THE CALIFORNIA KEPLER SURVEY VII. PRECISE PLANET RADII LEVERAGING GAIA DR2 REVEAL
THE STELLAR MASS DEPENDENCE OF THE PLANET RADIUS GAP

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ABSTRACT

The distribution of planet sizes encodes details of planet formation and evolution. We present the most precise planet size distribution to date based on \textit{Gaia} parallaxes, \textit{Kepler} photometry, and spectroscopic temperatures from the California-Kepler Survey. Previously, we measured stellar radii to 11\% precision using high-resolution spectroscopy; by adding \textit{Gaia} astrometry, the errors are now 2\%. Planet radius measurements are, in turn, improved to 5\% precision. With a catalog of $\sim$1000 planets with precise properties, we probed in fine detail the gap in the planet size distribution that separates two classes of small planets, rocky super-Earths and gas-dominated sub-Neptunes. Our previous study and others suggested that the gap may be observationally under-resolved and inherently flat-bottomed, with a band of forbidden planet sizes. Analysis based on our new catalog refutes this; the gap is partially filled in. Two other important factors that sculpt the distribution are a planet’s orbital distance and its host star mass, both of which are related to a planet’s X-ray/UV irradiation history. For lower mass stars, the bimodal planet distribution shifts to smaller sizes, consistent with smaller stars producing smaller planet cores. Details of the size distribution including the extent of the ‘sub-Neptune desert’ and the width and slope of the gap support the view that photoevaporation of low-density atmospheres is the dominant evolutionary determinant of the planet size distribution.

1. INTRODUCTION

NASA’s prime \textit{Kepler} mission (2009–2013; Borucki et al. 2010) is continuing to revolutionize our understanding of planetary astrophysics. \textit{Kepler}’s success flows from its near continuous high precision photometric monitoring of $\sim$150,000 stars over a four year mission. Among many discoveries, the large and homogeneous \textit{Kepler} dataset enabled demographic studies of large numbers of exoplanets as small as Earth (see, e.g., Howard et al. 2012; Fressin et al. 2013; Petigura et al. 2013). One startling result from these studies is that nearly every Sun-like star has a planet larger than Earth but smaller than Neptune. Given the lack of such planets orbiting the Sun, \textit{Kepler} demonstrated that the Solar System is not a typical outcome of planet formation, in at least that one key respect.

Initially, the basic structure of these ubiquitous 1 to 4 $R_\oplus$ planets was unknown. It was unclear whether these planets were predominately rocky or had substantial gaseous envelopes. Early clues came from mass measurements of a few tens of \textit{Kepler} planets based on the radial velocity (RV) and transit-timing variation (TTV) techniques (Marcy et al. 2014; Holman et al. 2010). These measurements revealed a transition in exoplanet bulk composition at $\approx 1.5 R_\oplus$, with smaller planets having bulk densities consistent with rock and larger planets having extended low-density envelopes (Weiss & Marcy 2014; Rogers 2015).

The distribution of \textit{Kepler} planets as a function of size, orbital period, and other properties encodes key aspects of planet formation physics including the growth of solid cores, the accretion/loss of gaseous envelopes, and the extent to which planets migrate. Insight into these processes requires accurate knowledge of host star properties. Until recently, the properties of the vast majority of \textit{Kepler} planet host stars were based on photometry alone, i.e. from the \textit{Kepler} Input Catalog (KIC) and its updates (Brown et al. 2011; Huber et al. 2014; Mathur et al. 2017). Importantly, stellar radii $R_\ast$ determined from photometry are uncertain at the $\approx 40\%$ level, which hides important features in the planet population.

To address the limitations of photometric stellar properties, our team conducted the California-Kepler Survey (CKS), which obtained high-resolution optical spectra of 1305 planet hosting stars (Petigura et al. 2017, P17 hereafter). Among other properties, these spectra enabled more precise stellar radii with $\approx 11\%$ precision (Johnson et al. 2017, J17 hereafter). In Fulton et al. (2017), F17...
hereafter, we recomputed planet occurrence given these improved properties and found that the radius distribution of small planets is bimodal with a paucity of planets between 1.5 and 2.0 R\(_{\oplus}\). In previous studies, this feature was washed out to large R\(_p\) uncertainties. The radius gap occurs at the transition radius separating planets with and without gaseous envelopes.

A gap in the radius distribution was predicted by several groups who considered the effect of photoevaporation on planetary envelopes by X-ray and extreme ultraviolet (XUV) radiation (Lopez & Fortney 2014; Owen & Wu 2013; Jin et al. 2014; Chen & Rogers 2016). The observation of the radius gap lends much credibility to photoevaporation as a key process that sculpts the population of sub-Jovian class planets. However, while photoevaporation is a leading theory explaining this feature, alternative mechanisms have been proposed, such as mass loss powered by luminosity of a planet’s cooling core (Ginzburg et al. 2018).

The apparent width of the radius gap in F17 was \(\approx25\%\) in R\(_p\). Because the gap was only marginally wider than the R\(_p\) uncertainties (\(\approx13\%\)), its true width and depth was uncertain. Indeed, Van Eylen et al. (2017) studied a smaller sample of \(\approx100\) planets with percent-level R\(_p\) precision enabled by asteroseismology, and suggested that the gap may be wider and deeper than it appears in F17.

Here, we re-examine the planet population at higher resolution by incorporating recently released parallax measurements from ESA’s Gaia mission (Gaia Collaboration et al. 2016a). Launched in 2013, Gaia is conducting an all-sky astrometric survey of \(\approx10^9\) stars. Gaia’s first data release (DR1) included 14 months of Gaia measurements, leveraging the Tycho catalog to constrain proper motions (Gaia Collaboration et al. 2016b; Lindegren et al. 2016). Gaia DR1 included parallax measurements of only a handful of Kepler planet hosts and were not precise enough to improve radii over those from spectroscopy alone. Gaia DR2 (Gaia Collaboration et al. 2018)\(^1\) is the first Gaia-only catalog and is based on 22 months of observations. DR2 provides sub-1% distances to the majority of Kepler planet hosts, enabling more precise stellar and planetary radii.

Our paper is organized as follows: Section 2 describes our sample selection. We derive new stellar radii in Section 3, with 2% precision. In Section 4, we derive new planet radii and examine the exoplanet population with our high-resolution sample. We also characterize astrophysical spread in the planet size distribution and note correlations between the exoplanet population and stellar mass. We conclude in Section 5, connecting our observations to planet formation theory.

2. INITIAL SAMPLE SELECTION

We began with the sample of planet host stars in the CKS sample. The CKS sample selection, spectroscopic observations, and spectroscopic analysis are described in detail in P17. In brief, the sample was initially constructed by selecting all Kepler Objects of Interest (KOIs) brighter than Kp = 14.2 mag. A KOI is a Kepler target star which showed periodic photometric dimmings indicative of planet transits. However, not all KOIs have received the necessary follow-up attention needed to confirm the planets. Over the course of the CKS project, we included additional targets to cover different planet populations, including multi-candidate hosts, ultra-short period candidates, and habitable zone candidates.

We cross-matched the CKS sample with the Gaia DR2 catalog by querying all Gaia sources within 1 arcsec of the KIC coordinates. In rare cases, Gaia detected more than one source within 1 arcsec, and we selected the source with the smallest difference between G and Kp magnitudes. We cross-matched 1257 targets in this way.

3. STELLAR RADII

3.1. Introduction

Our re-derived stellar radii (R\(_*\)) follow from the Stefan–Boltzmann law,

\[
R_* = \left( \frac{L_{bol}}{4\pi\sigma_{sh}T_{eff}^4} \right)^{1/2},
\]

where L\(_{bol}\) is the bolometric stellar luminosity, \(\sigma_{sh}\) is the Stefan–Boltzmann constant, and T\(_{eff}\) is the effective temperature. L\(_{bol}\) is related to bolometric magnitude M\(_{bol}\) via

\[
L_{bol} = L_010^{-0.4M_{bol}},
\]

where L\(_0\) is defined to be L\(_0\) = 3.0128 \times 10^{28} W.\(^2\) M\(_{bol}\) may be measured from a single broadband photometric apparent magnitude m, if the distance modulus \(\mu\), line-of-sight extinction A, and bolometric correction BC are known:

\[
M_{bol} = m - A - \mu - BC.
\]

Therefore, our derived stellar radii depend on five parameters: m, \(\mu\), T\(_{eff}\), BC. We discuss the provenance of these in parameters in Sections 3.2–3.6 along with their respective contributions to the R\(_*\) error budget, which are summarized in Table 1. Section 3.7 explains our detailed modeling of R\(_*\), which closely follows that of

\(^1\) Released on 2018-04-25

\(^2\) See IAU 2015 Resolution B2 and Mamajek et al. (2015).
Huber et al. (2017). We validate our stellar radii through a comparison with asteroseismology in Section 3.8. We also compare our radii to the purely spectroscopic measurements of J17 in Section 3.9 and to those computed by the Gaia project in Section 3.10.

3.2. Photometry

We used K-band photometric measurements because dust extinction is less severe in the infrared (see Section 3.3). The Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) measured $m_K$ for our target stars with a median precision of 0.022 mag, which corresponds to $\approx 1\%$ errors in $R_\star$.

We elected to use a single photometric band so that our $T_{\text{eff}}$ constraints would depend only on spectroscopy. Compared broadband colors, spectroscopy has the advantage that it yields more precise temperatures that are insensitive to reddening. For Kepler field stars, there are significant degeneracies between reddening and photometric $T_{\text{eff}}$ that result in uncertainties of $\approx 200$ K (see Pinsonneault et al. 2012 and P17). Given that $T_{\text{eff}}$ uncertainties often dominate the final $R_\star$ uncertainty, we restricted our analysis to $m_K$.

As an aside, we expect that Gaia DR2 will transform our understanding of the 3D distribution of dust in the Milky Way Galaxy. This will reduce reddening-$T_{\text{eff}}$ degeneracies for Kepler field stars, and result in improved measurements of $T_{\text{eff}}$ from broadband colors. However, such a dust modeling effort is beyond the scope of this work.

3.3. Extinction

We consulted the 3D dimensional dust map of Green et al. (2018) to quantify and correct for K-band extinction. The map tabulates reddening in PS1 and 2MASS passbands as a function of a function of galactic latitude, galactic longitude, and distance. Our median target has a $E(B-V)$ reddening of 0.049 mag.

To convert between $E(B-V)$ and $A_\lambda$, one must multiply $E(B-V)$ by an extinction vector $R_\lambda$. Green et al. (2018) adopted $R_\lambda$ from Schlafly et al. (2016) who studied the variation in observed stellar colors with reddening. Unfortunately, the Schlafly et al. (2016) methodology is insensitive to the gray component of the extinction curve, i.e. $R_\lambda \rightarrow R_\lambda + b$. As a matter of convenience, Green et al. (2018) resolved this ambiguity by setting $R_{\text{V-2}} = 0$, which implies $R_K = 0.161$. However, if one adopts $A_H/A_K$, one may derive $b$ by solving the following system of equations:

$$A_H = (R_H + b)E(B-V)$$
$$A_K = (R_K + b)E(B-V).$$

We adopted $A_H/A_K = 1.74$ from Nishiyama et al. (2008), which yields $b = 0.063$ and $R_K = 0.224$. The value of $A_H/A_K$ itself is uncertain. As a point of reference, Indebetouw et al. (2005) found $A_H/A_K = 1.55$, which yields $b = 0.141$ and $R_K = 0.302$. To account for the uncertainty in $R_K$, we add 30% additional fractional uncertainty to $A_K$.

The expected K-band extinction ranges from $A_K = 0.001–0.056$ mag, with a median value of $A_K = 0.011$ mag. The low typical extinction highlights the advantage of K-band. Neglecting extinction entirely would result in a $\approx 0.5\%$ error in $R_\star$ for our median target, which is smaller than other terms in the $R_\star$ error budget. For completeness, we corrected for extinction on a star-by-star basis by adding $A_K$ to the measured $m_K$ and adding uncertainties in quadrature.

3.4. Distances

Our distances come from Gaia DR2 which have a median precision of 1.4 % that contributes 1.4 % to our $R_\star$ error budget.

3.5. Effective Temperatures

Stellar effective temperatures factor into our measurement of stellar radii in two ways: through the Stefan–Boltzmann law (Section 3.1) and through the bolometric corrections (Section 3.6). We used the CKS spectroscopic $T_{\text{eff}}$ which have an internal precision 60 K (P17). We note that offsets of $\approx 100$ K are often observed when comparing different spectroscopic catalogs as well as when comparing spectroscopic temperatures to temperatures determined by other techniques, such as the infrared flux method or interferometry (Brewer et al. 2016). Therefore, these temperatures are accurate on an absolute scale to $\approx 100$ K. However, since our radii are all derived using CKS $T_{\text{eff}}$, the $T_{\text{eff}}$ precision, rather than its absolute accuracy, factors into the precision of our stellar radii. A precision of 60 K corresponds to $\approx 2\%$ errors on $R_\star$.

3.6. Bolometric Corrections

With $m_k$, $A_K$, and $\mu$ we may compute absolute K-band magnitude, $M_K$. Converting $M_K$ to $M_{\text{bol}}$ requires a bolometric correction $BC_K$. We computed $BC_K$ using the isoclassify package (Huber et al. 2017) which interpolates over the MIST isochrone models (Choi et al. 2016). For each star, we found the range of $BC_K$ consistent with our spectroscopically determined $T_{\text{eff}}$ and $[\text{Fe/H}]$. The uncertainties on $T_{\text{eff}}$ dominate the uncertainty of $BC_K$ because $T_{\text{eff}}$ has the largest influence on shape of the stellar SED. For a Sun-like star a 60 K uncertainty translates to a $\approx 0.03$ mag error on $BC_K$ or $\approx 1.5\%$ errors in $R_\star$. Errors on $BC_K$ stemming from uncertain log $g$ and $[\text{Fe/H}]$ are negligible by comparison.
We note that $T_{\text{eff}}$ errors enter into the Stefan-Boltzmann Law and $BC_K$ in ways that largely cancel. For our stars, $K$-band probes the Rayleigh-Jeans tail of the SED, where flux scales like $T_{\text{eff}}^4$. Therefore, at a fixed $m_K$, $L_{\text{bol}} \propto T_{\text{eff}}^4$, which is largely canceled by the $T_{\text{eff}}^{-4}$ term in Equation 1.

The bolometric corrections also include model-dependent errors. Huber et al. (2017) assessed these errors by comparing stellar radii derived from the MIST grids to those derived using the BASTA grids (Casagrande & VandenBerg 2014) and estimated 0.03 mag errors. As with $T_{\text{eff}}$, we expect these model-dependent errors to be largely common-mode and are thus more relevant for the accuracy rather than the precision of our stellar radii.

### 3.7. Detailed Modeling

In the previous sections, we enumerated the various measurements that we used to compute $R_\star$ and estimated their final contribution to the $R_\star$ error budget, which we summarize in Table 1. Our detailed modeling used the isoclassify package (Huber et al. 2017) to compute a number of stellar properties, including $R_\star$, given a set of observations and uncertainties. For each star, we provided isoclassify with $T_{\text{eff}}$, [Fe/H], $\pi$, and extinction-corrected $m_K$. Then, isoclassify computed the posterior probability on $R_\star$ by means of a direct integration using the MIST models. Figure 1 shows the distribution of the formal $R_\star$ precision, which have a median value of 2.2%. The radii are provided in Table 2.

### 3.8. Validation with Asteroseismic Radii

As in Paper-II, we assessed the final precision and accuracy of our stellar radii with a comparison to stellar radii derived using asteroseismology. We first compared against radii from Silva Aguirre et al. (2015), S15 hereafter, who performed an asteroseismic analysis of 33 Kepler planet hosts and achieved a median radius uncertainties of $\approx$1%. Importantly, the S15 analysis modeled individual oscillation frequencies, which achieves higher precision than simpler asteroseismic scaling relationships. We compared the stellar radii for the 29 CKS stars in common with the S15 study (Figure 2). Our radii are 1.8% larger on average, with a 1.8% RMS scatter in the ratio, which is consistent with the quadrature sum of the formal uncertainties of both sets of radii.

Because the S15 radii span a narrow range in $R_\star$ of 0.7–2.0 $R_\odot$, we performed a second comparison against radii from Huber et al. (2013), H13 hereafter, which span 0.7–10 $R_\odot$. H13 relied on scaling relationships using the small frequency separation $\delta \nu$ and peak frequency $\nu_{\text{max}}$. These relationships are lower precision than the more detailed analysis of S15 at 3% fractional precision. Our radii are 1.7% larger on average, with a 3.4% RMS scatter in the ratio, which is consistent with the quadrature sum of the formal uncertainties of both sets of radii.

Our comparisons with S15 and H13 show that our stellar radius precision is comparable to, or smaller than, those from asteroseismology. In principle our methodology for measure stellar radii can be used to test systematics in the asteroseismic scaling relationships as in (Huber et al. 2017). Such an effort is beyond the scope of this work.

### 3.9. Comparison with Johnson et al. (2017) Radii

Figure 3 compares our radii against those from J17, which relied on spectroscopy alone. The RMS scatter in the ratios is 13.2%, which is consistent with the 11% median uncertainty quoted in J17. We also note that the J17 radii on average fall below the one-to-one line between 1 and 3 $R_\odot$. We observed this trend in J17 when comparing the J17 radii to asteroseismic radii. It is not surprising that we observe this same trend in a larger sample given our new radii closely track asteroseismology. This demonstrates the potential for Gaia to serve as a benchmark with which to test synthetic spectra and model atmospheres. We also note a handful of outliers in the comparison. These could be due to stars with unresolved companions contributing extra $K$-band flux and making the CKS+Gaia radii seem larger. They may also be due to rare and unknown failure modes in the spectroscopic analysis of P17.

### 3.10. Comparison with Gaia DR2 Stellar Radii

The Gaia project also provided radii based on SED modeling that fits for effective temperature, extinction, and radius given the known distance. Figure 3 compares our radii with the Gaia project radii for 1074 stars in common. On average Gaia DR2 radii are 0.4% larger than ours with a 6.1% RMS scatter in the ratio, which is consistent with the formal median uncertainty of 6.9% reported in Gaia DR2.
Table 1. Error Budget

| Parameter | Median Uncert. |
|-----------|----------------|
| $T_{\text{eff}}$ | 60 K |
| $m_K$ | 0.02 mag |
| $A_K$ | 0.004 mag |
| $\mu$ | 0.01 mag |
| $BC$ | 0.03 mag |
| $R_*$ | 2.2% |
| $R_p/R_*$ | 4.1% |
| $R_p$ | 4.9% |

4. PLANET POPULATION

4.1. Distribution of Detected Planets

Using our updated stellar radii we derived planet radii using the values of $R_p/R_*$ tabulated in Mullally et al. (2015). We also computed the incident stellar flux $S_{\text{inc}}$ using our updated $R_*$ and $T_{\text{eff}}$. These $R_p$ and $S_{\text{inc}}$ measurements are listed in Table 3. Figure 4 shows the distribution of planets in the $P-R_p$ and $S_{\text{inc}}-R_p$ planes.

As in F17, we observe a narrow gap separating two populations of planets at $\approx 2 R_\oplus$. While the gap is clearly visible in this sample of 1944 planets, we caution that the distribution of detected planets does not convey the underlying distribution of planets, due to selection effects that we discuss in Section 4.2.

4.2. Intrinsic Distribution of Planets

Here, we measure planet occurrence, the number of planets per star, as a function of $P$, $R_p$, and $S_{\text{inc}}$. In order to measure the intrinsic distribution of planets, we must account for selection effects in the construction of the CKS target list, geometrical transit probability, and pipeline completeness. Our methodology follows that of F17.

We first identified a subset of CKS planets drawn from a well-defined population of parent stars by applying the following cuts to our planet sample:

1. Stellar brightness. We restricted our sample to the magnitude-limited CKS subsample, where $K_p < 14.2$ mag.

2. Stellar radius. We restricted our analysis to dwarf stars where

$$\log_{10} \left( \frac{R_*}{R_\odot} \right) < \left( \frac{T_{\text{eff}} - 5500 \text{ K}}{4000 \text{ K}} \right) + 0.2.$$  (2)

3. Stellar effective temperature. We restricted our planet sample to stars with $T_{\text{eff}} = 4700$–6500 K, where the CKS temperatures are reliable.

4. Stellar dilution (Gaia). Dilution from nearby stars can also alter the apparent planetary radii. For each target, we queried all Gaia sources within 8 arcsec (2 Kepler pixels) and computed the sum of their $G$-band fluxes. The ratio between this cumulative flux and the target flux $r_8$ approximates the $K_p$-band dilution for each transiting planet. We required that $r_8 < 1.1$.

5. Stellar dilution (imaging). Furlan et al. (2017) compiled high-resolution imaging observations performed by several groups. When a nearby star is detected, Furlan et al. (2017) computed a radius correction factor (RCF), which accounts for dilution assuming the planet transits the brightest star. We do not apply this correction factor, but conservatively exclude KOIs where the RCF exceeds 5%.

6. Planet false positive designation. We excluded candidates that are identified as false positives according to P17.

7. Planets with grazing transits. We excluded stars having grazing transits ($b > 0.9$), which have suspect radii due to covariances with the planet size and stellar limb-darkening during the light curve fitting.

After applying these cuts, we are left with 859 planets. Where possible, we applied the same filters on stellar properties to the Kepler field star population. For the stellar radius and temperature filters we used the Gaia DR2 parameters. We could not apply the imaging cut to the parent stellar population because it relies...
on follow-up resources directed specifically at KOIs not at the parent population. After filtering, 24981 stars remain.

We calculated planet occurrence using the methodology of F17. In brief, we account for the detection sensitivity of the survey using the injection-recovery tests performed by Christiansen et al. (2015). We calculated planet occurrence as the number of planets per star in discrete bins as

\[ f_{\text{bin}} = \frac{1}{N_*} \sum_{i=1}^{n_{\text{pl}, \text{bin}}} w_i, \]  

where \[ N_* = 24981 \] and \[ w_i \] is the product of the inverse pipeline detection efficiency \[ p_{\text{det}} \] and the inverse transit probability \[ p_{\text{tr}} \] for each detected planet. Values of \[ w_i, p_{\text{det}}, p_{\text{tr}} \] are listed in Table 5.

Computing these weights requires knowledge of the distribution of radii and noise properties of stars in the parent stellar sample. As in F17, we used the Combined Differential Photometric Precision computed by the Kepler project (Mathur et al. 2017) as our noise metric. Unlike F17, we used the \[ R_* \] from Gaia DR2 as opposed to photometric \[ R_* \] to characterize the distribution of parent stellar radii. F17 found that plausible statistic-

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**Figure 1.** Left: Distribution of fractional stellar radius uncertainties from this work (black) compared to those from J17 (grey). Right: Same as left but comparing fractional planet radius uncertainties.

**Figure 2.** Left: Comparison of stellar radii derived from asteroseismology (Silva Aguirre et al. 2015; S15) and spectroscopy+astrometry (this work) for 29 stars in common. Equality is represented by the dashed green line. Our radii are 1.8% larger on average and there is a 1.8% RMS dispersion in the ratios. Right: same as left but comparing our radii to Huber et al. 2013 (H13). Our radii are 1.7% larger on average and there is a 3.4% RMS dispersion in the ratios.
Figure 3. Left: Comparison of stellar radii derived from spectroscopy+astrometry (this work) and spectroscopy alone (J17). The J17 radii are 1.9% smaller on average and there is a 13.2% RMS dispersion in the ratios. Right: same as left but comparing our radii to the Gaia DR2 radii. The Gaia DR2 radii are 0.4% larger on average and there is a 6.1% RMS dispersion in the ratios.

The intrinsic astrophysical spread in the sizes of super-Earths and sub-Neptunes is considered in Section 4.3. Here, we consider the intrinsic astrophysical spread in the population of super-Earths and sub-Neptune planets and whether planets that appear to reside in the gap spanning 1.5 to 2.0 $R_\oplus$ could be explained by measurement uncertainties alone. Previous studies have struggled to measure the occurrence of planets over this narrow region of planet size. In F17, planet radius uncertainties were marginally smaller than the width of the gap, and the Van Eylen et al. (2017) asteroseismic analysis suffered from a small number of detected planets.

We show the filtered distribution of planets in Figure 7, and we identify two fiducial planet classes, “super-Earths” and “sub-Neptunes,” as well as the radius gap.
The large number of planets (125) residing within the gap appear to be inconsistent with scatter from above and below. To test this, we constructed a toy model to assess whether they could be explained by measurement uncertainties alone.

In our toy model, we took the observed planet detections and assigned them to one of the two planet classes, based on whether they resided in one of the two boxes shown in Figure 7. For each super-Earth and sub-Neptune we assigned a new radius from uniform distributions with centers at $1.2 \, R_\oplus$ or $2.4 \, R_\oplus$, respectively, which correspond to the locations of the observed peaks in the radius distribution. The fractional width shared by both distributions $W$ is a free parameter in this model.

We simulated planet detections over a range of $W$ and computed a figure of merit $FOM = \sum_i (N_{\text{real},i} - N_{\text{sim},i})^2$, where $i$ corresponds to the three boxes in Figure 7. Our FOM and visual inspection identified an intrinsic spread of $W = 60\%$ as a good match to the data (see Figure 7). In our best-fitting toy model, the super-Earth and sub-Neptune populations span $0.85$ to $1.55 \, R_\oplus$ and $1.7$ to $3.1 \, R_\oplus$, respectively; it is inconsistent with a population devoid of planets between $1.5$ and $2.0 \, R_\oplus$.

As a limiting case, we show a model with $W = 40\%$ in Figure 7. Here, the super-Earth and sub-Neptune population span $0.96$ to $1.44 \, R_\oplus$ and $1.92$ to $2.88 \, R_\oplus$, respectively, which approximate the upper and lower boundaries of the gap. This model produces a much emptier gap and is an obvious mismatch with the observations.

We recognize that this toy model does not capture the detailed radius distribution of planets, most notably the tail of planets larger than $3 \, R_\oplus$. A more detailed study might use a different distribution to model the planet radii, such as a Gaussian, Rayleigh, or a non-parametric distribution. Nonetheless, we have constrained the intrinsic dispersion in the size of the super-Earth and sub-Neptune populations to be $\approx 60\%$. While there is a dip in the occurrence of close-in planets from $1.5$ to $2.0 \, R_\oplus$, occurrence does not fall to zero. These interpretations were not possible in previous studies, due to larger radius uncertainties or limited numbers of detected planets.
4.4. Trends with Host-Star Mass

In order to investigate potential changes in the structure of the planet radius distribution as a function of stellar host mass, we split the sample into three bins of stellar mass: $M_\star < 0.96 \, M_\odot$, $0.96 - 1.11 \, M_\odot$, and $M_\star > 1.11 \, M_\odot$. We chose bin boundaries such that the three bins captured equal numbers of planets. Figure 8 shows the planet population in the $P-R_p$ and $S_{inc}-R_p$ planes for each of the three mass bins. The gap is clearly visible in each of the three stellar mass bins, and spans a larger range of planet radii compared to the full sample, shown in Figure 6.

We observe several trends with stellar mass. First, the typical size of super-Earth and sub-Neptune planets increases with increasing stellar mass, an observation that we quantify later in this section. This explains why the planet populations are better separated when one considers a narrow range of stellar mass; when all three mass groups are combined the distributions overlap. It also helps to clarify why the planet populations in Van Eylen et al. (2017) seemed to be more separated compared to those in F17. The asteroseismic sample was heavily weighted toward stars more massive than the sun, and is more directly comparable to the $P-R_p$ distribution of our high mass bin. The top right panel of our Figure 8 is a closer match to Figure 2 from Van Eylen et al. (2017) than the upper left panel of our Figure 8.

To quantify the change in typical planet size with stellar mass, we calculated the mean planet radius for sub-Neptunes ($1.7 - 4.0 \, R_\oplus$, and $P < 100$ days) and super-Earths ($1.0 - 1.7 \, R_\oplus$, and $P < 30$ days). We weighted
In the high stellar mass sample, 10% of planets have include planets out to 150
confirmed the existence of the F17 radius gap between
population of small planets at higher resolution. We
J17.

eeling, rather than the stellar radius uncertainties as in
are limited by uncertainties in the
radius precision is now 2% compared to 11% in J17. The
true component of the protoplanetary disk likely tracks both stellar metallicity and stellar mass. Therefore, we expect planet size to be correlated with both stellar mass and metallicity. Future studies spanning a larger range of stellar mass and metallicity are necessary to resolve this ambiguity.

Previous studies have noted a desert of highly-irradiated sub-Neptune planets (see, e.g., Lundkvist et al. 2016 and Mazeh et al. 2016). We observe this sub-Neptune desert in our three mass bins (Figure 8), but note that it shifts to higher incident stellar flux around high mass stars. This trend is highly significant. Figure 9 shows the average \( R_{\text{inc}} \) as function \( M_\star \). The mean \( \overline{S_{\text{inc}}} \) for both the super-Earths and sub-Neptunes increases by 3\times over a relatively narrow range of average \( M_\star \), 0.85 \( M_\odot \) to 1.2 \( M_\odot \). One explanation could be that the orbital periods of small planets decreases with stellar mass. However, the mean orbital periods for the three different mass bins are consistent to \( \approx 30\% \).

Figure 10 shows the cumulative fraction of hot \( \overline{S_{\text{inc}}} = 30-3000 \overline{S_\oplus} \) sub-Neptune size planets \( (R_p = 1.7-4.0 \overline{R_\oplus}) \) as a function of insolation flux, highlighting the shift of the \( \overline{S_{\text{inc}}} \) sub-Neptune desert with stellar mass. In the high stellar mass sample, 10% of planets have \( \overline{S_{\text{inc}}} > 300 \overline{S_\oplus} \). For the low stellar mass sample, one must include planets out to 150 \( \overline{S_{\text{inc}}} \) to encompass 10% of the population.

5. DISCUSSION AND CONCLUSIONS

We analyzed the Kepler planet population after improving the radius precision of the stellar hosts and their planets. This improvement leveraged both CKS spectroscopy and Gaia DR2 parallaxes. Our median stellar radius precision is now 2% compared to 11% in J17. The uncertainty in our planet radii are now typically 5% and are limited by uncertainties in the Kepler transit modeling, rather than the stellar radius uncertainties as in J17.

With these improved planet radii, we examined the population of small planets at higher resolution. We confirmed the existence of the F17 radius gap between 1.5 and 2.0 \( \overline{R_\oplus} \), with more precise and independently derived planet radii. The overall radius distribution is similar to that of F17, which demonstrates that we are resolving the intrinsic spread of the super-Earth and sub-Neptune populations, which span \( \approx 60\% \) in radius. We also demonstrated that the gap from 1.5 to 2.0 \( \overline{R_\oplus} \) is not devoid of planets, a conclusion previously obscured by measurement uncertainties or small sample sizes. We observed a correlation of the average planet size and average insolation flux with stellar host mass. However, there is no significant correlation in the average orbital period as a function of average stellar host mass.

Here, we interpret our findings in the context of two theories that have been proposed to explain the distribution planets between the size of Earth and Neptune:

1. **Mass loss by photoevaporation.** In this mechanism, X-ray and UV radiation heats the outer layers of a planet’s envelope and drives mass loss. Several groups considered photoevaporation and predicted the planet radius gap before it was observed in F17, including Owen & Wu (2013), Lopez & Fortney (2014), Jin et al. (2014), and Chen & Rogers (2016). Following F17, Owen & Wu (2017) developed additional analytic photoevaporation theory and performed a population synthesis analysis comparing their simulated populations to the F17 occurrence measurements.

2. **Core-powered mass loss.** In this mechanism, luminosity from a cooling rocky core heats a planet’s envelope and drives mass loss. Ginzburg et al. (2016) developed the theory of core-powered mass loss and computed mass loss rates. Ginzburg et al. (2018) performed a population synthesis with comparisons to the F17 radius distribution and demonstrated that core-powered mass loss could explain the bimodal radius distribution.

Both theories can explain a bimodal population of planet sizes composed of two subpopulations: a population of bare rocky cores and a population with H/He envelopes with mass fractions of a few percent. Because both mass loss mechanisms are more efficient at high levels of incident stellar flux, they both predict that the population of sub-Neptunes should be offset to lower insolation fluxes compared to the super-Earths.

A key difference between the two mechanisms is the expected dependence on stellar mass. Core-powered mass loss depends only on properties of the planet and bolometric incident stellar flux. All else being equal, this mechanism predicts no dependence of the planet population as a function of \( M_\star \). In contrast, the efficiency of photoevaporation depends on the time-integrated XUV flux, or “fluence.” This quantity is a strong function of
Figure 8. Top row: the two-dimensional distribution of planet size and orbital period for three bins of stellar mass. The typical size of super-Earths ($R_p = 1.0–1.7 \, R_\oplus$) and sub-Neptunes ($R_p = 1.7–4.0 \, R_\oplus$) increases with stellar mass while typical orbital periods are roughly constant. Bottom row: same as top row, but with insolation flux on the horizontal axis. The population of super-Earths and sub-Neptunes shifts to higher incident flux for higher mass stars.

stellar mass since $\int (L_X/L_{bol}) \, dt \propto M_\star^{-3}$ (Jackson et al. 2012). Therefore, photoevaporation predicts that the population of sub-Neptunes should shift to lower $S_{inc}$ with decreasing stellar mass, due to increased activity around lower mass stars. The shifts in the $S_{inc}$-$R_p$ distribution of planets with $M_\star$ are consistent with this prediction from photoevaporation.

The lack of a strong $P$-$M_\star$ dependence is also consistent with photoevaporation. Owen & Wu (2017) showed that the mass loss timescale $t = M/M_\star \propto P^{1.4} M_\star^{-0.48} \propto S_{inc}^{1.06} M_\star^{2.2}$. Photoevaporation thus has a steeper dependence on $M_\star$ at fixed $S_{inc}$ than at fixed $P$. This naturally explains why we see a strong trend in planet $S_{inc}$ with stellar mass and no significant trend with $P$ in Figure 9.

We interpret the observed stellar mass dependence of the planet population as evidence supporting photoevaporation model. However, these two mechanisms are not mutually exclusive and both could be operating simultaneously. If photoevaporation is the dominate mechanism for sculpting planet envelopes, one may fit the observed distribution of planets to constrain important quantities like the distribution of planet core masses, envelope fractions, and core compositions (Owen & Wu 2017).

Due to the magnitude-limited nature of CKS, our analysis was restricted to a fairly narrow range in $M_\star$, spanning 0.85 to 1.2 $M_\odot$. Previous studies of the radius distribution of planets orbiting M dwarfs have shown that these planets tend to be smaller on average (Morton & Swift 2014; Dressing & Charbonneau 2015). This may be an extension of the stellar mass dependence of the planet population observed in this work. However, no study of planets orbiting low-mass stars to date has detected a gap in the radius distribution. Such a detection (or lack thereof) would reveal insights into the structure and formation of planets around low-mass stars. This motivates future high precision studies of large samples of planets orbiting K and M dwarfs. Such studies would provide additional leverage on $M_\star$ to test the dependence of the planet population on stellar mass and to constrain the mechanisms that form and sculpt planets.

Facility: Keck:I (HIRES), Kepler, Gaia

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Figure 9. Mean planet properties as a function of mean stellar mass for super-Earths and sub-Neptunes (left and right columns respectively). The top, middle, and bottom rows show the weighted average of planet radius, insolation flux, and orbital period, respectively. Planets around more massive stars tend to be larger and hotter than those around lower mass stars, but their orbital periods are similar.

extinction. We thank Alberto Krone-Martins for discussions regarding the Gaia mission and its data products. Daniel Huber kindly assisted with the isoclassify package.

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Figure 10. Cumulative distribution of planets as a function of insolation flux. The solid lines are corrected for completeness and the dashed lines are not corrected. Planets residing in very high insolation flux environments tend to be more rare around low mass stars. For example, ~20% of the planet population orbiting stars more massive than 1.11 M⊙ have $S_{\text{inc}} > 200 S_{\oplus}$, compared to only ~10% of planets orbiting stars less massive than 0.96 M⊙.
Table 2. Stellar Properties

| KOI    | $T_{\text{eff}}$ | [Fe/H] | $m_K$ | $\pi$ | $A_K$ | $R_*$ | $M_*$ | $\log_{10}$(age) | Dilution | RCF |
|--------|------------------|--------|-------|-------|-------|-------|-------|-----------------|----------|-----|
| K00001 | 5819             | 0.01   | 9.8   | 4.62  | 0.003 | 1.05  | 0.99  | 9.75            | 1.00     | 1.01 |
| K00002 | 6449             | 0.20   | 9.3   | 2.90  | 0.099 | 2.00  | 1.53  | 9.25            | 1.00     | 1.03 |
| K00006 | 6348             | 0.04   | 11.0  | 2.07  | 0.012 | 1.31  | 1.20  | 9.37            | 1.00     | 1.001 |
| K00007 | 5827             | 0.18   | 10.8  | 2.02  | 0.004 | 1.54  | 1.16  | 9.77            | 1.00     | ... |
| K00008 | 5891             | -0.07  | 11.0  | 2.96  | 0.014 | 0.94  | 0.99  | 9.27            | 1.00     | ... |
| K00010 | 6181             | -0.08  | 12.3  | 0.95  | 0.011 | 1.60  | 1.17  | 9.65            | 1.01     | 1.001 |
| K00017 | 5660             | 0.36   | 11.6  | 1.67  | 0.011 | 1.28  | 1.10  | 9.82            | 1.03     | ... |
| K00018 | 6332             | 0.02   | 11.8  | 1.08  | 0.041 | 1.74  | 1.32  | 9.45            | 1.02     | 1.005 |
| K00020 | 5926             | 0.03   | 12.1  | 1.11  | 0.008 | 1.56  | 1.10  | 9.81            | 1.00     | ... |
| K00022 | 5891             | 0.21   | 12.0  | 1.35  | 0.007 | 1.29  | 1.13  | 9.70            | 1.00     | ... |
| K00041 | 5854             | 0.10   | 9.8   | 3.25  | 0.006 | 1.54  | 1.10  | 9.84            | 1.00     | 1.008 |
| K00046 | 5661             | 0.39   | 12.0  | 1.05  | 0.008 | 1.72  | 1.24  | 9.73            | 1.00     | ... |

Note—Properties of planet hosting stars. $T_{\text{eff}}$ and [Fe/H] are from P17, $m_K$ is the K-band apparent magnitude from the Two Micron All Sky Survey (2MASS, Skrutskie et al. 2006), $\pi$ is the trigonometric parallax from Gaia DR2 (Gaia Collaboration et al. 2018). $A_K$ is the modeled line-of-sight extinction in K-band (Section 3.3). Table 2 is published in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content.

Table 3. CKS Planet Parameters

| Planet candidate | $P$ | $R_p/R_*$ | $R_p$ | $a$ | $S_{\text{inc}}$ |
|------------------|-----|-----------|-------|-----|-----------------|
| K00001.01        | 2.5 | 0.12385   | 14.24 | 0.03566 | 896             |
| K00002.01        | 2.2 | 0.07541   | 16.44 | 0.03819 | 4243            |
| K00006.01        | 1.3 | 0.29402   | 42.17 | 0.02524 | 3912            |
| K00007.01        | 3.2 | 0.02474   | 4.16  | 0.04476 | 1224            |
| K00008.01        | 1.2 | 0.01856   | 1.92  | 0.02158 | 2070            |
| K00010.01        | 3.5 | 0.09358   | 16.34 | 0.04782 | 1464            |
| K00017.01        | 3.2 | 0.09514   | 13.35 | 0.04419 | 778             |
| K00018.01        | 3.5 | 0.08013   | 15.25 | 0.05001 | 1749            |
| K00020.01        | 4.4 | 0.11794   | 20.12 | 0.05460 | 905             |
| K00022.01        | 7.9 | 0.09394   | 13.28 | 0.08082 | 277             |
| K00041.01        | 12.8 | 0.01403 | 2.36  | 0.11077 | 203             |
| K00041.02        | 6.9 | 0.00806   | 1.35  | 0.07320 | 466             |
| K00041.03        | 35.3 | 0.00921 | 1.54  | 0.21773 | 53              |
| K00046.01        | 3.5 | 0.03302   | 6.19  | 0.04840 | 1158            |

Table 3 continued
Table 3 (continued)

| Planet candidate | $P$ | $R_p/R_\star$ | $a$ | $S_{inc}$ |
|------------------|-----|---------------|-----|----------|
| K00046.02        | 6.0 | 0.00686       | 1.29| 0.06971  | 558 |

**Note**—Planetary properties. Period $P$ and planet-to-star radius ratio $R_p/R_\star$ are from Mullally et al. (2015). Planet size $R_p$, semi-major axis $a$, and incident stellar flux relative to Earth $S_{inc}$ are derived from the updated stellar properties in Table 2. Table 2 is published in its entirety in machine-readable format with full numerical precision and uncertainties. A portion is shown here for guidance regarding its form and content.

Table 4. Planet Detection Statistics

| Planet candidate | SNR  | Detection probability | Transit probability | Weight |
|------------------|------|-----------------------|---------------------|--------|
| K00958.01        | 186.24 | 0.97                   | 0.02                | 47.60  |
| K04053.01        | 21.03  | 0.77                   | 0.17                | 7.62   |
| K04212.02        | 8.77   | 0.83                   | 0.06                | 21.86  |
| K04212.01        | 16.53  | 0.93                   | 0.08                | 13.37  |
| K01001.01        | 37.27  | 0.99                   | 0.03                | 31.51  |
| K02534.01        | 22.64  | 0.94                   | 0.12                | 9.09   |
| K02534.02        | 11.91  | 0.85                   | 0.08                | 14.85  |
| K02403.01        | 17.98  | 0.79                   | 0.04                | 29.14  |
| K00988.01        | 60.03  | 0.97                   | 0.04                | 27.90  |
| K00988.02        | 34.80  | 0.94                   | 0.02                | 51.33  |

**Note**—Table 5 is available in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content. This table contains only the subset of planet detections that passed the filters described in Section 4.