Revisiting the star-planet composition link: a tale of devolatilization

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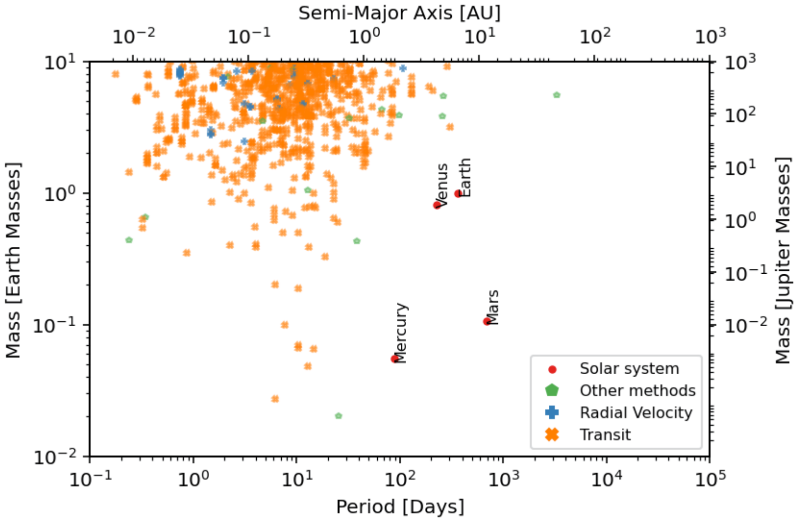
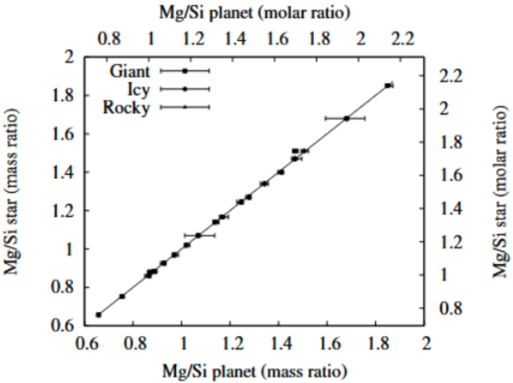
Rocky exoplanets show diverse internal compositions

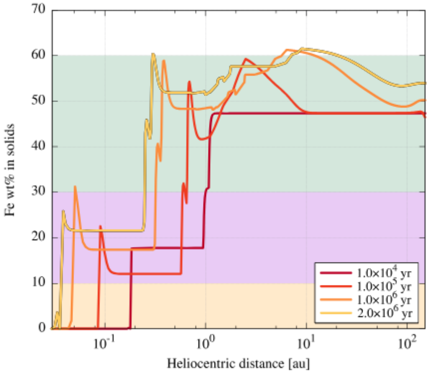


NASA Exoplanet Archive

Planetary composition is linked to host star composition



Thiabaud et al. 2015



Aguichine et al. 2020

Traditionally, it's assumed planets match their host star's composition.

- Planets and stars form from the same molecular cloud.
- In our Solar System, CI chondrites match the solar photosphere's composition.

Fe/Si in the Planet is higher than in the Star

- Many exoplanets appear enriched in iron relative to their stars .
- Proposed explanations: mantle stripping, giant impacts.

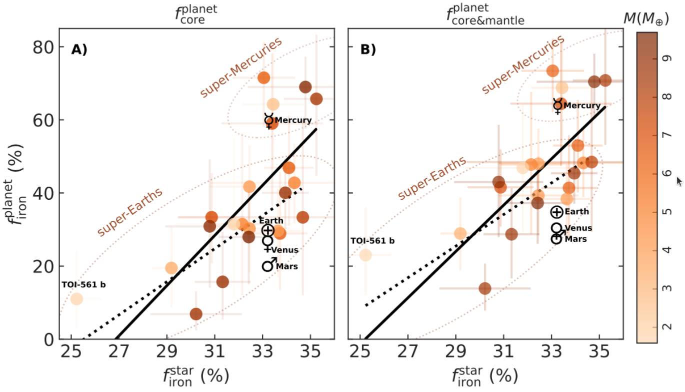


Figure: After Adibekyan et al. 2021

Devolatilization on Earth

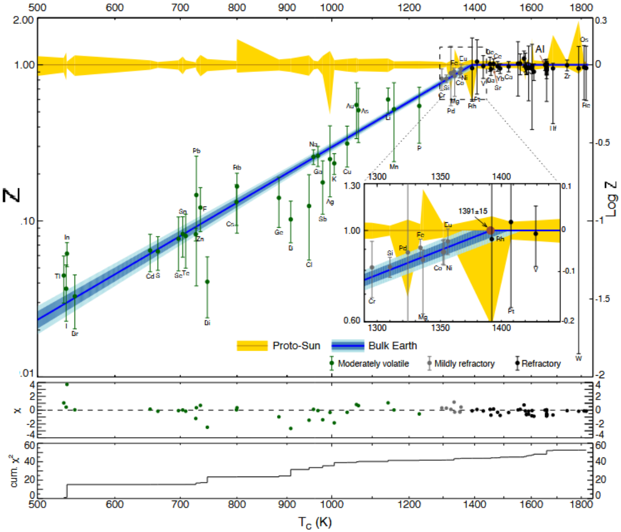
Z = relative molar fraction

$$Z_x = \left(\frac{N_x}{N_{\mathrm{Al}}}\right)_p \Big/ \left(\frac{N_x}{N_{\mathrm{Al}}}\right)_\star \quad (1)$$

- Volatiles (e.g., O, S) are depleted relative to refractories (Fe, Mg).
- Earth shows such a devolatilization trend. Fig. after Wang et al. 2019

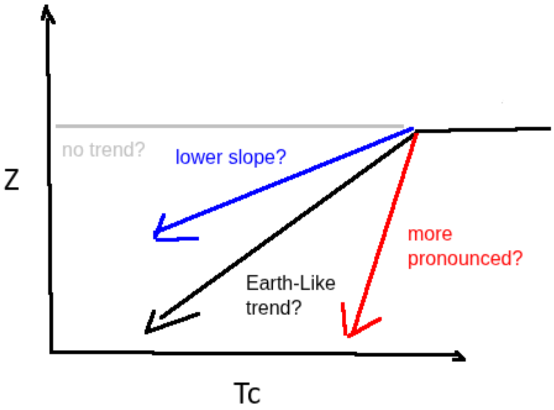
Note

Volatility is determined by the condensation temperature (T_c)



Aim of this work

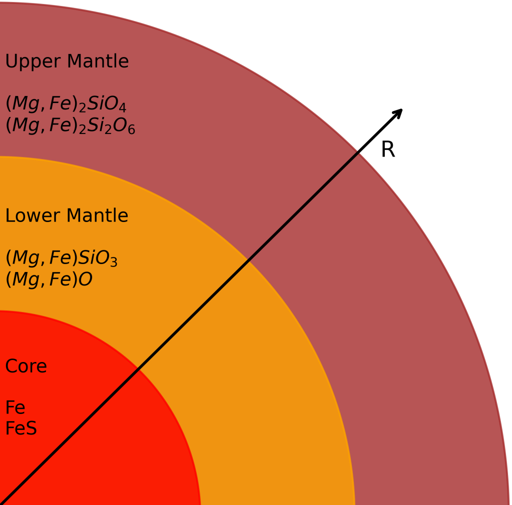
- Do rocky exoplanets follow a devolatilization trend?
- Is it Earth-Like or something else?
- Can this explain exoplanet iron excess?



Methods

The Marseille Super-Earth Interior (MSEI)

Brugger et al. 2016, 2017



Radial profiles

Solves for $g(r)$, $P(r)$, $T(r)$, and $\rho(r)$ using physical laws and Vinet EoS.

Inputs

Mass, Core-Mass Fraction (CMF), core alloy fraction (f_{alloy}), Magnesium to Silicon ratio (Mg/Si), and magnesium mantle number (Mg#).

Outputs

Planet radius and elemental mole fractions (Fe, Si, Mg, S, O) from internal mineralogy and layer composition.

Grid and Forward Model

Why a Grid?

Each MSEI model takes ∼10 seconds. Retrievals require thousands of evaluations, so we precompute a 6D grid and interpolate instead.

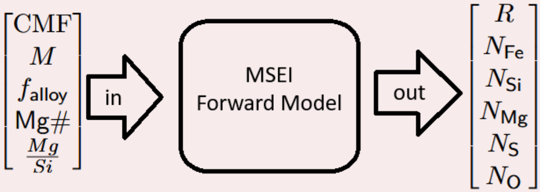
Grid Setup

We sample mass, CMF, f_{alloy}, Mg#, and $\frac{Mg}{Si}$ uniformly.

Interpolation Method

We use `RegularGridInterpolator` from `SciPy` for fast, multidimensional linear interpolation.

We define the forward model



Interior composition retrievals

Framework

We use Bayesian statistics to retrieve the compositional parameters with corresponding uncertainties from the observed mass and radius.

Log-Likelihood function

$$\mathcal{L}(\boldsymbol{\theta} \mid \mathbf{R}_{\text{obs}}, \mathbf{M}_{\text{obs}}) = -\frac{1}{2}\left[\left(\frac{M - M_{\text{obs}}}{\sigma_M}\right)^2 + \left(\frac{R - R_{\text{obs}}}{\sigma_R}\right)^2\right], \quad (2)$$

$$\boldsymbol{\theta} = (CMF, f_{\text{alloy}}, Mg/Si, Mg\#) \quad (3)$$

Implementation

We use the `Python` package `emcee` to run MCMC

Planet/Star relative abundances and devolatilization model

We obtain the condensation temperatures

Element	$T_{50\%x}$
Fe	1328
Mg	1327
Si	1302
S	655
O	875

Table: Lodders et al. 2009

We obtain the Planet/Star molar fraction of element x:

$$Z_x = \left(\frac{N_x}{N_{\text{Fe}}}\right)_p \Big/ \left(\frac{N_x}{N_{\text{Fe}}}\right)_\star \quad (4)$$

Finally, we fit the devolatilization trend with `emcee`

$$\log_{10}(Z_x) = m \log_{10}(T_{50\%x}) + c \quad (5)$$

Sample

Selection criteria:

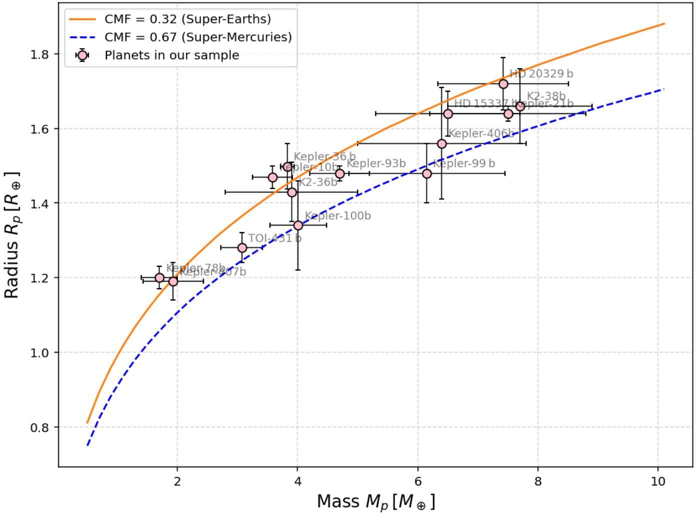
- $0.5M_{\oplus} < M_p < 10M_{\oplus}$
- $0.5R_{\oplus} < R_p < 2R_{\oplus}$
- Stellar abund. of Fe, Si, Mg, O and S available

Sources

- We use the NASA exoplanet archive to preselect candidates
- Stellar abundances from Hypatia/Literature

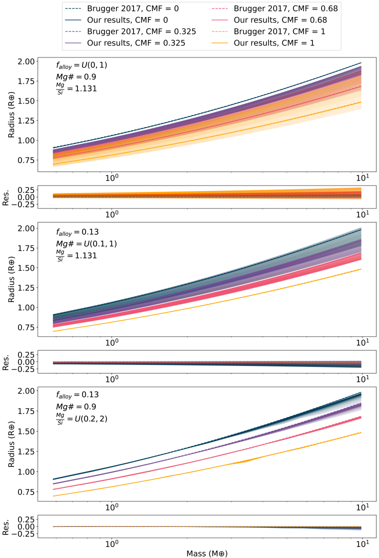
Final sample size

13



Results

Forward model sensitivity to chemical composition



The forward models gives the radius as a function of the mass and the compositional parameters:

$$R = R(M, CMF, f_{\text{alloy}}, \text{Mg\#}, \frac{Mg}{Si})$$

Which compositional parameter has a larger impact on the radius?

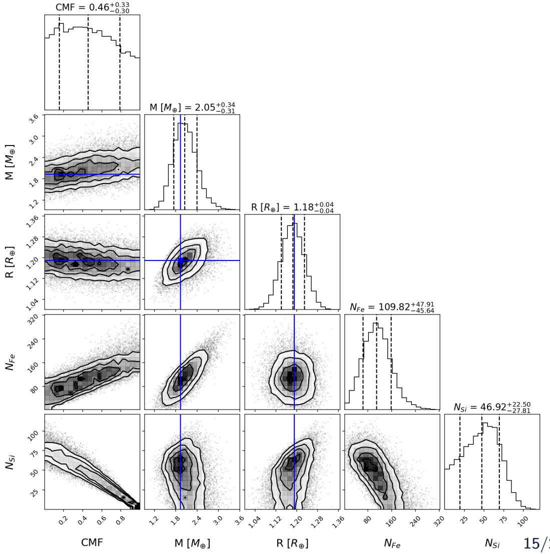
We let each compositional parameter vary individually and plot R(M). Repeat for CMF = 0, 0.25, 0.68 and 1.

% change in the radius over the full range of compositional parameters:

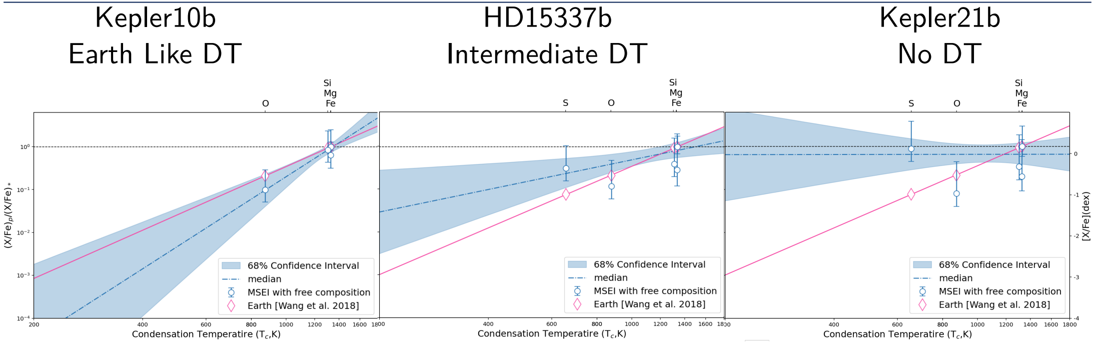
$f_{\text{alloy}} : < 20\%$ $\quad Mg\# : < 15\%$ $\quad \frac{Mg}{Si} : < 5\%$

Example Retrieval: Kepler-407b

- The MCMC converges on the observed values of Mass and Radius
- Correlation between CMF, Iron and Silicon



Devolatilization trends in exoplanets



Result

While 8 out of 13 planets in our sample show Earth-Like DTs, some show less or no DT.

Result

No planets show negative slope.

Discussion

Devolatilization trends vs orbital/physical parameters

Result:

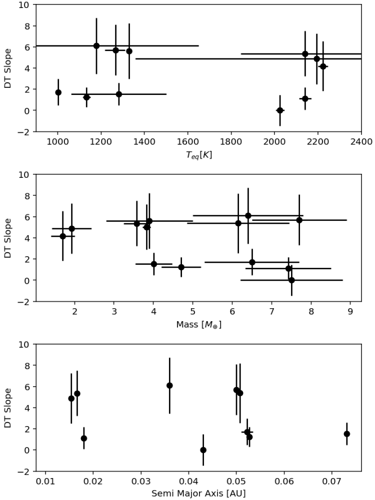
We observe no correlation between T_{eq} Mass, Planet-Distance and the devolatilization trend slope

Scenario 1:

There is no correlation

Scenario 2:

There is correlation but is masked by noise systematics errors



Conclusions

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- Many rocky planets fit an Earth-like devolatilization trend.
- Rocky planets show diverse mineralogy, with implications to habitability (out-gassing)
- PLATO will help by providing highly accurate measurements of radius and expanding the sample coverage at large orbital distances. (Precision $<3\%$ for Earth-sized planets!)

picture from 5M website .

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