A self-consistent thermodynamic approach to compute the interiors of irradiated ocean planets

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Abstract

Planetary interior models rely on the thermodynamic properties of the used materials. Equations of states (EOSs) are key ingredients to compute internal structures, as they link the pressure and density profiles, and leave a unique solution satisfying all equations describing the interior of the planet. Often, when thermodynamic data are lacking, the formulation of EOSs allow extrapolation in both pressure and temperature. The effect of temperature on EOSs is often minor, implying that models of isothermal planets provide consistent results. This approach meets limitations in the case of fluids (liquids, gases and supercritical fluids), whose properties are very sensitive to variations in temperature. Here we propose a way to compute the relevant thermodynamic parameters in supercritical water from the most recent EOSs, in order to compute the internal structures of irradiated ocean planets, coupled with a 1D convective-radiative atmospheric model. Our results allow a better understanding of the diversity of observed sub-Neptunes, linking their internal structure to formation conditions.

Methods

Planet structure model

The internal structure of a planet is obtained by solving the set of 4 equations [1]:

$$
\begin{aligned}
\frac{\mathrm{d}g}{\mathrm{d}r} &= 4\pi G\rho - \frac{2Gm}{r^3}, && (1)\\
\frac{\mathrm{d}P}{\mathrm{d}r} &= -\rho g, && (2)\\
\frac{\mathrm{d}T}{\mathrm{d}r} &= -g\gamma T\frac{\mathrm{d}\rho}{\mathrm{d}P}, && (3)\\
P &= f(\rho, T). && (4)
\end{aligned}
$$

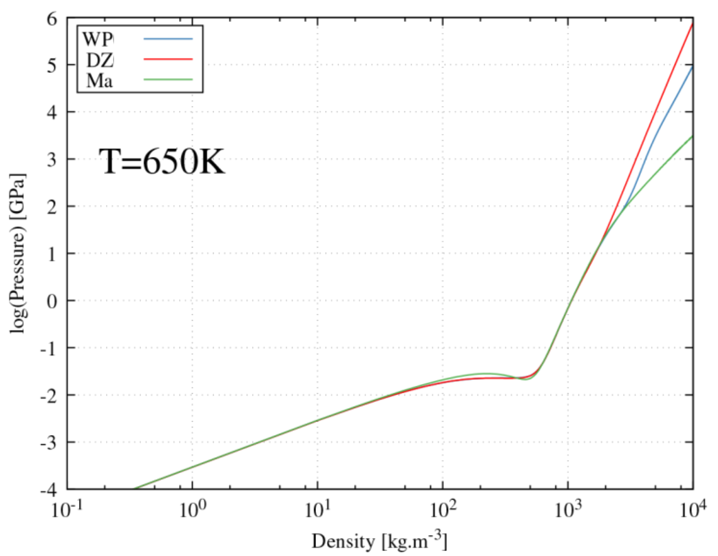
We consider a planet formed of 3 layers :
- Fe - FeS core;
- silicate Earth-like mantle;
- pure H_2O hydrosphere.

The internal structure model is connected to the atmospheric model from [2], giving the atmosphere mass, thickness, equilibrium temperature and albedo.

H_2O EoS

Solving Eq. (4) requires the equation of state (EoS) of species composing a layer. Solid species (core and mantle) EoS behave well and can be extrapolated. On the other hand, H_2O is very sensitive to change in pressure, and can undergo many phase changes at planetary scales (liquid, vapor, supercritical, high pressure ice, superionic, plasma). We wish to compare 3 EoS :

- IAPWS95 release by Wagner & Pruss 2002 [3], **noted WP**;
- Duan & Zhang 2006 [4], **noted DZ**;
- Mazevet et al. 2019 [5], **noted Ma**.



At a given pressure, WP and DZ EoS underestimate the density. Internal structures computed with these EoS will have greater radiuses.

Methods

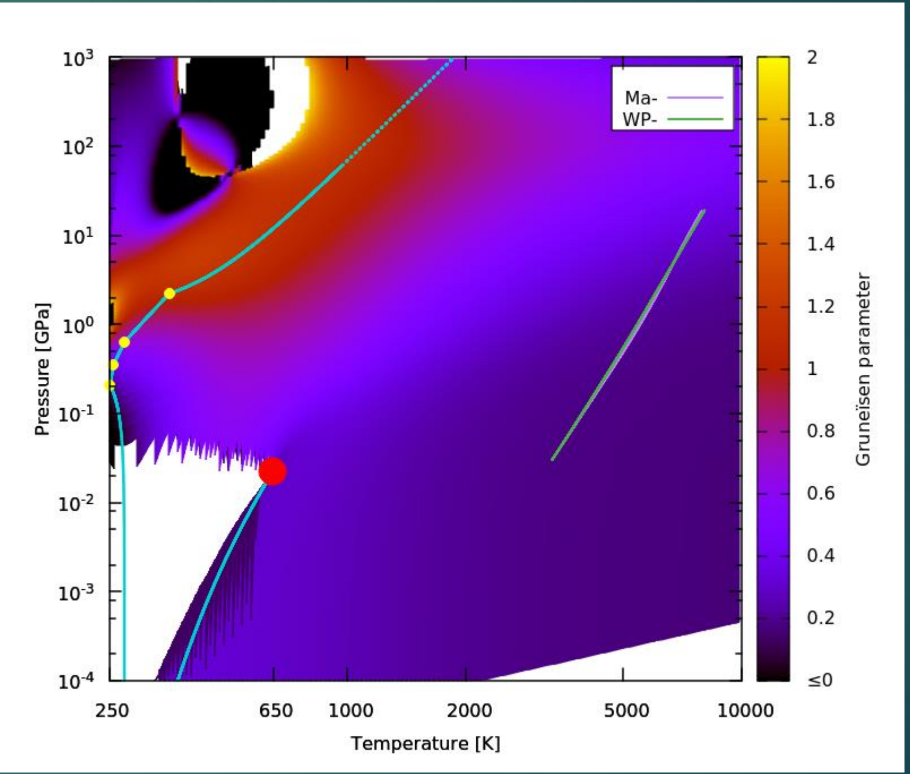
Grüneisen parameter

Integrating Eq. (3) requires the knowledge of the Grüneisen parameter γ, producing the temperature profile. Solid phases EoS (core, mantle, ices) are moderately sensitive to temperature, so that isothermal profiles produce good estimates of internal structures. As phase transitions occur for H2O (liquid, gas, supercritical, plasma, superionic), the temperature profile impacts greatly mass-radius relationships, since H2O atmospheres have little mass but can become very extended. Using the Helmholtz free energy, computing the Grüneisen from [3] **(label -)**:

$$\gamma = -\frac{1+\delta\phi^{\mathrm{r}}_{01}-\delta\tau\phi^{\mathrm{r}}_{11}}{\tau^2\left(\phi^{\circ}_{20}+\phi^{\mathrm{r}}_{20}\right)}.$$

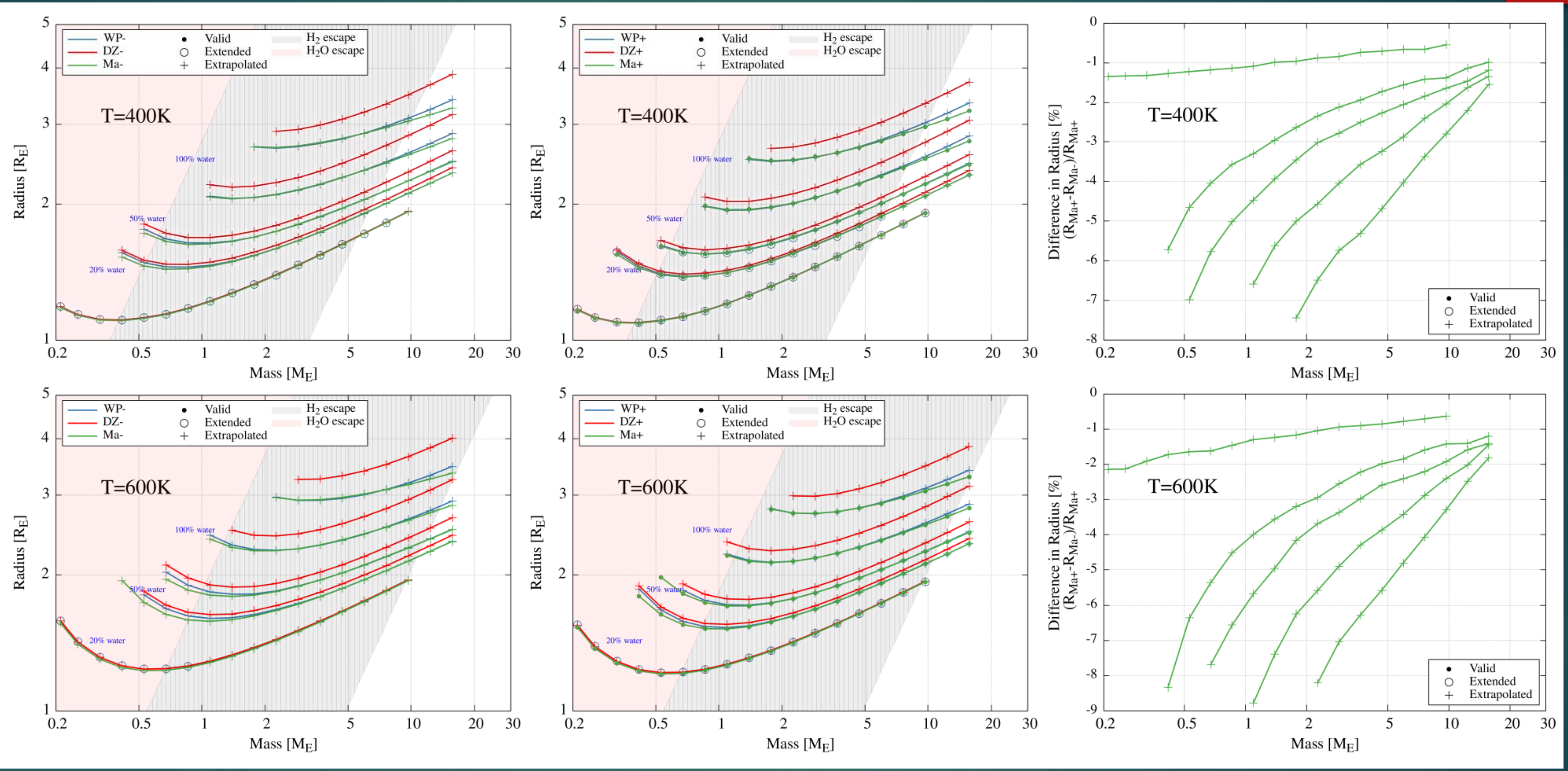
Similarly, computing from [5] **(label +)**:

$$\gamma = \frac{P(\rho,T)\left(\frac{\partial \ln P}{\partial \ln T}\right)_V}{\rho c_V T}.$$



Grüneisen parameter computed from IAPWS95 Helmholtz free energy. Green and purple tracks are (P,T) correspond to a 1 MEarth planet made of 100% H2O for T=600K, using WP and Ma EoS.

Results



Left pannels : M-R relationships using **WP**, **DZ** and **Ma** EoS, with IAPWS95 [3] Grüneisen parameter **(label -)**.
Middle pannels : same, but with [5] Grüneisen parameter **(label +)**.
Right pannels : difference, in percentage, between **Ma-** and **Ma+** parametrizations.
M-R relationships were computed for 1%, 10%, 20%, 50% and 100% of water content, with an Earth-like core to mantle mass ratio.
Current presentation shows M-R relationships for T=400K and T=600K of equilibrium temperature.

Results

Main findings of this study:

- Extrapolating beyond the range of validity of EoSs produces greater radiuses.
- Computed γ from [5] **(label +)** is smaller than γ from [3] **(label -)**, producing cooler, and thus denser, interiors. This difference is at most of ~10%.

Computations for T=800K and T=1000K lead to similar conclusions. This work highlights the **difficulty of producing reliable mass-radius relationships** with fluid phases, and the **necessity for EoS of high exactitude**.

Computed planets are subject to **H_2-He atmospheric escape**. The existence of irradiated ocean planets have great implications for sub-Neptunes internal structure, and gives insights on the **origin of the Fulton gap** [6].

References

[1] Brugger, B., Mousis, O., Deleuil, M., et al. 2017, ApJ, 850, 93

[2] Marcq, E., Baggio, L., Lefèvre, F., et al. 2019, Icarus, 319, 491

[3] Wagner, W., & Pruss, A. 2002, Journal of Physical and Chemical Reference Data, 31, 387

[4] Duan, Z., & Zhang, Z. 2006, GeoCoA, 70, 2311

[5] Mazevet, S., Licari, A., Chabrier, G., et al. 2019, A&A, 621, A128

[6] Mousis, O., Deleuil, M., Aguichine, A., et al. 2020, ApJL, 896, L22