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Inner Planetary System Gap Complexity is a Predictor of Outer Giant Planets

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Abstract

The connection between inner small planets and outer giant planets is crucial to our understanding of planet formation across a wide range of orbital separations. While Kepler provided a plethora of compact multiplanet systems at short separations ($\lesssim$1 au), relatively little is known about the occurrence of giant companions at larger separations and how they impact the architectures of the inner systems. Here, we use the catalog of systems from the Kepler Giant Planet Search to study how the architectures of the inner transiting planets correlate with the presence of outer giant planets. We find that for systems with at least three small transiting planets, the distribution of inner-system gap complexity ($\mathcal{C}$), a measure of the deviation from uniform spacings, appears to differ ($p \lesssim 0.02$) between those with an outer giant planet ($50M_\oplus \leqslant M_p \sin i \leqslant 13M_{\rm Jup}$) and those without any outer giants. All four inner systems (with three or more transiting planets) with outer giant(s) have a higher gap complexity ($\mathcal{C} > 0.32$) than 79% (19/24) of the inner systems without any outer giants (median $\mathcal{C} \simeq 0.06$). This suggests that one can predict the occurrence of outer giant companions by selecting multitransiting systems with highly irregular spacings. We do not find any correlation between the outer giant occurrence and the size (similarity or ordering) patterns of the inner planets. The higher gap complexities of inner systems with an outer giant hints that massive external planets play an important role in the formation and/or disruption of the inner systems.

Unified Astronomy Thesaurus concepts: Exoplanet systems (484); Exoplanet detection methods (489); Exoplanet dynamics (490); Exoplanet formation (492); Exoplanets (498); Extrasolar gaseous giant planets (509); Extrasolar rocky planets (511); Planetary system formation (1257); Radial velocity (1332)

1. Introduction

NASA's Kepler mission has populated our view of extrasolar systems by discovering thousands of planets smaller than Neptune around the inner reaches (within $\sim$1 au) of solar-type stars (Borucki et al. 2010). While compact systems containing multiple sub-Neptune-sized planets are very common around solar-type stars (with recent estimates of $\gtrsim$60%; e.g., He et al. 2020), the distribution of Kepler multitransiting systems still presents some unsolved puzzles. For example, the role of in situ formation versus orbital migration remains unclear for the majority of planetary systems. While in situ formation is unlikely to explain all Kepler systems (Raymond & Cossou 2014; He & Ford 2022), most Kepler planets are not in mean-motion resonances (Fabrycky et al. 2014), a hallmark of convergent migration (Lee & Peale 2002). The period ratios of systems with three or more transiting planets are highly correlated (Weiss et al. 2018) to an extent that current population models still struggle to reproduce, however (Mulders et al. 2018; He et al. 2019; Gilbert & Fabrycky 2020; He et al. 2020).

A chief concern in disentangling the signatures of planet formation among the Kepler planetary systems is that very little is known about the basic properties of planets these systems might harbor in their outer regions (beyond $\sim$1 au). Planets at larger separations are rarely detected with transit surveys such as Kepler because (1) their geometric probability of transiting is low compared to that of close-in planets, and (2) even if they do transit, they only transit once every few years (thus requiring a long baseline for a transit detection; Winn 2010). In contrast, ground-based radial velocity (RV) surveys, although still limited by the observing baselines, readily detect Jupiter-mass planets at distant separations out to several AU (e.g., Marcy et al. 2014; Neveu-VanMalle et al. 2016; Mills et al. 2019; Weiss et al. 2020; Zhang et al. 2021).

Do outer giant (OG) planets tend to enhance, hinder, or otherwise not affect the formation of the inner compact multiplanet systems that are so prevalent around Sun-like stars? This is a challenging question to address observationally because until recently, there was very little overlap between stars with known transiting planets and stars with long-term RV follow-up. A few studies have attempted to estimate the occurrence of distant giant companions among systems that have close-in small planets (SPs) using Bayesian inference (Zhu & Wu 2018; Bryan et al. 2019; Rosenthal et al. 2022; Van Zandt et al. 2023; Bonomo et al. 2023). However, these studies do not address how the multiplanet architectures of the inner (transiting) systems relate to the presence of OG companions. In this paper, we take a different approach and focus on the architectures of transiting systems as a function of whether they have OGs using a new catalog of Kepler systems with RV measurements.

The Kepler Giant Planet Search (KGPS; Weiss et al. 2023, hereafter KGPS I) is a decade-long survey of Kepler stars known to host small, sub-Neptune-sized transiting planets via long-term RV monitoring to search for giant planet companions. With RV observations obtained from the W. M. Keck Observatory going back to 2009, KGPS collected at least 10 epochs of RVs for each target that indicated the presence of Jupiter-mass planets, enabling precise orbit determinations. The full RV data set was recently analyzed using the new systematic KGPS algorithm to produce a curated catalog of 63 planetary systems with 20 RV-detected companions (13 of which are planets more massive than Saturn, and 8 of which are newly announced; KGPS I). This sample provides an unprecedented opportunity to not only provide an updated estimate of the conditional occurrence of OGs to inner transiting planets, but also to assess potential correlations between these OGs and the architectures of the inner systems in a statistical manner.

In this study, we use KGPS I to look for correlations between the inner architectures of the multitransiting systems and the occurrence of OG planet companions. We outline this paper as follows: in Section 2 we summarize the KGPS sample and how we divide the sample (including how we define an OG planet). In Section 3 we review the concept of gap complexity and present our main result, that the inner systems tend to have higher gap complexities when they also have an OG planet than when they do not. In Section 4 we analyze whether there are any correlations between the metrics that describe the size similarity patterns and the occurrence of OGs. We address potential biases and discuss theoretical implications in Section 5. Finally, we summarize our findings in Section 6.

2. Planet Sample

We use the table of planetary systems from the KGPS I catalog. This sample consists of 63 systems with 177 planets (157 transiting and 20 nontransiting, RV-detected planets). The orbital periods (and thus semimajor axes) of the transiting planets, central to the analyses of this study, are known to a high degree of precision because the planets transit their stars many times over the course of the Kepler primary mission; the orbital periods of the nontransiting planets are also measured, although less precisely, from the RV fitting. The planet masses of the nontransiting planets are all RV-measured minimum masses ($M_p \sin i$), while the masses of the transiting planets are either measured from RVs or are, for planets with small radii or few RV measurements, estimates from a mass–radius (M-R) relation (Weiss & Marcy 2014).

Throughout this paper, we primarily use the planet mass to distinguish between "small" and "giant" planets. SP denotes a small planet that has a minimum planet mass, $M_p \sin i < 50 M_\oplus$, if measured from the RVs. All transiting planets without measured $M_p \sin i$'s are also considered SPs as they are smaller than $4 R_\oplus$ and have M-R masses lower than $\sim 10 M_\oplus$, and most of the SPs are also transiting planets. OG planets are defined as any planet with a measured minimum mass between $50 M_\oplus \leqslant M_p \sin i \lesssim 4000 M_\oplus \simeq 13 M_{\rm Jup}$ from the KGPS survey[1] (the upper limit is defined to exclude close-in stellar companions, which are present in three systems as described below), which also has a longer period than any of the SPs in the same system. The criterion of being exterior to any SPs in the same system only affects (excludes) KOI-94d, which has a mass of $79.6 \pm 8.7 M_\oplus$, but is interior to KOI-94e ($M_p = 8.1 \pm 8.2 M_\oplus$). The choice of $50 M_\oplus$ for the boundary between small and giant planets is motivated by a combination of studies that find $M_{\rm core} \simeq$ 10–20$M_\oplus$ for the critical core mass necessary to trigger runaway gas accretion (e.g., Stevenson 1982; Pollack et al. 1996; Piso et al. 2015), with at least a similar mass assumed to be accreted in the envelope, as well as empirical studies defining giant planets based on an observed transition in the mass–density relation at $\sim 0.3 M_{\rm Jup} \simeq 95 M_\oplus$ (Weiss et al. 2013; Hatzes & Rauer 2015). However, we note that our main results are rather insensitive to the exact choice of boundary provided it is between $\sim$50 and $150 M_\oplus$. By our definition, a system can have multiple OGs. The full list of KGPS systems with OGs includes KOI-85, KOI-104, KOI-142*, KOI-148*, KOI-244, KOI-246*, KOI-273*, KOI-275, KOI-316, KOI-351, KOI-1241*, KOI-1442, and KOI-1925 (those marked with an asterisk contain more than one OG).

Three systems also have significant long-term RV trends that are indicative of massive companions in the stellar regime. One is KOI-69, which hosts a small transiting planet ($R_p = 1.63 \pm 0.06 R_\oplus$ and $M_p \sin i = 3.6 \pm 0.6 M_\oplus$) at $a = 0.053$ AU and is excluded from the subsequent analyses because we focus on systems with at least two planets. The other two are KOI-2169 (Kepler-1130) and KOI-3158 (Kepler-444), which are known to host four and five transiting planets, respectively (and no OG planets). For the outer stellar companion (SC) in KOI-2169 (Kepler-1130 B), we rely on the KGPS-constrained values for its orbital separation (a = 11.5 au) and minimum mass ($M_p \sin i \simeq 218 M_{\rm Jup} \simeq 0.21 M_\odot$). For KOI-3158, the long-term RV trend is not well constrained by KGPS. This system has a known stellar binary at 52.2 au with a combined mass of $0.60 M_\odot$ (Kepler-444 BC; Zhang et al. 2023). Both of these SCs have quite eccentric orbits around their primaries, and their eccentricities are higher than that of any OG in our sample: $e = 0.66$ for Kepler-1130 B (KGPS I) and $e \simeq 0.55$ for Kepler-444 BC (Zhang et al. 2023). The inclusion or exclusion of these two systems is clearly indicated in the following analyses.

3. Gap Complexity and the Presence of Outer Giant Planets

The orbital periods and spacings of planets in a system encode key information about their migration and formation histories. The formation of giant planets may influence the subsequent orbital evolution of existing planets and/or the formation of additional planets in the system, which may produce observable features in their final architectures. A useful metric for quantifying the orbital spacings of planets in a multiplanet system is the gap complexity, $\mathcal{C}$, introduced by Gilbert & Fabrycky (2020),

$$\mathcal{C} \equiv -K\left(\sum_{i=1}^{n} p_i^* \log p_i^*\right) \cdot \left(\sum_{i=1}^{n}\left(p_i^* - \frac{1}{n}\right)^2\right), \quad (1)$$

$$p_i^* = \frac{\log \mathcal{P}_i}{\log(P_{\rm max}/P_{\rm min})}, \quad (2)$$

where $n = m - 1$ is the number of adjacent planet pairs (i.e., gaps) in the system, $\mathcal{P}_i \equiv P_{i+1}/P_i$ are their period ratios, $P_{\rm min}$ and $P_{\rm max}$ are the minimum and maximum periods in the system, respectively, and $K = 1/\mathcal{C}_{\rm max}$ is a multiplicity-dependent normalization constant chosen such that $\mathcal{C}$ is always in the range (0, 1). At least three planets are required to compute this quantity. Gilbert & Fabrycky (2020) provide a table of $\mathcal{C}_{\rm max}(n)$ for $n = 2,\ldots,9$ along with an empirically fit relation $\mathcal{C}_{\rm max} \approx 0.262 \ln(0.766 n)$; the exact value of $\mathcal{C}_{\rm max}$ must be computed numerically (Anteneodo & Plastino 1996). Defined in this way, $\mathcal{C}$ quantifies how far a system deviates from perfectly regular spacings, from 0 (evenly spaced planets in log-period) to 1 (maximum complexity).

[1] The only exception we make is Kepler-126 d, the outermost (and also transiting) planet in the KOI-260 system, because (1) its RV-measured mass, $M_p = 55 \pm 23 M_\oplus$, is relatively uncertain, and (2) its radius is very small: $R_p = 2.54 \pm 0.06 R_\oplus$ (for reference, all the other transiting planets with $M_p \geqslant 50 M_\oplus$ have radii larger than $10 R_\oplus$).

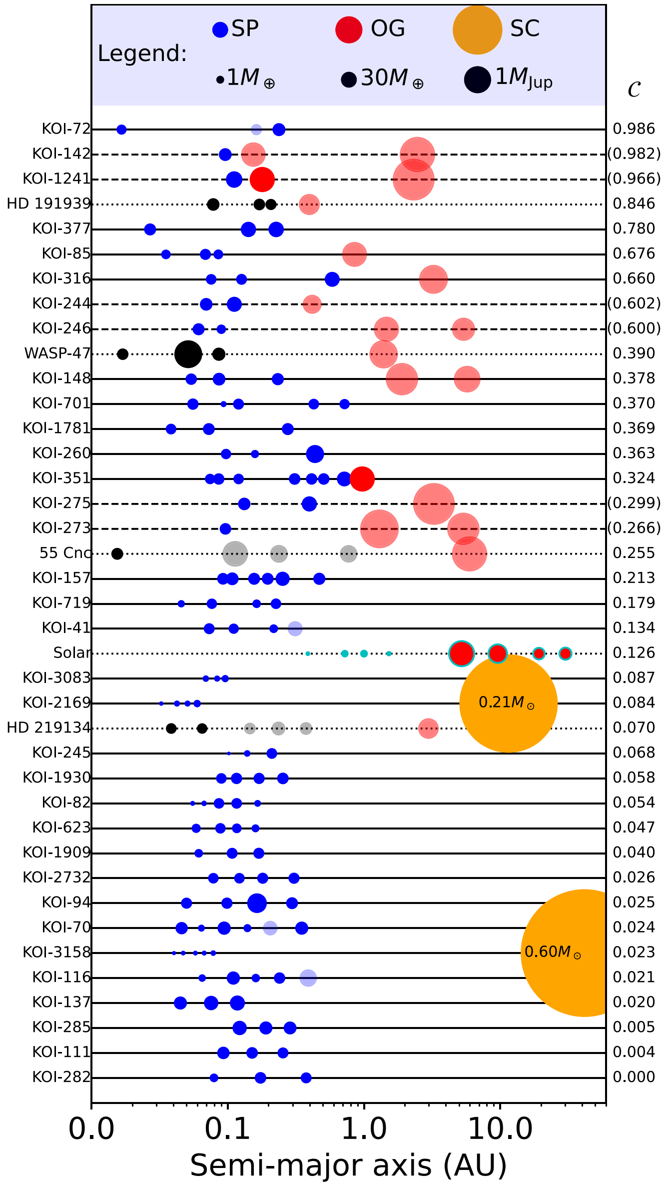

Figure 1. Architecture gallery of the KGPS and other systems with at least three planets. Each row corresponds to one planetary system (as labeled on the left y-axis) and is plotted along the semimajor axis (x-axis, log scale). The point sizes are proportional to the square root of the planet masses ($M_p \sin i$ or masses from a mass–radius relation). The point colors denote SPs (blue), OGs (red), and SCs (orange), as also labeled in the legend. Black points indicate inner planets in systems that are not part of the KGPS sample (also denoted by dotted lines). Faded points indicate nontransiting planets. The systems are sorted by the gap complexity ($\mathcal{C}$) of the inner system (where there are at least three planets, excluding any OGs or SCs), as labeled on the right y-axis, or $\mathcal{C}$ of the whole system when there are fewer than three SPs (in parentheses; these systems are also denoted by the dashed lines). For reference, the solar system is also plotted (cyan points) with the same convention, where the planets from Jupiter and beyond are categorized as OGs and are excluded from the calculation of $\mathcal{C}$.

3.1. Ranking Systems by Gap Complexity

Here, we explore whether there is any correlation between the gap complexity of the inner system and the presence or lack of OG planets. The KGPS sample contains 34 systems with at least three planets for which we can compute the gap complexity. Of these systems, 28 have at least three SPs: 4 have OG(s), 2 have SC(s), and 22 have no OGs or SCs. The remaining 6 systems all have at least one OG but fewer than three SPs. In Figure 1 we plot a gallery of these KGPS systems. Following our definitions in Section 2, SPs are denoted by blue circles, OGs are denoted by red circles, and SCs are shown as orange circles (as also labeled in the legend); faded colors indicate nontransiting planets. Each row denotes a separate system, where they have been sorted by the gap complexity of the inner system (i.e., SPs only, when there are at least three) or of the full system (i.e., SPs and OGs, when there are fewer than three SPs, as denoted by the dashed lines and numbers for $\mathcal{C}$ in parentheses).

It is immediately apparent that the systems with a higher gap complexity tend to have OG planets. Six of the top eight KGPS systems in $\mathcal{C}$ all have at least one OG planet (and often two). One may be concerned that the inclusion of a giant planet biases the calculation of $\mathcal{C}$, and it is unclear how to compare the systems with three or more planets only after including the OG(s) versus those with three or more SPs in addition to the OG(s). However, even if we ignore the systems with fewer than three SPs (dashed lines), a high gap complexity of the inner transiting system alone appears indicative of OG planet occurrence. All four inner systems with three or more SPs and at least one OG rank in the top quartile of all systems with three or more SPs.

The bottom two-thirds of KGPS systems with three or more SPs (19/28 systems) all have no OG planets (within the region KGPS was sensitive to, $\lesssim$10 au). However, two of them have stellar companions (KOI-2169 and KOI-3158). Based on the gap complexity of their inner systems, we argue that these systems with outer SCs are more similar to systems without OGs than those with OGs. However, we test the effect of this assumption on our results in the following analyses.

3.2. Distributions of the Inner-system Gap Complexity for Systems with versus without Outer Giants

In Figure 2 we plot the cumulative distributions of the gap complexity for various subsets of the KGPS sample. In the left panel, we also plot the distribution for the Kepler DR25 catalog (NASA Exoplanet Archive 2020; all systems with three or more transiting planets within $P < 1$ yr, around a sample of FGK dwarfs defined in He et al. 2020) as a comparison. The full KGPS sample (i.e., all systems with three or more SPs, regardless of whether there are OGs) with the same period cut has a very similar distribution of $\mathcal{C}$ that is indistinguishable from being drawn from the same distribution (as shown in the first row of Table 1). Thus, we have high confidence that the KGPS inner systems with small planets (the vast majority of which are transiting, as depicted in Figure 1) form an unbiased and representative sample for characterizing the gap complexity of all Kepler multitransiting systems.

In the right panel, we split the systems with three or more SPs up into those without OGs (blue) and those with OGs (red); the two systems with SCs and the six systems with fewer than three SPs are excluded from this plot in order to provide a clean comparison. The solid or dashed red lines denote whether the OG planets are excluded from or included in the calculations of $\mathcal{C}$, respectively. While we are limited by small number statistics for the systems with three or more SPs with OGs (there are only four systems in the red lines), it is suggestive that their distribution of inner-system $\mathcal{C}$ is markedly different from that of the systems with three or more SPs without any OGs.

To test the significance of the differences between the inner transiting systems with and without OG planet(s), we also

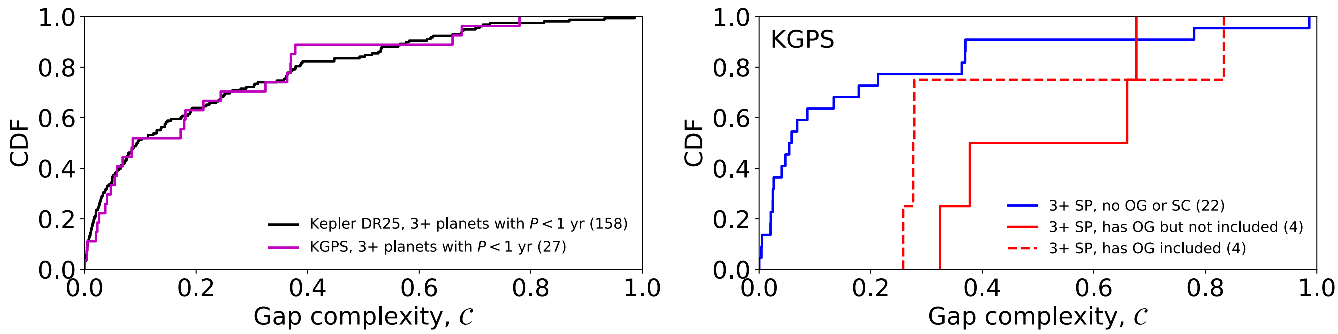

Figure 2. Cumulative distributions of the gap complexity ($\mathcal{C}$). Left: distributions for all systems with at least three planets within 1 yr in the Kepler DR25 catalog (black) and in the KGPS sample (magenta). While there are fewer such systems in the KGPS sample (as indicated by the numbers in parentheses), the distribution of $\mathcal{C}$ is consistent with being drawn from the same distribution as the Kepler DR25 systems. Right: distributions for subsets of the KGPS sample (all with at least three inner SPs); the blue line includes systems without OGs, and the red lines include only the systems with at least three SPs and at least one OG planet, where the OG(s) are either excluded from (solid) or included in (dashed) the calculation of $\mathcal{C}$.

perform a number of two-sample Kolmogorov–Smirnov (KS) and Anderson-Darling (AD) tests. The full results are provided in Table 1. First, the systems without OGs or SCs versus those with OGs (i.e., the solid blue versus red lines in Figure 2) are compared: we find $p = 0.017$ (0.015) using the KS (AD) tests. Second, we also include the two systems with SCs (computing $\mathcal{C}$ for just the SPs) combined with the sample of systems without OGs, as motivated by our observation that these inner systems look similar in terms of gap complexity: the p-values decrease slightly. In both of these cases, the differences are statistically significant at $p < \alpha = 0.05$, using both KS and AD tests. However, this significance threshold only controls the false-positive probability of a single test, and we perform several additional tests in Section 4. We discuss the multiple-comparisons problem and the statistical significance of our results in greater detail in Section 5.1. Last, we combine the two systems with SCs with the sample of systems with OGs instead[2] (again, still computing $\mathcal{C}$ for just the SPs): the p-values are increased because the inner systems with SCs have quite low gap complexities. The statistical significance of this difference here is less clear, and the null hypothesis cannot be ruled out at the $\alpha = 0.05$ level using either test.

These results suggest that the distribution of gap complexities for inner systems at least appears to be different (tends to have higher values) for systems with OG planets compared to systems without any OGs. Our finding has two key implications: (1) the gap complexity of an inner planetary system appears to be a good predictor of OG planets, and (2) the existence of OG planets appears to be connected to the orbital spacings of their inner systems, perhaps as a result of their impact on planet formation or dynamical evolution. We discuss some theoretical implications in Section 5.

3.3. Impact of Outer Giant Planets on the Gap Complexity

3.3.1. The KGPS Systems

To further visualize the distributions of the gap complexity for systems with and without OG planets, and to assess how the giant planet(s) themselves alter the gap complexity of the full systems when considered along with the inner transiting planets, in Figure 3 we present a scatter plot of the highest minimum mass versus gap complexity for each system with three or more planets (i.e., each system displayed in Figure 1). The y-axis represents either the highest minimum mass ($M_p \sin i$) or the highest mass drawn from a mass–radius relation (for systems with only small transiting planets without RV-measured masses). The systems without any OGs are shown as hollow blue circles. The systems with OGs are each shown as two red circles connected by a dashed line, where the hollow circle denotes the inner system (SPs only, excluding the OGs) and the filled circle denotes the full system (SPs and OGs). Likewise, the two hollow orange circles and filled orange stars denote the systems with three or more SPs excluding and including the outer SCs, respectively. From this figure, it is clear that (1) the inner systems with OGs indeed tend to have higher gap complexities than most of those without OGs, and (2) the inclusion of the OG planet(s) more often decreases, rather than increases, the gap complexity of the full system. This latter observation suggests that the orbital separations of OG planet companions relative to their inner systems are not extreme compared to the mutual spacings of the SPs. However, we caution that this result is still limited by small number statistics, and consideration of other known exoplanetary systems gives more varied results, as we show in Section 3.3.3.

In Figure 3 we also plot the systems with at least one OG planet but fewer than three small planets as filled triangles (these are the six systems denoted by dashed lines in Figure 1). Unlike the red circles, these systems can only be represented as single points (because their inner systems contain fewer than three SPs and thus a gap complexity cannot be computed), but it is noteworthy that they also all tend to have high gap complexities and occupy a similar region as the filled red circles. In particular, the KOI-142 and KOI-1241 (Kepler-56) systems both have extremely high gap complexities ($\mathcal{C} = 0.982$ and 0.966, respectively) because they each have a giant planet very close to their innermost planet ($P_c/P_b \sim 2$) and a second giant planet at a much greater separation ($P_d/P_c \gtrsim 45$).

3.3.2. The Solar System

For comparison, we also plot several combinations of the solar system planets in Figure 3 as cyan markers. We consider three groupings: (1) the inner solar system, composed of just the four terrestrial planets (hollow square), (2) the terrestrial planets and Jupiter (filled pentagon), and finally, (3) the full solar system with all eight planets (filled pentagon). Both the inner and the full solar system have very similar gap

[2] One may posit that the existence of outer SCs may have a similar effect as that of OG planets on the architectures of the inner systems, perhaps as a result of influencing their formation or dynamical evolution.

Table 1
Significances of the Differences in the Architectures of KGPS Inner Systems with SPs, with and without OGs or SCs

Distribution	Samples compared	KS dist.	KS $p-$ value	AD dist.[b]	AD $p-$ value
(1) Testing differences in orbital-spacing uniformity …					
Gap complexity, $\mathcal{C}$	3+ SP: Kepler DR25 (158) versus KGPS (27)	0.12	0.87	0.25	>0.25
	3+ SP: no OG or SC (22) versus has OG (4)	0.77	0.017[a]	3.33	0.015[a]
	3+ SP: no OG (24) versus has OG (4)	0.79	0.012[a]	3.58	0.011[a]
	3+ SP: no OG or SC (22) versus has OG or SC (6)	0.44	0.25	1.66	0.14
(2) Testing differences in size similarity …					
Mass partitioning, $\mathcal{Q}$	2+ SP: no OG or SC (37) versus has OG (7)	0.27	0.68	0.47	>0.25
	2+ SP: no OG or SC (37) versus has OG or SC (9)	0.27	0.56	0.54	>0.25
Mass dispersion, σ_M^2	2+ SP: no OG or SC (37) versus has OG (7)	0.38	0.29	0.90	>0.25
	2+ SP: no OG or SC (37) versus has OG or SC (9)	0.27	0.57	0.50	>0.25
(3) Testing differences in size ordering …					
Mass monotonicity, $\mathcal{M}$	2+ SP: no OG or SC (37) versus has OG (7)	0.15	0.99	0.22	>0.25
	2+ SP: no OG or SC (37) versus has OG or SC (9)	0.28	0.53	0.60	>0.25

Notes. In all the samples we compared, the metrics are applied to only the inner SPs, regardless of whether there is an OG/stellar companion. In the "Samples compared" column, the total number of systems in each sample is denoted in parentheses.
[a] These $p-$values are statistically significant at the $\alpha = 0.05$ level for the whole family of tests even after correcting for the multiple-comparisons problem (see Section 5.1). We use the Bonferroni correction ($p \leqslant \alpha/m$; Bonferroni 1936) and the Šidák correction ($p \leqslant 1-(1-\alpha)^{(1/m)}$; Šidák 1967), where $m = 3$ is the number of independent hypotheses being tested; thus, both corrections require $p \lesssim 0.017$ for a significant difference in any individual test.
[b] This is the value of $A^2_{\rm akN}$ given by Equation (7) of Scholz & Stephens (1987) as implemented in SciPy v1.9.3 (Virtanen et al. 2020). We choose to report this value instead of the test statistic returned by SciPy's Anderson k-sample test, which is a transformation of A^2_{akN} and can be negative due to the subtraction of $k-1$.

complexities ($\mathcal{C} = 0.126$ and 0.119, respectively), which are lower than that of any KGPS inner system with OGs. The motivation for considering grouping (2) is based on the detection limit for the KGPS survey, which is sensitive to giant planets out to separations roughly between the orbits of Jupiter and Saturn. Since Jupiter is well separated from the terrestrial planets by the asteroid belt, the gap complexity is modestly increased, in contrast to most of the KGPS systems with OG planets.

While Jupiter, Saturn, Uranus, and Neptune are typically all thought of as "giant" planets, with Jupiter being the prototypical example, we note that these planets technically do not meet our definition of an OG as used throughout this paper because both Uranus and Neptune are less massive than $50 M_\oplus$ and exterior to all of the other planets. However, the KGPS survey was not sensitive to less massive planets beyond $\sim$10 au (e.g., Uranus and Neptune analogs). Thus, it may be unremarkable that the full solar system has a lower gap complexity than any of the KGPS systems with an OG. Nevertheless, it is intriguing that despite the existence of Jupiter (and Saturn), the inner solar system also has a relatively low gap complexity compared to the inner KGPS systems with an OG planet.

3.3.3. Other Exoplanetary Systems with an Outer Giant

Last, we consider several other notable exoplanetary systems with a known OG planet and at least three inner planets (though not all transiting and/or smaller than $50 M_\oplus$). We include them in Figure 3 (black circles, with lines as labeled), following the same convention of using a hollow circle to denote the inner system only, and a filled circle for the full system (including the OG planet). These systems are also plotted in Figure 1 (dotted lines, with black points indicating the inner planets and translucent colors indicating nontransiting planets).

The 55 Cancri (HD 75732) system contains five known planets (Marcy et al. 2002; Fischer et al. 2008; Dawson & Fabrycky 2010; Butler et al. 2017), with the outermost planet having a period of 5574.2 days and a minimum mass of $991.6 M_\oplus$ (Bourrier et al. 2018). The inner four planets have a gap complexity of $\mathcal{C} = 0.255$, which is higher than 19/24 KGPS systems without OGs.

WASP-47 hosts four known planets (Hellier et al. 2012; Becker et al. 2015; Neveu-VanMalle et al. 2016), with an outermost planet at 588.5 days and $M_p \sin i = 398.2 M_\oplus$ (Vanderburg et al. 2017); its inner system exhibits an even higher gap complexity, $\mathcal{C} = 0.390$. We note, however, that both of these systems have an inner planet that is also massive ($M_p \sin i = 255.4 \pm 2.9 M_\oplus$ for 55 Cnc b and $M_p = 363.1 \pm 7.3 M_\oplus$ for WASP-47b; Vanderburg et al. 2017; Bourrier et al. 2018).

HD 191939 (TOI-1339) has three inner transiting planets and a fourth RV-detected outer planet with a period of 101.5 days and a minimum mass of $108 \pm 3 M_\oplus$ (Badenas-Agusti et al. 2020; Lubin et al. 2022). Remarkably, the inner transiting planets of this system exhibit a very high gap complexity ($\mathcal{C} = 0.846$), which is decreased with the inclusion of the OG planet ($\mathcal{C} = 0.326$). However, recent observations have also indicated an additional low-mass ($M_p \sin i = 13.5 \pm 2.0 M_\oplus$) planet exterior to the giant planet, at a period of 284^{+10}_{-8} days (Orell-Miquel et al. 2023). Including this planet would further decrease $\mathcal{C}$ to 0.169. There is also evidence for a distant giant planet ($M_p = 2$–$11 M_{\rm Jup}$), although its period is poorly constrained between 1700–7200 days (Lubin et al. 2022). Periods within this range yield $\mathcal{C} \in [0.176, 0.428]$ for all six planets.

The last system we include is HD 219134, which appears to host six planets (Motalebi et al. 2015; Vogt et al. 2015, although two of the planets have been debated; Gillon et al. 2017). Adopting the six-planet model, the outermost planet orbits with a period of 2100.6 days and a lower limit of $98 M_\oplus$ (Van Zandt et al. 2023). The inner system has a low gap complexity comparable to the median of the KGPS systems

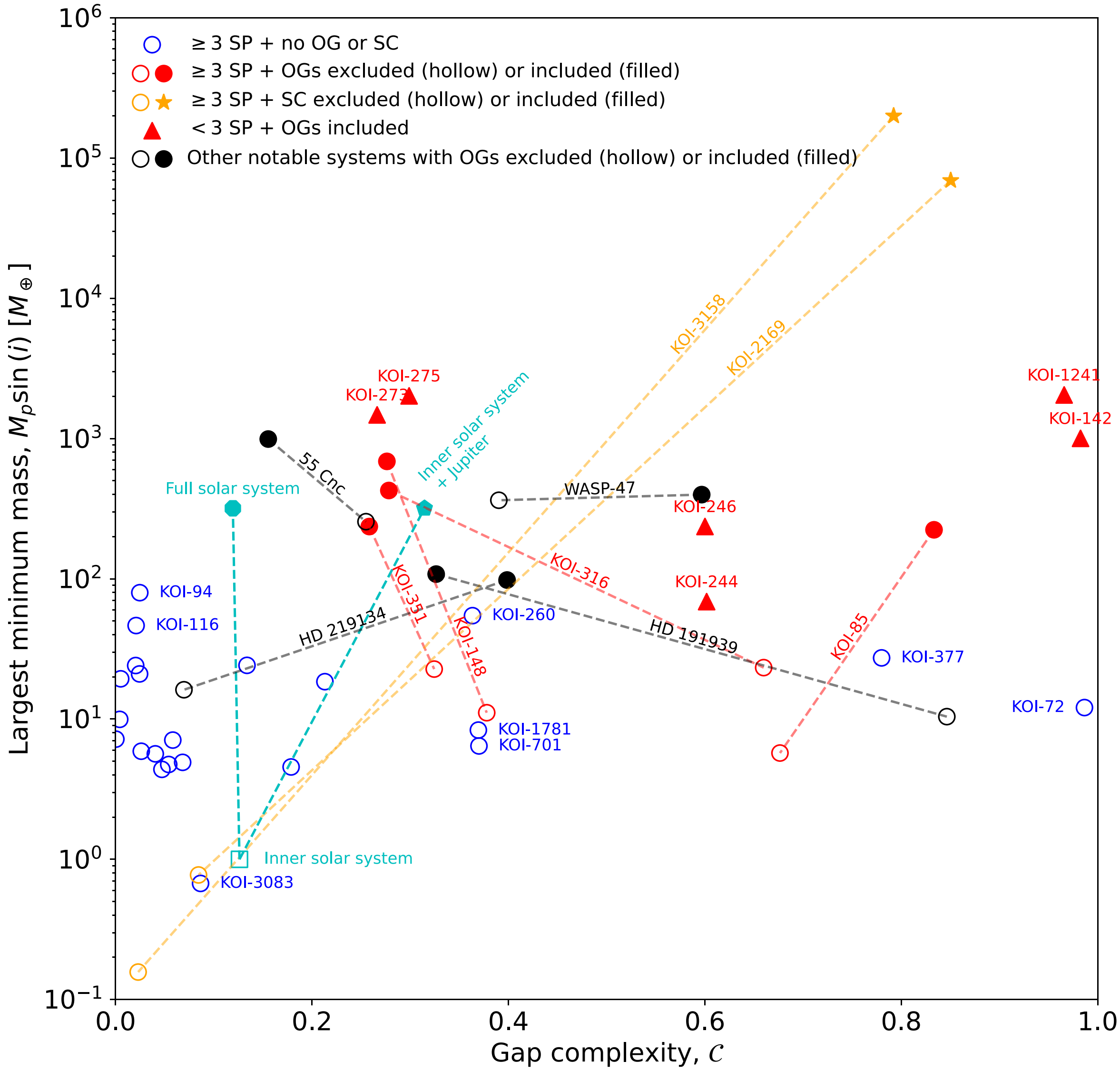

Figure 3. The highest planet mass ($M_p \sin i$ or mass from an M-R relation; y-axis) vs. the gap complexity ($\mathcal{C}$; x-axis) of the system for the KGPS and various other planetary systems. Blue circles denote systems with at least three inner SPs and no OGs (i.e., those included in the blue line of Figure 2). Red circles indicate systems with at least three small inner planets and at least one OG planet, where the OG(s) are either excluded (hollow circles) or included (filled circles), corresponding to the solid and dashed red lines in Figure 2, respectively; the dashed lines connecting these points indicate which system they belong to, as labeled. The four inner small-planet systems with OG(s) (hollow red circles) have preferentially high gap complexities, higher than the majority of the inner small-planet systems without any OGs (hollow blue circles). Red triangles denote systems with three or more planets only after including the giant(s) in the systems. Two systems (KOI-2169 and KOI-3158; orange) have stellar binary companions in addition to $\geqslant 3$ transiting planets; the inclusion of the stellar companions significantly increases both $M_p \sin i$ and $\mathcal{C}$, as expected. For reference, the solar system is also plotted (cyan markers), including (1) just the inner/terrestrial planets (square), (2) the inner planets and Jupiter (pentagon), and (3) all eight planets (octagon), as labeled. Four other known exoplanetary systems with at least three inner planets (though not necessarily transiting or small) and an outermost giant planet (55 Cnc, WASP-47, HD 219134, and HD 191939) are also shown in this plot for comparison (black circles/lines).

without OGs, but this is significantly increased with the inclusion of the OG planet ($\mathcal{C} = 0.07$–0.4).

While we do not include these four systems in our statistical tests because they were not part of the KGPS survey (and not all of their inner planets are small and/or transiting), it is notable that their inner systems also tend to have relatively high gap complexities (three of the four have $\mathcal{C} > 0.25$). The impact of the OG decreases $\mathcal{C}$ in two systems and increases $\mathcal{C}$ in the other two.

4. Size Similarity and the Presence of Outer Giant Planets

Are the size patterns of inner-system planets correlated with the occurrence of OG planets? To explore this question, we also consider three additional metrics for quantifying the size similarity patterns of multiplanet systems, first defined in Gilbert & Fabrycky (2020) and Weiss et al. (2022), but restated below:

1. mass partitioning, which quantifies the mass uniformity of planets (Gilbert & Fabrycky 2020):

$$\mathcal{Q} \equiv \left(\frac{N}{N-1}\right)\left(\sum_{k=1}^{N}\left(M_{p,k}^{*} - \frac{1}{N}\right)^2\right), \quad (3)$$

$$M_{p,k}^{*} = \frac{M_{p,k}}{\sum_{i=1}^{N} M_{p,i}}, \quad (4)$$

where N is the number of planets in the system, and $M_{p,k}$ is the mass of the kth planet. By definition, this metric is normalized to be between zero (identical mass planets) and one (one planet dominates the total mass of the planetary system).

2. mass dispersion, which also quantifies the mass similarity of planets:

$$\sigma_M^2 \equiv \text{Variance}\{\log_{10}(M_{p,k}/M_\oplus)\}. \quad (5)$$

This is equivalent to the size dispersion metric defined in Weiss et al. (2022), but applied to the planet masses instead of planet radii. It is also minimized to zero for identical mass planets, but is unbounded above.[3]

3. mass monotonicity, which quantifies the size ordering of planets (Gilbert & Fabrycky 2020):

$$\mathcal{M} \equiv \rho_S \mathcal{Q}^{1/N}, \quad (6)$$

where ρ_S is the Spearman rank correlation coefficient of the planet masses (compared to their indices sorted by period) and $\mathcal{Q}$ is the mass partitioning defined earlier, which accounts for the magnitude of the size ordering. Positive (negative) values indicate systems with planet masses that tend to increase (decrease) toward larger separations.

Each of these metrics can be computed given at least two planets. In Figure 4 we show the distributions of $\mathcal{Q}$, σ_M^2, and $\mathcal{M}$ (from top to bottom) for several subsets of the KGPS sample. In each panel, the solid red and blue lines correspond to systems with at least two SPs, with and without OGs, respectively. The dashed red lines show the distributions with the inclusion of the OGs; these are the same systems as those in solid red lines, but are always shifted to higher values because by definition, these OG planets are always exterior and more massive than the inner SPs and therefore increase all three metrics. For completeness, we also show the distributions of all KGPS systems with at least two planets (52 systems) in the dashed gray lines; there are more systems than in the solid blue and red lines combined because some systems have only one transiting planet and one (or more) OG planet(s).

The primary comparison we are interested in is between the distributions of the inner systems with versus without OGs (solid red and blue lines in Figure 4, respectively). There is considerable overlap between the two for any of the three metrics. We note that the inner 2+ systems with the highest $\mathcal{Q}$ (top panel) all do not have any OGs (comparing the high tail of the solid blue line with that of the solid red line). This is also apparent in the distributions of σ_M^2. However, we do not find any statistically significant differences using KS or AD tests for any of the three metrics, as reported in Table 1. All p-values clearly exceed 0.05, and this is even before correcting for multiple-hypothesis testing (which we perform in Section 5.1). There is not enough evidence to reject the hypothesis that there is no difference in the mass similarity (partitioning or dispersion) or ordering (monotonicity) of the inner transiting planets in systems with versus without OG planets. These results are largely unaffected by whether we include the two systems with stellar companions (the inner systems of which have relatively high values of $\mathcal{M}$, but more medium values of $\mathcal{Q}$ and σ_M^2) with the OG sample or not (also reported in Table 1).

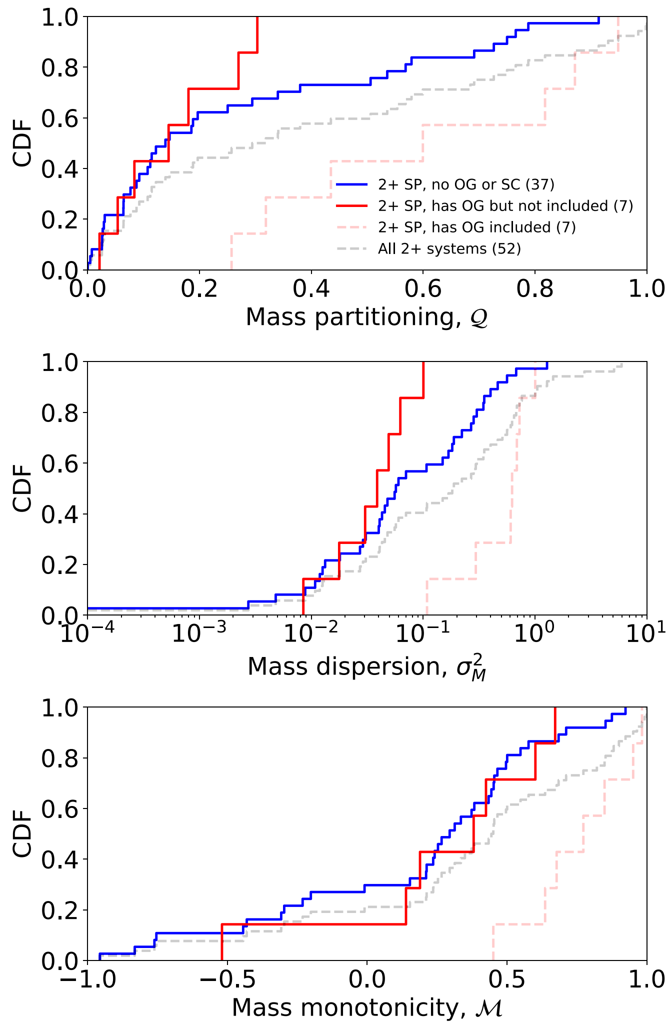

Figure 4. Cumulative distributions of planet mass partitioning ($\mathcal{Q}$; top), mass dispersion (σ_M^2; middle), and mass monotonicity ($\mathcal{M}$; bottom) for various subsets of the KGPS sample (systems with at least two planets). In each panel, the solid lines include the inner small planets for systems with no OG planets (blue) and for systems with OG planet(s) (red). We also show the distribution for the latter sample including the OG planets in the calculation (dashed red line), which by definition typically increase all three metrics. For reference, all KGPS systems with at least two planets are denoted by the dashed gray line; there are more systems in this sample than the sum of the samples in the blue and red lines because some systems have exactly one transiting planet and one OG planet.

To visualize the architectures of these systems as a function of these metrics, we plot galleries of all KGPS systems with at least two planets in Figure 5. The systems are sorted by $\mathcal{Q}$ (left), σ_M^2 (middle), and $\mathcal{M}$ (right), of the inner SPs only (when there are at least two) or of the full system (numbers in parentheses, when there is only one SP), as labeled on the right y-axis margin of each panel. Ignoring the systems with only one SP and one or more OGs (dashed lines), which have high values of $\mathcal{Q}$, σ_M^2, and $\mathcal{M}$ by definition, the OGs are scattered across systems with a wide range of inner-system values. This is unlike their correlation with the inner-system gap complexities as seen in Figure 1. We conclude that the size similarity and ordering patterns of inner planetary systems are uncorrelated with, and therefore also a poor predictor of, the occurrence of OG planets.

[3] In practice, σ_M^2 is at most a few, as it is closely related to the number of orders of magnitude in difference that the planet masses can span, which ranges from $\sim 1 M_\oplus$ to $\sim 10^3 M_\oplus$ (several Jupiter masses) in the KGPS sample.

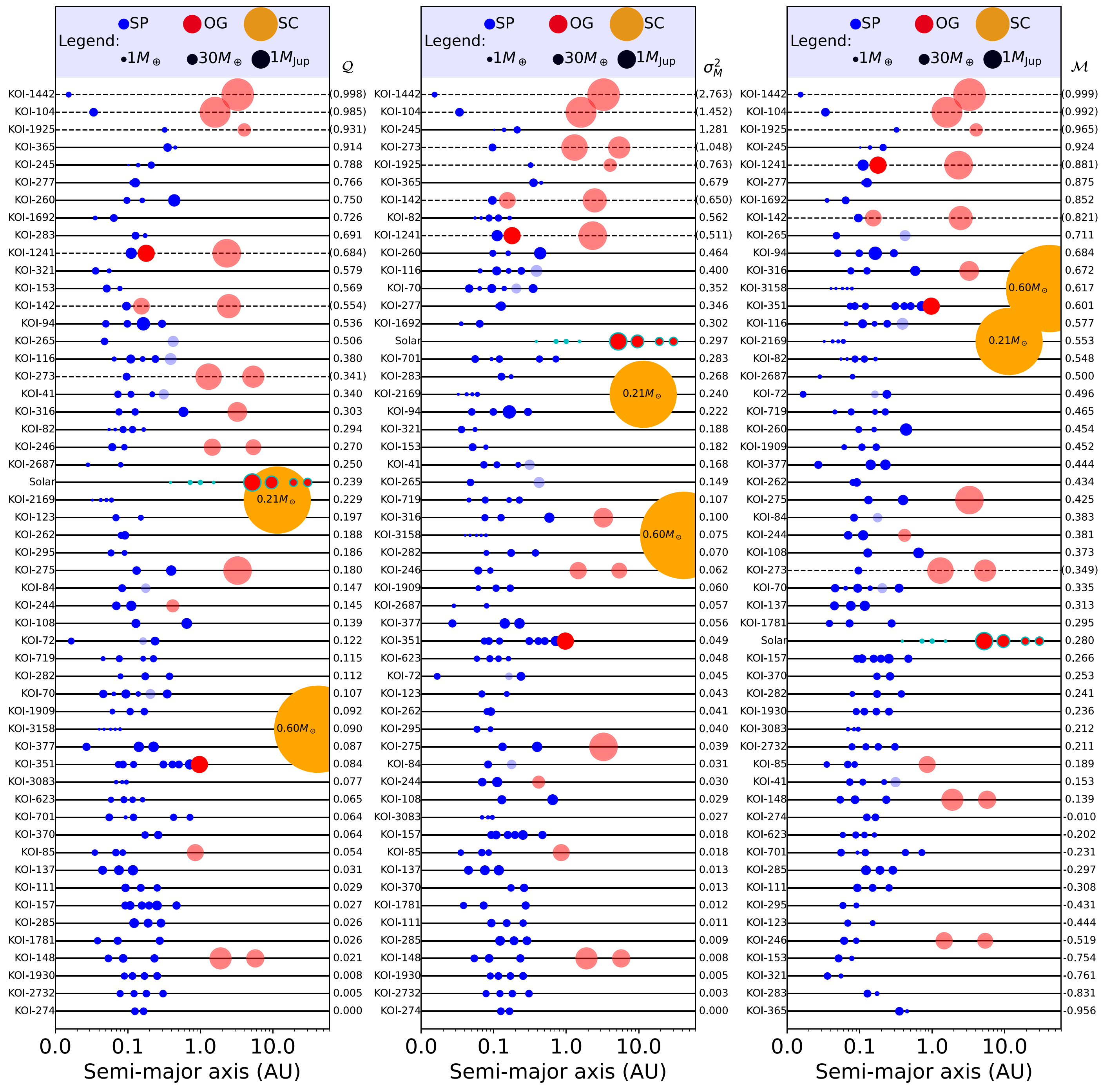

Figure 5. Architecture gallery of the KGPS systems with at least two planets. The axes, legend, and conventions are identical to those in Figure 1. Left: The systems sorted by the mass partitioning ($\mathcal{Q}$) of the inner system (i.e., SPs only, where there are at least two), as labeled on the right *y*-axis, or the mass partitioning of the whole system when there are fewer than two SPs (denoted by the numbers in parentheses; these systems are also denoted by the dashed lines). Middle: The same systems, sorted and labeled by mass dispersion (σ_M^2). Right: The same systems, sorted and labeled by mass monotonicity ($\mathcal{M}$). As in Figure 1, the solar system is also plotted (cyan points) with the same convention, where the planets from Jupiter and beyond are excluded from the calculation of $\mathcal{Q}$ or σ_M^2 or $\mathcal{M}$. For all three metrics, there is no apparent correlation between the inner system and the occurrence of OG planets.

5. Discussion

5.1. Statistical Significance given Multiple Comparisons

In this paper, we have tested whether there are differences in the architectures of inner systems for those with versus without OG planets using several tests and metrics. Thus, one may be concerned about the multiple-comparisons problem (also known as the look-elsewhere effect), that seemingly statistically significant differences can arise even when there are no real differences due to the large number of hypothesis tests being performed (e.g., Shaffer 1995; Miller 2012). However, not all of the tests we performed are independent. We have effectively tested three unique null-hypotheses for whether there are any differences between giant-hosting versus non-giant-hosting systems in their patterns of (1) orbital-spacing uniformity, (2) size similarity, and (3) size ordering.

It might be wondered how the large number of rows in Table 1 corresponds to three independent hypotheses. First, we note that mass partitioning and mass dispersion are quantities that measure very similar properties, so these are not independent metrics (in fact, they are highly correlated); see Section 4. For each metric we tested, we also used multiple subsamples as well as both KS and AD tests (i.e., each row in Table 1). The subsamples were solely used to test how the inclusion of the two systems with stellar companions affected the results, and thus, they largely overlap. The combination of KS and AD tests mainly serves as a consistency check; it is reassuring that all of their results are in agreement for the per-test significance threshold of $\alpha = 0.05$ (and remain in agreement after the threshold correction described below).

In order to assess the statistical significance of any single test in the context of the family of three different types of tests, the thresholds for the $p-$values must be corrected. Using the Bonferroni correction ($p \leqslant \alpha/m$; Bonferroni 1936) and the Šidák correction ($p \leqslant 1-(1-\alpha)^{(1/m)}$; Šidák 1967), where $\alpha = 0.05$ is now the desired family wise significance threshold and $m = 3$ is the number of independent hypotheses, the necessary per-test significance threshold is $\alpha \simeq 0.017$. Thus, the $p-$values for the gap complexity tests (marked by the superscript "a" in Table 1) remain statistically significant given the corrected threshold, although some are close to the threshold. In any case, more data (specifically, more systems with multiple inner planets accompanied by at least one OG) would help to further support or refute the apparent trend of an increased inner gap complexity with OG occurrence.

5.2. Potential Biases

The KGPS target sample was carefully chosen to provide a magnitude-limited unbiased sample for the homogeneous search of OG planet companions to Kepler transiting planets around Sun-like stars via long-term RV monitoring (see KGPS I for details). The systems were specifically chosen for their lack of previously identified giant planets beyond 1 au.[4] Furthermore, we showed in Section 3.2 that the distribution of gap complexities for the KGPS sample is statistically indistinguishable from that of the full Kepler DR25 catalog (both including systems with three or more transiting planets within 1 yr).

One potential cause for concern is the role of reducing multiplicity in the computation of the gap complexity. In order to make a direct comparison between the inner systems with and without any OGs, we had to select only systems with at least three small planets, and thus the systems with OG(s) all have at least four known planets. For these systems, at least one planet (i.e., the OG(s) that by definition is also the outermost/longest-period planet) is excluded from the calculation of $\mathcal{C}$, whereas no planets are excluded in systems without an OG. Does the mere process of excluding the outermost planet introduce a bias in the gap complexity of the remaining planets in the system?

First, we recall that the gap complexity is always normalized to the range (0, 1) for any number of planets $\geqslant 3$ (see Section 3 and Gilbert & Fabrycky 2020); thus, any potential differences in multiplicity would not bias the comparison. Second, to test the effect of excluding the outermost planet, we consider all systems with at least four small planets (14 systems). We then compute $\mathcal{C}$ both with and without the outermost small planet (any OGs or stellar companions are excluded from this calculation and thus are irrelevant). We find no strong systematic bias in the value of $\mathcal{C}$ due to the exclusion of the outermost (small) planet; nine systems exhibit an increase, while five systems exhibit a decrease in $\mathcal{C}$. Moreover, the change in $\mathcal{C}$ is typically quite small ($|\Delta\mathcal{C}| \lesssim 0.12$ for all but one system). These results provide confidence that the higher gap complexities of the inner small-planet systems with OGs are not due to any biases in our procedure, but rather are a reflection of real differences in the physical spacings of the inner systems due to the presence or lack of OG planets.

It is also worth considering some limitations of the KGPS survey that may potentially impact the detectability of planets at wide separations and our classification of the systems into those with/without OGs. While the KGPS targets all have at least 10 RV observations with the earliest from 2018 or earlier, not all targets have the same number of RV observations or the same sensitivity to planets of a given mass and semimajor axis (see KGPS I for the exact observations of each Kepler target). To assess whether any biases in the observations could have affected our results, we plot the residual RV root mean square (rms; top panel), and the number of RV observations (bottom panel) versus the gap complexity for the KGPS systems in Figure 6. We do not see a meaningful correlation between either the RV rms or the number of RVs and the gap complexities of the inner systems. Thus, it is unlikely that the

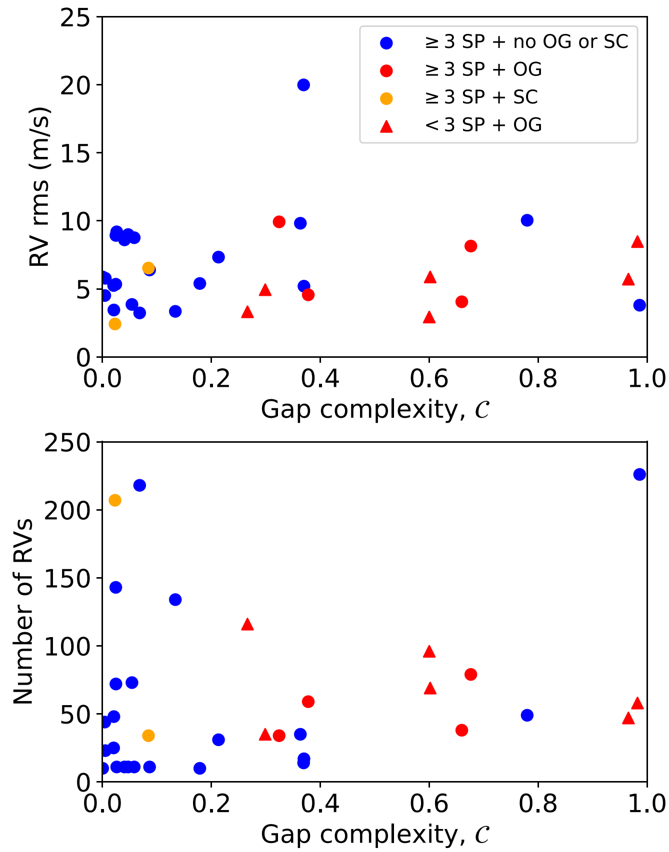

Figure 6. The root mean square (rms) of the RV residuals (top) and the number of RV observations (bottom) vs. the gap complexity for the KGPS targets with at least three planets. The points are plotted using a similar convention as in Figure 3, where the gap complexity only includes the inner small planets (except for the red triangles, which also include the OG planets). The gap complexity is uncorrelated with the RV rms or the number of RV observations.

[4] An exception is KOI-1241 (Kepler-56); see KGPS I. However, this system does not affect our main results because there is only one transiting small planet, and thus this system is excluded from the statistical tests presented in Sections 3 and 4.

properties of the RV observations could have affected the detectability of OG planets in a way that would create a spurious dependence on the inner-system gap complexity. While beyond the scope of this study, mapping the completeness of the detected giant planets for all the stars in the KGPS survey would be necessary to more robustly determine the variable mass sensitivity of the KGPS sample.

Last, although its long baseline spans over a decade for some targets, the KGPS survey was not uniformly sensitive to planets beyond ∼5–10 au (which is important to consider when comparing to the solar system, as in Section 3.3.2). The results in this paper are agnostic to any OG planets that may exist beyond these separations, and current data do not yet allow us to address whether massive planets at extreme separations may affect the observable architectures of the compact multiplanet systems. To date, the KGPS catalog provides by far the best available sample for studying the connections between the inner architectures of high-multiplicity planetary systems and the giant planets at scales of several au.

5.3. Theoretical Implications

As we have shown, the KGPS sample suggests that the inner small planets in systems with OG planet(s) tend to exhibit more complex orbital spacings than their giant-less counterparts. This finding implies at least one of the following two physical scenarios: (1) the mutual inclinations between planets are higher in systems with OG planets, thereby often leading to nontransiting planets in between transiting planets that would make the systems appear to have especially irregular gaps, and/or (2) there are no planets hiding at moderate inclination in the gaps, and the irregular spacings of the transiting planets are sculpted by the presence of OG planets during formation or dynamical interactions. There are physical mechanisms in both planet formation theory and dynamical evolution that support either explanation above. For example, giant planets that are inclined with respect to the inner-system planets can dynamically excite their mutual inclinations (as well as their stellar spin–orbit angles; e.g., Becker & Adams 2017; Lai & Pu 2017; Zhang et al. 2021). In our solar system, Jupiter is thought to have migrated inward to ∼1.5 au before migrating outward to its present location due to interactions with Saturn, which would have cleared the inner region and explain the low masses of the terrestrial planets (Batygin & Laughlin 2015). Unfortunately, our sample size is too small to discern whether the inner-system architectures correlate with any physical properties of the giant planets. As more OG planets are discovered in systems with multiple small planets, future studies may test whether the inner-system gap complexity correlates with the giant planet mass, separation, or eccentricity, or whether the existence of multiple giant planets may imprint stronger signatures.

The early formation of OGs can influence and is generally seen as an obstacle to the subsequent formation of their inner systems, perhaps halting the inward flow of planet-building materials or the migration of fully formed planets (e.g., Lambrechts et al. 2014; Izidoro et al. 2015, 2021; Schlecker et al. 2021). On the other hand, recent simulations show that OGs can also induce a secular resonance sweeping propagating inward through the planet-forming disk, leading to an enhancement of planetesimal rings in the inner regions from which super-Earths can form (Best et al. 2023). One pathway that has been proposed to broadly explain the observed architectures of inner multiplanet systems is the so-called "inside-out planet formation (IOPF)" whereby planets form in successive rings of material building up at the magnetorotational instability (MRI) boundary starting at ∼0.1 au (Chatterjee & Tan 2014, 2015; Hu et al. 2016; see Tan et al. 2016 for a summary; see also Batygin & Morbidelli 2023 for the formation of multiple small planets from a single narrow ring). As one planet forms and carves a gap in the gaseous disk, the MRI boundary retreats farther out, producing another ring and repeating the process. Critically, these rings are fueled by an inward stream of small pebbles drifting via gas-drag forces. Thus, one can imagine that the formation or existence of a giant planet at several AU would halt the pebble stream and subsequent planet formation in the inner system. This mechanism may explain the recently discovered outer edges of the compact multiplanet systems that underlie the bulk of the Kepler systems (Millholland et al. 2022). The IOPF model predicts that the relative separation (in Hill radii) between planets decreases for outer planets in the formation sequence, due to incrementally more modest retreating of the MRI boundary (Hu et al. 2016; Tan et al. 2016). It remains to be seen how these trends would be affected by OG planets that prematurely shut off the delivery of planet-building pebbles, or whether these processes would imprint measurable patterns in the orbital spacings (e.g., in the form of gap complexity). Intriguingly, recent planet formation and migration simulations by Bitsch & Izidoro (2023) appear to indicate that OGs (between 0.3 and 3 au) may not suppress the formation of inner small planets, but instead reduce their survival rate through scattering such that systems with OGs mostly only harbor one inner small transiting planet.

The early formation of giant planets can also prevent the inward migration of fully formed planets. For example, Izidoro et al. (2015) showed that the existence of a giant planet at a few au (perhaps formed from the runaway gas accretion of the innermost planet in a sequence of super-Earths) can act as a strong dynamical barrier against the inward migration of the outer super-Earths. However, their simulations also show that occasionally, one or more planets can jump past the giant planet into the inner region and remain stable. Depending on the initial disk conditions and numbers of migrating planets, the model predicts a rare but nonzero fraction of systems with three or more jumpers (one can also imagine that some small planets formed interior to the giant and some are jumpers). While additional studies are needed to test if this mechanism would produce the inner architectures seen in the KGPS systems with OGs, it is at least plausible that the resulting inner systems would exhibit more irregular spacings if they survive the process.

Finally, we briefly comment on our lack of finding evidence for any correlation between the metrics of planet size similarity or ordering and OG occurrence (Section 4). Using RV-detected multiplanet systems, Wang (2017) showed that the intrasystem mass uniformity, although strong for systems with planet masses lower than $30M_\oplus$, breaks down for systems with more massive planets $\gtrsim 100M_\oplus$. Adams (2019) and Adams et al. (2020) derived from first principles that the assembly of equal-mass planets in the same system, under the conservation of angular momentum, total mass, and constant orbital spacing, is an energetically favorable configuration until the total mass in planets exceeds a critical value of $\sim 40M_\oplus$. It is unclear if there is significant tension between these studies and our results because these previous works considered the size uniformity of the whole systems (i.e., including any giant planets), whereas we focused on the size uniformity of the inner systems only and how that may or may not be affected by the presence of OGs. If supported by future observations, our findings would suggest that any process that may explain the gap complexity result must also not significantly alter the patterns in the sizes of the resulting planets.

6. Summary

In this work, we use the recently presented catalog of exoplanetary systems from the Kepler Giant Planet Search (KGPS I) to look for potential correlations between the presence of OG planets and the inner-system architectures. This catalog was compiled using a decade of RV observations from the W. M. Keck Observatory specifically targeting Kepler systems without previously known giant planets so as to produce an unbiased sample for statistical studies, and it contains 63 systems with 157 transiting planets and 18 OG planets ($M_p \sin i \geqslant 50 M_\oplus$ and exterior to any small planets). Using previously defined measures of intrasystem uniformity in orbital spacings and planet sizes (Gilbert & Fabrycky 2020; Weiss et al. 2022), we find the following main observational results:

1. The inner systems (with three or more small planets) tend to have more irregularly spaced orbits in the form of higher gap complexities ($\mathcal{C}$) when they are accompanied by OG planet(s) than when they are not. The median $\mathcal{C} = 0.06$ for systems without any OGs, while the lowest value is $\mathcal{C} = 0.32$ for systems with OGs. Although the sample size of systems with OGs is small (four systems), the differences in their distribution of $\mathcal{C}$ compared to the systems without OGs are statistically significant ($p = 0.017$ and 0.015 using KS and AD tests, respectively).
2. The finding above suggests that one may predict the existence of OG planets by selecting multitransiting systems with a high degree of irregularity in their orbital spacings. To this point, the KGPS catalog implies that if one were to select any system with three or more transiting planets from the KGPS catalog with a high gap complexity $\mathcal{C} > 0.3$, there would be a $\sim$44% (4/9) chance of finding an OG planet within 5 au. Conversely, no such systems with $\mathcal{C} < 0.3$ have been found to host any OG planets.
3. Considering all Kepler systems with three or more small transiting planets within 1 au around FGK stars, there are an additional $\sim$40 such systems not part of the KGPS with $\mathcal{C} > 0.3$. While many of these systems are too faint for ground-based RV follow-up, we estimate that $\sim$18 of these systems may harbor at least one (and potentially multiple) yet-to-be-discovered OG planets within $\sim$5 au.
4. Six KGPS systems contain OG(s) but two or fewer inner small planets. While we cannot compute the gap complexity of their inner systems, we note that the full systems (i.e., including the giants) also have relatively high values of $\mathcal{C} > 0.25$.
5. There are no statistically significant differences in the size similarity or ordering patterns of the inner systems with versus without any OGs. Both samples of systems have similar distributions of mass partitioning, dispersion, and monotonicity (three metrics for quantifying the peas-in-a-pod size patterns) when considering the masses of the inner/transiting planets.

To date, only a few studies have attempted to estimate the conditional occurrence rate of OG companions to inner small planets (Zhu & Wu 2018; Bryan et al. 2019; Rosenthal et al. 2022; Van Zandt et al. 2023; Bonomo et al. 2023), and the connection between the inner and outer systems remains largely unexplored. Our study is unique in that it is the first attempt to discern correlations between the architectures of high-multiplicity inner systems (<1 au) and the giant planets that exist in their outer reaches. While the sample size is small (since computing gap complexity requires a restriction to systems with at least three planets), the KGPS sample provides tantalizing evidence, as we have shown, that OGs play an important role in the assembly of the inner systems, likely in the form of disrupting their orbital spacings and/or inclinations. More systems with multiple inner planets accompanied by OGs (perhaps detected by continued RV surveys with long baselines) are needed to further support or test these hypotheses. Remarkably, our finding suggests that one way of potentially detecting OG planets with a higher probability is to target known multiplanet systems with highly irregular spacings.

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Software: NumPy (Harris et al. 2020), Matplotlib (Hunter 2007), SciPy (Virtanen et al. 2020), SysSimPyPlots (He 2022).

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References

Adams, F. C. 2019, MNRAS, 488, 1446
Adams, F. C., Batygin, K., Bloch, A. M., & Laughlin, G. 2020, MNRAS, 493, 5520
Anteneodo, C., & Plastino, A. R. 1996, PhLA, 223, 348
Badenas-Agusti, M., Günther, M. N., Daylan, T., et al. 2020, AJ, 160, 113
Batygin, K., & Laughlin, G. 2015, PNAS, 112, 4214
Batygin, K., & Morbidelli, A. 2023, NatAs, 7, 330
Becker, J. C., & Adams, F. C. 2017, MNRAS, 468, 549
Becker, J. C., Vanderburg, A., Adams, F. C., Rappaport, S. A., & Schwengeler, H. M. 2015, ApJL, 812, L18
Best, S., Sefilian, A. A., & Petrovich, C. 2023, arXiv:2304.02045
Bitsch, B., & Izidoro, A. 2023, arXiv:2304.12758
Bonferroni, C. 1936, Pubblicazioni del R Istituto Superiore di Scienze Economiche e Commerciali di Firenze, 8, 3
Bonomo, A. S., Dumusque, X., Massa, A., et al. 2023, arXiv:2304.05773
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Bourrier, V., Dumusque, X., Dorn, C., et al. 2018, A&A, 619, A1
Bryan, M. L., Knutson, H. A., Lee, E. J., et al. 2019, AJ, 157, 52
Butler, R. P., Vogt, S. S., Laughlin, G., et al. 2017, AJ, 153, 208

Chatterjee, S., & Tan, J. C. 2014, ApJ, 780, 53
Chatterjee, S., & Tan, J. C. 2015, ApJL, 798, L32
Dawson, R. I., & Fabrycky, D. C. 2010, ApJ, 722, 937
Fabrycky, D. C., Lissauer, J. J., Ragozzine, D., et al. 2014, ApJ, 790, 146
Fischer, D. A., Marcy, G. W., Butler, R. P., et al. 2008, ApJ, 675, 790
Gilbert, G. J., & Fabrycky, D. C. 2020, AJ, 159, 281
Gillon, M., Demory, B.-O., Van Grootel, V., et al. 2017, NatAs, 1, 0056
Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Natur, 585, 357
Hatzes, A. P., & Rauer, H. 2015, ApJL, 810, L25
He, M. Y. 2022, hematthi/SysSimPyPlots: v1.1.0: New functions for plotting galleries of systems, v1.1.0, Zenodo, doi:10.5281/zenodo.7098044
He, M. Y., & Ford, E. B. 2022, AJ, 164, 210
He, M. Y., Ford, E. B., & Ragozzine, D. 2019, MNRAS, 490, 4575
He, M. Y., Ford, E. B., Ragozzine, D., & Carrera, D. 2020, AJ, 160, 276
Hellier, C., Anderson, D. R., Collier Cameron, A., et al. 2012, MNRAS, 426, 739
Hu, X., Zhu, Z., Tan, J. C., & Chatterjee, S. 2016, ApJ, 816, 19
Hunter, J. D. 2007, CSE, 9, 90
Izidoro, A., Bitsch, B., & Dasgupta, R. 2021, ApJ, 915, 62
Izidoro, A., Raymond, S. N., Morbidelli, A., Hersant, F., & Pierens, A. 2015, ApJL, 800, L22
Lai, D., & Pu, B. 2017, AJ, 153, 42
Lambrechts, M., Johansen, A., & Morbidelli, A. 2014, A&A, 572, A35
Lee, M. H., & Peale, S. J. 2002, ApJ, 567, 596
Lubin, J., Van Zandt, J., Holcomb, R., et al. 2022, AJ, 163, 101
Marcy, G. W., Butler, R. P., Fischer, D. A., et al. 2002, ApJ, 581, 1375
Marcy, G. W., Isaacson, H., Howard, A. W., et al. 2014, ApJS, 210, 20
Miller, R. 2012, Simultaneous Statistical Inference, Springer Series in Statistics (New York: Springer)
Millholland, S. C., He, M. Y., & Zink, J. K. 2022, AJ, 164, 72
Mills, S. M., Howard, A. W., Weiss, L. M., et al. 2019, AJ, 157, 145
Motalebi, F., Udry, S., Gillon, M., et al. 2015, A&A, 584, A72
Mulders, G. D., Pascucci, I., Apai, D., & Ciesla, F. J. 2018, AJ, 156, 24
NASA Exoplanet Archive 2020, Kepler Objects of Interest DR25, Version: 2020-10-16 10:34, NExScI-Caltech/IPAC, doi:10.26133/NEA5
Neveu-VanMalle, M., Queloz, D., Anderson, D. R., et al. 2016, A&A, 586, A93
Orell-Miquel, J., Nowak, G., Murgas, F., et al. 2023, A&A, 669, A40
Piso, A.-M. A., Youdin, A. N., & Murray-Clay, R. A. 2015, ApJ, 800, 82
Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, Icar, 124, 62
Raymond, S. N., & Cossou, C. 2014, MNRAS, 440, L11
Rosenthal, L. J., Knutson, H. A., Chachan, Y., et al. 2022, ApJS, 262, 1
Schlecker, M., Mordasini, C., Emsenhuber, A., et al. 2021, A&A, 656, A71
Scholz, F. W., & Stephens, M. A. 1987, JASA, 82, 918
Shaffer, J. P. 1995, Annu. Rev. Psychol., 46, 561
Stevenson, D. J. 1982, P&SS, 30, 755
Šidák, Z. 1967, JASA, 62, 626
Tan, J. C., Chatterjee, S., Hu, X., Zhu, Z., & Mohanty, S. 2016, IAUFM, 29A, 6
Van Zandt, J. E., Petigura, E. A., MacDougall, M., et al. 2023, AJ, 165, 60
Vanderburg, A., Becker, J. C., Buchhave, L. A., et al. 2017, AJ, 154, 237
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, NatMe, 17, 261
Vogt, S. S., Burt, J., Meschiari, S., et al. 2015, ApJ, 814, 12
Wang, S. 2017, RNAAS, 1, 26
Weiss, L. M., Fabrycky, D. C., Agol, E., et al. 2020, AJ, 159, 242
Weiss, L. M., Isaacson, H., Marcy, G. W., et al. 2023, arXiv:2304.00071
Weiss, L. M., & Marcy, G. W. 2014, ApJL, 783, L6
Weiss, L. M., Marcy, G. W., Petigura, E. A., et al. 2018, AJ, 155, 48
Weiss, L. M., Marcy, G. W., Rowe, J. F., et al. 2013, ApJ, 768, 14
Weiss, L. M., Millholland, S. C., Petigura, E. A., et al. 2022, arXiv:2203.10076
Winn, J. N. 2010, arXiv:1001.2010
Zhang, J., Weiss, L. M., Huber, D., et al. 2021, AJ, 162, 89
Zhang, Z., Bowler, B. P., Dupuy, T. J., et al. 2023, AJ, 165, 73
Zhu, W., & Wu, Y. 2018, AJ, 156, 92