HYDRODYNAMIC ESCAPE OF A PROTO-ATMOSPHERE JUST AFTER A GIANT IMPACT.

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Introduction: The recent works on the planetary formation show that several tens of Mars-sized protoplanets are formed through a successive accretion of planetesimals in the terrestrial planet region [1]. Then, these protoplanets collide each other as their orbit crosses owing to gravitational interaction among them [2]. Therefore, it is generally thought that several giant impacts of Mars-sized proto-planets occur at the late stage of the terrestrial planet formation.

Protoplanets would have a mixed proto-atmosphere [3] of an impact-induced gas [4] and a gravitationally-attracted solar-type gas [5]. The giant impacts modify such a proto-atmosphere. First, a large amount of the proto-atmosphere may be blown-off by the globally strong ground motion caused by a giant impact (the "mechanical" escape) [6–8]. Second, release of enormous impact energy may heat the atmosphere as well as the planet, and the hydrodynamic outflow of the proto-atmosphere may occur (the "thermal" escape). Therefore, thermal escape as well as mechanical escape should have affected the origin and evolution of planetary atmosphere.

Genda and Abe [9] clarified that significant fraction of the proto-atmosphere (35–90%) survived the mechanical blow-off event. In this study, we investigate the thermal escape, especially the hydrodynamic escape of a proto-atmosphere.

Mixed Atmosphere of a Proto-Atmosphere and Silicate Vapor: Due to the large energy released by a giant impact, especially reaccretion of enormous ejecta from the target planet and/or impactor, the temperature of the planetary surface becomes extremely high (5000–10,000K) [10, 11]. During the reentry of ejected materials into the atmosphere, ejected materials are at least partially vaporized. The residual parts of materials impact on the planetary surface, and then the substantial parts of them would be ejected again into the atmosphere with the surface materials. These ejecta materials interact with the atmosphere. Finally, an well-mixed atmosphere of the proto-atmosphere and silicate vapor with the temperature of 5000–10,000 K is likely formed on the planetary surface after a giant impact.

If the hydrodynamic escape of the mixed atmosphere occurred, the adiabatic flow would be expected rather than the flow driven by radiative heating from the high-temperature planetary surface, because the mixed atmosphere is optically very thick.

Criterion for Onset of Hydrodynamic Escape: The criterion for the onset of the hydrodynamic escape of a polytropic atmosphere is given by $\lambda_0 < \gamma/(\gamma-1)$ [12], where γ is the polytropic exponent and λ_0 is the escape parameter, defined by $\lambda_0 = GMm/(kT_0r_0)$, where m, k, T_0, and r_0 are the mass of the molecule, the Boltzmann constant, the temperature at the planetary surface, and the planetary radius, respectively. In the case of the adiabatic flow, the polytropic exponent is equal to the specific heat ratio.

First, we consider the hydrogen, which is one of the major components in the proto-atmosphere, and is the lightest gas. Hydrogen molecule with $\gamma = 1.4$ satisfies the criterion for onset of the hydrodynamic escape, when $T_0 > 4200$K. Since the surface temperature just after a giant impact is extremely high (5000–10,000K), if the atmosphere is composed of pure hydrogen, the adiabatic expansion of the atmosphere results in rapid escape from the planetary surface. However, silicate vapor should inevitably exist in the very hot planetary atmosphere. Since silicate vapor has large molecular weight (m = 30 g/mol [13]), the escape requires extremely high temperature ($T_0 > 21{,}000$ K in the case of $\gamma = 1.1$ [14]). Moreover, the proto-atmosphere is composed of the species with large molecular weight other than hydrogen, such as H_2O, CO_2, and N_2. For example, H_2O with m = 18 g/mol and $\gamma = 1.33$ requires extremely high temperature ($T_0 > 30{,}000$ K) for the hydrodynamic escape. Therefore, it is impossible for the bulk of the mixed atmosphere to escape adiabatically. Instead, it is a question whether or not hydrogen selectively escapes from the mixed atmosphere. We perform simulations of hydrogen escape from the mixed atmosphere, and calculate the time scale of hydrogen escape.

Numerical Model: In calculating the hydrodynamic escape of hydrogen, we have made the following assumptions. (1) The atmospheric motion is spherically symmetric. (2) The atmosphere is composed of two kinds of ideal gases. One is hydrogen. The other is silicate vapor with the mean molecular weight of 30 g/mol, or heavy gas composed of either H_2O or CO_2. (3) The motion of hydrogen is steady. The other gas (i.e., silicate vapor or heavy gas) is bounded by the planetary gravity, namely, hydrostatically equilibrated. (4) The flow is adiabatic.

We consider various surface temperatures up to 10,000 K. Since it is expected that a large amount of

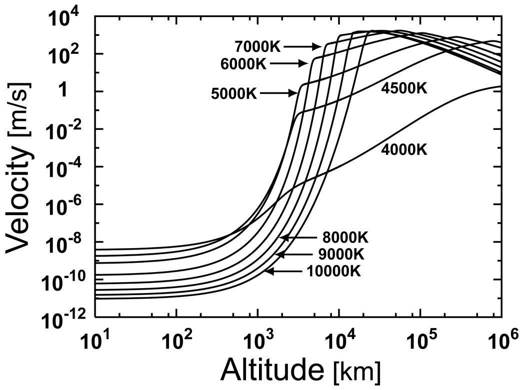

Fig. 1. The velocity distributions of escaping hydrogen. The temperatures in figure correspond to the planetary surface ones.

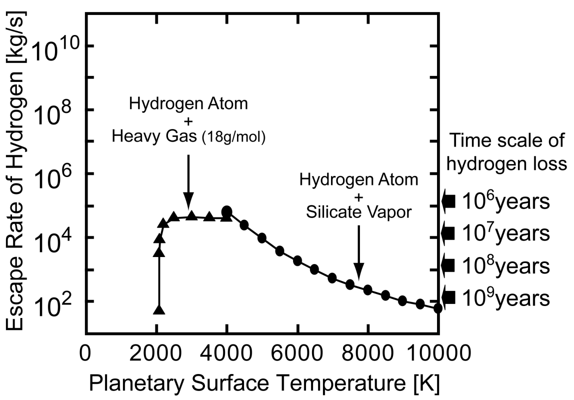

Fig. 2. Escape rate of hydrogen for various surface temperatures. The arrows in the right-hand side correspond to the time scale of the hydrogen loss. The partial pressure of hydrogen and heavy gas at the planetary surface are 10 bar. The partial pressure of silicate vapor at the planetary surface is given by 2.2×10^6 exp $(-4.89\times10^4/T_0)$ bar.

silicate is vaporized above ~ 4000 K, the atmosphere composed of hydrogen and silicate vapor is considered. On the other hand, the combination of hydrogen and heavy gas is considered below ~ 4000 K.

Results: Fig. 1 shows the velocity distributions of escaping hydrogen from silicate vapor for various planetary surface temperatures (> 4000K). At the low altitude ($< 10^3$ km), the velocity is extremely low owing to the drag of the silicate vapor. It should be noted that the velocity at the low altitude of a high temperature surface is lower than that of a low temperature one. This is because the partial pressure of silicate vapor is high at high surface temperature, and silicate vapor suppresses the velocity of escaping hydrogen.

Fig. 2 shows the escape mass of hydrogen per unit time. The circles and triangles in Fig. 2 indicate hydrogen escape from hydrostatically bounded silicate vapor and heavy gas, respectively. The typical escape time scale of hydrogen is longer than 10^6 years for all temperature range.

Discussion: The estimated cooling time scale of an extremely heated planet by a giant impact is less than 4×10^4 years. Since it is much shorter than the escape time scale of hydrogen (typically $> 10^6$ years), a large-scale escape of hydrogen cannot occur just after a giant impact.

Pepin [15] suggested that the fractionated Xe of the present Earth's atmosphere was mathematically explained by the large-scale (> 99.9%) and short-time scale thermal escape of hydrogen (< 2000 years). Pepin suggested that such an extensive escape could be triggered by a giant impact. However, our results indicate no such large-scale escape of hydrogen just after a giant impact. Therefore, other mechanisms are needed in order to generate the fractionated Xe, or Xe needs to be originally fractionated at the formation stage of planetesimals [16].

Though the large-scale escape of hydrogen cannot occur just after a giant impact, hydrogen mainly included in a proto-atmosphere needs to be lost and/or hidden by some other mechanisms. This is because the present Earth's and Venusian (also Martian) atmospheres do not have a large amount of hydrogen gas. The promising candidate is the escape by solar-EUV with a long timescale (~ 10^8years) [e.g., 17].

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