosphere, hydrodynamic escape, radiative cooling

