Architectures of Exoplanetary Systems: A Forward Model for Planets around Kepler's FGK Stars with Clustered Periods and Sizes

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Introduction

Thousands of exoplanet candidates have been discovered to date, thanks to NASA's Kepler mission. This explosion in the number of known exoplanet systems has enabled population studies, allowing us to probe system architectures and to develop theories for planet formation.

We present several statistical models in the context of a forward modeling framework for the Kepler mission, which can generate underlying populations of exoplanets that reproduce the observed data and allows us to infer properties of planetary systems in general.

We forward model the Kepler mission

$f(P, R)$ **Step 1:** Define a statistical model for the intrinsic distribution of exoplanetary systems.

Step 2: Generate an underlying population of exoplanetary systems (*physical catalog*) from a given model.

Step 3: Generate an observed population of exoplanetary systems (*observed catalog*) from the *physical catalog*.

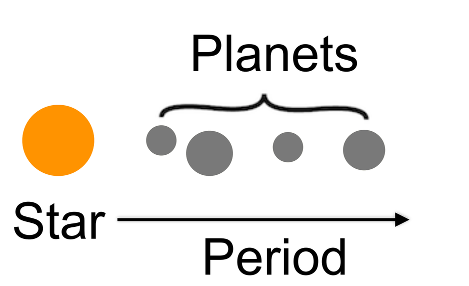
Step 4: Compare the simulated *observed catalog* with the Kepler data.

Step 5: Optimize a distance function to find the best-fit model parameters.

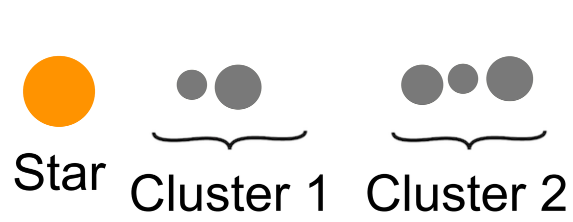
Step 6: Explore the posterior distribution of model parameters using a Gaussian Process (GP) emulator.

Models for intrinsic planetary systems

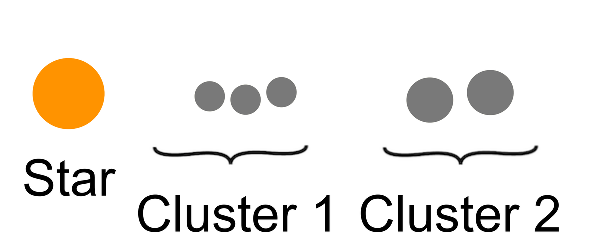
Non-clustered:
Planets are drawn independently with power-law for orbital periods and broken power-law for radii.



Clustered Periods:
Planets are drawn from clusters, where their periods are conditional on each cluster's period scale.



Clustered Periods and Sizes:
Planets are drawn from clusters, where their periods and radii are conditional on each cluster's period and radius scale.



Exoplanetary systems are clustered

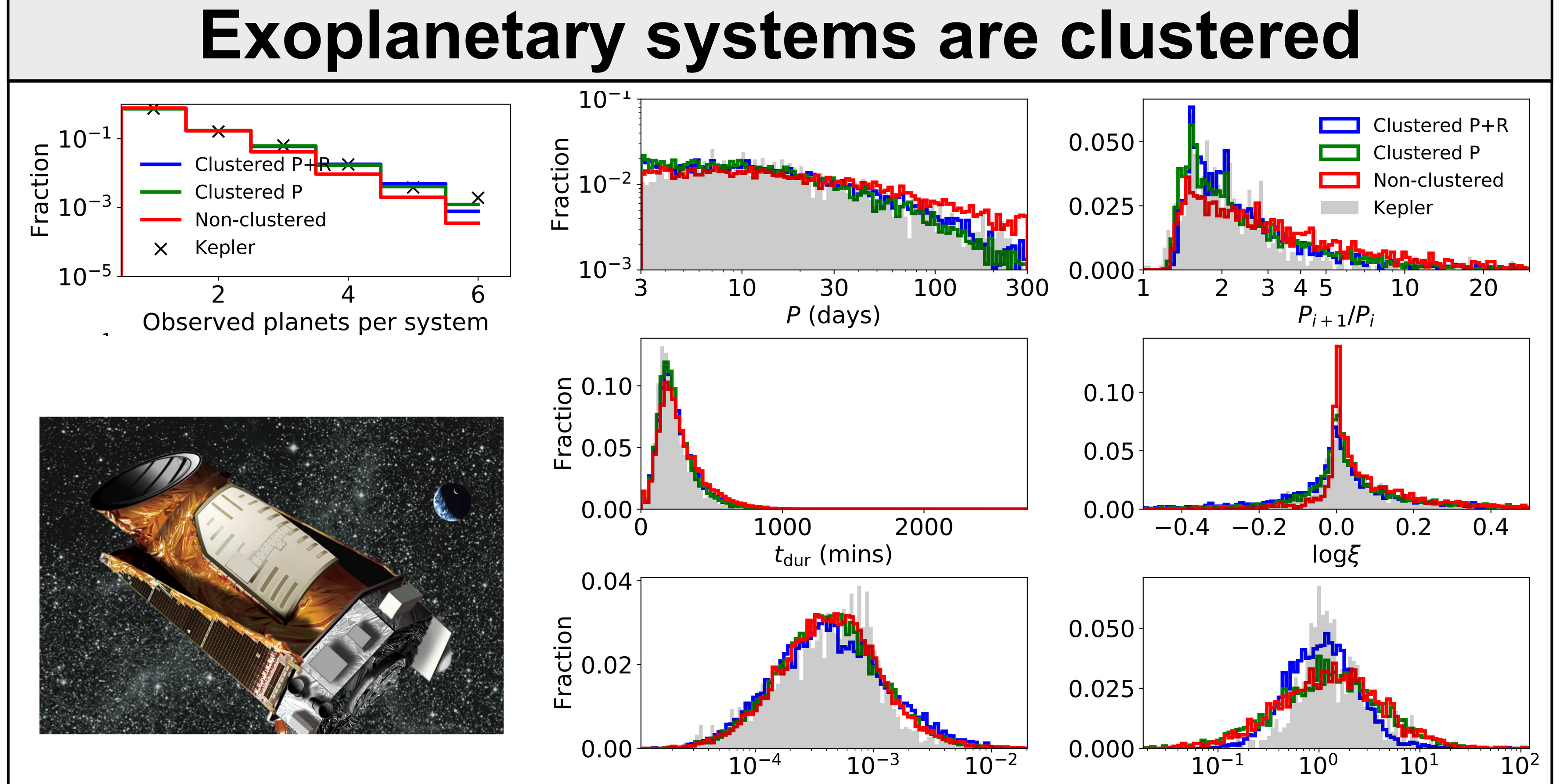


Figure 1: Simulated *observed catalogs* for each of our three models (colored histograms as labeled), with the Kepler data plotted in gray (we include all planet candidates from DR25 with orbital periods between 3—300 days and measured radii between 0.5—10 $R_\oplus$).

The Clustered Periods and Sizes model best fits the Kepler data.

Predictions for the intrinsic planetary systems

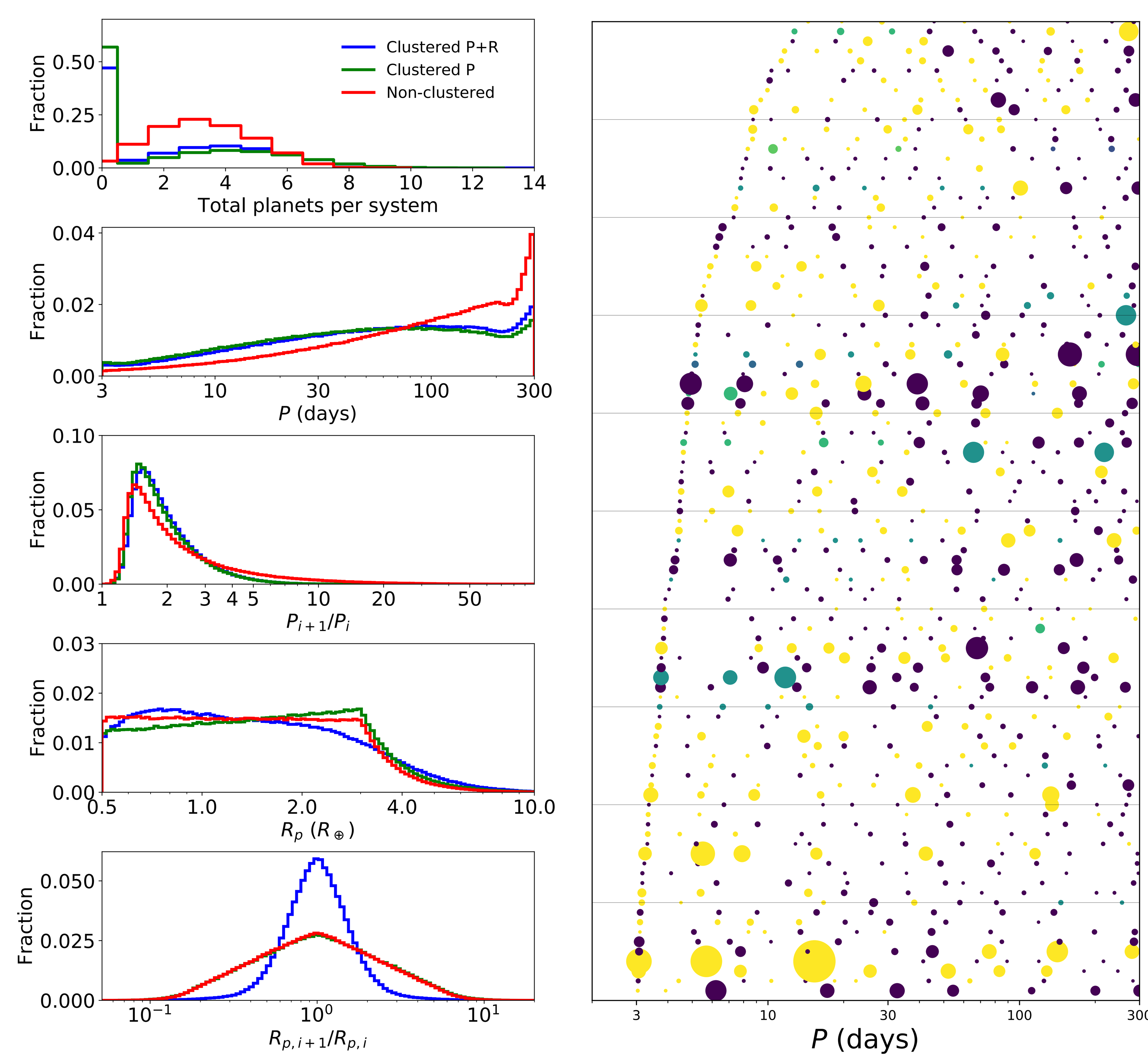
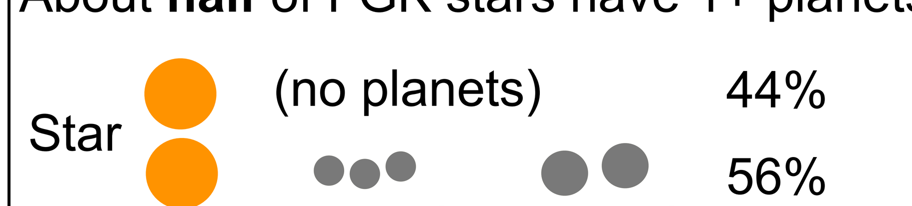


Figure 2: Simulated *physical catalogs* for each of our three models (colored as labeled): distributions of the true number of planets per system, orbital periods, period ratios, planet radii, and planet radii ratios. The right side shows a sample of 100 systems with 8+ planets from our Clustered Periods and Sizes model, with colors denoting various clusters of planets.

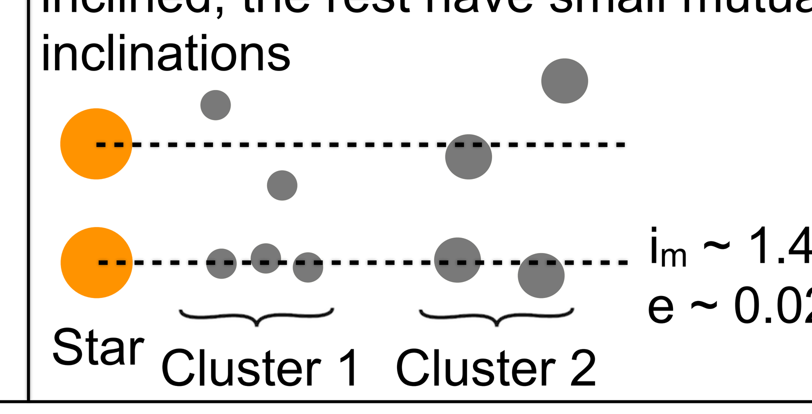
The fraction of stars with planets and the Kepler dichotomy

About **half** of FGK stars have 1+ planets



The typical planetary system has one (79%) or two (19%) clusters with an average of ~4 planets per system

About ~40% of systems are highly-inclined; the rest have small mutual inclinations



Summary

We present a pipeline for generating populations of intrinsic exoplanetary systems and simulating observed catalogs of transit detections under the conditions of a Kepler-like mission. Using this program, we developed and fit three physically motivated, statistical models to the Kepler data.

A simple model involving independently drawn periods and sizes is inadequate for describing the Kepler population, especially that of the multi-transiting systems. We provide a forward model for generating planetary systems with planets clustered in both periods and sizes that reproduces the key features of the Kepler exoplanet population.

References and Acknowledgements

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2. Weiss et al. (2018), AJ, 155, 48
3. Hsu et al. (2018), AJ, 155, 205, & (2019), arXiv:1902.01417
4. **He, Ford, & Ragozzine (2019), submitted to MNRAS; arXiv:1907.07773**

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