Atmospheric Evolution of the Terrestrial Planets during the Heavy Bombardment: the Effects of the Element Partitioning

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The atmospheres on terrestrial planets are believed to be formed as a consequence of the impact degassing and erosion of volatiles during the Heavy Bombardment Period. Despite their common origin, there are distinct gaps in the noble gas abundances in the atmospheres on Venus, Earth, and Mars; compared to Earth, Venus is enriched and Mars is depleted in noble gases roughly by two orders of magnitude, respectively. The origin of these gaps has been poorly understood.

A possible mechanism to create these gaps is the partitioning of elements in the different surfacial environments: the runaway greenhouse on Venus, the carbon cycle on Earth, and the CO_2-ice formation on Mars. Although noble gases are mainly partitioned into the atmosphere, the distinct environments on the three planets create the differences in the noble gas concentrations in their atmospheres, leading the differences in the escape rates of noble gases due to the impact erosion.

We calculated the evolution of early atmospheres during the Heavy Bombardment Period by solving deterministic differential equations. Atmospheric components are, H_2O, CO_2, N_2, and noble gases. Because the abundances of noble gases are small, we treated both N_2 and noble gases as a component N_2 in our numerical model. The new idea of this work is to consider the partitioning of elements between atmosphere and other reservoirs. Whereas all volatiles are partitioned into atmosphere on Venus, H_2O and CO_2 are partitioned into oceans and carbonates on Earth and into ice on Mars. We set the upper limits of the partial pressures of H_2O and CO_2 considering the phase equilibrium and the steady state of the carbon cycle. Impact erosion of atmospheres and impactors are taken into account by using models of Svetsov (2000) and Shuvalov (2009). We assumed carbonaceous chondrites from the main asteroid belt as impactors. Total masses of impactors correspond to 1% of the planetary masses.

We found that the resulting abundances of N_2 and noble gases differ only by ~10% among the three planets. This is caused by the dominance of the replenishment of atmophiles over the erosion. The small differences in the abundances were due to the differences in the surface temperature and in the size of planets. The partitioning of elements was found to be less important for the abundances of N_2 and noble gases in the assumed conditions, where the delivery of atmophiles dominates. We also investigated the dependences on the impact erosion models, impactor size distributions, and types of impactors. Based on the results, we discuss the implications for the origins of volatiles and early planetary environments at ~4 Ga.

Keywords: Heavy Bombardment Period, impact erosion, noble gases

