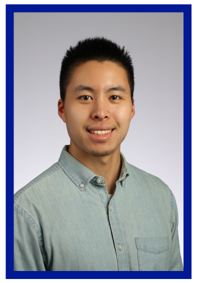
Architectures of Exoplanetary Systems:

Towards a Multi-planet Model for Reproducing the Kepler Patterns in Planet Sizes



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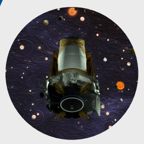
1. Intro: Kepler and Exoplanets



Over 15 years after its initial launch and ~4000 transiting exoplanet detections later, NASA's **Kepler mission**[1] continues to drive population studies of exoplanetary systems.

Two striking patterns that have emerged from examining the distribution of planet sizes are:

1. A clear bimodal distribution of planet radii, marked by a so-called "radius valley" at ~2 Earth radii[2] (see Fig. 1);
2. The size similarity (and preferential ordering) of planets in the same system[3].

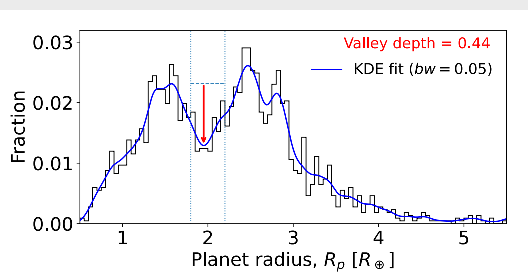


Fig. 1: The Kepler-observed distribution of planet radii, exhibiting a radius valley. We include transiting planet candidates in the DR25 catalog around FGK dwarfs.

2. Forward Modeling with SysSim

By simulating the Kepler transit survey and its detection pipeline, powerful inferences into the ***intrinsic distribution*** of planetary system architectures can be derived from comparing simulations to the ***observed distribution***.

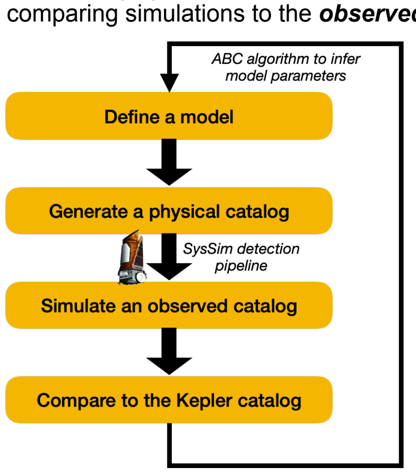


Fig. 2: Summary of the SysSim forward modeling pipeline.

These steps are iterated millions of times using the process of Approximate Bayesian computation (ABC), in order to find the posteriors of the model parameters.

The "SysSim" (Exoplanets Systems Simulator) codebase is a software for forward modeling the Kepler primary mission and performing model inference[4,5].

3. A "Hybrid" Population Model: Combining Multi-planet Architectures with Photoevaporation

The previous SysSim models can reproduce the orbital architectures and correlated planet sizes within multi-planet systems but cannot produce any planet radius valley (intrinsic or observed)[4,5]. **Therefore, we develop a "hybrid" model between the SysSim (H20) model[5] and the Neil and Rogers (2020; NR20) model[6]**, which incorporates photoevaporation, in order to find a multi-planet model that can reproduce both the observed planet radius valley and intra-system similarity patterns.

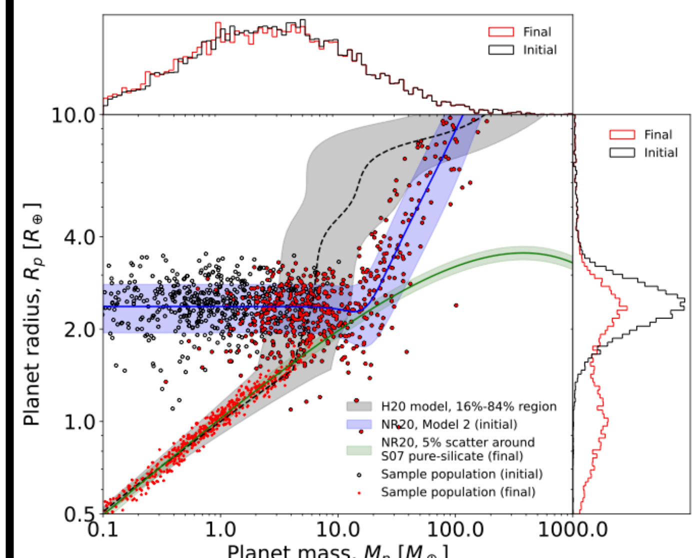


Fig. 3: Planet radius-mass relationships of the H20 model (gray), the initial radius-mass relation from the NR20 models (blue), and a pure-silicate relation[7] (green) from which the radii of photoevaporated planets are assigned. The black circles denote simulated planets with their initial properties (i.e. before envelope mass-loss), and the red points denoting the same planets with their final properties (i.e. after mass-loss).

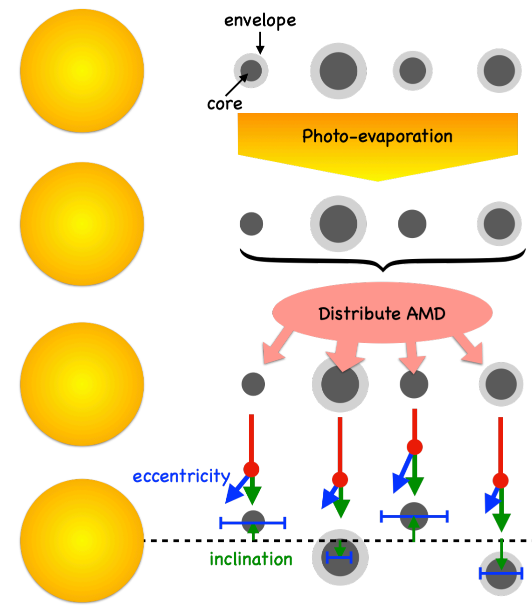


Fig. 4: Cartoon illustration of the hybrid model. The initial masses and radii are drawn from a broken power-law (blue curve in Fig. 3), and the photoevaporation mass-loss timescale is computed to determine which planets lose their atmospheres, following NR20. The final orbital architectures are drawn in a way to ensure mutual Hill radii stability and angular momentum deficit (AMD) stability, following H20.

4. Can the Hybrid model Reproduce the Observed Radius Valley?

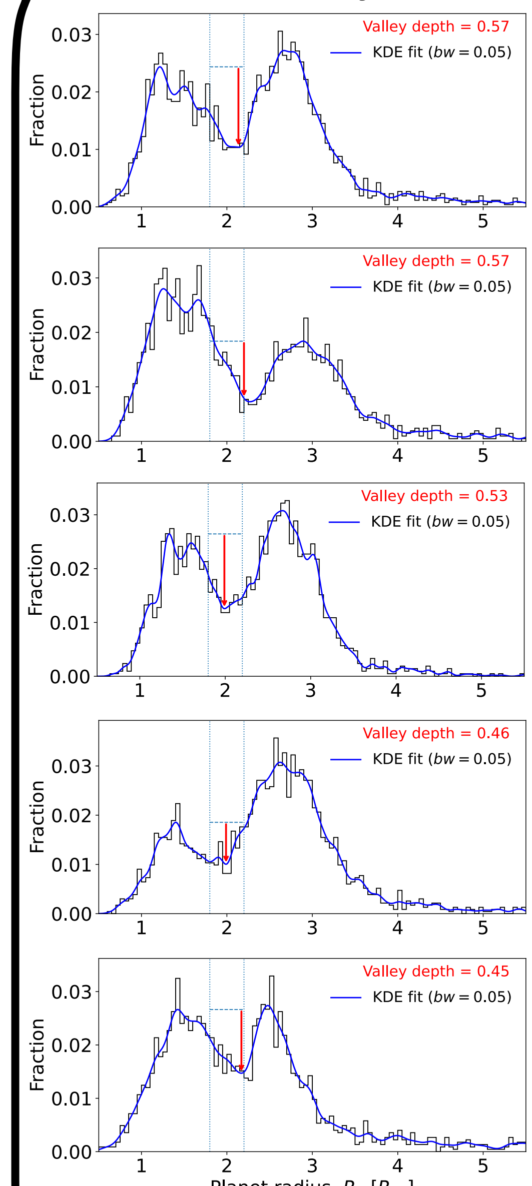


Fig. 5: Simulated catalogs from the hybrid model. Each of these exhibit a significant radius valley, with depths at least as large as in the Kepler data. However, not all catalogs produce a radius valley.

5. Model Comparison and Improvements

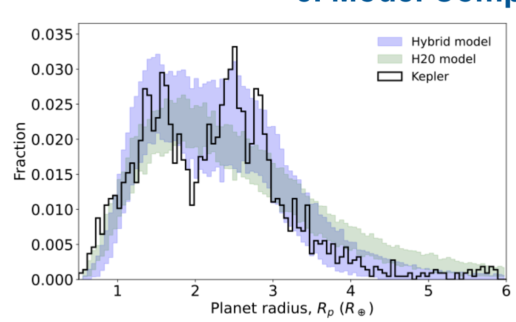


Fig. 6: Credible regions (16-84% quantiles) for the observed distributions of planet radii from the H20 (green) and hybrid (blue) models. The Kepler data is shown in black (same as in Fig. 1). While only some catalogs from the hybrid model produce a strong radius valley (see Fig. 5), it is a clear improvement over the H20 model.

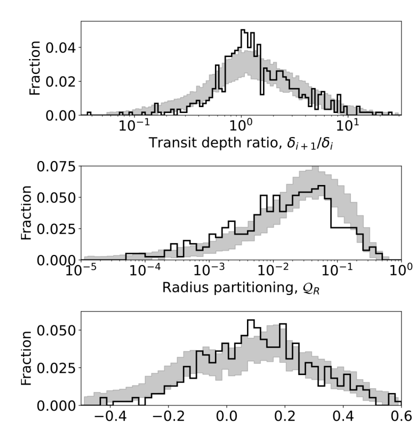


Fig. 7: The observed distributions[4,5,8] of:
(1) transit depth ratios of adjacent planets,
(2) radius partitioning, and
(3) radius monotonicity,
for the Kepler catalog (black) and the hybrid model (gray region).

The distributions of (1) and (2) suggest that the patterns of size similarity are even stronger in the Kepler exoplanetary systems.

References + Acknowledgements

1. Borucki et al. (2010), Science, 327, 977
2. Fulton et al. (2017), AJ, 154, 109
3. Weiss et al. (2018), AJ, 155, 48
4. **He et al. (2019), MNRAS, 490, 4575**
5. **He et al. (2020), AJ, 160, 276**
6. Neil & Rogers (2020), ApJ, 891, 12
7. Seager et al. (2007), ApJ, 669, 1279
8. Gilbert & Fabrycky (2020), AJ, 159, 281

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