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# Numerical modeling of hydrodynamic escape from early Earth atmosphere

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The anoxic early Earth's atmosphere is considered to change its composition from some reduced one to oxidative one associated with hydrogen escape to space. Its changing rate is a clue for discussing whether the early Earth's surface environment is better suited for synthesizing organic compounds or not and for understanding climate changes on early Earth. In previous studies, escape of hydrogen was believed to occur rapidly by hydrodynamic escape driven by strong EUV radiation from the young Sun. Recently, Tian et al. (2005, hereafter T05) investigated numerically the hydrodynamic escape of hydrogen from the atmosphere of early Earth and indicated that the escape rate was lower than previously thought and thereby reduced surface environment might be maintained for long periods. However, the calculation of T05 has a critical problem that the conservation of mass is not satisfied.

In this study, we first performed recalculations of T05 and tested the accuracy of calculation for hydrodynamic escape with the Lax-Friedrichs scheme which they adopted. As a result, we found that their calculation does not satisfy the mass conservation owing to the strong numerical diffusion and the calculated escape rate increases with decreasing contribution of numerical diffusion by changing the configration of numerical grids. We therefore conclude that T05 underestimates the hydrodynamic escape rate.

We then constructed a new numerical model of the one-dimensional time-dependent nonviscous hydrodynamic equations for a single constituent atmosphere in spherical geometry with CIP & CIP-CSL2 method and performed the calculation with same parameter as T05. As a result, our new model predicts hydrodynamic escape rates are 5-10 times larger than those of T05 when the number density at the bottom is larger than $n_0 = 5\text{x}10^{18}\ m^{-3}$ and the solar EUV flux is larger than 2.5 times than that of today. However, decreasing the energy deposition rate to atmosphere, the hydrodynamic escape rates of this study becomes smaller than those of T05. This is because the energy loss by heat conduction from upper boundary, which is taken to be zero in T05, becomes significant under such conditions.

Using our new results, we may estimate the hydrogen mixing ratio of about 7% for the anoxic atmosphere in the late Archean by balancing the geologically estimated volcanic hydrogen outgassing rate with hydrodynamic escape rate under the solar EUV 2.5 times that of today. In addition, the hydrogen mixing ratio had been rising through Archaean because of the decrease in solar EUV flux. The increase in hydrogen mixing ratio might result in $CO_2$-poor atmosphere, which would destabilize climate system. This result might be consistent with the occurrence of snowball earth event at 2.2 Gyr ago.

Keywords: Hydrodynamic escape