INTERIOR STRUCTURE AND POSSIBLE EXISTENCE OF WATER WORLDS AMONG SUB-NEPTUNES

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Abstract

Water-rich planets should be ubiquitous in the universe, and could represent a notable fraction of the sub-Neptune population. Among the detected exoplanets that have been characterized as sub-Neptunes, many are subject to important irradiation from their host star. As a consequence, hydrospheres of such planets are not in condensed phase, but are rather in supercritical state, with steam atmospheres on top. Such irradiated ocean planets (IOP) are good candidates to explain the distribution of masses and radii in the sub-Neptune category of exoplanets.

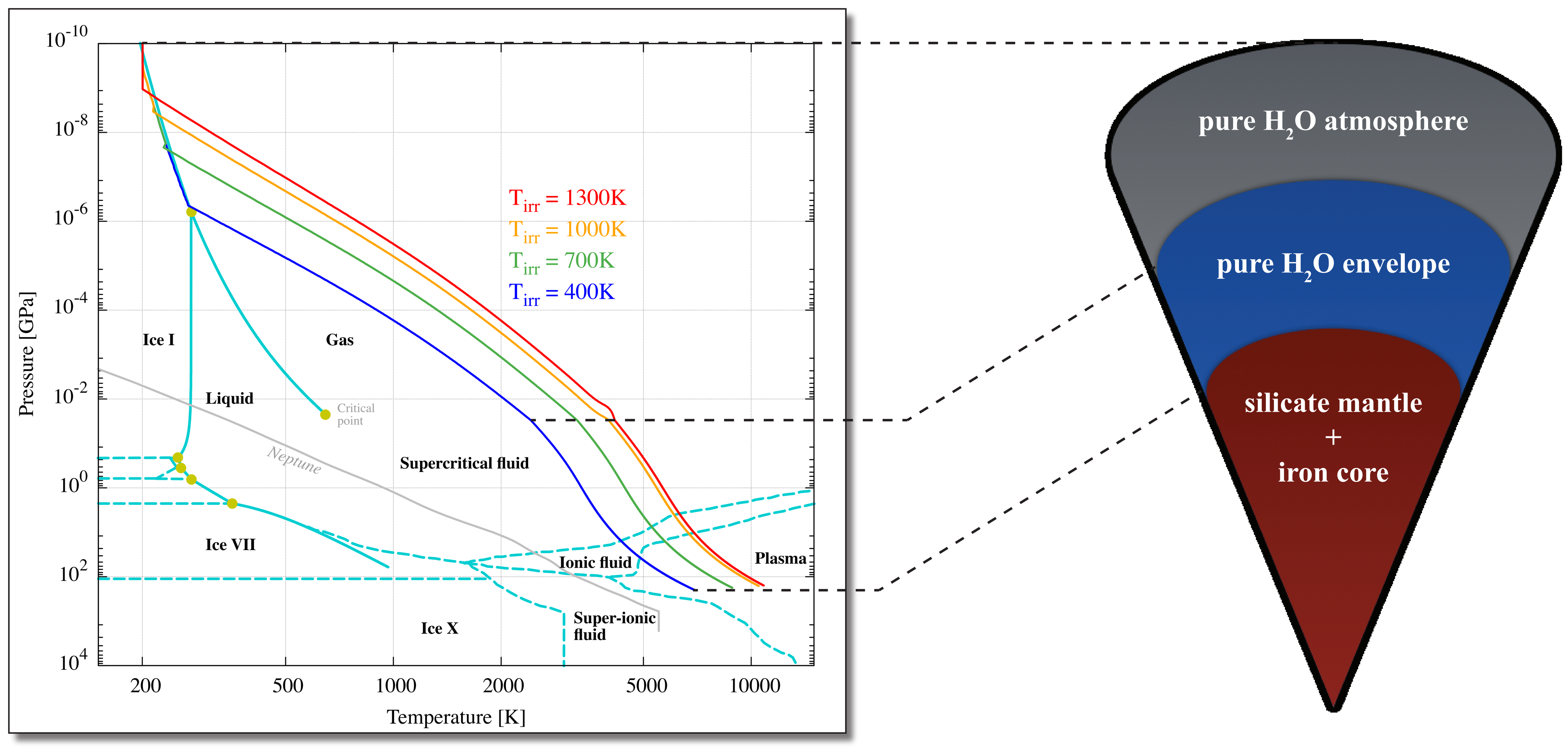
Here, we present a state-of-the-art coupled interior-atmosphere model [1] that computes the structure of water-rich planets that have high equilibrium temperatures. The interior model accounts for several refractory layers (iron core and rocky mantle), and on top of them an hydrosphere with an updated equation of state (EOS) that remains valid even when water is in plasma state. The atmosphere model connects the top of the interior model with the host star by solving the equations of radiative transfer.

Our model produces a new set of mass-radius relationships that can be used to characterize exoplanets by computing possible water mass fractions (WMF). We do so for the GJ 9827 system as a test case, and find that planets b and c are compatible with Earth- and Venus-like interiors, respectively. Planet d could be an irradiated ocean planet with a water mass fraction of ~20 ± 10%.

Due to their high irradiation temperatures, sub-Neptunes are expected to be subject to strong atmospheric escape. We also investigate how this argument can help breaking the degeneracy between H_2-He dominated envelopes and water worlds.

Coupled atmosphere-interior model for H_2O

The numerical model is described in [1], which combines an interior model [2] and an atmosphere model [3]. The two models are connected at a pressure P_{surf} = 300 bar, close to the critical temperature of H_2O.



Atmosphere [3]: radiative transfer in the mesosphere, and adiabatic gradient below

Deep hydrosphere [2]: H_2O in supercritical to plasma state

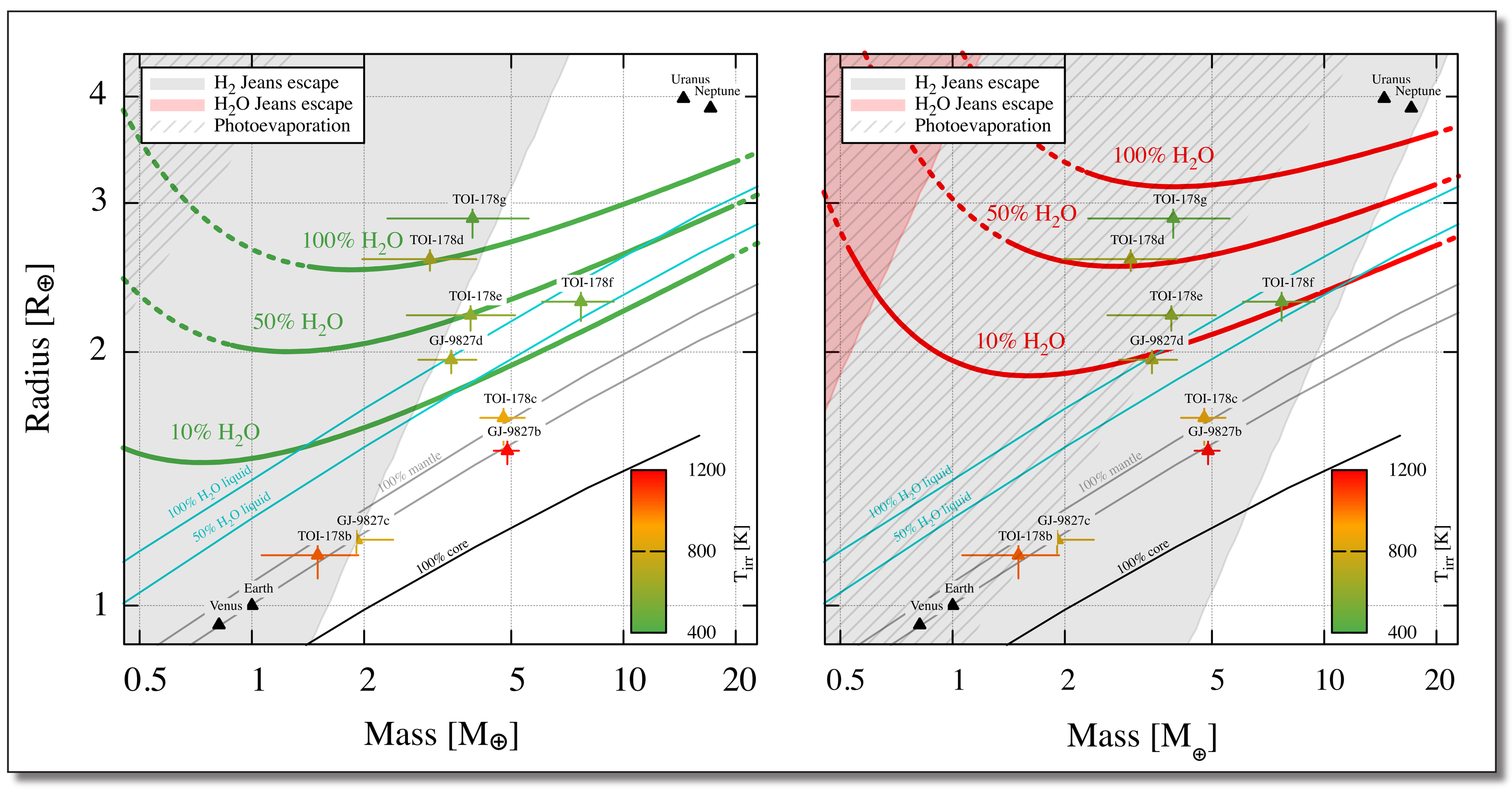
Refractory interior [2]: silicate mantle + iron core

Revised mass-radius relationships

Iso-composition curves are very well approximated (≤1.2% difference) by analytical functions of the form:

$$\log R_p = a \log M_p + b + \exp(-d(\log M_p + c)),$$

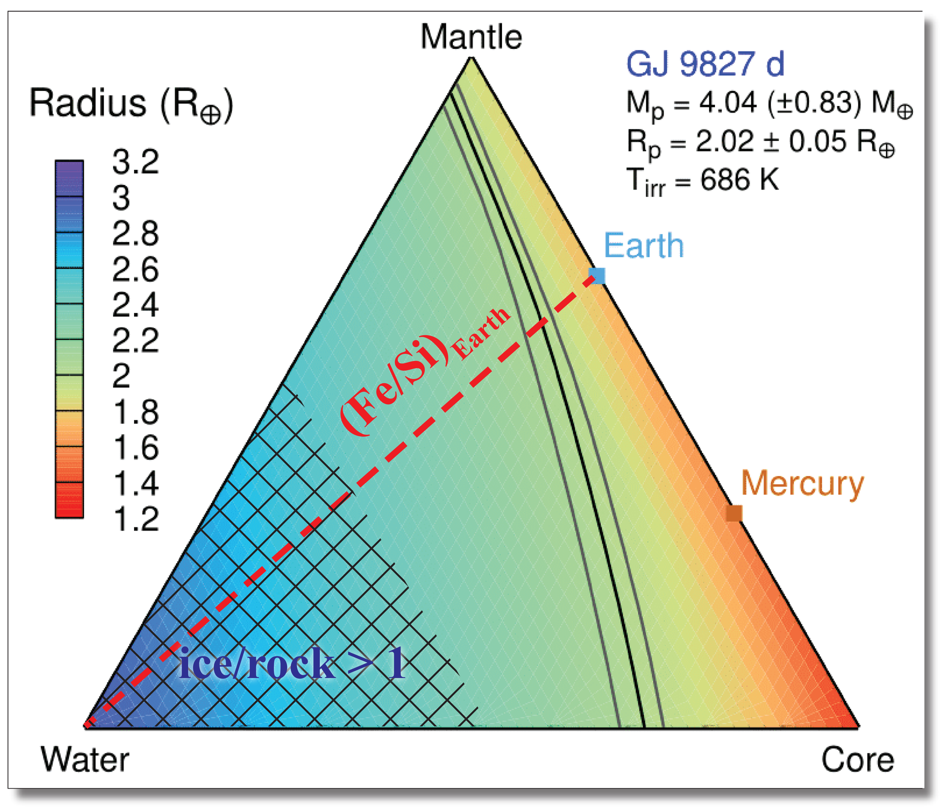
where a, b, c and d are coefficients obtained by fit. Mass-radius relationships and values of the coefficients are available at: https://archive.lam.fr/GSP/MSEI/IOPmodel/



Thick lines: iso-composition curves from [1] compared to standard relations used in the litterature. Shaded regions correspond to regimes of efficient atmospheric escape, suggesting that hot sub-Neptune cannot retain substantial amounts of H_2 in their atmospheres.

[1] Aguichine, A., Mousis, O. Deleuil, M., et al. 2021, ApJ, 914, 84A
[2] Brugger, B., Mousis, O., Deleuil, M., et al. 2017, ApJ, 850, 93
[3] Marcq, E., Baggio, L., Lefèvre, F., et al. 2019, Icarus, 319, 491
[4] Lopez, E. D. & Fortney, J. J 2014, ApJ, 792, 1.
[5] Rice, K., Malavolta, L., Mayo, A., et al. 2019, MNRAS, 484, 3731.

Compositional degeneracy



For a given composition of the envelope (atmosphere + deep interior, pure H_2O for the figure on the left), possible values of the core mass fraction (CMF) are degenerate. **This degeneracy can be lifted by using the host star Fe/Si ratio.**

Planetary formation processes fix an **upper limit of 50% on the water mass fraction (WMF)**, which corresponds to a 1:1 ice to rock composition.

A second degeneracy exists for the nature of the volatile (in the figure below, pure H_2O or H_2-He [4]). Nevertheless, the dichotomy between sub-Neptunes and super-Earths persists, **implying that a classification by volatile mass fraction is possible.**

In particular, the **radius gap** is observable in the H_2O vs H_2-He plane.

For the system GJ-9827 [5] we find:

- planet b: terrestrial dry
- planet c: terrestrial wet
- planet d: **potential water-world**