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Escape of moderately volatile elements from protoplanets and its potential effect on habitability

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Large planetesimals and planetary embryos ranging from several hundred to a few thousand kilometers can develop magma oceans through mutual collisions, gravitational energy, and the heating of short-lived radioactive elements. After the evaporation of the protoplanetary gas disk, one can divide such planetary embryos into two distinct populations. If they grow to a certain mass of about >0.5 M_{Earth} before the dissipation of the disk, they will start to accrete a substantial primordial hydrogen-dominated atmosphere, while the gravitational potential of the smaller ones (≤0.5 M_{Earth}) will be too low to support this type of primordial atmosphere. For the smaller planetary embryos, the initial magma ocean will subsequently solidify, and a steam atmosphere will be catastrophically outgassed that, if it does not condense, may be lost efficiently via hydrodynamic escape. The escaping H-atoms will further drag heavier trace elements like noble gases and outgassed moderately volatile elements (MVEs) such as K, Na, Si, and Mg into space. For the larger population of planetary embryos, however, the magma ocean below the primordial atmosphere will not solidify until most of the gaseous envelope will be lost, thereby providing favorable conditions for MVEs to be dissolved within such atmosphere.

In our first study (Benedikt et al. 2020), we applied an upper atmosphere hydrodynamic escape model that includes the dragging of heavier species by escaping H-atoms and investigated atmospheric and elemental escape from planetary embryos between 1 M_{Moon} and 1.5 M_{Mars} (that is, the population of small protoplanets that does not accrete a primordial hydrogen-dominated atmosphere) by assuming that the noble gases and MVEs mostly reside within the escaping atmosphere. Our results indicated that the steam atmospheres and the embedded trace elements will be lost efficiently before they condense for masses ≤0.5 M_{Mars} and orbital distances up to 1 AU. For heavier embryos of up to 1.5 M_{Mars} the atmosphere together with the trace elements can only be lost completely if a shallow magma ocean remains below the gaseous envelope which might be achieved through frequent impacts onto the planetary embryo. For embryos with masses ≤M_{Moon}, on the other hand, the gravity is too weak for a dense atmosphere to build up against the high magma ocean related surface temperatures and all outgassed elements will escape immediately into space. The studied planetary embryos will, therefore, be severely depleted in noble gases and MVEs.

In a follow-up study (Erkaev et al. 2022), we are currently focusing on the loss of the heat producing element ^{40}K from initially bigger planetary embryos (that is, the population of protoplanets that was able to accrete a substantial primordial atmosphere). Contrary to our first study, we additionally applied equilibrium condensation models with the equilibrium chemistry GG_{CHEM} code (Woitke et al. 2018) and found that for magma ocean surface temperatures of ≥2500 K no condensates that fix potassium are thermally stable, and ^{40}K isotopes indeed populate such a primordial atmosphere to a great extent. By applying a sophisticated multispecies hydrodynamic upper atmosphere evolution model to study the loss of the atmosphere together with ^{40}K, we found that depending on the initial size of the protoplanet and the early evolution of the host star, this process can indeed remove substantial amounts of ^{40}K from protoplanetary bodies that are ≥0.5 M_{Earth}. This effect alone can, together with the loss of MVEs from the smaller planetary embryos that serve as building blocks for the bigger ones, result in a wide variety of different potassium abundances at the fully grown planet.

Since different abundances of heat producing elements have a significant influence onto the subsequent thermal and tectonic evolution of a planet, and therewith connected, on its tectonic modes (e.g., O'Neill et al. 2020), the process of early hydrodynamic escape of the heat producing isotope ^{40}K can significantly impact the habitability, since not all rocky planets will end up with the "right" amount of heat production in its interior. However, this process cannot be viewed separately; other factors will additionally determine the initial heat budget of a planet such as collisional erosion, the feeding zone of the growing protoplanet or the initial composition of the protoplanetary disk.

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