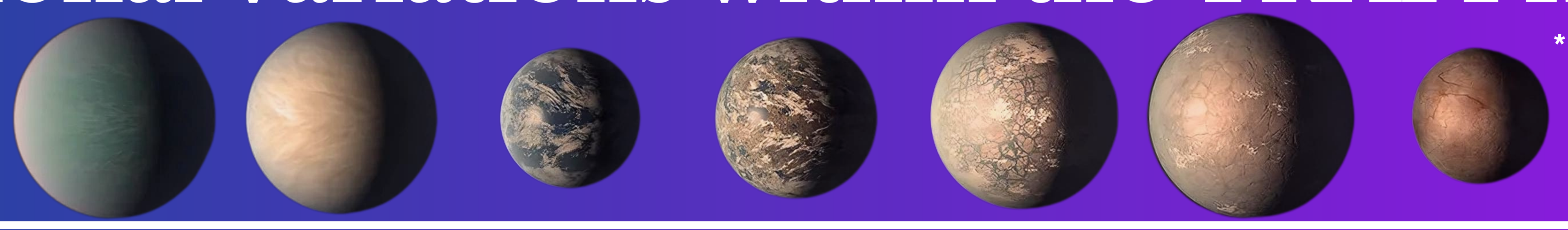
Compositional variations within the TRAPPIST-1 planets



Alexander Thamm (1), Alexander Balduin (1), Ludmila Carone (2) and Lena Noack (1)

(1) Department of Earth Sciences, Freie Universität Berlin,Berlin, Germany, (2) Space Research Institute, Austrian academy of sciences, Graz, Austria

a.thamm@fu-berlin.de

I

Indroduction

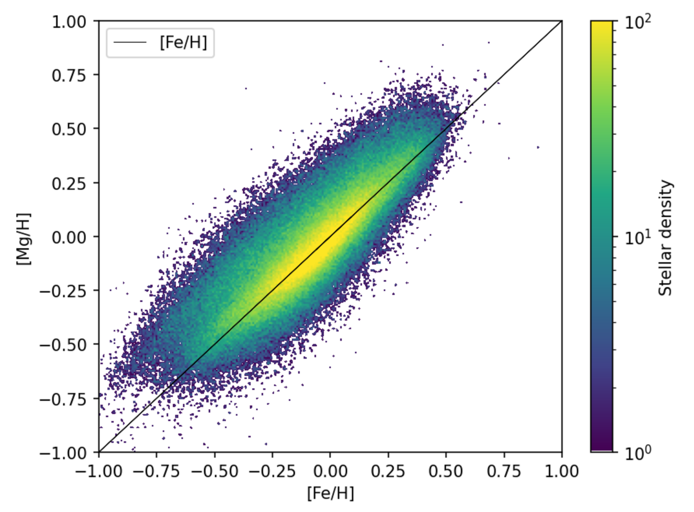
The metallicity of a main sequence star is directly related to the composition of its protoplanetary disk and influences the chemical elements and the distribution of planetary building blocks. Equilibrium condensation simulations are used to understand this relationship. Here we present a model that predicts the composition of planetary building blocks based on the metallicity of the parent star. In contrast to complex models such as GGChem or FastChem, this model emphasizes speed and simplicity and provides for a fast, accessible first approximation for integration into more complex models. As a first application of this model, we estimate the composition of the TRAPPIST-1 planets and use these as input for an interior structure model. We predict the core mass fraction and radii for the inner planets, which agree well with the observed values from Agol et al. (2021), and suggest that the outer planets should have a maximum water fraction below 20 wt% to match their observed radii.

II

Datasets and boundaries

- we derived the data for metallicity ([Fe/H]) from the GALAH+ Survey: Third Data Release [1] and the Hypatia catalogue [2]

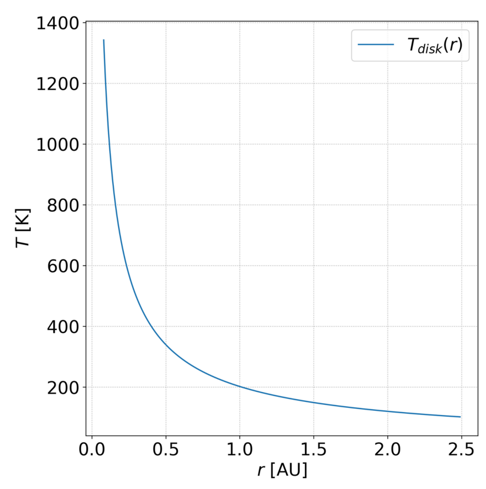
stellar constraints	
$[Fe/H]_\star$	$-0.75 \le x \le 0.75$
Teff	< 6000 K
Surface gravity	log g > 4.0



III

Model - boundary conditions

- with $[Fe/H]_\star$ + solar abundance = elemental abundance
- simple chemical equilibrium
  - all molecules are formed in the gas phase
  - stoichiometric mixing ratios
- constant disk pressure
- no disk dynamics
- simple inverse power law for the temperature profile

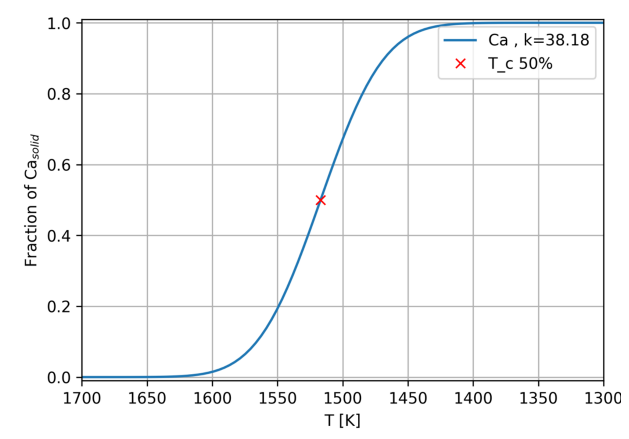


Model - condensation

- elements condensate into host phases [3]
- Hill radius determines feeding zone

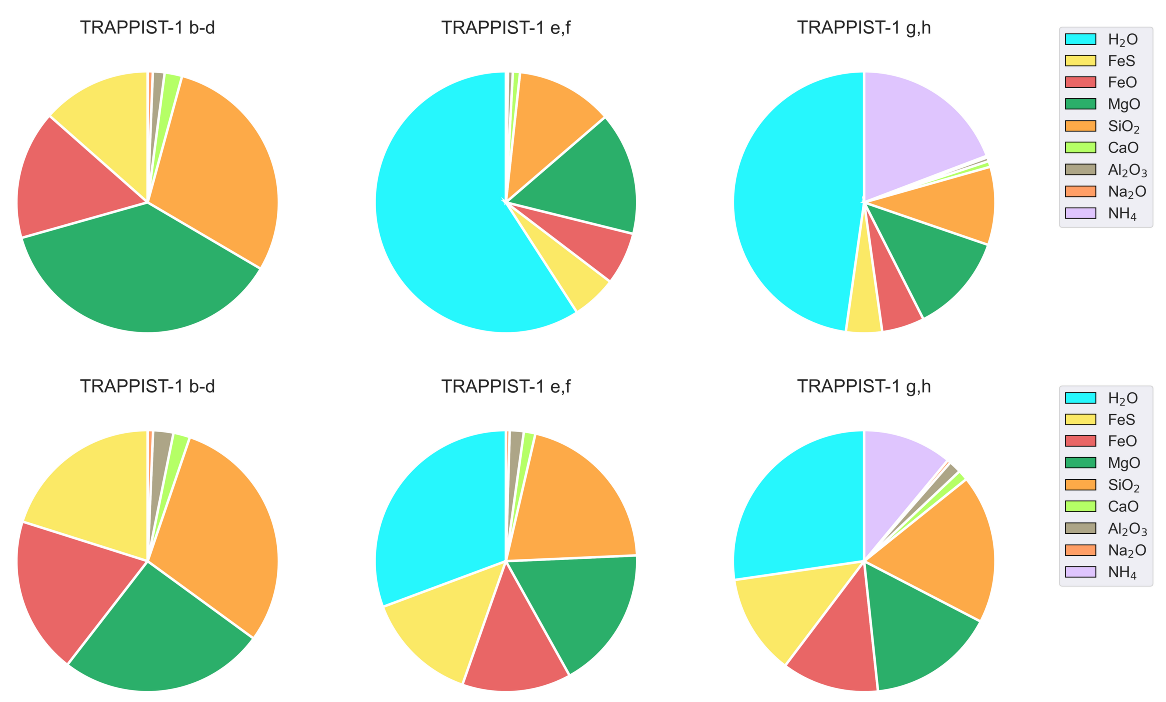
precipitated fraction at given T:

$$N(T, T_c, k) = \int_{T_1}^{T_2} \frac{1}{k\sqrt{2\pi}} e^{-\frac{(T-T_c)^2}{2k^2}} \, dT.$$



'condensation curve' for calcium

TRAPPIST-1



calculated composition as mol% (top) and as wt% (bottom) of **planetary building blocks.**

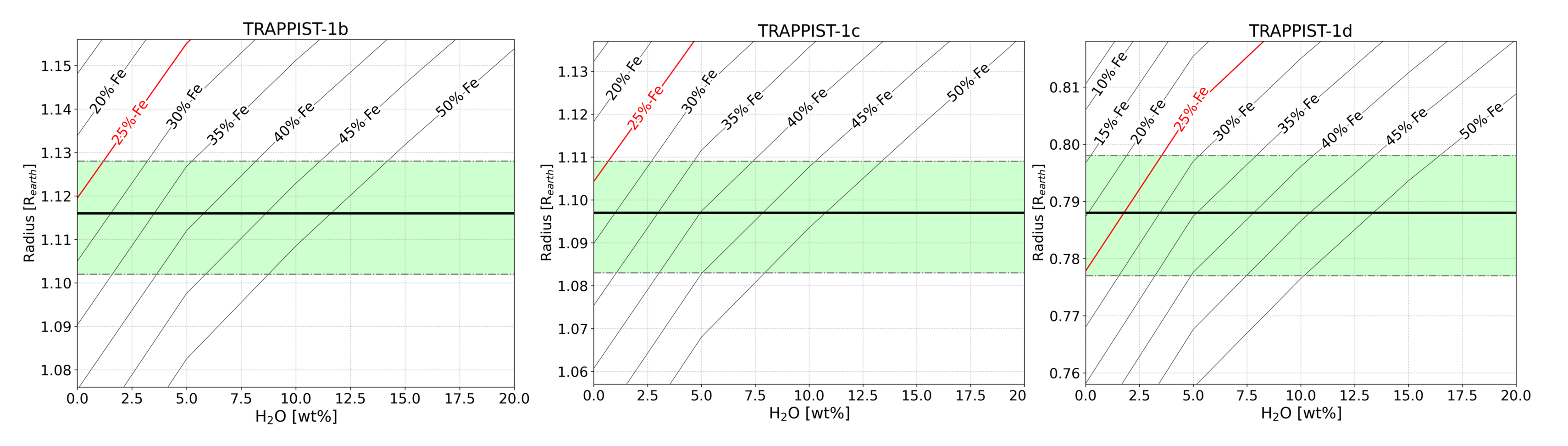
....served as input for perple_x [4] to archive thermodynamic mantel properties, which we eventually incorporated into an interior structure model [5]

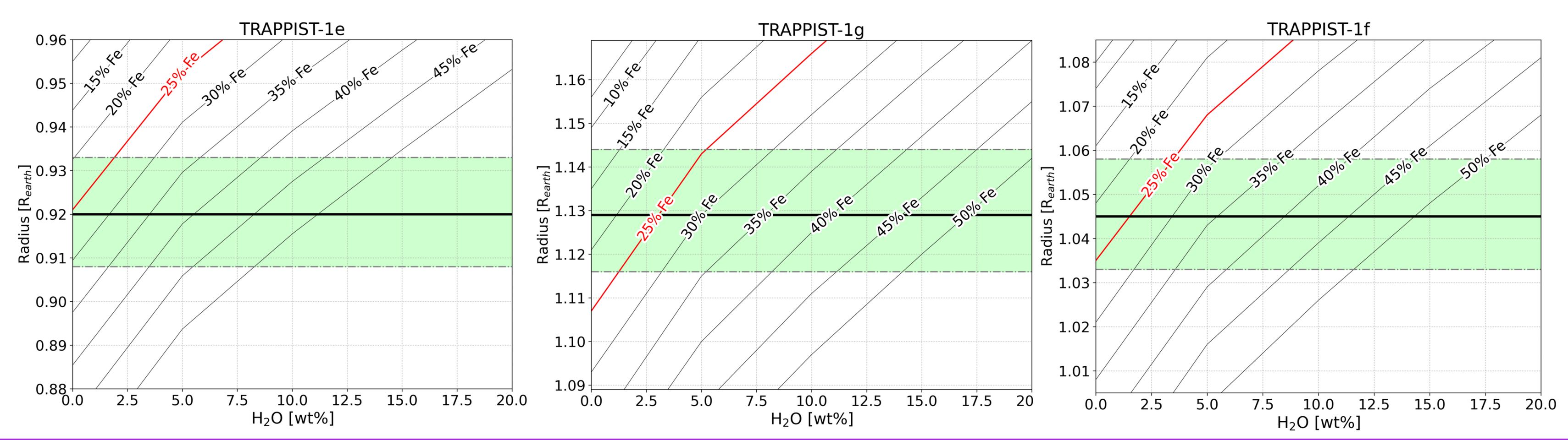
Radii of TRAPPIST-1 b to d		
Planet	Model	Agol et al. [6]
b	1.119	1.116 (+0.012/-0.014)
c	1.104	1.097 (+0.012/-0.014)
d	0.777	0.788 (+0.01/-0.011)

Calculated Radii of TRAPPIST-1 b, c and d with a core-mass fraction of 25% (Fe)

	H2O [wt%]		
Fe [wt-%]	e	f	g
15	-	-	0
20	-	0	1.1
25	0	1.5	3.1
25	$0.3^{-0.3}_{+1.8}$	$1.9^{-1.3}_{+1.5}$	$3.5^{-1.3}_{+1.6}$
50	11.2	14.4	17.1

Combinations of core mass fractions and water mass fractions for TRAPPIST-1 e, f and g that match the observed radii from Agol et al.





Conclusion

- the predicted radii for TRAPPIST-1 b, c and d matches the measured radii within the observational error
  - this suggest that our compositional model is able to correctly predict the composition of planetary building blocks of these planets
- for the outer planets of the system, the appearance of volatiles adds a degeneracy to our interior structure
- we show different combinations of core mass fractions and water mass fractions to match the data of Agol et al. for TRAPPIST-1 e, f and g
  - but we never reach a water mass fraction > 20 %
  - late accretion processes will change the the composition of planetary building blocks. These effects are not included in the compositional model

[1] Buder, Sven et al. (May 2021). "The GALAH+ survey: Third data release". In: Monthly Notices of the Royal Astronomical Society 506.1, 150–201. ISSN: 1365-2966. DOI: 10. 1093/mnras/stab1242.
[2] Hinkel, Natalie R. et al. (Aug. 2014). "STELLAR ABUNDANCES IN THE SOLAR NEIGHBORHOOD: THE HYPATIA CATALOG". In: The Astronomical Journal 148.3, p. 54. ISSN: 1538-3881. DOI: 10.1088/0004-6256/148/3/54.
[3] Lodders, Katharina (July 2003). "Solar System Abundances and Condensation Temperatures of the Elements". In: The Astrophysical Journal 591.2, pp. 1220–1247. DOI: 10.1086/375492.
[4] J. A. D. Connolly (2009). "The geodynamic equation of state: What and how". In: Geochemistry, Geophysics, Geosystems DOI: 10.1029/2009GC002540
[5] L. Noack, D. Höning et al. (Dec. 2016). "Water-rich planets: How habitable is a water layer deeper than on Earth?". In: Icarus 277, A10. DOI: 10.1016/j.icarus.2016.05.009.
[6] E. Agol, C. Dorn et al. (2021) "Refining the Transit-timing and Photometric Analysis of TRAPPIST-1: Masses, Radii, Densities, Dynamics, and Ephemerides DOI: 10.3847/PSJ/abd022
⋆ Artistic impression of the stellar system TRAPPIST-1. Credit: NASA/JPL-Caltech

Freie Universität Berlin
Geodynamics Mineral physics