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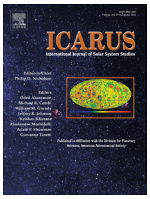

Escape and fractionation of volatiles and noble gases from Mars-sized planetary embryos and growing protoplanets

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ABSTRACT

Planetary embryos form protoplanets via mutual collisions, which can lead to the development of magma oceans. During their solidification, significant amounts of the mantles' volatile contents may be outgassed. The resulting H_2O/CO_2 dominated steam atmospheres may be lost efficiently via hydrodynamic escape due to the low gravity of these Moon- to Mars-sized objects and the high stellar EUV luminosities of the young host stars. Protoplanets forming from such degassed building blocks after nebula dissipation could therefore be drier than previously expected. We model the outgassing and subsequent hydrodynamic escape of steam atmospheres from such embryos. The efficient outflow of H drags along heavier species like O, CO_2, and noble gases. The full range of possible EUV evolution tracks of a young solar-mass star is taken into account to investigate the atmospheric escape from Mars-sized planetary embryos at different orbital distances. The estimated envelopes are typically lost within a few to a few tens of Myr.

Furthermore, we study the influence on protoplanetary evolution, exemplified by Venus. In particular, we investigate different early evolution scenarios and constrain realistic cases by comparing modeled noble gas isotope ratios with present observations. Isotope ratios of Ne and Ar can be reproduced, starting from solar values, under hydrodynamic escape conditions. Solutions can be found for different solar EUV histories, as well as assumptions about the initial atmosphere, assuming either a pure steam atmosphere or a mixture with accreted hydrogen from the protoplanetary nebula. Our results generally favor an early accretion scenario with a small amount of residual hydrogen from the protoplanetary nebula and a low-activity Sun, because in other cases too much CO_2 is lost during evolution, which is inconsistent with Venus' present atmosphere. Important issues are likely the time at which the initial steam atmosphere is outgassed and/or the amount of CO_2 which may still be delivered at later evolutionary stages. A late accretion scenario can only reproduce present isotope ratios for a highly active young Sun, but then unrealistically massive steam atmospheres (few kbar) would be required.

1. Introduction

In the early evolution of planetary systems, protoplanetary cores originate from the coagulation of dust and ice and initially reside embedded in the gas of the circumstellar disks. Terrestrial planet-formation models indicate that Earth-like planets originate from differentiated planetesimals to large planetary embryos with sizes of several hundred to a few thousand kilometers (e.g. Kokubo and Ida, 2000; Raymond et al., 2004; 2009; Alibert et al., 2010; Lunine et al., 2011; Walsh et al., 2011; Morbidelli et al., 2012). Although the processes that are responsible for the growth of the solid bodies from centimeter size up to the size of Moon- and Mars-size planetary embryos are not well understood (Morbidelli et al., 2009; Johansen et al., 2014), if one accepts the scenario of core-accretion for the formation of gaseous Jovian-type planets (Perri and Cameron, 1974; Mizuno, 1980), massive planetary embryos and even protoplanetary cores with several Earth-masses ($M_\oplus$) exist even at an early stage of evolution of the protoplane-

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tary disk. The initial volatile inventory, including H_2O, of terrestrial planets is related to a complex interplay between:

- the nebula dissipation time,
- the growth rate/time from planetesimals and planetary embryos to protoplanets,
- the orbit location and H_2O content of the initial building blocks (i.e., planetesimals and planetary embryos),
- outgassing processes from the interior,
- the impact history, and
- the host star's radiation and plasma environment.

The growth of planetary embryos to protoplanets within the accretion disk begins during the nebula lifetime, which lasts only between ≈ 1–10 Myr (Montmerle et al., 2006; Hillenbrand, 2008). Mars for instance formed within a few Myr and remained as a large planetary embryo that never grew to a more massive rocky planet (Brasser, 2013). Depending on the gravitational potential of the embedded planetary embryos and protoplanets, a certain amount of the nebula gas will be captured. As it was shown by Erkaev et al. (2014) and Stökl et al. (2015), cores with masses up to $\approx 0.1 M_\oplus$ capture only a negligible amount of nebula gas which is lost fast by thermal escape shortly after the nebula dissipates. Depending on the solar nebula parameters and the EUV activity of the young Sun, Erkaev et al. (2014) showed that early Mars which has a mass of $\approx 0.1 M_\oplus$ should have lost its captured nebular-based hydrogen envelope in a very short time. For less massive bodies, or objects at closer orbital distances, the timescales are even shorter because of either the lower gravitational attraction or the higher EUV fluxes and effective temperatures. Thus, for planetary embryos, accumulated nebular gas does not play an important role for the bodies' evolution into larger planetary objects.

After the evaporation of the gas in the disk due to the extremely high X-ray, EUV and far ultraviolet (FUV) emissions of the young T Tauri Sun/star, protoplanets continue to grow through the capture and collisions of large planetesimals and planetary embryos. Depending on the orbit locations, embryos may form dry or wet, meaning that near and beyond the ice line the planetary building blocks contain more water and icy material compared to that which originated and orbit closer to the Sun. From dynamical models one can expect that most of Mars' building blocks consisted of material that formed in orbital locations just beyond the ice line which could have contained $\approx 0.1 - 0.2$ wt% of H_2O, while embryos formed in Earth's orbit should have had lower values within a range of $\approx 0.05 - 0.1$ wt% (e.g. Morbidelli et al., 2000; Brasser, 2013). In the case of the Earth, geochemical studies indicate that a fraction of Earth's initial H_2O inventory originated from comets, while the majority came from chondritic meteoritic materials (Mumma and Charnley, 2011; Alexander et al., 2012; Marty, 2012). Meteorites are therefore the main candidates for building blocks of planetary embryos and hence protoplanets.

The study of different solar system objects that resemble planetary embryos (such as Earth's Moon, Mars, the asteroid Vesta, and dwarf planets like Ceres) shows that they have been differentiated in their interiors like the terrestrial planets (e.g. Canup and Ward, 2002; Schubert et al., 2004; Thomas et al., 2005; Russell et al., 2013). It is thus reasonable to expect that the silicate and metal materials of large planetary embryos of similar size were largely molten during the formation process (e.g. Albarède and Blichert-Toft, 2007; Elkins-Tanton, 2008; 2012).

The formation of large and deep magma oceans can also be caused by gravitational heating of the accreted material, accretionary impacts, and radiogenic heating from short-lived radioisotopes, (e.g. Urey, 1955; Safronov, 1969; Wetherill, 1980; LaTourrette and Wasserburg, 1998; Halliday et al., 2001; Albarède and Blichert-Toft, 2007; Elkins-Tanton, 2012). Magma oceans are responsible for the compositional differentiation that affects the final volatile contents of the planetary building blocks, including large planetesimals, planetary embryos, protoplanets or large moons, whose radii range from tens to hundreds, or even thousands of kilometers. The melting related to the differentiation results in compositionally distinct layers, where the denser materials sink to the center, and less dense materials rise to the surface. Such processes finally create a core and mantle in planetary bodies.

Volatiles such as H_2O and carbon compounds (e.g., CO_2, CH_4, CO) are integrated in the magma ocean liquids and as solidification proceeds they are degassed into a growing steam atmosphere (Matsui and Abe, 1986; Abe and Matsui, 1988; Zahnle et al., 1988; Massol et al., 2016). The quantity of volatiles available for degassing depends on the bulk composition of the magma ocean. The solidification of a magma ocean starts at the bottom because the steep slope of the adiabat with respect to the solidus in the pressure-temperature space causes them to intersect first at depth (e.g. Walker et al., 1975; Solomatov, 2000; Elkins-Tanton, 2008; 2011; 2012). Depending on the assumed H_2O ($\approx 0.05-0.1$ wt%) and CO_2 ($\approx 0.01-0.02$ wt%) content with bulk magma ocean depths between $\approx 500-2000$ km for a Mars-size body, minimum and maximum partial surface pressures P_{H_2O} and P_{CO_2} of catastrophically outgassed steam atmospheres are estimated to be $\approx 30-120$ bar and $\approx 7-25$ bar (Elkins-Tanton, 2008; Lebrun et al., 2013; Erkaev et al., 2014).

As pointed out by Lammer et al. (2013), depending on the EUV flux evolution of the young Sun/star, Moon- or Mars-sized planetary embryos will lose a fraction of their outgassed volatiles and their initial water inventories because of the formation of magma oceans within the growth process to larger protoplanets. It has been known for decades that the Sun's radiation in the EUV region of the spectrum was higher in the past (e.g. Zahnle and Walker, 1982; Güdel et al., 1997; Guinan and Ribas, 2002; Ribas et al., 2005; Claire et al., 2012). Recently, Tu et al. (2015) showed that the star's initial rotation rate and its subsequent rotational evolution (Johnstone et al., 2015a) play an important role for the EUV flux enhancement, until the time when the radiation flux converges to similar age dependent values after about 1.5 Gyr in the case of solar-like G stars. About 70% of the solar mass stars studied by Johnstone et al. (2015a) are slow and moderate rotators, but there is a non-negligible possibility for the early Sun to have been a fast rotator. These findings have enormous implications for the initial volatile inventories of terrestrial planets and, later on, their atmospheric evolution.

If one assumes that the young Sun was initially a fast rotator, then its EUV emission could have been enhanced up to about 500 times compared to its present value for more than 200 Myr. If the Sun was once a moderate rotator then the EUV emission would have been about 100 times higher during the first 100 Myr. If the Sun was a slow rotator then its EUV luminosity would have been about 25–30 times higher for $\approx 30 - 300$ Myr. According to Tu et al. (2015), the EUV flux decreases for all rotators following power laws until the different evolutionary paths merge after about 1.5 Gyr. Because the EUV radiation heats the upper atmospheres of planets one can expect a huge variety of evolution scenarios depending on the stars' different rotation and activity evolution during the first 1.5 Gyr. As a consequence, planetary embryos which form and grow in a system where the host star is a slow rotator should remain wetter and more volatile-rich compared to those which grow in a system of moderately or fast rotating young stars.

The discovery of a large number of sub-Neptune type exoplanets indicates that fast formation of sufficiently large cores which then accrete residual nebula gas is common. Stökl et al. (2016) found that a core of $0.7 M_{\rm Venus}$ ($\sim 0.6 M_\oplus$) may accrete gas of up to 2–3% of its mass within a typical nebula lifetime. The core luminosity can drive efficient outflow of such ac-

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