THE EFFECT OF THE RADIATIVE COOLING ON HYDRODYNAMIC ESCAPE OF A REDUCED PROTO-ATMOSPHERE ON EARTH. T. Yoshida[1] and K. Kuramoto[2] [1]Faculty of Science, Tohoku University (Sendai, Miyagi 980-8578, Japan: tatsuya@tohoku.ac.jp), [2]Faculty of Science, Hokkaido University (Sapporo, Hokkaido 060-0810, Japan)

Introduction: Recent studies of isotopic compositions of Earth's materials and primitive meteorites indicate that most Earth's building blocks were close to enstatite meteorites, which have the most reduced oxidation state among primitive meteorites [1]. This implies that the volatile elements accreted on Earth were reduced by metallic iron in building blocks to form impact-generated vapour enriched in reduced species like H_2 and CH_4 [2, 3].

Atmospheres with reduced compositions are promising sites for photochemical production of organic matters [4], as demonstrated by organic haze aerosols that arise through CH_4 photolysis in the Titan's atmosphere [5]. If a reduced proto-atmosphere was formed and maintained on early Earth, efficient synthesis of organic matters potentially linked to the emergence of living organisms could be expected. Furthermore, the reduced species may have been important greenhouse gases on early Earth under the faint young Sun [6]. Therefore, it is crucial to estimate the duration of the reduced environment to understand the prebiotic chemical evolution and the climate on early Earth.

A reduced atmosphere on early Earth would have been largely lost by hydrodynamic escape. Hydrodynamic escape occurs when radiative heating of an atmosphere accelerates atmospheric radial outflow against planetary gravity. Intense X-ray and extreme ultraviolet (XUV) radiation from the young Sun [7] may have induced hydrodynamic escape on early Earth.

Several numerical studies have been made on the hydrodynamic escape of pure hydrogen atmospheres supposing a gas envelope trapping solar nebula gas [8]. However, these studies treated the heating efficiency, i.e. the fraction of absorbed XUV energy partitioned to net atmospheric heating, as a parameter poorly constrained. Chemical reactions induced by XUV photons were also neglected and/or highly simplified supposing perfect decomposition to monoatomic molecules for instance. Therefore, escape flux and timescale for hydrogen depletion of Earth's proto-atmosphere remain highly uncertain.

Carbon species such as CH_4 that likely contained in a hydrogen-rich atmosphere may have large effects on hydrodynamic escape. We constructed a hydrodynamic escape model considering photochemical processes and radiative cooling processes for a Martian proto-atmosphere composed of H_2, CH_4, CO, and their photochemical products, indicating that the atmospheric escape is significantly suppressed by the effect of radiative cooling [9]. On Earth, photolysis may proceed more efficiently than that on Mars due to its deeper gravitational well and stronger solar XUV flux. Even in such a case, other radiatively active molecules like H_3^+, CH, and CH_3 may increase and their thermal line emission may also suppress atmospheric escape significantly.

In this study, we present a 1D hydrodynamic escape model for Earth's proto-atmosphere employing expanded chemical networks and radiative cooling processes to reveal reliable atmospheric escape rates and atmospheric evolution on early Earth (see [10] for details).

Model: A 1D hydrodynamic escape model considering radiative processes and chemical processes for multi-component atmospheres [9] is applied in this study with some modifications to simulate the outflow of a reduced atmosphere on early Earth.

In this modelling, an H_2-CH_4 atmosphere is supposed referring to the thermodynamic analysis of growing Earth [2].

The basic equations in this model are the fluid equations of continuity, momentum, and energy for a multi-component gas on the assumption of spherical symmetry. They are solved by numerical integration about time until the physical quantities settle into steady profile.

As chemical processes, 97 chemical reactions such as photolysis and bimolecular reactions are considered for H_2, CH_4, and their chemical products.

The absorption of X-ray and UV by molecules and atoms is considered. The X-ray and UV spectrum from 0.1 to 165nm estimated for the young Sun at the age of 100 Myr are adapted [11].

We consider the thermal line emission by CH_4, CH, CH_3, and H_3^+, and calculate the radiative cooling rate by applying the method formulated by Yoshida & Kuramoto [9] which includes the Doppler shift of emission line wavelength caused by outflow acceleration.

Results and Discussion: In the escape outflow, CH_4 is efficiently dissociated into CH and CH_3 by photolysis and reactions with ion species.

The energy balance in the subsonic region is shown in Fig. 1. ~75 % of the energy obtained by the XUV absorption is lost by the chemical expense and the radiative cooling by H_3^+ almost independently of the CH_4 mixing ratio. The radiative cooling by CH and CH_3 produced by photolysis of CH_4 has a significant effect on the atmospheric energy balance. As the basal CH_4/H_2 ratio increases from zero to 0.007, the heating efficiency decreases from ~ 25 % to ~ 5 %. This shows that radiative cooling by CH and CH_3 suppresses atmospheric escape significantly even when the basal CH_4 mixing ratio is small.

The dependence of the escape mass fluxes of main gas species on the basal CH_4/H_2 ratio is shown in Fig. 2. As the basal CH_4/H_2 ratio increases, the escape mass flux decreases because the heating efficiency decreases by radiative cooling. The dashed line in Fig. 2 indicates the critical flux, i.e. the minimum flux of H_2 that can drag CH_4 up to outside the planetary gravitational well. The H_2 flux reaches the that only H_2 escapes to space leaving CH_4 behind when CH_4/H_2 > ~0.01 under the assumed XUV flux.

A significant decrease in heating efficiency suggested from our numerical results implies a prolonged Earth's proto-atmosphere with reduced composition. We estimated the possible early evolution of Earth's proto-atmosphere which is consistent with the current inventories and the isotopic compositions of volatiles on the Earth's surface (see [10] for details). The timescale for H_2 escape consistent with the constraints of the isotopic compositions and the amount of C and N on the present Earth is possibly more than several hundred million years. This result suggests that a long-lived hydrogen-rich reduced environment played important roles in climate warming and the generation of organic matters linked to the emergence of living organisms during the Hadean and early Archean.

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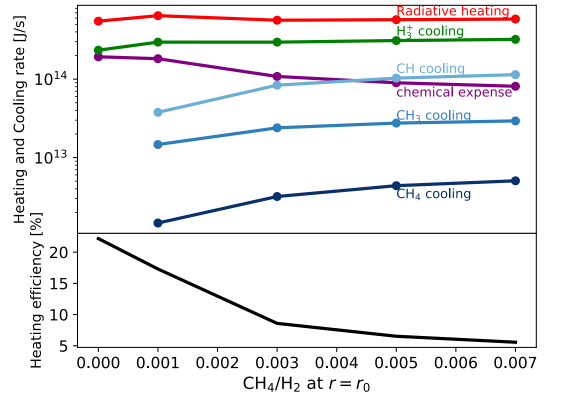

Figure 1: Heating rate and cooling rate in the subsonic region. 'Radiative heating' is the heating rate by XUV absorption, 'chemical expense' is the net chemical expense of energy, and 'CH_4 cooling', 'CH cooling', 'CH_3 cooling', and 'H_3^+ cooling' are the radiative cooling rate by CH_4, CH, CH_3, and H_3^+, respectively. The black line in the lower panel represents the heating efficiency.

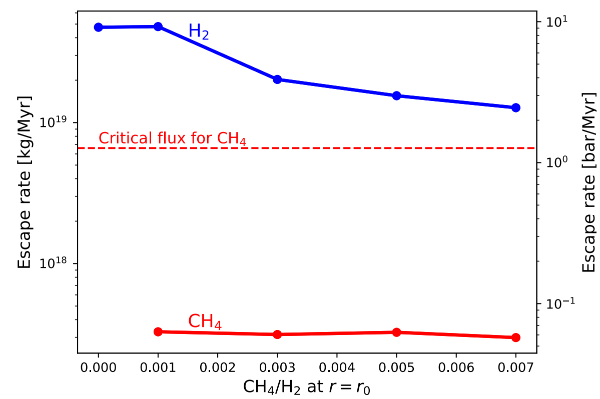

Figure 2: Escape mass fluxes of main gas species per 1 Myr as a function of the basal CH_4/H_2 ratio. The right vertical axis represents the flux normalized by the mass of the present Earth's atmosphere: 5.3 × 10^{18} kg. The blue solid line represents the H_2 mass flux, and the red solid line represents the CH_4 mass flux. The dashed line represents the critical flux which is the minimum flux of H_2 that can drag CH_4 upwards.