CONSTRAINTS ON H_2O AND H_2 PROPORTIONS IN THE VOLATILE ENVELOPES OF YOUNG, H_2-PRODUCING, SMALL-RADIUS EXOPLANETS

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Small-radius exoplanets with low densities discovered by *Kepler* could have either accreted volatile envelopes from the nebular disk, or produced them via water-rock interaction.

We place constraints on *f*O2 conditions and H_2/H_2O proportions in volatile envelopes and dissolved in magma oceans given the upper limit of ~ 1.7 wt. % for envelopes of terrestrial-like planets.

Volatiles in *Kepler* extrasolar planets

- *Kepler* and the *K2* have discovered nearly 2000 confirmed extrasolar planets (March 2016) through Transit-Timing Variations and Radial Velocities [1]. ~ 300 of these exoplanets are $1.6 < R_{Earth} < 2.5$ [1].
- From calculations of their mass and density we assume that they are rocky Earth-like core compositions under low molecular weight envelopes dominated by H_2 [e.g., 2].
- Possibly, the planets do not accrete H_2 from the nebula, but produce it through reactions such as:

$$Fe^0 + H_2O \rightarrow FeO + H_2 \quad \text{[e.g. 3]}$$

and:

$$6Fe_2SiO_4 \text{ (fayalite)} + 11H_2O \rightarrow 3Fe_2Si_2O_5(OH)_4 \text{ (serpentine)} + 2Fe_3O_4 \text{ (magnetite)} + 5H_2 \quad \text{[e.g. 4]}$$

- Before testing the potential to generate a $H_2O + H_2$ inventory from water-rock reactions, the equilibrium H_2O/H_2 needs to be constrained for plausible fO_2 conditions during planetary formation, since the upper weight limit of the envelope is ~ 1.7 wt. % for terrestrial-like rocky core compositions, if all Fe^0 is oxidized to Fe^{3+} [5, 6, 7]:

$$\sim 32 \text{ wt\% } Fe^0 \times (3\,e^- / 2\,e^-) \times (2 \text{ amu} / 56 \text{ amu}) \approx 1.7 \text{ wt\%}$$

(For cores with Fe contents similar to Solar System rocky planets.)

Hypothesis test:

- Low H_2O/H_2 = low molecular weight — envelope could be achieved by outgassing.
- High H_2O/H_2 = high molecular weight envelope – a "water-world" different from the two-layer (core + envelope) models of e.g., [8, 9]. This envelope cannot be achieved by outgassing.

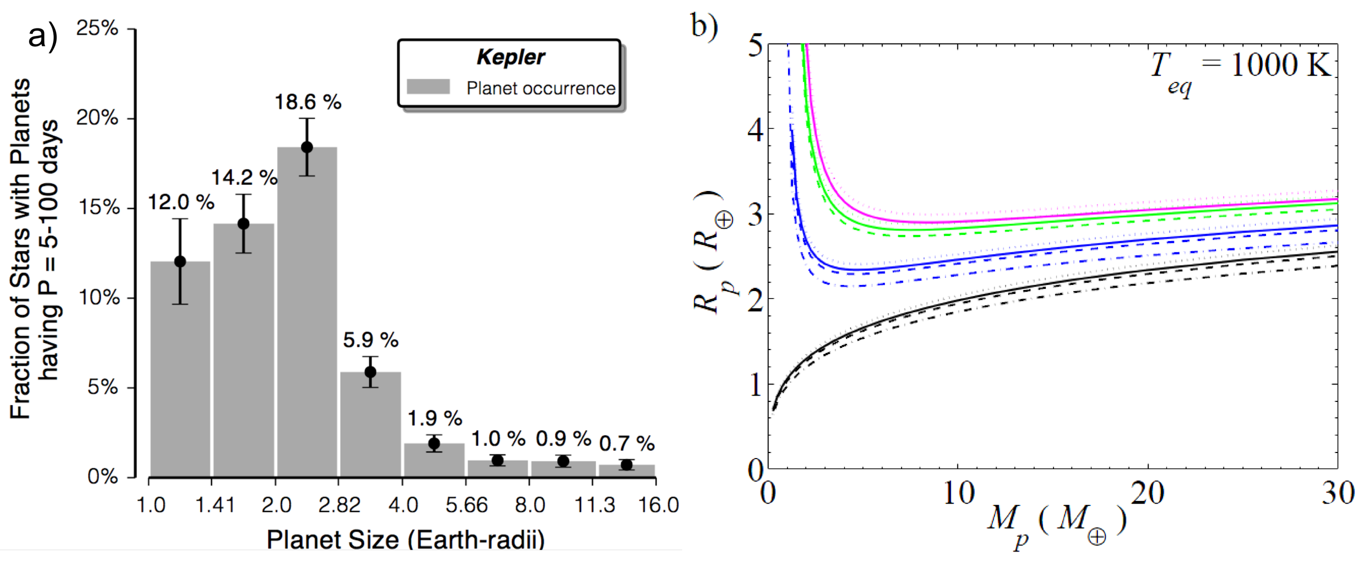
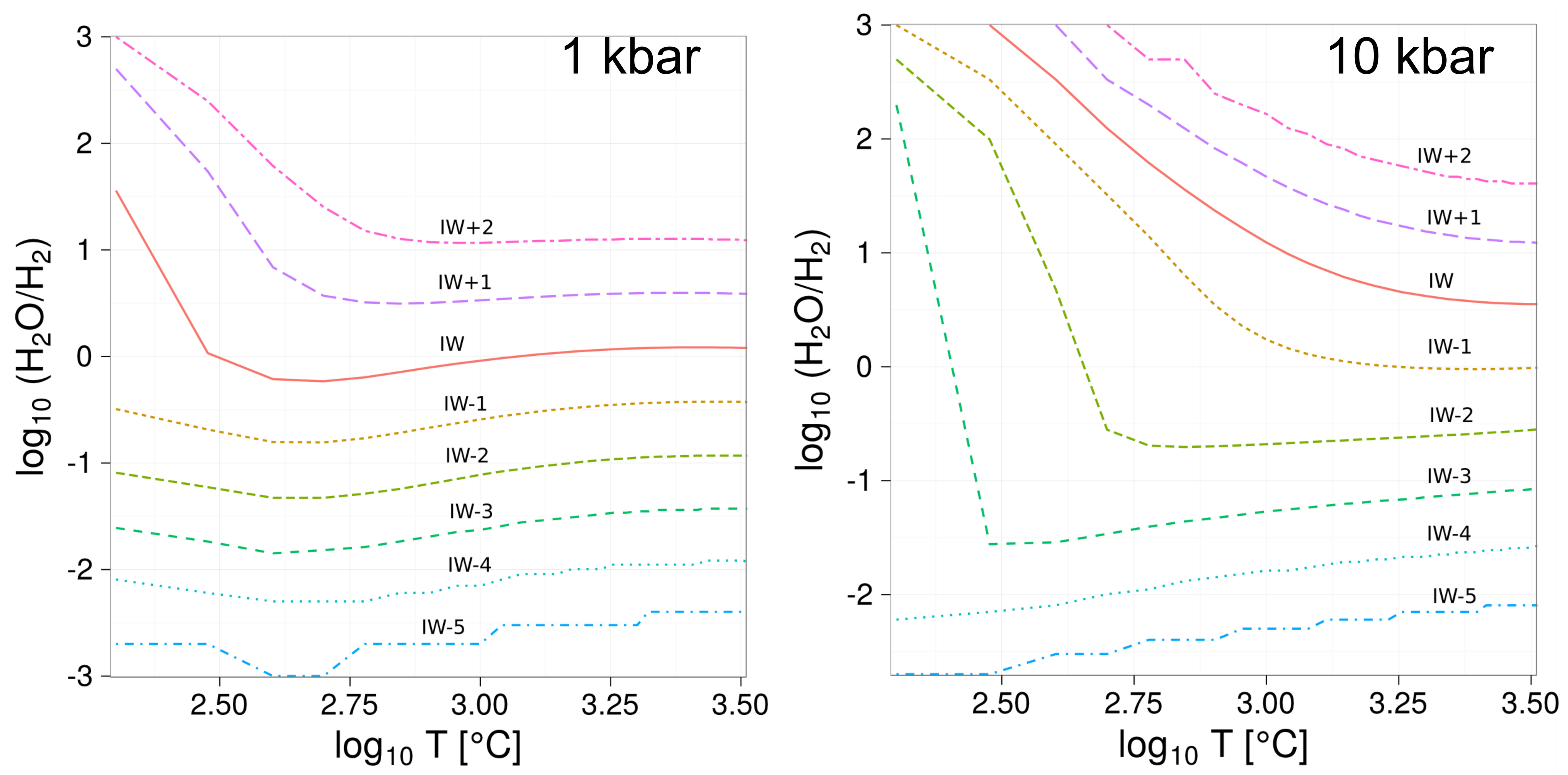


***Fig. 1a)** [From 10.] Occurrence rate of exoplanets. Note the drop-off in occurrence at sizes over ~ 2.5 R_E. Could it be related to the limit of H outgassing? **b)** [From 7.] Radii for exoplanets with maximum outgassed atmospheres (pink), all Fe converted to FeO (green), ~ 15 % Fe reacted (blue), and no outgassing (black). Dotted lines = 20 wt. % H_2O ice accreted, solid lines = 13 wt. % H_2O, dashed = 8.6 wt. % H_2O.*

Fig. 2a)



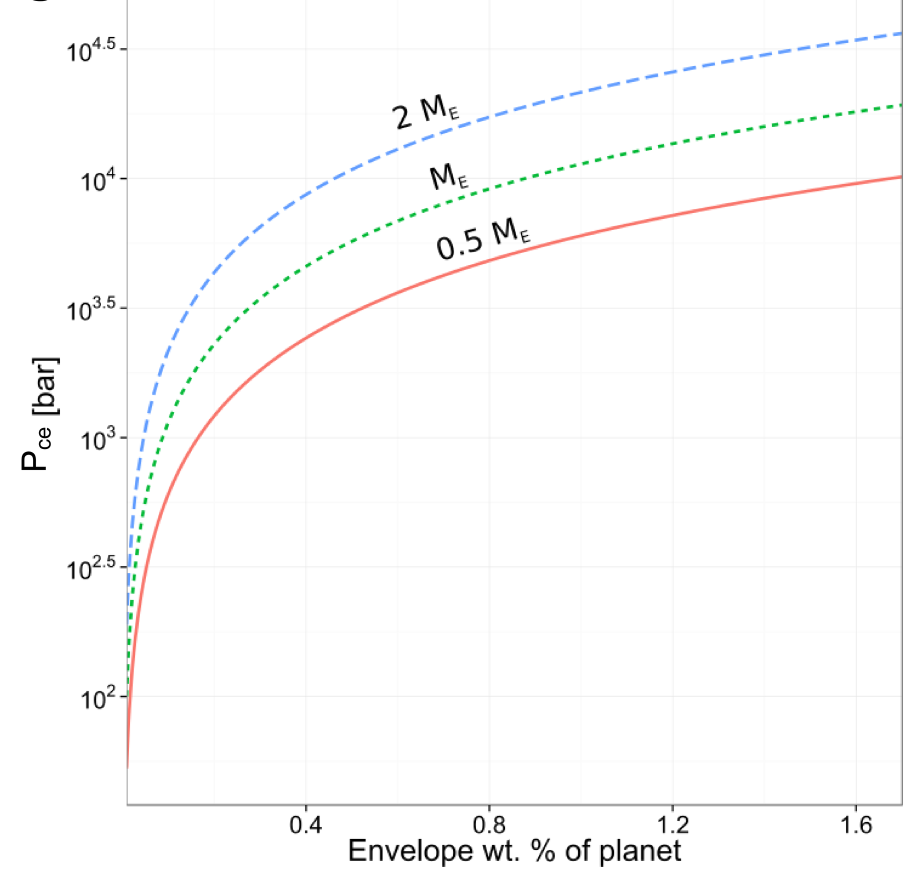
H_2O/H_2 proportions in envelopes

- H_2O/H_2 was calculated using the van Laar gas mixing model [11] and the compensated-Redlich-Kwong ("CORK") equation of state and CHO software by T. Holland [12]. The effects on H_2O/H_2 are shown with varying temperature and fO_2 (relative to IW) for 1 kbar (Fig. 2a) and 10 kbar (Fig. 2b).
- We assume planet radius scales with mass [e.g. 13]

$$r_{Earth} \propto m_{Earth}^{0.27}$$

- Volatile outgassing from the core increases the pressure at the core-envelope interface (P_{ce}), as seen in Fig. 3 for planets of different masses (units Earth mass, M_E). For $1M_E$, $P_{ce} \approx 1.9 \times 10^4$ bar at the 1.7 wt. % outgassing limit.

Fig. 3



Conclusions + further work

- We now have H_2O/H_2 constraints for the envelope at a variety of conditions.
- Increased volatile outgassing increases pressure at the core-envelope interface.
- Calculations will be expanded to ~ 6000 K and we will calculate the $H_2O + H_2$ in the coexisting magma.
- Model results will be compared to volatile abundance constraints of *Kepler* and *K2* planets.

Acknowledgements

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