The Radius Valley as a by-product of Planet Formation: Observational Signatures of the Core-Powered Mass-Loss Mechanism

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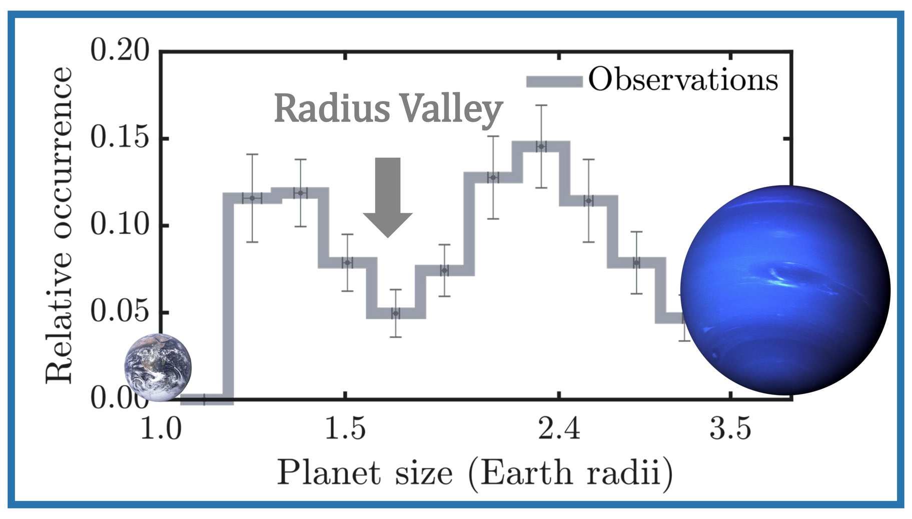
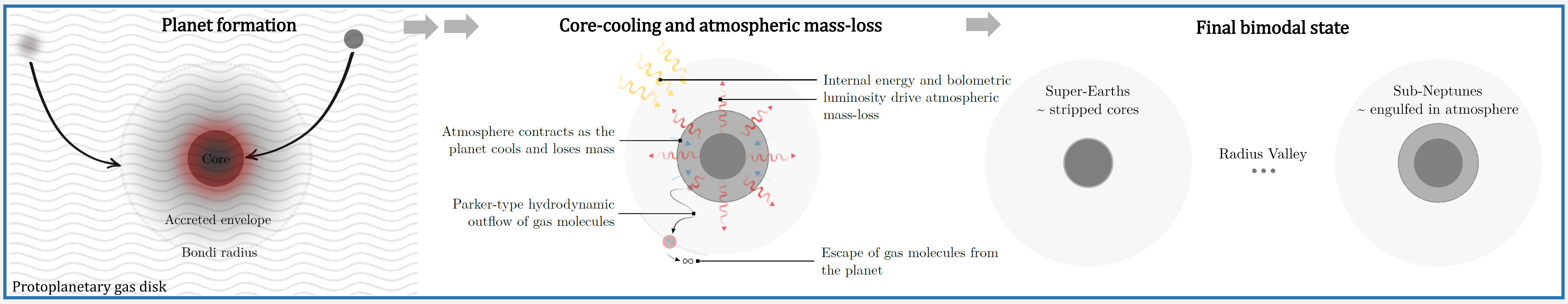
Recent Observations: the Radius Valley [e.g., 1, 2, 3]

- Most common planets known to-date are 1-4 Earth radii in size
- However, there are very few exoplanets of sizes 1.5-2.0 Earth radii. This intriguing feature in the planet size distribution is known today as the **radius valley** and separates the small planet population into super-Earths (planets < 1.5 R_{Earth}) and sub-Neptunes (planets > 2.0 R_{Earth})
- In addition, the radius valley also coincides with a bimodality in planet densities or bulk compositions
  - Super-Earths have higher densities → consistent with planets having rocky 'Earth-like' composition
  - Sub-Neptunes have lower densities → consistent with planets engulfed in H/He envelopes



[Based on data from Fulton et al. 2017]

The Core-Powered Mass-Loss Mechanism can Explain the Origin of the Radius Valley



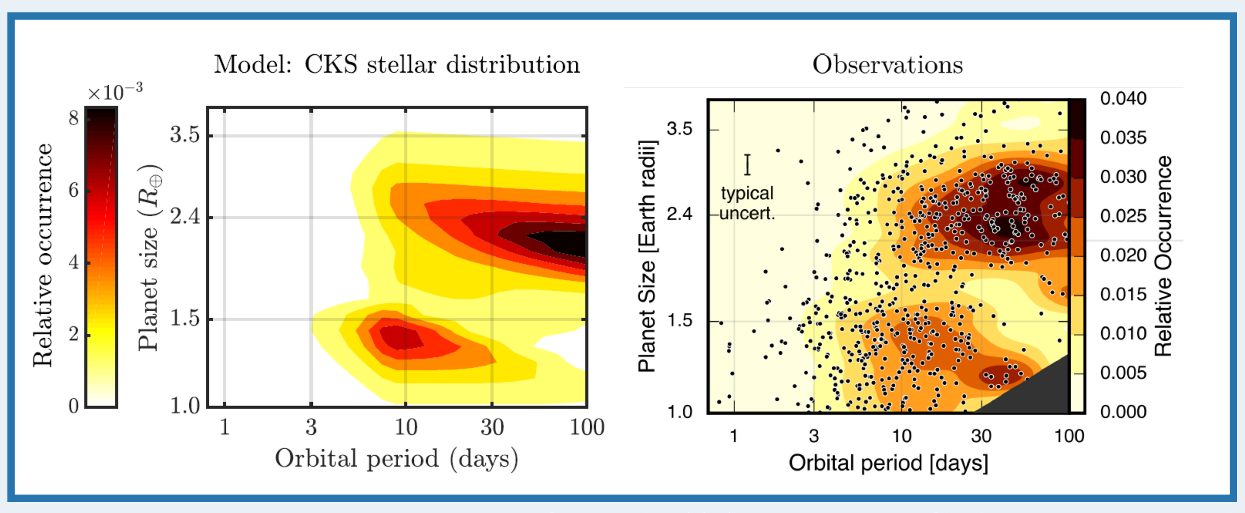
- **What is core-powered mass-loss?** [5,6,7]
  - Under the core-powered mass-loss mechanism, a planet can undergo atmospheric mass-loss via a Parker-like hydrodynamic wind driven by the internal luminosity of the cooling planet and the bolometric luminosity of its host star. Super-Earths are planets that consequently lose their primordial atmospheres entirely whereas sub-Neptunes are those that can retain some of their primordial H/He atmospheres.
- **What is the source of this internal luminosity?**
  - During the formation of a planet, gravitational binding energy of the accreted material gets converted into thermal energy – this can be significant, equivalent to core temperatures of ~ 10^4-10^5 K for planets 1-4 R_{Earth}
  - If a planet forms in the presence of the protoplanetary disk, it also accretes a H/He envelope which, once optically thick, acts as a 'thermal blanket' for the planet → allows the planet to hold on to a significant fraction of its primordial energy of formation
- **What dictates if a planet becomes a super-Earth or a sub-Neptune or why is there a size bimodality?**
  - If a planet has enough cooling energy to overcome the binding energy of its atmosphere or not
  - More importantly: the competition between a planet's cooling t_{cool} & mass-loss timescale t_{loss}
    - $t_{cool} < t_{loss}$: any mass loss quickly ceases as the cooling of the planet will shrink its atmosphere deeper into the gravitational well of the planet, making it harder for the rest of it to escape → a sub-Neptune.
    - $t_{cool} > t_{loss}$: a planet will lose atmosphere more quickly than it can cool and shrink → a super-Earth.
  - An envelope corresponding to an atmosphere-to-core mass fraction of even a few percent almost doubles the size of a planet in comparison to a planet without any atmosphere
  - Together these points explain the bimodality in the distribution of planet sizes and densities (smaller rocky cores w/ higher densities vs. planets w/ envelopes and thus lower densities)

Observational Signatures of the Core-Powered Mass-Loss Mechanism

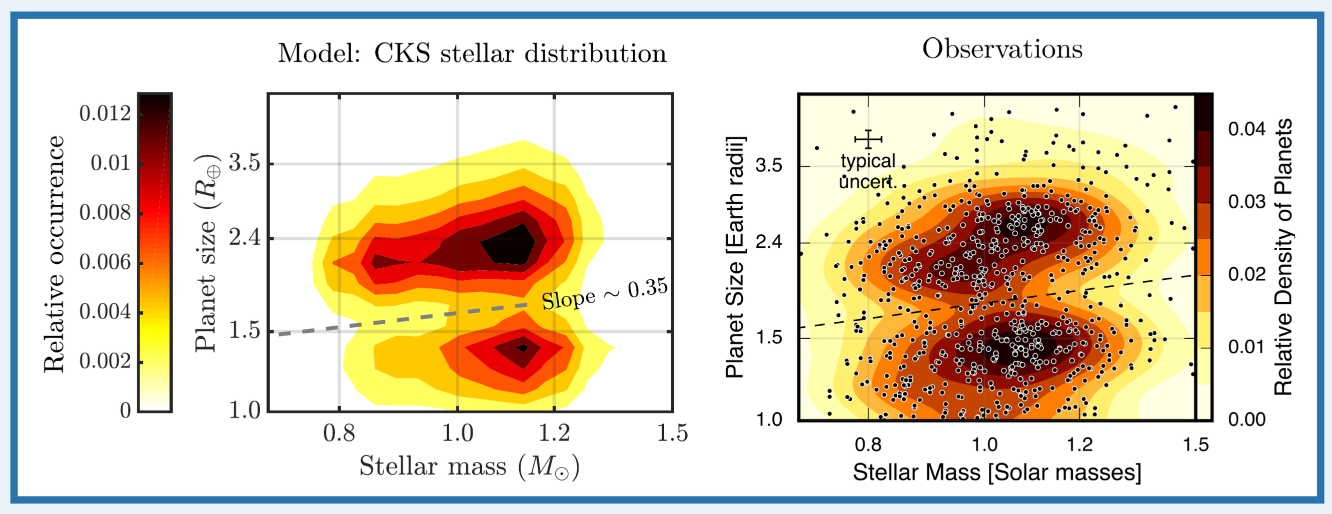
In planet demographics? [5,6]

examples from Gupta & Schlichting (2019, 2020)

Assuming core-powered mass-loss dictates planet evolution, one can investigate how the **planet size** distribution depends on different planetary and stellar parameters such as **insolation flux, core composition, orbital period stellar age, stellar metallicity and stellar mass** by simulating populations of planets varying in their core masses and orbital periods and that form in the protoplanetary disks, accreting primordial H/He envelopes in the process.



[Gupta & Schlichting, 2019, 2020][Fulton & Petigura, 2018]



[Gupta & Schlichting, 2020][Fulton & Petigura, 2018]

Our results (left panels) show how the core-powered mass-loss mechanism can explain a multitude of observations (right panels) pertinent to the radius valley. Such results not only help us understand the physics behind the correlations observed between the planet size distribution and the different planetary and stellar properties, but also allow us to make predictions that could be tested through future observations. For more details on comparisons with observations, inferences and predictions, please refer to Gupta & Schlichting (2019, 2020).

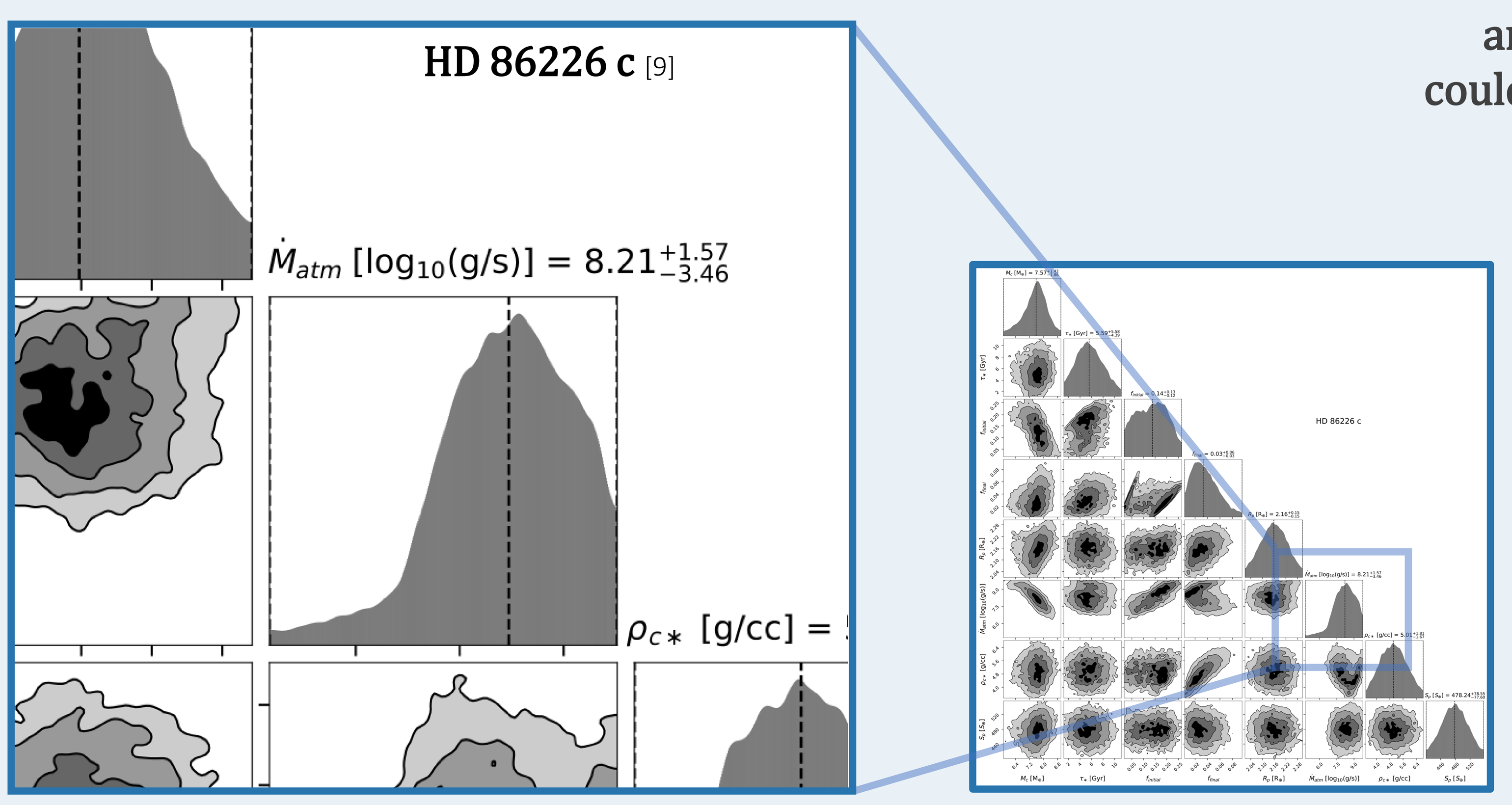
also see Rogers, Gupta, Owen and Schlichting (2021) on investigating the radius valley in the three-dimensional phase space of planet size, insolation flux and stellar mass.

For individual planets? [7]

Given a **planet's size, mass, insolation flux and its host star's properties such as mass and age** one can use Bayesian inference analysis, under the assumption that core-powered mass-loss dominates evolution, to estimate the **current and primordial state of the planet**, e.g., its **atmosphere mass fraction, core composition and mass-loss rate.**

Applying this to the various planets known today helps us find planets that could be

- **undergoing atmospheric escape today, or**
- **harboring atmospheres abundant with high molecular weight species, low-density interiors, or both**



an example of a planet (HD 86226 c) that could be undergoing considerable mass-loss today, from Gupta & Schlichting (2021)

In Gupta & Schlichting (2021), we share a non-exhaustive list (also shared below) of planet candidates that can serve as useful input for target selection for future surveys and for testing the importance of core-powered mass-loss in individual planetary systems.

Selected Observational Predictions of the Core-Powered Mass-Loss Mechanism [5,6,7]

- Observed planets have Earth-like core composition
- Valley's slope is a function of stellar mass, i.e., it depends on the stellar mass-luminosity relation
- Planets that could be undergoing atmospheric escape today:
  - pi Men c, Kepler-60 d, Kepler-60 b, HD 86226 c, EPIC 249893012 b, Kepler-107 c, HD 219134 b, Kepler-80 e, Kepler-138 d, and GJ 9827 d
- Relative abundance of super-Earths to sub-Neptunes increases even after the first 500 Myrs
- Metal-rich stars host larger sub-Neptunes
- Planets that could be harboring atmospheres abundant with high molecular weight species, low-density interiors, or both:
  - WASP-47 e, Kepler-78 b,Kepler-10 b, CoRoT-7 b, HD 80653 b, 55 Cnc e, and Kepler-36 b

References

[1] Owen & Wu 2013, ApJ, 775, 105 [2] Fulton et al. 2017, AJ, 154, 109 [3] Fulton & Petigura, 2018, AJ, 156, 264. [4] Ginzburg et al. 2018, MNRAS, 476, 759 [5] Gupta & Schlichting, 2019, MNRAS, 487, 24. [6] Gupta & Schlichting, 2020, MNRAS, 493, 792. [7] Gupta & Schlichting, 2021, MNRAS, 504, 4634. [8] Rogers, Gupta, Owen & Schlichting, 2021, arXiv:2105.03443. [9] Teske et al. 2020., AJ, 160, 96.