THE EFFECT OF RADIATIVE COOLING ON THE HYDRODYNAMIC ESCAPE OF A MARTIAN PROTO-ATMOSPHERE.

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Introduction: 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 [1]. During the rapid accretion of Mars suggested from the chronology of Martian meteorites [2,3], 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 [4].

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 [5]. This would be powerful enough for the initial Martian atmosphere to be largely lost by hydrodynamic escape.

Previous numerical studies [6,7] 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.

Model: We solve the one-dimensional time-dependent inviscid fluid equations for a H_2-CO atmosphere. To solve EUV radiative transfer process in an extended spherical atmosphere, we adopt a two-dimensional energy deposition calculation method [8]. To calculate radiative cooling rate by CO, we consider 468 line transitions which HITRAN database provides, and calculate photon escape probability [9]. The solar EUV flux was given to be 100 times the present mean flux with the time-averaged present solar EUV spectrum. Heating efficiency which corresponds to the fraction of absorbed EUV radiation transformed into thermal energy is taken to be 15%. We use CIP method to solve fluid equations [10,11] and obtain steady state solutions by long time integration.

Result and Discussion: When the mixing ratio of CO is lower than 1%, the escape mass flux is not different from the result for the case neglecting radiative cooling (Fig. 1). In general, gas obtains thermal energy required to outflow to space in the subsonic region below the transonic point. Under the low CO mixing ratios, the radiative cooling by CO in this region is suppressed because the gas temperature is kept low by adiabatic expansion. Thus, the radiative cooling little affects escape rate in these cases.

However, as the mixing ratio of CO increases greater than 1%, the escape mass flux begins to decrease (Fig. 2). At the same time, gas temperature increases gradually in the subsonic region with increasing CO mixing ratio. Hence, the radiative cooling by CO becomes significant in the subsonic region where gas acquires the energy for escape to space.

The increase in the gas temperature in the subsonic region appears to occur by the following mechanisms. As the mean molecular weight in the atmosphere increases, EUV absorption becomes to occur at smaller radial distances from the planetary center due to the decrease in atmospheric scale height. This has an effect reducing the net radiative absorption by the entire atmosphere, resulting in the slowdown of outflow and therefore the decrease in the adiabatic expansion rate along gas stream. Therefore, EUV heating becomes to more effectively raise the gas temperature in the subsonic region.

As the mixing ratio of CO increases, the crossover mass, i.e. the largest molecular mass of atmospheric constituents that can be dragged up by H_2, decreases (Fig. 3). When the radiative cooling is considered, 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 present model considers only CO as an infrared active molecule, but it is likely that other infrared active molecules such as CH_4 and H_2O existed in the proto-atmosphere [4]. CH_4 and H_2O are stronger cooling sources than CO. So, the escape rate may decrease more rapidly as the mean molecular weight of the atmosphere increases by adding CH_4 and H_2O. On the other hand, production of atoms by photo dissociation may suppress radiative cooling and increase escape rate. Further study is needed to estimate more realistic escape rates.

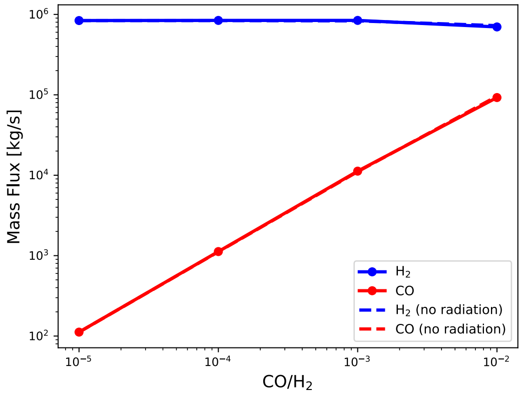

Figure 1: The relationship between the escape mass flux and the number density ratio of CO/H_2 at the lower boundary when the mixing ratio of CO is smaller than 1%. The solid curves are results for the case of considering radiative cooing. The dashed curves are results for the case neglecting radiative cooling. (blue: H_2, red: CO).

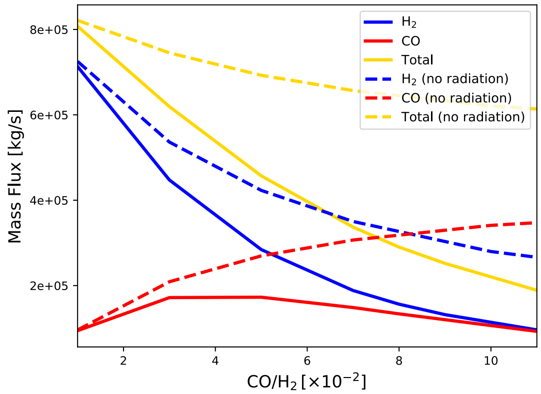

Figure 2: The relationship between the escape mass flux and the number density ratio of CO/H_2 at the lower boundary for larger CO mixing ratios. The blue and red curves represent H_2 and CO mass fluxes in the same manner as shown in Fig. 1. The yellow curves represent the total escape mass fluxes.

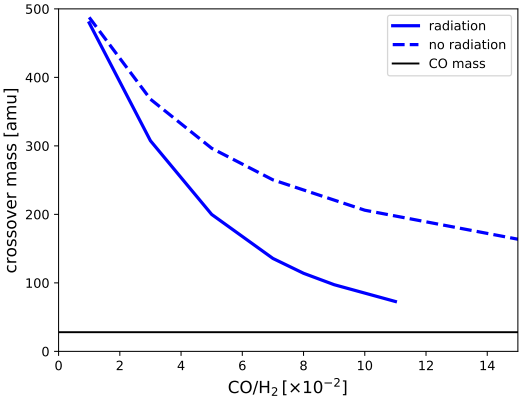

Figure 3: The relationship between the crossover mass and the number density ratio of CO/H_2 at the lower boundary. The solid curve is the result considering radiative cooling. The dashed curve is the results neglecting radiative cooling. The black line indicates the mass of CO.

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