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LOSS OF VOLATILES AND WATER FROM PLANETARY EMBRYOS

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ABSTRACT

Terrestrial planets may form by collisions of smaller building blocks such as Mars- to Moon-sized embryos. Such bodies are able to sustain magma oceans and outgas secondary H_2O/CO_2 dominated steam atmospheres during their solidification.

We calculate the loss of such steam atmospheres for a range of embryo masses, atmospheric surface pressures and orbits within the habitable zone of a young Sun-like host star to investigate if larger planets forming at later stages by collisions of such embryos may be drier than previously expected.

We find that Moon-type embryos may likely lose their volatile content within a few Myr, whereas for Mars-type bodies a wide range of scenarios is possible, which strongly depend on the assumed orbital distance, stellar XUV flux, and atmospheric mass.

INTRODUCTION

Formation of terrestrial planets starts from small dust concentrations within the protoplanetary nebula which accumulate to form planetesimals via various physical processes. Collisions of such objects result in larger bodies called planetary embryos. Embryos then form full planets via collisions between each other and remaining planetesimals. The water content of a young terrestrial planet is often assumed to be determined from the initial composition of its building blocks and may be altered later via escape processes provided that H_2O is (partly) in steam form. However, atmospheric escape may already be relevant during intermediate stages of planet formation. Due to frequent collisions, the surfaces of embryos are likely molten, resulting in surface magma oceans. Solidification of magma oceans may lead to degassing of their volatile content, forming a steam atmosphere. Thus, atmospheric escape processes may take place and lead to loss of a significant fraction of the volatile content of embryos already before the final planets are assembled. This is especially relevant because both planets and embryos can experience multiple magma ocean phases during their early evolution. However, due to their lower gravity, embryos may lose their volatiles more efficiently than full-grown planets.

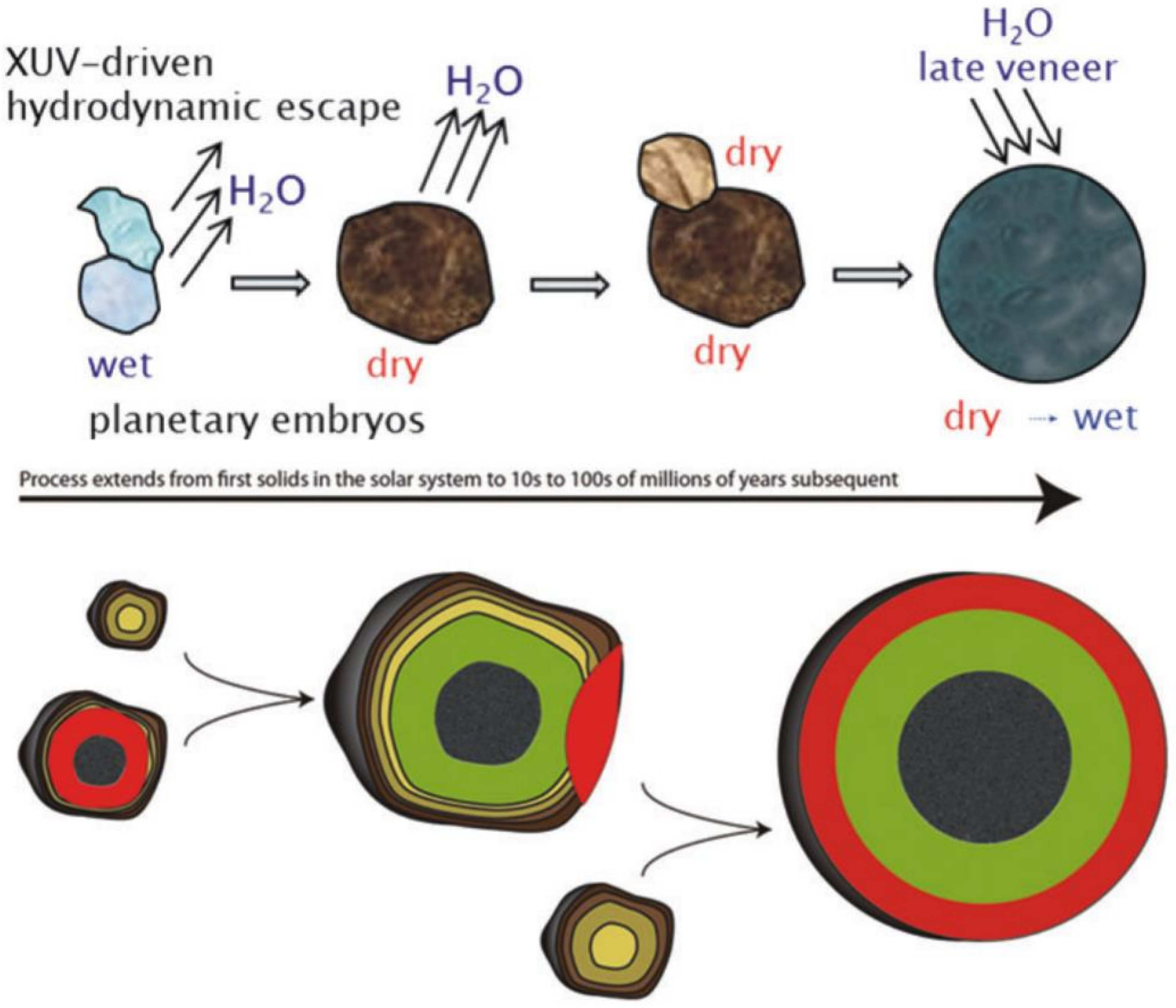

Figure 1: Sketch of the process addressed in this study. The water content of planetary embryos may decrease before final planet formation due to thermal escape of steam atmospheres which are degassed during the solidification of surface magma oceans (taken from Lammer et al. 2013, AsBio 13, 793).

MODEL DESCRIPTION

We aim to calculate the escape of an outgassed H_2O/CO_2 steam atmosphere due to the high XUV radiation from a young Sun. Assuming that H_2O is dissociated into H and O atoms, the escaping light H may be able to drag along the heavier constituents of the atmosphere. The atmospheric mass-loss rate is computed using the energy-limited equation and the fractionation factors for the heavy species are calculated after Zahnle et al. (1990, Icarus 84, 502).

Mass-loss rates:	Fractionation factors $x_{\mathrm{O/CO_2}}$:
$\dot{M} = \dot{M}_{\mathrm{H}} + \dot{M}_{\mathrm{O}} + \dot{M}_{\mathrm{CO_2}} = \dfrac{\pi R_0 R_{\mathrm{XUV}}^2 \eta F_{\mathrm{XUV}}}{GM}$,	$x_{\mathrm{O}} = 1 - \dfrac{\Phi_{\mathrm{O}}}{1 + f_{\mathrm{O}}}$
with $\dot{M}_{\mathrm{O/CO_2}} = \mu_{\mathrm{O/CO_2}} f_{\mathrm{O/CO_2}} x_{\mathrm{O/CO_2}} \dot{M}_{\mathrm{H}}$,	$x_{\mathrm{CO_2}} = \dfrac{1 - \Phi_{\mathrm{CO_2}} + \frac{b_{\mathrm{H,CO_2}}}{b_{\mathrm{H,O}}}(1 - x_{\mathrm{O}}) f_{\mathrm{O}} + \frac{b_{\mathrm{H,CO_2}}}{b_{\mathrm{O,CO_2}}} x_{\mathrm{O}} f_{\mathrm{O}}}{1 + \frac{b_{\mathrm{H,CO_2}}}{b_{\mathrm{O,CO_2}}} f_{\mathrm{O}}}$
$\mu_{\mathrm{O/CO_2}} = \dfrac{m_{\mathrm{O/CO_2}}}{m_{\mathrm{H}}}$, $f_{\mathrm{O/CO_2}} = \dfrac{N_{\mathrm{O/CO_2}}}{N_{\mathrm{H}}}$.	with $\Phi_{\mathrm{O/CO_2}} = \dfrac{4\pi m_{\mathrm{H}} GM (m_{\mathrm{O/CO_2}} - m_{\mathrm{H}}) b_{\mathrm{H},O/CO_2}}{\dot{M}_{\mathrm{H}} kT}$

RESULTS

We study the escape of steam atmospheres from two planetary embryos with masses and radii of Mars and Moon orbiting at distances between Venus and Mars (0.7-1.5 AU, i.e. approximately in the habitable zone of a G star) around a young Sun-like host star with XUV emission 100× higher than that of the present Sun.

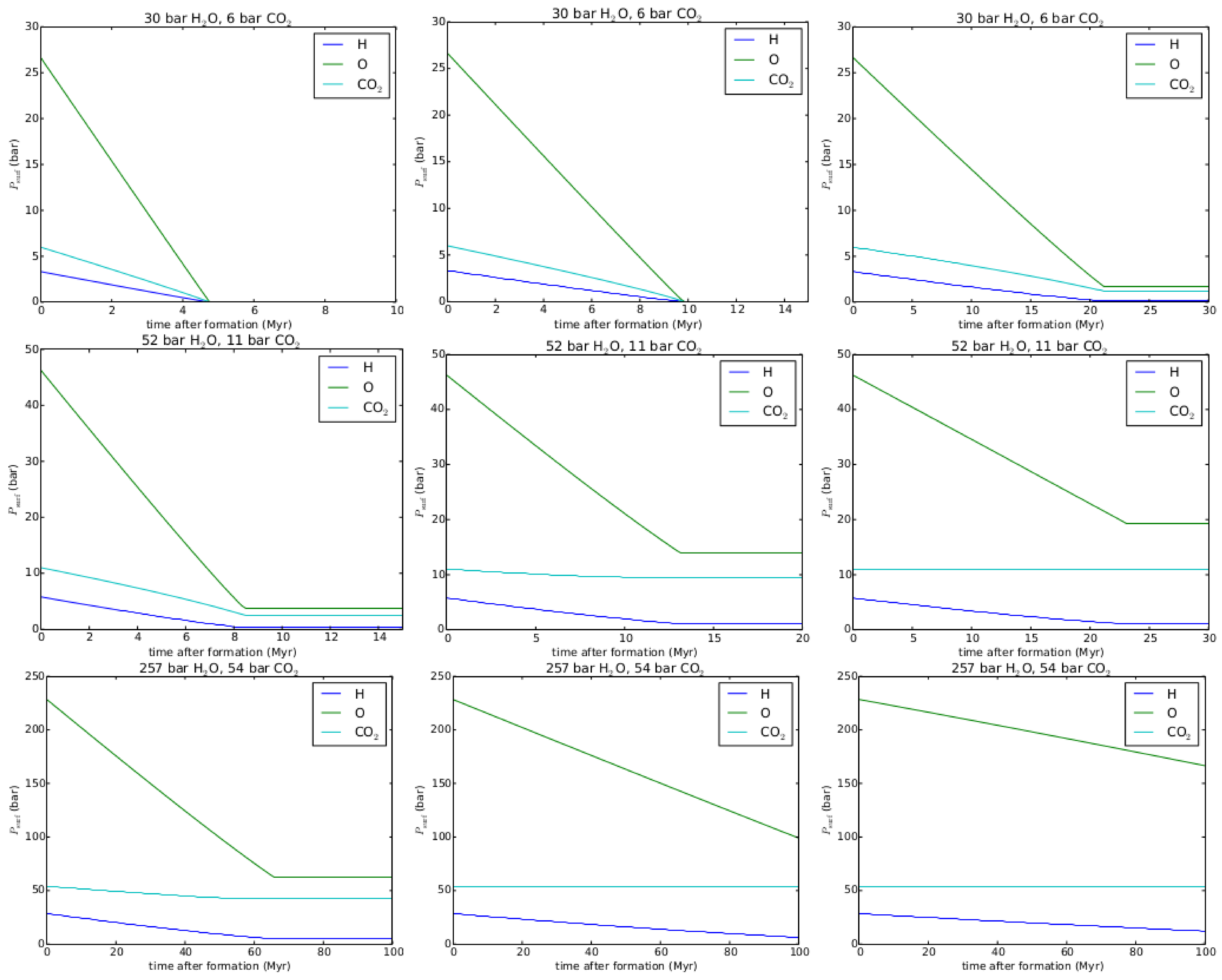

Figure 2: Evolution of the partial surface pressures of steam atmosphere constituents around planetary embryos with masses of Moon (upper row) and Mars (middle and bottom rows) at orbits of Venus (left column), Earth (middle column) and Mars (right column). Total partial surface pressures of H_2O and CO_2 at t=0 are indicated and were taken from Erkaev et al. (2014, PSS 98, 106).

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SUMMARY

Moon-type embryos in the habitable zone likely lose outgassed steam atmospheres (almost) completely within a few Myr and are therefore likely drier than at their formation when accumulating into full planets.

Mars-type embryos may lose their total atmospheres only if they are at close-in orbits and/or around stars with higher than average activity levels and/or were not able to build up very massive atmospheres. For massive atmospheres, wide orbits, and/or stars with lower than average activity levels a large fraction of the atmosphere, and hence volatile inventory, is kept. For intermediate scenarios volatiles may become partly depleted.

Outlook: We aim to develop a multi-species hydrodynamic thermal escape model with which we will be able to address this topic in a more detailed and physically self-consistent way.

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