Architectures of Exoplanetary Systems: Towards a Multi-planet Model for Reproducing the Planet Radius Valley and Intra-system Size Similarity

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PRESENTED AT:

1. KEPLER'S UNANSWERED MYSTERIES

Over 15 years after its initial launch and ~4000 transiting exoplanet detections later, the results from the Kepler mission continue to drive population studies of exoplanetary systems.

The 4-year Kepler primary mission revealed that small (1-4 Earth radii) planets with short periods (<1 year) orbiting FGK dwarf stars are ubiquitous (existing around ~50-100% of all such stars). Furthermore, the prevalence of multi-transiting systems (systems with two or more transiting planets), combined with detailed simulations of their detectability, imply that these planets are rarely alone and have small mutual inclinations (a few degrees from coplanarity).

In addition, two striking patterns that have emerged from examining the distribution of exoplanets discovered by Kepler are: (1) the clear bimodal distribution of planet radii, marked by a so-called "radius valley" at ~2 Earth radii apparently separating super-Earths from sub-Neptune planets, and (2) the intra-system correlations between the sizes of planets in the same system, as well their uniformly spaced orbital periods (collectively known as the "peas-in-a-pod" patterns).

Despite numerous population studies on each of these patterns, ***no single model has been able to explain both!*** More specifically, the following key questions remain:

- **How prevalent is the "radius valley" in the *underlying* distribution of planet sizes?**
- How is the radius valley entangled with the correlated radii of planets in multiplanet systems? **Which processes can explain both features?**

In this work, we develop a detailed population model to address these questions.

2. FORWARD MODELING WITH SYSSIM

The Kepler catalog remains the most uniformly vetted catalog of exoplanet candidates to date. By simulating the Kepler transit survey and its detection pipeline, powerful inferences into the ***intrinsic distribution*** of planetary systems and their architectures can be derived from comparing simulations to the ***observed distribution*** of planetary systems.

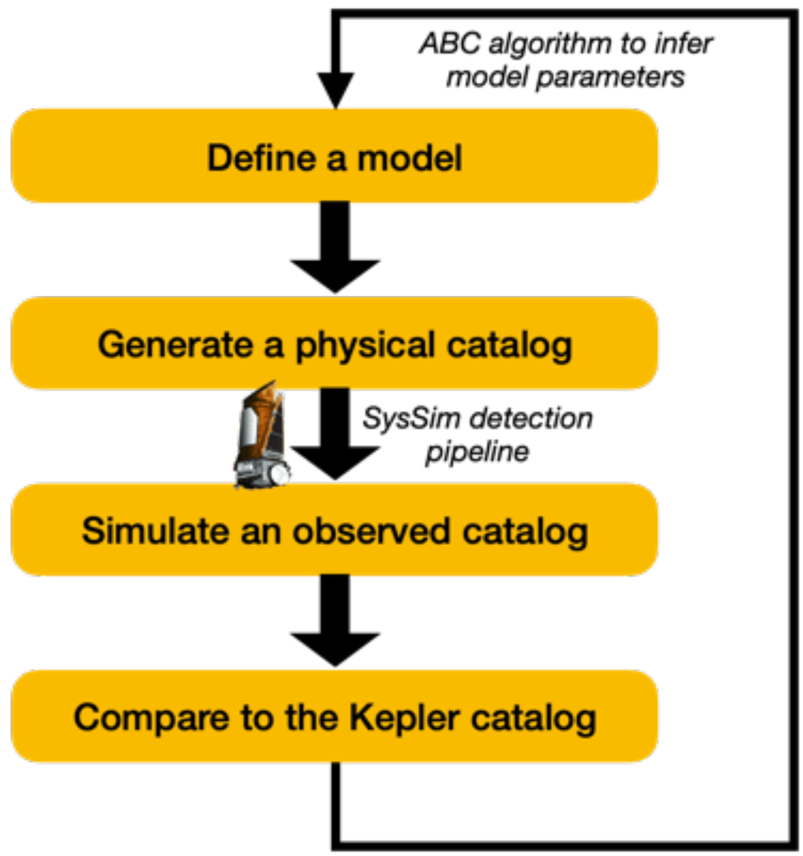

Figure 1: Diagram summarizing the SysSim forward modeling framework.

The "SysSim" (Exoplanets Systems Simulator) codebase is a software for forward modeling the Kepler primary mission. It allows users to simulate synthetic catalogs for performing model inference via the following steps (Figure 1):

1. Define a model for the true, underlying distribution of exoplanetary systems.
2. Generate a "physical catalog" by drawing stars from the Kepler target list and a planetary system from the model assigned to each star.
3. Generate an "observed catalog" from the physical catalog, by running the SysSim pipeline for simulating Kepler's detection efficiency for each planet.
4. Compare the synthetic observed catalog to the Kepler catalog using many statistical metrics, which go into a "distance function".

The above steps are iterated many millions of times using the process of Approximate Bayesian computation (ABC), in order to find the best-fit model parameters as well as their credible regions (i.e. the ABC posterior distributions).

SysSim has already been used to develop a suite of statistical, population models:

- *Paper I (He+2019)* introduced the first "clustered" models in which planets are drawn from a Poisson point process, where planets within the same cluster have correlated periods and radii.
- *Paper II (He+2021a)* modeled the change in occurrence of planetary systems as a function of host stellar type and found that the fraction of stars with planets increases towards later type dwarfs (redder stars).
- *Paper III (He+2020)* invented a procedure for drawing the orbital eccentricities and mutual inclinations for multi-planet systems by enforcing the angular momentum deficit (AMD)-stability criteria, producing the state-of-the-art "maximum AMD model" which can reproduce a surprising number of features seen in the Kepler catalog. **This model is hereafter referred to as the "H20" model, and we will build on this model in this work.**

3. A "HYBRID" POPULATION MODEL: COMBINING MULTI-PLANET ARCHITECTURES WITH PHOTOEVAPORATION

The previous SysSim models can produce correlated planet sizes within multi-planet systems but cannot reproduce any planet radius valley (intrinsic or observed).

Alternatively, Neil and Rogers (2020) (hereafter NR20) introduced a series of population models for producing a radius valley. Their models define a joint mass-radius-period distribution and adopt an analytical prescription for photoevaporation to sculpt the final planet radius distribution. However, these models treat planets independently and do not account for planet multiplicity or attempt to fit the multi-planet statistics.

In this work, we develop a "hybrid" model between the existing SysSim (H20) model and the NR20 model, in order to find a multi-planet model that can reproduce both the observed planet radius valley and intra-system similarity patterns.

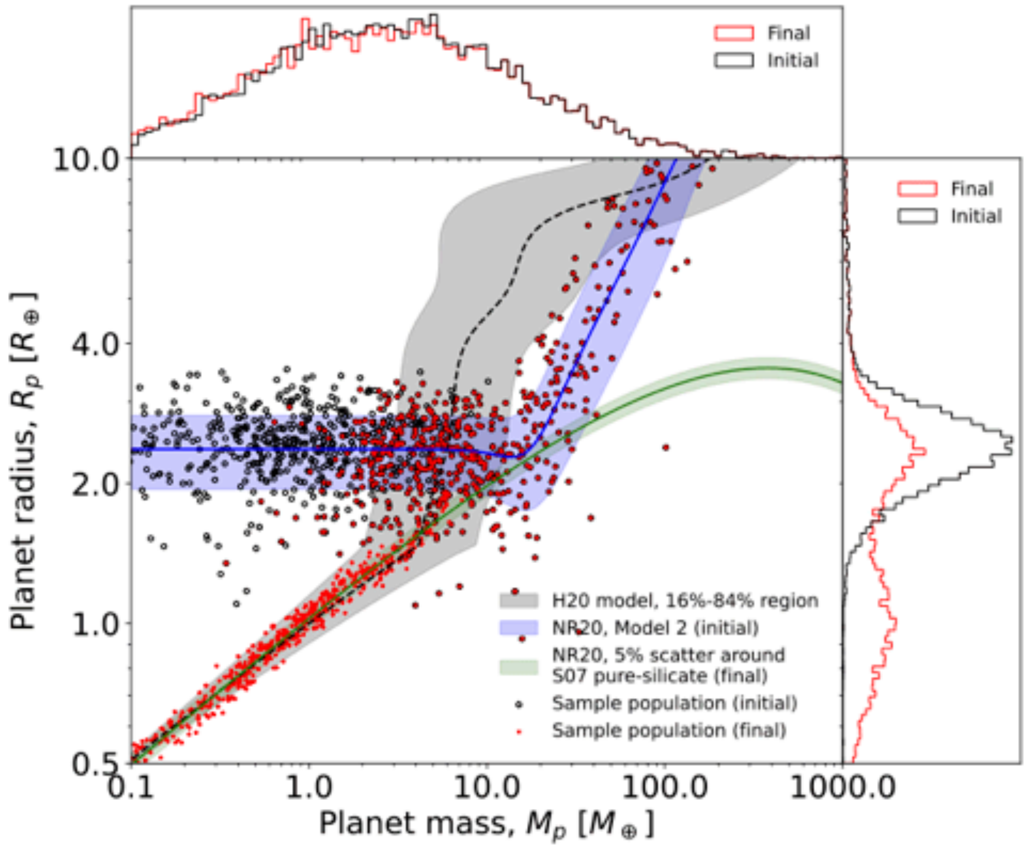

Figure 2: Planet radius-mass relationships of various models. The mass-radius relation of the H20 model is shown as the gray shaded region. Likewise, the initial radius-mass relation from the NR20 models is shown in blue. The green curve shows a pure-silicate relation (Seager+2007) from which the radii of photoevaporated planets are assigned in NR20.

A sample of planets drawn from the NR20 model is shown as the scatter points, with black hollow circles denoting the 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).

Defining the hybrid model

Preliminary work shows that simply adopting the photoevaporation model from NR20 to sculpt the radii of the planets in the H20 model does not adequately reproduce the observed radius valley.

We swap out the planet mass-radius component of the H20 model with the planet radius-mass distribution of the NR20 model (Figure 2). This involves adopting:

- a lognormal distribution of initial planet masses,
- a flexible radius-mass relation for assigning initial planet radii from the initial masses, and

- an envelope-mass fraction relation (Thorngren+2016).

The envelope mass-loss timescale is then computed for each planet (Lopez+2012) and compared to the system age to model the probability of envelope mass-loss due to photoevaporation. For planets that have lost their gaseous envelopes, their final radii are computed using a pure-silicate relation (Seager+2007).

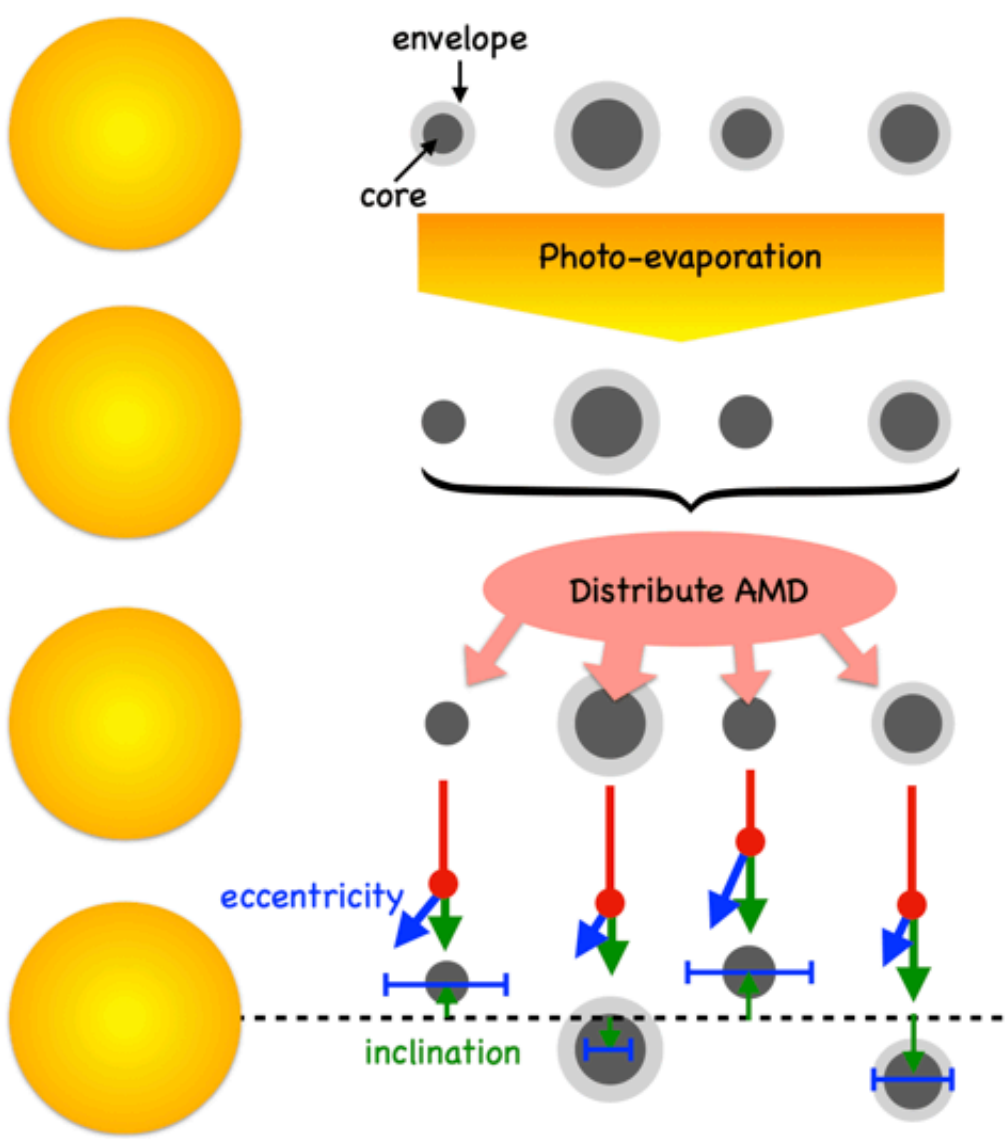

Figure 3: Cartoon illustration of our procedure for drawing a planetary system from the hybrid model.

We keep all other components of the H20 model (the parametric forms of the fraction of stars with planets and the multiplicity distribution, the clustered periods distribution, and the AMD stability criteria). The procedure for drawing a planetary system from the hybrid model is thus outlined below (Figure 3):

1. Draw a number of planet-clusters and planets per cluster in the system.
2. Draw the initial physical properties (initial masses, envelope masses, radii, and orbital periods) of the planets.
3. Compute the mass-loss timescale and then the probability of envelope mass-loss for each planet. Flip a coin weighted by this probability to determine whether the planet loses its envelope.
4. For planets that have lost their envelopes, compute their final radii from their core masses.
5. Draw the orbital eccentricities and mutual inclinations of the planets using the procedure of distributing AMD from the H20 model.

The SysSim pipeline for modeling the Kepler detection efficiency is then applied to simulate the observed planets and their measured properties!

4. CAN THE HYBRID MODEL REPRODUCE BOTH THE RADIUS VALLEY AND INTRA-SYSTEM SIZE SIMILARITY?

The observed radius valley

We demonstrate that the hybrid model is *capable* of produce a planet radius valley for some combination of model parameters.

However, the model struggles to *reliably* reproduce an observed radius valley due to:

- large uncertainties in the model parameters
- the high stochastic noise in generating simulated catalogs

The simulated-observed radius distribution from the hybrid model only rarely produces a valley as deep as seen in the Kepler catalog (Figure 4)!

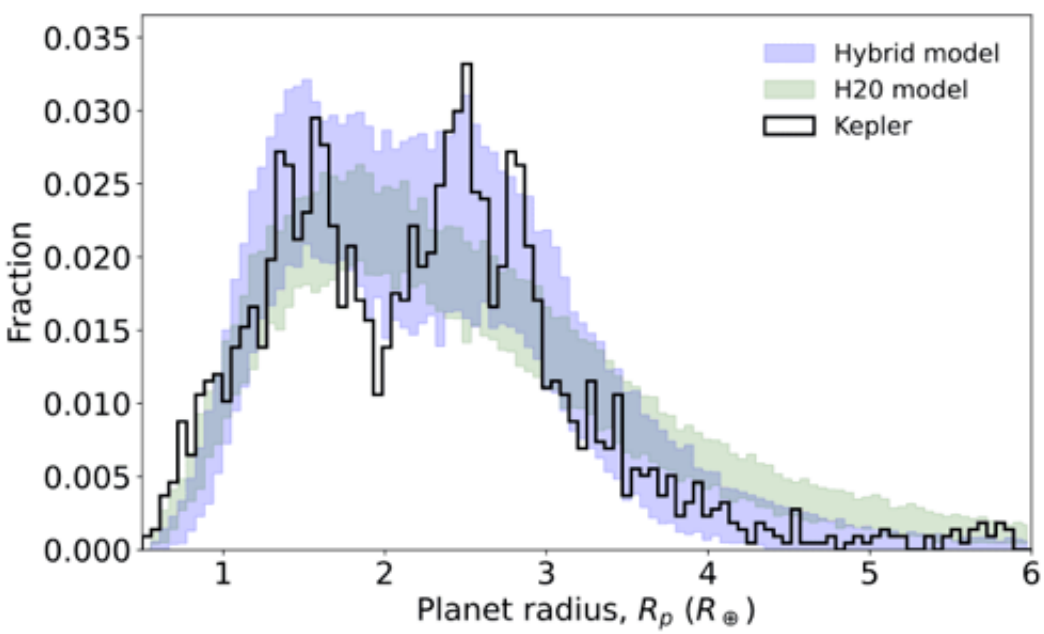

Figure 4: The observed distributions of planet radii for the Kepler catalog (black) and simulated catalogs from the H20 (green) and hybrid (blue) models. The shaded regions are the 16-84% credible regions. An observed "radius valley" (around ~2 Earth radii) is clearly seen in the Kepler distribution, but is not well reproduced by either model. The hybrid model (blue) occasionally generates a radius valley, but only rarely produces one as deep as the Kepler data.

Nevertheless, the hybrid model provides a better fit to the radius distribution than the H20 model!

- The hybrid model can occasionally generate a radius gap, unlike the H20 model which never produces a bimodal distribution of planet radii.
- The hybrid model also more closely reproduces the tail of the distribution towards larger planets, unlike the H20 model which generates too many planets larger than 3.5 Earth radii compared to Kepler.

Intra-system size similarity

Several metrics have been previously devised and used to quantify the degree of planet size similarity in multi-planet systems (He+2019,2020, Gilbert and Fabrycky 2020):

- The transit depth ratios of adjacent planets, which are equivalent to the planet radii ratios squared (since the stellar radius cancels out for planets transiting the same star).
- The "radius partitioning" metric which quantifies the degree of size similarity of the system as a whole. It ranges from 0 (identically sized planets) to 1 (one planet is significantly larger than the rest).
- The "radius monotonicity" metric which quantifies the degree of size ordering. Positive values indicate a trend of increasing planet size towards longer periods (and the opposite for negative values).

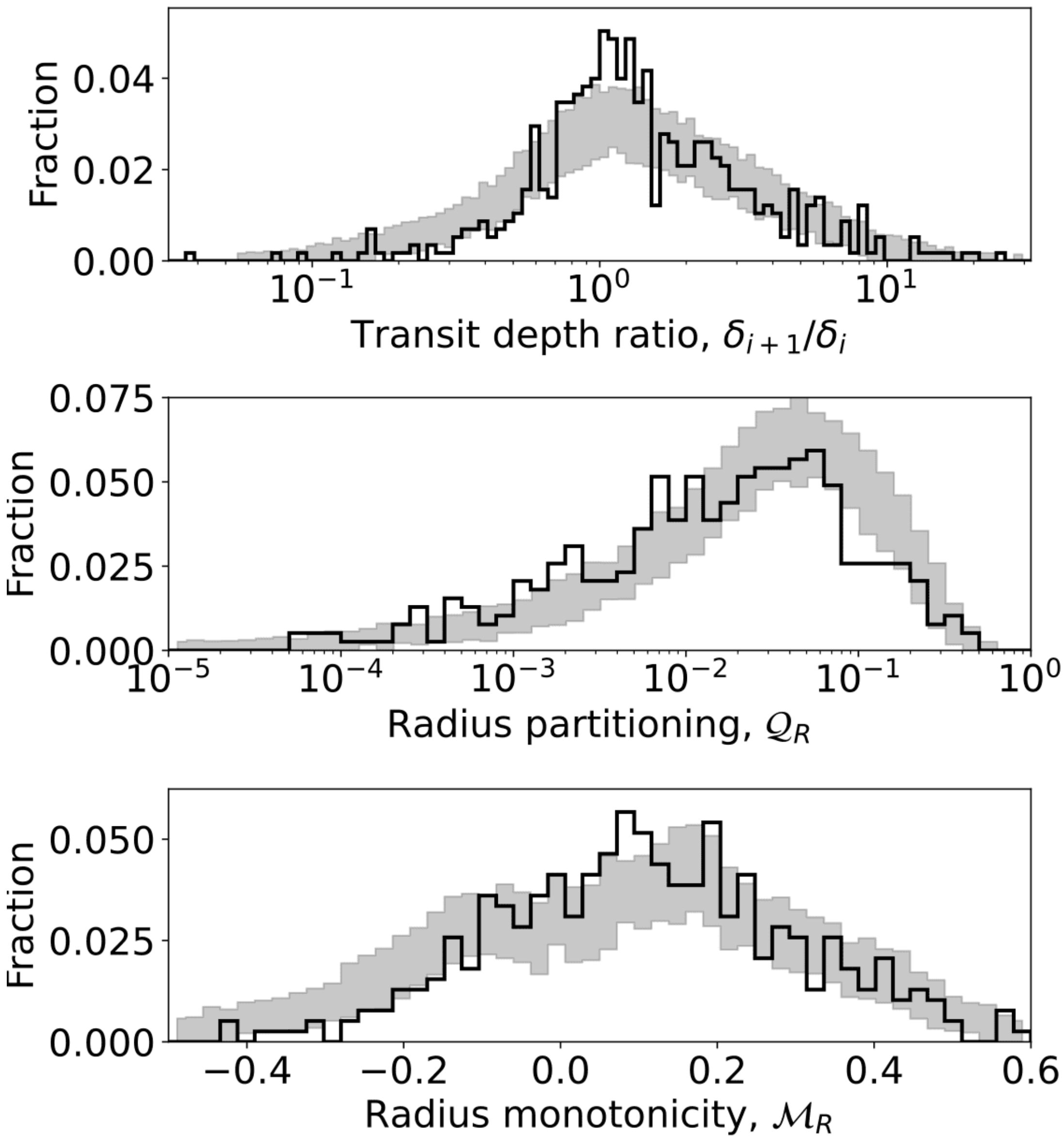

Figure 5: The observed distributions of metrics quantifying the planet radii patterns within multi-planet systems, for the Kepler catalog (black) and simulated catalogs from the hybrid model (gray). The distribution of transit depth ratios of adjacent planets (top), radius partitioning (middle), and radius monotonicity (bottom) are compared between the hybrid model and the Kepler data.

The hybrid model assumes a lognormal distribution of initial planet masses, but does not otherwise enforce any correlation between the initial planet radii. *Some natural clustering may occur due to the radius-mass relation and/or photoevaporation.* Figure 5 shows how simulated catalogs from the hybrid model compare to the Kepler data in terms of the size similarity metrics.

This model also struggles to fit the observed transit depth ratio distribution. The peak is around unity is stronger in the Kepler data. The distribution of radius partitioning is also shifted towards slightly larger values in the simulated catalogs compared to Kepler, **suggesting that the pattern of size similarity is even stronger in the real exoplanetary systems!**

For the distribution of radius monotonicity, we would expect more values greater than zero from the effects of photoevaporation (which is more significant for planets with shorter periods). We see this effect and the hybrid model is comparable to the Kepler data.

5. MODEL PREDICTIONS AND IMPROVEMENTS

We will further examine our hybrid model to understand what it predicts for the underlying planetary population.

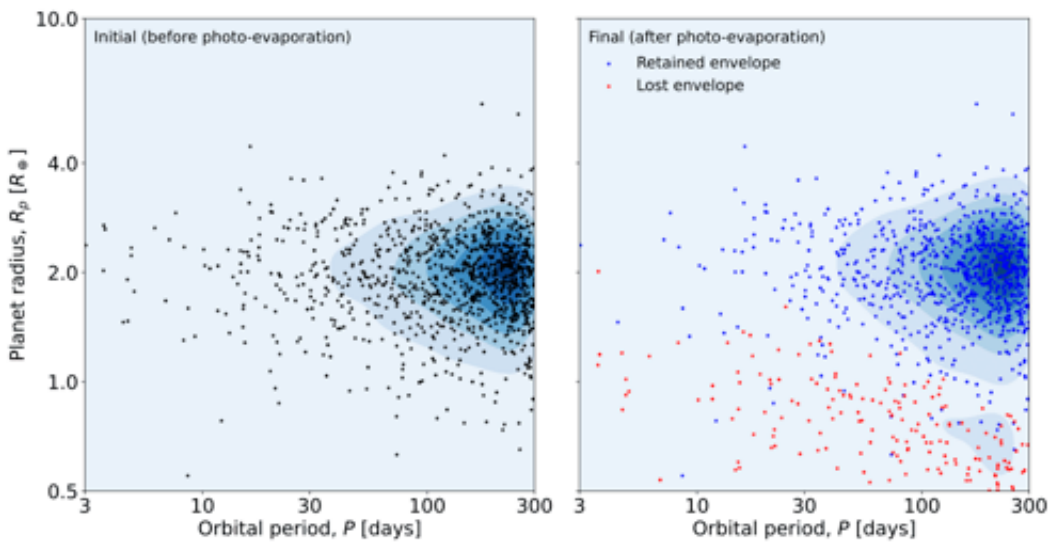

Figure 6: The underlying period-radius distribution for a sample population drawn from the hybrid model, before (left) and after (right) photoevaporation. In right panel, the planets that have retained or lost their envelopes are denoted by blue and red points, respectively. This iteration produces a very shallow radius valley.

Figure 6 shows an intrinsic sample population drawn from an iteration of the hybrid model, in period-radius space. The initial (before photoevaporation) and final (after photoevaporation) distributions are shown in the left and right panels, respectively.

We will also explore the initial planet mass and core mass distributions inferred from the hybrid model.

Future improvements

While the hybrid model is an improvement over the H20 model, it still does not fully capture the observed planet radius features seen in the Kepler catalog. Additional work is needed to further understand these patterns:

- Which combinations of model parameters can generate the deepest radius valley?
- How much additional clustering in planet sizes is needed to match the observed size similarity patterns?

6. REPOSITORIES

The SysSim codebase is made publicly available via the following repositories:

SysSimExClusters (https://github.com/hematthi/SysSimExClusters (https://github.com/hematthi/SysSimExClusters)) -- Julia package for simulating physical and observed catalogs of planetary systems from models

SysSimPyPlots (https://syssimpyplots.readthedocs.io/en/latest/ (https://syssimpyplots.readthedocs.io/en/latest/)) -- Python package for visualizing the simulated catalogs and multi-planet statistics

DISCLOSURES

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TRANSCRIPT

ABSTRACT

Multi-planet systems provide crucial insights into the architectures and correlations within planetary systems, which in turn offer clues into their formation and evolution histories. Through the thousands of exoplanet candidates that it discovered, NASA's Kepler mission revealed that systems with multiple transiting planets are common. We describe a new model for inferring the exoplanet population observed by Kepler, which combines a semi-parametric description of planetary systems with a prescription for envelope mass-loss due to photoevaporation. This new model is a "hybrid" of the maximum AMD (angular momentum deficit) model in which the orbital excitations of the planets are drawn by distributing the system's critical AMD (He et al. 2020), and a photoevaporation model for sculpting the observed radius valley (Neil & Rogers 2020). This is an update to the SysSim suite of exoplanet population models derived from forward modeling the Kepler detection pipeline. The hybrid model is constrained by the observed statistics of multi-transiting systems, including additional constraints from the distribution of planet radii and their intra-system size patterns. This model is capable of producing a planet radius valley as well as a preference for planet size similarity. However, we find that the Kepler catalog exhibits features that are even more significant (i.e., it has a deeper observed radius valley and stronger size similarity) than the best-fit model. We use this model to infer the intrinsic planet radius valley as well as the distribution of primordial planet masses and core masses.

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