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Hydrodynamic escape from early terrestrial atmospheres and effects of solar flares

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There are very small H2O contents in the atmosphere and on the surface of contemporary terrestrial planets compared to the H2O contents in proto-atmosphere and in accreting materials during the late-stage accretion. To remove this large H2O contents, massive escape to space and/or to underground is needed. Hydrodynamic escape is a mechanism that could cause a massive atmospheric escape and largely influence the evolution of planetary atmospheres. In this study, we investigated quantitatively the effects of hydrodynamic escape on the evolution of early terrestrial atmospheres, and also the effects of solar flares on the hydrodynamic escape process. Hydrodynamic escape is a sort of thermal escape of neutral gas, driven by a strong X-ray and extreme ultraviolet (EUV) radiation that causes expansion and upward flow of a planetary atmosphere. On the other hand, solar flare is accompanied by a rapid increase in X-ray and EUV radiation, leading to the temporal heating of the upper atmosphere of a planet. It is pointed out that solar flares in early days (solar age of 0.1 Gyr) were about two orders of magnitude stronger than the present-day solar flares and such huge flares occurred a few times a day (Audard et al., 1999). Therefore, it is important to study the influences of solar flares on the early terrestrial atmospheres. However, previous models have a difficulty in investigating the effects of solar flares. For example, the model of Tian et al. (2008) cannot trace time variation and that of Sasaki (2007) does not consider the effects of CO2-15 micrometer cooling and chemical reactions. So, in this study, we tried to develop a numerical transonic hydrodynamic escape model to trace the time variations, and as a first step, we investigated the escape rates and the structures of a hydrogen-rich atmosphere for Earth, Venus and Mars conditions, and also their responses to solar flares.

First, we investigated the escape rates and the structures of a hydrogen-rich atmosphere for solar ages of 4.56 Gyr, 1.0 Gyr and 0.1 Gyr for Earth, Venus and Mars. As a result, it is found that for the hydrodynamic escape, the planetary mass is more important than the intensity of X-ray and EUV radiation. The heavier planetary mass is, the more influenced by the increase in X-ray and EUV radiation. Also, it is found that the initial H2O inventories estimated by Raymond et al. (2006) could not be removed by the hydrodynamic escape for Earth but could be for Mars throughout their histories.

Second, we investigated the effects of solar flares on the hydrodynamic escape for the Earth's mass and orbit condition. Solar X-ray and EUV radiation is changed up to 60 times more intense for 1-20 nm wavelength range and up to 6 times for 20-105 nm. As a result, the exobase temperature of a hydrogen-rich atmosphere rises by about 12K in 1.5 hours and keeps about 6K higher than the pre-flare level for more than 8 hours after a solar flare. Then, it takes a week to recover to the pre-flare level. Also, the escape rate calculated at the exobase rises up to 4 times in 2 hours after a solar flare. The escape rate at the upper boundary (20 planet radii) rises up to 1.5 times. Both the escape rates at the upper boundary and the exobase keep about 10% higher than the pre-flare levels for a week. For a sequence of solar flares, we find the cumulative effect on the escape rate and the exobase temperature.

Keywords: Atmospheric escape, Atmospheric evolution, Venus, Mars, Earth