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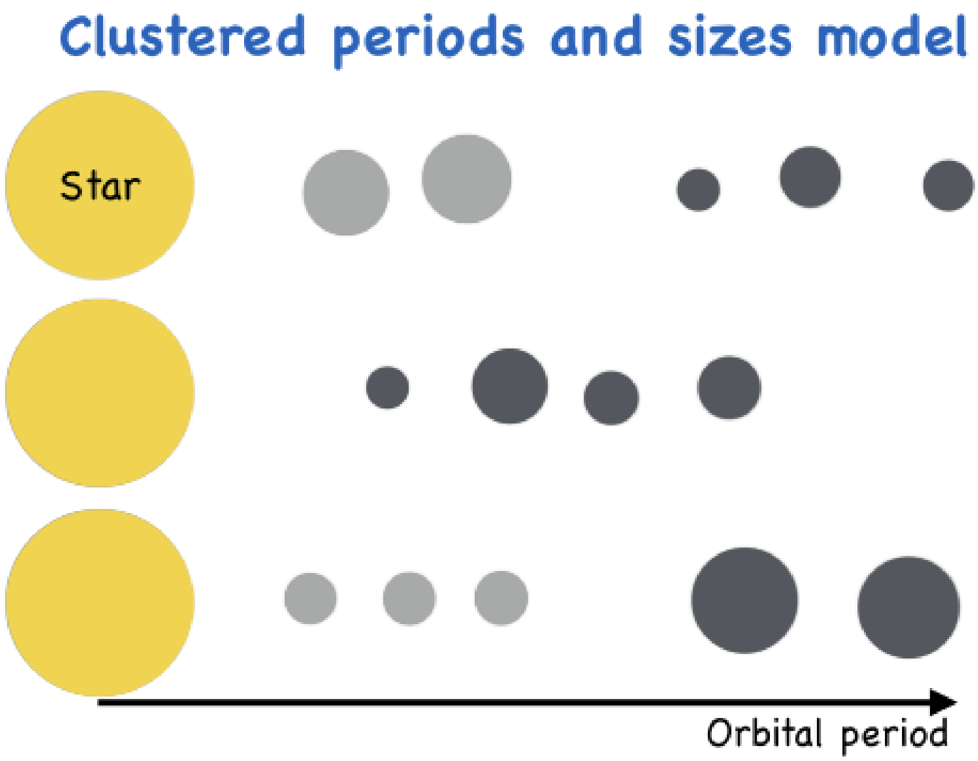
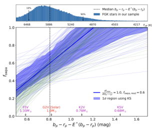
The Occurrence, Architectures, and Correlations of AMD-Stable Planetary Systems

Matthias He[1], Eric Ford[1], and Darin Ragozzine[2]
[1]Department of Astronomy & Astrophysics, The Pennsylvania State University, State College PA, United States of America
[2]Department of Physics & Astronomy, Brigham Young University, Provo UT, United States of America

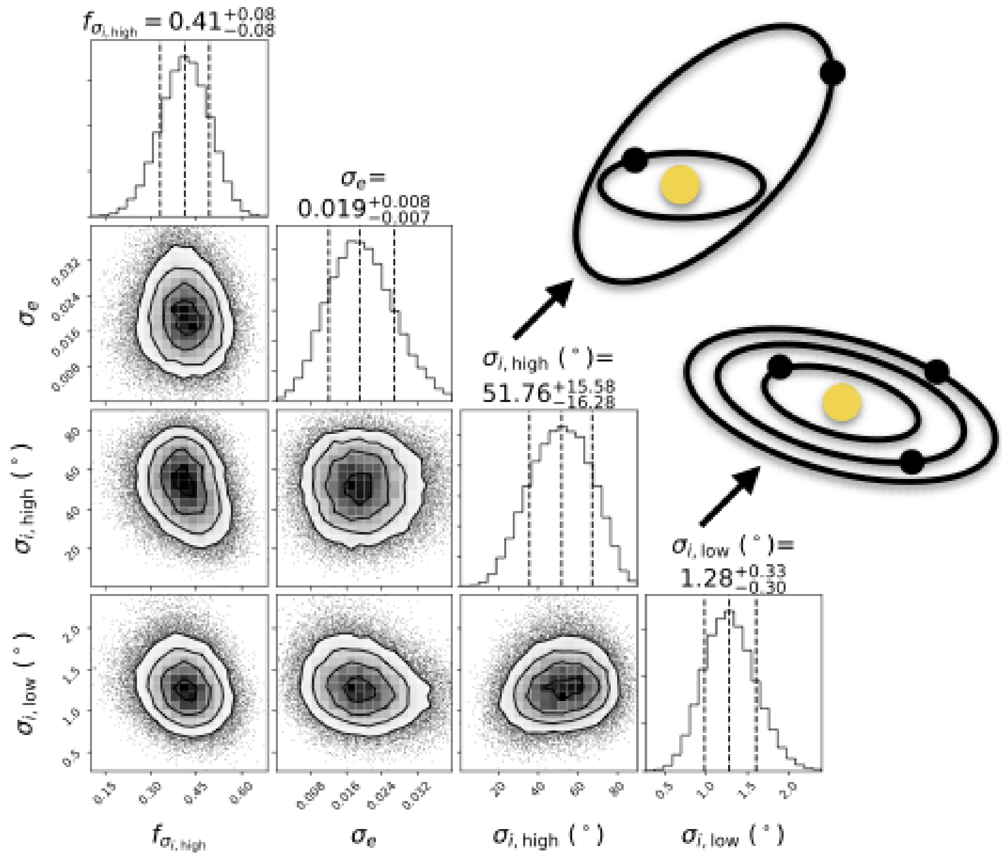
The Kepler mission revealed thousands of exoplanet candidates, providing key insights into the distributions and demographics of planetary systems. Many of these planets are in multiple-transiting planet systems, which yield additional information about the correlations within planetary systems and their architectures. However, these properties are shrouded by complex detection biases, which must be properly accounted for in order to disentangle the intrinsic system architectures from the observational biases.



Cartoon illustration of our clustered models. We find that a model with clustered periods and planet sizes best fits the Kepler catalog. In this model, a number of clusters and planets per cluster are drawn from zero-truncated Poisson distributions. The periods and radii of planets in the same cluster are each correlated, resulting from draws from a lognormal distribution.

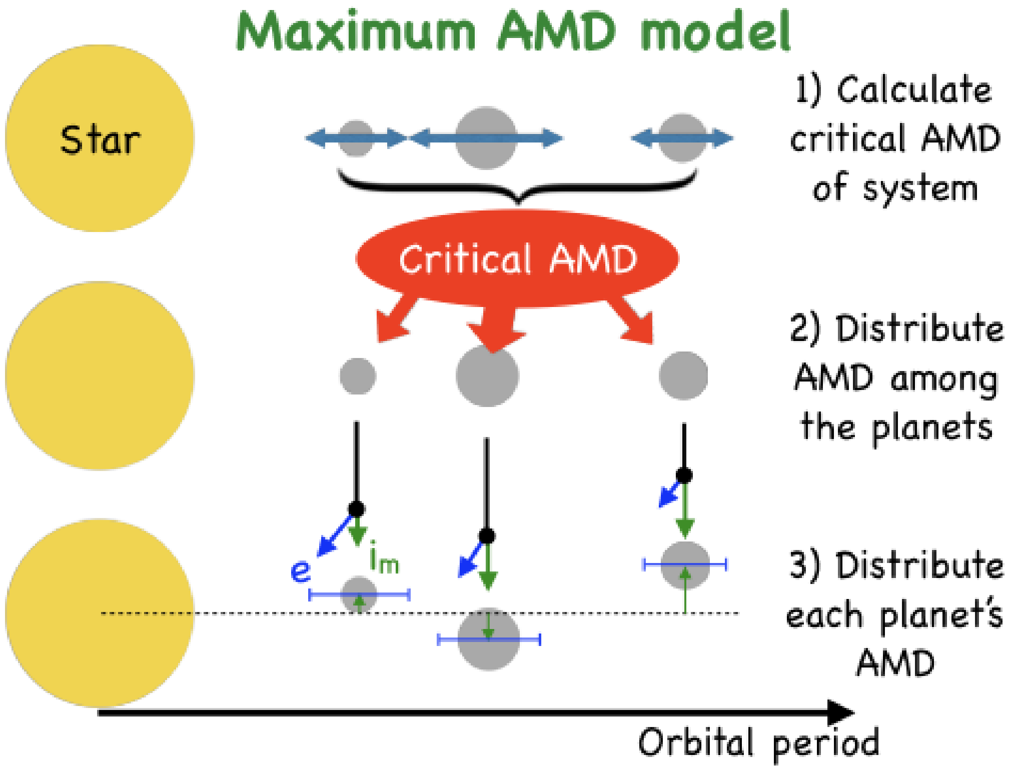


In He, Ford, & Ragozzine (2019, 2020), we developed an advanced forward model (SysSim) to infer the intrinsic distributions of planetary systems around FGK dwarfs, by constructing parametric models for drawing planetary systems, simulating the Kepler detection efficiency to produce synthetic observed catalogs, and comparing these catalogs to the Kepler catalog. We show that planetary systems around FGK dwarfs are clustered in periods and in sizes, as evidenced by fitting to the observed distributions of multiplicities, period ratios, and transit depth ratios. We also find that the fraction of stars with planets (with $R_p > 0.5\ R_{\oplus}$ and 3d < P < 300d) increases significantly towards later type (cooler) stars, rising by over a factor of two from early F to mid K dwarfs. The observed multiplicity distribution can be well matched by two populations consisting of a low and a high mutual inclination component (a Kepler dichotomy).

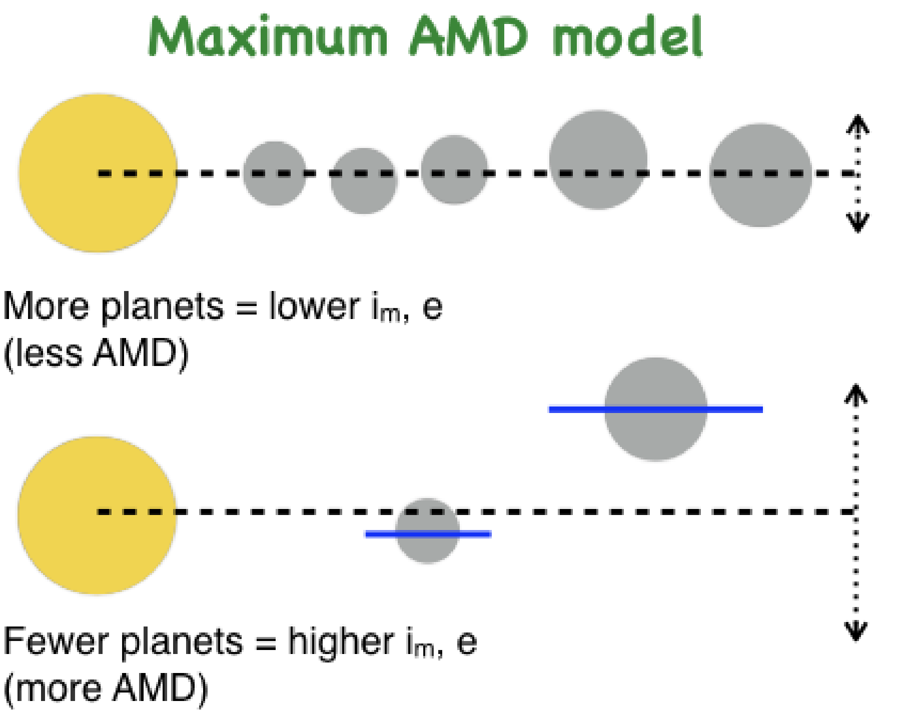


A two-Rayleigh model of mutual inclinations (including a low and a high mutual inclination population) can fit the Kepler observed multiplicity distribution well, providing one solution to the "Kepler dichotomy".

Here, I will also present a new model to show that a broad distribution of eccentricities and mutual inclinations arising from systems at the angular momentum deficit (AMD) stability limit can also reproduce the observed population. The AMD stability limit provides a dynamically motivated view of orbital architectures and serves to constrain the high mutual inclination systems. In our new model, we distribute the maximum AMD of each multi-planet system amongst the planets and show that this results in a multiplicity-dependent distribution of eccentricities and mutual inclinations. Systems with intrinsically more planets have lower eccentricities and mutual inclinations. For each intrinsic multiplicity order, the distributions of eccentricities and mutual inclinations are close to lognormal, instead of the previously assumed Rayleigh distributions. This trend with multiplicity arises from the dependence of the critical AMD on the minimum period ratio in the system, as systems with tightly-spaced planets must have low AMD in order to remain long-term stable. We also find evidence that intrinsic single planets have higher eccentricities than multi-planet systems, although their distribution is not well constrained. I will show that there is evidence for these trends with multiplicity in the Kepler distributions of circular-normalized transit durations and transit duration ratios.

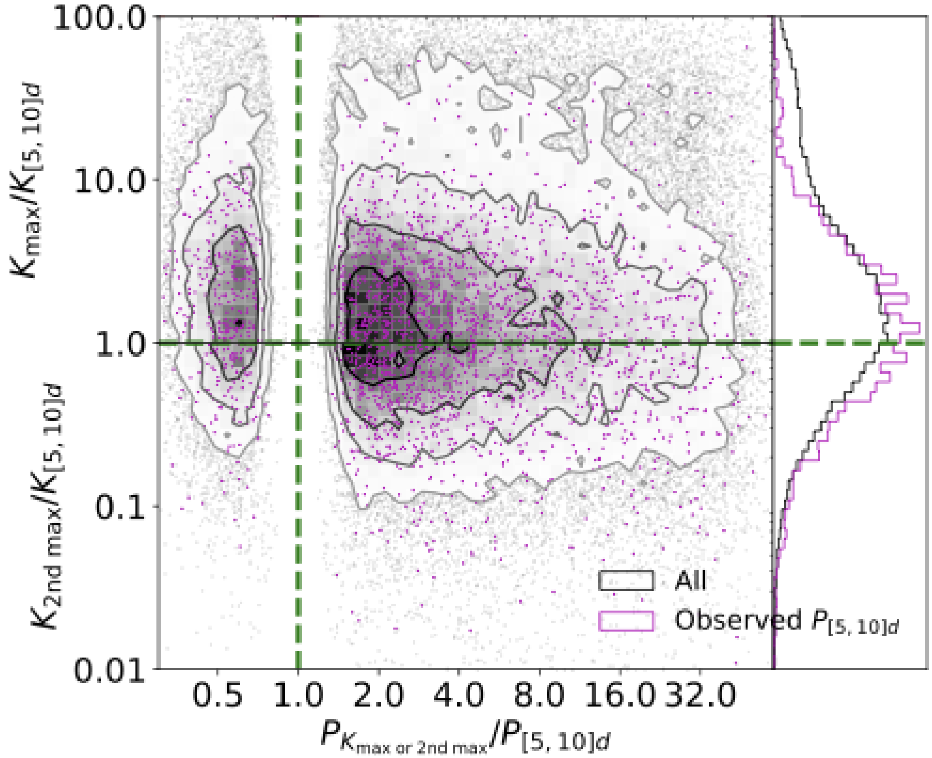


Cartoon illustration of our "maximum AMD model". We first (1) compute the critical AMD given a set of planet masses and orbital periods, (2) distribute the critical AMD amongst the planets, and (3) distribute the AMD of each planet amongst their eccentricity and mutual inclination components to excite their orbits.



The “maximum AMD model” results in a multiplicity-dependent distribution of mutual inclinations (i_m) and eccentricities (e). Systems with intrinsically more planets have a lower critical AMD to remain stable, leading to more circular and coplanar orbits. Systems with intrinsically fewer planets have a higher critical AMD, allowing for more excited orbits.

Our code for simulating planet catalogs from our state-of-the-art models is available publicly. We share simulated catalogs of both intrinsic systems and observed (under a Kepler-like mission) systems. These catalogs can be used to inform radial velocity follow-up efforts in the search for additional planet companions in systems with transiting planets, such as those discovered by the TESS mission. Our models can also be used as a point of comparison with planet formation simulations, and for future studies of planetary system architectures.



Scatter plot of RV semi-amplitude (K) ratio vs. period ratio for a simulated physical catalog. TESS is finding many planets between 5 and 10 days. For each of these planets in our simulations, we plot the K ratio compared to the maximum or second maximum RV amplitude in the system. Our models can be used to inform RV follow-up of systems with short-period transiting planets.