Draft version September 24, 2019
Typeset using LaTeX **modern** style in AASTeX63

Evolution of the Radius Valley Around Low Mass Dwarf Stars with *KEPLER* and *K2*

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ABSTRACT

Recent observational studies refining the planet radii around Sun-like stars have revealed a gap in the occurrence-rate of close-in planet sizes. Resolving the so-called radius valley around low mass stars provides valuable constraints on the physical mechanisms sculpting the valley and so far are largely limited by relatively poor counting statistics. Here we calculate the occurrence-rate of small close-in planets around low mass stars from the primary *Kepler* and *K2* missions. The radius valley is clearly resolved in the maximum-likelihood occurrence-rate although the gap is not completely void of planets, a feature whose prominence increases with decreasing stellar mass. In agreement with competing models of photoevaporation and core-powered mass-loss, we show that the valley location evolves to smaller planet radii with decreasing stellar mass. Robust inferences regarding the valley's dominant formation pathway will require $\mathcal{O}(N)$ additional confirmed planets which are expected to be uncovered by *TESS* within its extended mission.

1. INTRODUCTION

NASA's *Kepler* space telescope has discovered thousands of exoplanets over its lifetime and consequently enabled robust investigations of the occurrence rate of planets within our galaxy. (e.g. Youdin 2011; Howard et al. 2012; Dressing & Charbonneau 2013; Fressin et al. 2013; Petigura et al. 2013; Morton & Swift 2014; Dressing & Charbonneau 2015). Furthermore, mass measurements of many of these transiting planets via transit-timing variations or precision radial velocity follow-up campaigns revealed that the majority of planets smaller than ~ 1.6 $R_\oplus$ are consistent with having bulk terrestrial compositions (e.g. Weiss & Marcy 2014; Dressing et al. 2015; Rogers 2015). Early studies of the *Kepler* population hinted at the distribution of planet radii at small orbital separations featuring a bimodality (e.g. Owen & Wu 2013)—commonly

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referred to as the radius valley—that is thought to represent two populations of predominantly rocky super-Earths plus inflated sub-Neptunes at slightly longer orbital periods that have retained significant H/He envelopes.

Consequently, numerous studies of planet formation/evolution sought to explain the apparent bimodality in the distribution of close-in planetary radii. One such proposed mechanism is that of photoevaporation wherein the gaseous envelopes of small close-in planets may be stripped by X-ray and extreme ultraviolet (XUV) radiation from their host stars during the first $\sim$ 100 Myrs of the planet's lifetime (Owen & Wu 2013; Jin et al. 2014; Lopez & Fortney 2014; Chen & Rogers 2016; Lopez & Rice 2016; Owen & Wu 2017; Jin & Mordasini 2018). Another possible explanation invokes gas-poor formation wherein gas accretion is delayed by dynamical fraction whilst the protoplanet is still embedded within the protoplanetary disk until a point at which the gaseous disk has almost completely dissipated after just a few Myrs (Lee et al. 2014; Lee & Chiang 2016). More recently, the radius valley may also be explained by core-powered mass loss wherein the luminosity from a planetary core's primordial energy reservoir from formation drives atmospheric escape over Gyr timescales (Ginzburg et al. 2018; Gupta & Schlichting 2019a,b).

Observational tests of the aforementioned theoretical frameworks have become feasible in recent years as a result of the precise refinement of measured planet radii following improved stellar host characterization via spectroscopy, asteroseismology, and *Gaia* parallaxes (e.g. Fulton et al. 2017; Van Eylen et al. 2018; Fulton & Petigura 2018; Martinez et al. 2019). These studies clearly resolved the radius valley among small close-in planets around Sun-like stars. They also observed a variety of trends in either the raw or in the completeness-corrected (i.e. the occurrence rate) distributions of close-in planets. Firstly, the location of the radius valley around FGK stars is period-dependent with slope $\mathrm{d}\log r_p/\mathrm{d}\log P \sim -0.1$ (Van Eylen et al. 2018; Martinez et al. 2019), a result that is consistent with both photoevaporation and core-powered mass loss models but is inconsistent with the late formation of terrestrial planets in a gas-poor environment. Secondly, the feature locations (i.e. the weighted average radius of the peaks and valley) appear to exist at smaller planet radii with decreasing stellar mass (Fulton & Petigura 2018; Wu 2019).

In this study, we extend the investigation of close-in planets to systems hosted by low mass dwarf stars later than mid-K. The known planet population in this stellar mass regime features nearly ten times fewer planets than around Sun-like stars thus making the detection of the radius valley around low mass stars more difficult and at a lower signal-to-noise. This fact is clearly evidenced in the empirical *Kepler* planet population for which the radius valley around Sun-like stars ($T_{\rm eff} \in [4700, 6500]$ K) is clearly evident whereas any valley in the planet population around low mass stars ($T_{\rm eff} < 4700$ K) is not easily discernible by-eye (Fig. 1). Our study leverages the precise stellar parallaxes from the *Gaia* DR2 (Lindegren et al. 2018) for low mass stars obseved by *Kepler* and *K2* to refine the stellar parameters and compute precise

Figure 1. Empirical distributions of *Kepler* planet radii. Histograms of *Kepler* planet radii from Berger et al. (2018) for planets with host stellar effective temperatures $T_{\rm eff}$ $\in [4700, 6500]$ K (*blue*) or $T_{\rm eff} < 4700$ K (*red*). The former subset of 2816 planets corresponds to the effective temperature range considered in the CKS (Fulton et al. 2017). The radius valley is clearly resolved in the empirical distribution of this sample (i.e. without completeness corrections). A similar bimodal structure is not resolved in the empirical disitribution of the latter subset of 350 planets around cooler stars.

occurrence rates of close-in planets with the goal of resolving the radius valley and accurately measuring the locations of the radius valley features and their uncertainties. Although it is unlikely that a single physical mechanism is responsible for sculpting the radius valley, investigation the evolution of the valley features with stellar mass can allude to which process—if any—dominates the evolution of close-in planets.

2. POPULATION OF SMALL CLOSE-IN PLANETS AROUND LOW MASS DWARF STARS FROM KEPLER AND K2

The goal of this study is to extend measurements of the radius valley and its properties to planetary systems hosted by low mass dwarf stars later than K3.5V (Pecaut & Mamajek 2013) with effective temperatures $T_{\rm eff} < 4700$ K: the lower limit of $T_{\rm eff}$ considered by the California Kepler Survey where the radius valley was first revealed Fulton et al. (2017). Our stellar sample of interest therefore includes such stars from either *Kepler* or *K2* and up to maximum Kepler magnitudes of $K_p < X$ and $K_p < \mathbf{X}$ respectively. The stellar radii are refined based on their spectroscopically-derived effective temperatures (Gaidos et al. 2016; Mathur et al. 2017; Petigura et al. 2017) and measured luminosities which are derived from 2MASS K_s-band magnitudes (Cutri et al. 2003) and *Gaia* DR2 stellar parallaxes (Lindegren et al. 2018) (see Methods). To investigate the evolution of the inherent planet population with stellar mass, we employ a stellar mass-radius relation—applicable to K and M dwarfs—to derive stellar masses from their measured radii (Boyajian et al. 2012).

We consider two planet populations separately. Our initial sample of transiting planets were retrieved from the NASA Exoplanet Archive (Akeson et al. 2013) on June 15, 2019 and only includes confirmed planets with orbtial periods $P \in [0.5, 100]$ days. By considering confirmed planets only, we focus on the true empirical population of small close-in planets without being contaminated by various astrophysical false positive scenarios that plague the planet candidates that are excluded from our sample. The refined stellar parameters enable us to refine the planet radii by resampling the stellar radius from its uncertainties and the scaled planet radius r_p/R_s from its retreived point estimates to derive the planet radius. Similarly, we refine each planet's level of received insolation given its orbital period plus its host star's $T_{\rm eff}$, R_s, and M_s. Our final sample of confirmed small close-in planets with $P \in [0.5, 100]$ days and $r_p \in [0.5, 4]$ $\mathrm{R}_\oplus$ contains **262** *Kepler* and **47** *K2* planets respectively (Fig. 2).

To improve the counting statistics in our upcoming investigation of the population of small close-in planets, we also consider an ancillary planet population that

Figure 2. Empirical populations of small close-in planets around low mass stars. *Top panel*: the distribution of confirmed *Kepler* and *K2* planets in the orbital period-planetary radius and insolation-planetary radius planes. The two-dimensional maps are Monte-Carlo sampled from the measurement uncertainties of the planetary radius and insolation while the fractional orbital period uncertainties are inflated to 20%. *Bottom panel*: same as the top panel but for an enhanced planet population that includes *K2* planet candidates approximately corrected for false positives.

includes **N** additional planet candidates (PCs) from *K2* campaigns 0-8 that orbit stars contained in our stellar sample (Kruse et al. 2019) . By definition, we cannot identify which PCs are true planets of interest for this study and which PCs are instead produced by an astrophysical false positive (FP) such that the inclusion of *K2* PCs requires that we account for sample contamination by FPs probabilistically. We do so by considering a number of *K2* planet searches from the literature that attempt to validate their uncovered PCs statistically using follow-up observations (Crossfield et al. 2016; Dressing et al. 2017; Livingston et al. 2018; Mayo et al. 2018). Each study utilized some combination of ground-based photometry to validate planet ephemerides, reconnaissance stellar spectroscopy to identify spectroscopic binaries, and speckle or AO-assisted imaging to search for nearby stellar companions to their PC host stars. Each study used th statistical validation tool `vespa` (Morton 2012, 2015) to classify their PCs as either a validated planet (VP), a FP, or some other inconclusive disposition We calculate the FP rate of small planets (< 4 R$_\oplus$) around cool stars as the ratio of number of reported FPs to the total number of FPs and VPs after noting that FP rates are dependent on the measured planet size as giant PCs have a larger likielhood of being a FP (Crossfield et al. 2016). We find that $\sim 5\%$ of *K2* PCs of interest turn out to be FPs such that when constructing planet populations that include PCs, we Monte-Carlo sample the PC distribution and reject 5% of PCs and FPs in each iteration. Our final sample of confirmed planets + PCs still contains **262** *Kepler* planets along with **N** *K2* planets. A random iteration of this planet population is included in Fig. 2.

3. TRANSITING PLANET DETECTION COMPLETENESS

In order to derive planet occurrence rates the empirical distribution of planet detections must be corrected by the imperfect survey completeness. The completeness correction is treated separately for each subset of planets from *Kepler* or *K2* in the following subsections. Each set of corrections accounts for detection biases arising from the imperfect sensitivity of the employed detection pipelines as well as for the geometric probability of a planetary transit to occur.

3.1. *Kepler Sensitivity*

The derivation of the *Kepler* planet detection sensitivity follows from the methodology outlined in Christiansen et al. (2016) and used by Fulton et al. (2017) to resolve the radius valley around FGK stars. Per-target *Kepler* completeness products for

Figure 3. Average detection sensitivity for *Kepler* and *K2*. The *solid curves* represent the average transiting planet detection sensitivity for the *Kepler* and *K2* stars in our sample as a function of the transit S/N (Eq. 1). The shaded regions mark the 16^{th} and 84^{th} percentiles of the measured detection sensitivities.

Figure 4. Average detection sensitivity and completeness versus orbital period and planetary radius. *Top panels*: the average detection sensitivity for the *Kepler* and *K2* stars in our stellar sample as functions of planetary radius and orbital period. *Bottom panels*: the average completeness for the *Kepler* and *K2* stars computed as the product of the detection sensitivity and transit probability (Eq. 2).

DR25 and the SOC 9.3 version of the *Kepler* pipeline (Jenkins et al. 2010) are available for all of the planet-host stars in our *Kepler* sample (Burke et al. 2015; Burke & Catanzarite 2017). Detection sensitivities (or efficiencies) were computed via transiting planetary signal injections at the pixel level (Christiansen et al. 2015, 2017). The injected signals were processed by the *Kepler* pipeline from which the detection sensitivity as a function of the Multi-event statistic (MES) is computed as the fraction of injected signals that are sucessfully recovered by the pipeline.

Other necessary per-target products were obtained including the

$$\mathrm{S/N} = \frac{Z}{\mathrm{CDPP}_D}\sqrt{n_{\mathrm{transits}}(\mathbf{t}, P, T_0)} \tag{1}$$

where $Z = (r_p/R_s)^2$ is the transit depth, CDPP_D is the Combined Differential Photometric Precision on the timescale of the transit duration D, and n_{transits} is the number of observed transits given the window function of observations $\mathbf{t}$, the planet's orbital period P, and its time of mid-transit T_0.

3.2. *K2 Sensitivity*

`EVEREST` light curves (Luger et al. 2016, 2018)

as stated in Kruse+2019 section 4.1, Luger et al. (2016) find that everst outperforms k2sff and k2sc by $\sim 20 - 50\%$ in terms of photometric precision

`ORION` (Cloutier 2019)

3.3. *Survey Completeness*

Only transiting planets are detectable in transit surveys. To correct for the non-detection of otherwise detectable but non-transiting planets around low mass stars in any *Kepler* or *K2* field, we computed the geometric transit probability for each star and at each grid cell ij to be

$$p_{t,nij} = \frac{R_{s,n} + r_{p,j}}{a_{ni}}. \tag{2}$$

Note that we are only interested in the relative occurrence rate and therefore do not consider fixed scalar modifications to $p_{t,nij}$ for effects such as grazing transits or eccentricity corrections (Barnes 2007).

Figure 5. Planet occurrence rate versus orbital period and planetary radius.

Figure 6. Occurrence rate of planets as a function of size. Histogram depicting the relative occurrence rate of close-in planets—with orbital periods < 100 days—derived from the joint sample of confirmed planets from *Kepler* and *K2* around low mass stars. The bimodal distribution of planet radii peaking at 1.15 and 2.0 $R_\oplus$ is resolved which highlights the presence of the radius valley at 1.6 $R_\oplus$. Uncertainties in the planet occurrences follow from binomial statistics and are limited by the relatively small number of confirmed planets around low mass stars from *Kepler* and *K2*.

Figure 7. 2D and 1D planet occurrence rates in various stellar mass bins. *Top panels*: planet occurrence rate maps as a function of orbital period and planet radius. *Bottom panels*: histograms of the relative planet occcurrence rate as a function of planet size. Each column corresponds to a unique cut in stellar masses representing the full stellar sample ($M_s \in [0, 0.8]$ $M_\odot$), the early half ($M_s \in [0.63, 0.8]$ $M_\odot$), the late half ($M_s \in [0, 0.63]$ $M_\odot$), and low mass cutoff ($M_s \in [0, 0.42]$ $M_\odot$). As the stellar mass range is decreased the statistics become poorer which muddles the detection of the radius valley in any subset other than the full sample.

Combining each star's detection sensitivity with the geometric transit probability yields our completeness correction over the ij grid. The average completeness maps for our *Kepler* and *K2* stars are also included in Fig. **??** as functions of r_p, P, and F.

4. THE OCCURRENCE RATE OF SMALL CLOSE-IN PLANETS AROUND LOW MASS DWARF STARS

The detection and confirmation of planets from the *Kepler* and *K2* surveys enable to measurement of the occurrence rate of planets given the completeness corrections derived in Sect. 3. For the indices i and j representing a planet's orbital period and radius, the probability of detecting k_{ij} such planets around the N_s stars in our sample is given by the binomial distribution

$$\mathcal{L}_{nij}(k_{ij}|N_s, p_{nij}) = \binom{N_s}{k_{ij}} \prod_{n=1}^{N_s} p_{nij}^{k_{ij}} (1 - p_{nij})^{N_s - k_{ij}} \tag{3}$$

where

$$p_{nij} = f_{ij} \cdot s_{nij} \cdot p_{t,nij}, \tag{4}$$

is the probability of detecting a planet around the n^{th} star and is dependent on the intrinsic occurrence rate of planets f_{ij}, the detection sensitivity to such planets s_{nij}, the the transit probability of such planets $p_{t,nij}$.

5. ON THE PHYSICAL ORIGIN OF THE RADIUS VALLEY

6. IMPROVEMENTS AFFORDED BY TESS

NASA's Transiting Exoplanet Survey Satellite (*TESS*; Ricker et al. 2015) will provide hundreds of new transiting planet dicsoveries in the vicinity of the radius valley

Figure 8. Evolution of the radius valley with stellar mass. *Solid markers*: the occurrence rate-weighted locations of the super-Earth peak (*blue markers*), the radius valley (*green markers*). and the sub-Neptune peak (*red markers*) as a function of host stellar mass for three M_s bins considered in this work: $M_s \in [0, 0.8]$ $\mathrm{M}_\odot$, $M_s \in [0, 0.8]$ $\mathrm{M}_\odot$, and $M_s \in [0, 0.8]$ $\mathrm{M}_\odot$. The median stellar masses are depicted along with their uncertainties calculated from the 16^{th} and 84^{th} percentiles their respective stellar mass distribution. Uncertainties on the peak and valley locations are derived by sampling the measured occurrence rates and their uncertainties along with samples of the hyperparameters controlling map smoothing, minimum detection sensitivity, and the assumed feature ranges in planet radius. Similar measurements for Sun-like stars from Fulton & Petigura (2018) are plotted as *open markers*. The remaining curves represent theoretical predictions of the location of the radius valley based on models of atmospheric loss from core-powered luminosity with a constant mass-luminosity relation (*dashed*; Gupta & Schlichting 2019b), an empirical mass-luminosity relation (*dotted*; Gupta & Schlichting 2019b), and photoevaporation (*solid*; Wu 2019). The model curves are anchored at the valley location for $M_s = \mathrm{M}_\odot$.

Figure 9. Expected improvement in the measurement precision of the radius peak and valley locations with additional confirmed planets around stars with $M_s \sim 0.3$ $\mathrm{M}_\odot$. Assuming a fixed detection probability (**dont do this**), the shaded regions depict the degree of improvement in the upper and lower limits on location of the super-Earth peak (*blue*), the radius valley (*green*), and the sub-Neptune peak (*red*) as additional planets are detected by missions like TESS. For stars with $M_s \sim 0.3$ $\mathrm{M}_\odot$, model predictions of the valley location from photoevaporation and core-powered mass loss differ by ~ 0.4 $\mathrm{R}_\oplus$ (*dashed horinzontal line*). Based on the performance of TESS to-date, the expected time to confirm such planets is parameterized as a linear function of time and is depicted on the secondary x-axis.

(Barclay et al. 2018). *TESS* is particularly well-suited to the discovery of close-in planets around low mass stars due to its red bandpass and its high cadence observations of $\sim 94\%$ of the sky following its first extended mission.

given the TOIs that we have so far from TESS, reduced by the FP rate thus far, and scaled up to 1) the full TESS mission and 2) its extended mission, we can estimate the number of close-in M dwarf planets that are expected from TESS from the two aforementioned campaigns. from this we can add that planet population to those in this paper (maybe also add K2 candidates) and recalculate the position of the radius gap to improve its precision as a function of stellar mass. maybe we will be able to push down to lower mass stars

kk no better yet, lets compute the number of planets we need in different stellar mass bins to say something interesting about how the gap evolves with stellar mass. then using the calculation above, say how close to we come to doing that with TESS primary, TESS extended, TESS FFIs, and K2 candidates.

7. DISCUSSION & CONCLUSIONS

Many new and up-coming RV spectrographs (e.g. HARPS; Mayor et al. 2003, HIRES; , HARPS-N; , APF; , PFS; , NEID; , ESPRESSO; , SPIRou; , NIRPS; , HPF; , IRD; , Minerva-Australis;) will be partially focused on characterizing the masses of planets spanning the radius valley in order to improve our physical understanding of the nature of those planets. The subset of those spectrographs operating in the near-IR in particular will focus on M dwarf planetary systems. This work elucidates the location of the radius valley around M dwarf host stars and guides observers to the planetary radii from transit surveys that are of interest for fully characterizing the radius valley in terms of planetary bulk densities.

mass dependence of the gap:

The weighted feature radii are also effected by planetary magnetic fields which directly impact the efficiency of atmospheric stripping in the photoevaportation scenario (**?**). The persistence of a planetary magnetic field acts to shield the planet's atmosphere from XUV stellar photons thus enhancing the retention of the atmosphere and shifting the location of the radius valley to larger radii.

In the photoevaporation scenario, the partial filling of the gap around low mass stars may be explained by their lower XUV luminosities relative to Sun-like such as those included in the CKS stellar sample ().

This explanation seems to be supported by the stellar mass dependent gap measurements from Fulton & Petigura (2018).

summary of McDonald+2019 (https://ui-adsabs-harvard-edu.ezp-prod1.hul.harvard.edu/abs/2019Ap
X-rays only since XUV observations are difficult for non-Sun-like stars and X-rays are the dominant driver of atmospheric loss by photoevaporation. Jackson+12 & Shkolnik+14 derived scalings from data for the LX/Lbol evolution over time for 0.3 - 1.3 solar mass stars on the MS, low mass stars ($\lesssim$ 0.8 M$_\odot$) exhibit a LX/Lbol that is typically a few to ten times greater than around Sun-like stars ($0.8 - 1.12$ M$_\odot$) (fig 1 in McDonald+2019). scaling these values by the typical bolometric luminosities of stars in the various mass bins reveals that Sun-like stars having higher absolute X-ray luminosities which contributes to more efficient clearing of the gap by photoevaporation.

8. METHODS

The goal of this study is to extend measurements of the radius valley and its properties to planetary systems hosted by low mass dwarf stars later than K3.5V (Pecaut & Mamajek 2013) with effective temperatures $T_{\rm eff} < 4700$ K: the lower limit of $T_{\rm eff}$ considered by the California Kepler Survey where the radius valley was first revealed Fulton et al. (2017). Our sample of *Kepler* stars is drawn from the cross-matched list of *Kepler* targets with the *Gaia* DR2 (Berger et al. 2018) which reports stellar parallaxes, 2MASS K_s-band apparent magnitudes, and spectroscopic measurements of $T_{\rm eff}$, $\log g$, and [Fe/H] for $\sim 178,000$ *Kepler* stars. The stellar parameters were applied to the spectral classification code `isoclassify` (Huber et al. 2017) to calculate the stellar luminosities and consequently refine the stellar radii using the Stefan-Boltzmann law for FGK *Kepler* stars. However, bolometric corrections for M dwarfs with $T_{\rm eff}$ $<$ 4100 K are known to suffer significant inaccuracies owing to incomplete molecular line lists. The stellar radii for these stars are instead refined using empirically-derived M dwarf radius-luminosity relations (Mann et al. 2015). Effective temperatures and measured luminosities were also used to derive stellar evolutionary flags that enable us to reject sub and red giants from our *Kepler* sample. Stellar mass values are derived from the stellar radii using mass-radius relations applicable to K and M dwarfs (Boyajian et al. 2012).

Our *K2* stellar sample was compiled by first retrieving the list of probable low mass dwarf stars from the Ecliptic Plane Input Catalog (EPIC) available on MAST[1] and using conservative restrictions on the assumed stellar parameters of interest. We search was limited to stars with *Kepler* magnitude $K_p < \mathbf{15.55}$: the dimmest probable low mass star with a confirmed transiting planet from *K2* (NASA Exoplanet Archive; Akeson et al. 2013). The stellar parameters are refined by cross-matching our initial *K2* sample with *Gaia* DR2 using the *Gaia*-*K2* data products from Megan Bedell[2]. *K2* stars that lack *Gaia* measurements are omitted from our sample. Stellar radius measurements follow from the methodology applied to the *Kepler* stars wherein stellar parallaxes are transformed to distances(Bailer-Jones et al. 2018) which are then used along with the source's celestial coordinates to interpolate the dust extinction maps using `mwdust` (Bovy et al. 2016) to derive extinction coefficients. For the earliest stars in our sample ($M_{K_s} \leq 4.6$) for which the bolometric corrections are still reliable, we interpolate the MIST bolometric correction grids (Choi et al. 2016) over T_{eff}, $\log g$, [Fe/H], and A_V to derive the K_s-band bolometric corrections BC_{K_s}. At this point we compute the stellar bolometric luminosity via

$$L_{\text{bol}} = 3.0128 \times 10^{28}\text{W } 10^{-0.4M_{\text{bol}}}, \tag{5}$$

where $M_{\text{bol}} = M_{K_s} + BC_{K_s}$ is the absolute bolometric magnitude. The refined stellar radii are then calculated using the Stefan-Boltzmann law given L_{bol} and T_{eff} with measurement uncertainties propagated throughout.

For the remaining late type stars with $M_{K_s} > 4.6$ we revert to the empirically-derived radius-luminosity relation from Mann et al. (2015) to calculate the M dwarf stellar radii. Mann et al. (2015) fit a second-order polynomial to R_s as a function of M_{K_s} which has a characteristic dispersion in the fractional radius uncertainty of 2.89%. To quantify the final R_s uncertainty we sample M_{K_s} from its posterior PDF and transform each M_{K_s} draw to an R_s value using the aforementioned radius-luminosity relation. To each star's dericed R_s PDF, we add in quadrature an additional dispersion term whose fractional radius uncertainty is 2.89%.

Given the refined stellar radii for our *K2* sample, we proceed with deriving stellar masses identically to the method applied to the *Kepler* sample (see Sect. **??**) using the Boyajian et al. (2012) stellar mass-radius relation.

We define our final *K2* stellar sample of low mass dwarf stars similarly to our definition of the *Kepler* sample. Explicitly, we focus on stars that obey the following criteria:

[1] Mikulski Archive for Space Telescopes, https://archive.stsci.edu/k2/.

[2] https://gaia-kepler.fun/

Figure 10. Stellar samples from *Kepler* and *K2*. Distributions of Kepler magnitudes, effective temperatures, stellar radii, and stellar masses for stars in our final stellar sample from either *Kepler* (*left panels*) or *K2* (*right panels*).

Table 1. *K2* false positive rates for small planets around cool stars

Reference	$N_{\rm FP}$	$N_{\rm VP}$	FP rate [%]
Crossfield et al. (2016)	2	39	$4.9^{+6.0}_{-1.4}$
Dressing et al. (2017)	2	34	$5.6^{+6.4}_{-2.0}$
Livingston et al. (2018)[a]	0	14	< 21.0
Mayo et al. (2018)[b]	8	14	$< 36.3^{+10.4}_{-8.9}$

NOTE—Within each study we only consider PCs with $r_p < 4$ R$_\oplus$ and orbiting cool stars with $T_{\rm eff} < 4700$ K.

[a] Livingston et al. (2018) do not detect any FPs such that the reported FP rate is represented by its 95% confidence interval.

[b] Mayo et al. (2018) did not explicitly classify their non-validated planets such that their reported number of FPs actually includes PCs as well as FPs. The resulting FP rate should therefore be considered an upper limit only.

1. $T_{\rm eff} - \sigma_{T_{\rm eff}} \leq 4700$ K,
2. $R_s - \sigma_{R_s} \leq 0.8$ R$_\odot$,
3. $M_s - \sigma_{M_s} \leq 0.8$ M$_\odot$, and
4. $R_s > R_{s,\rm max}$.

Because our *K2* sample lacks any evolutionary flags, we adopt the following ad hoc upper limit on R_s from Fulton & Petigura (2018) that aims to reject evolved stars:

$$R_{s,\rm max} = \mathrm{R}_\odot 10^{0.00025(T_{\rm eff}/\mathrm{K}-5000)+0.2}. \tag{6}$$

Based on these criteria we retrieve **13565** low mass *K2* stars that are relevant to our study. The distribution of *K2* stellar parameters are depicted in Fig. 10. The stars in this sample exhibit a median fractional radius uncertainty of $\sim$ **4**%.

REFERENCES

Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, PASP, 125, 989, doi: 10.1086/672273

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, AJ, 156, 58, doi: 10.3847/1538-3881/aacb21

Barclay, T., Pepper, J., & Quintana, E. V. 2018, ArXiv e-prints. https://arxiv.org/abs/1804.05050
Barnes, J. W. 2007, PASP, 119, 986, doi: 10.1086/522039
Berger, T. A., Huber, D., Gaidos, E., & van Saders, J. L. 2018, ApJ, 866, 99, doi: 10.3847/1538-4357/aada83
Bovy, J., Rix, H.-W., Green, G. M., Schlafly, E. F., & Finkbeiner, D. P. 2016, ApJ, 818, 130, doi: 10.3847/0004-637X/818/2/130
Boyajian, T. S., von Braun, K., van Belle, G., et al. 2012, ApJ, 757, 112, doi: 10.1088/0004-637X/757/2/112
Burke, C. J., & Catanzarite, J. 2017, Planet Detection Metrics: Per-Target Flux-Level Transit Injection Tests of TPS for Data Release 25, Tech. rep.
Burke, C. J., Christiansen, J. L., Mullally, F., et al. 2015, ApJ, 809, 8, doi: 10.1088/0004-637X/809/1/8
Chen, H., & Rogers, L. A. 2016, ApJ, 831, 180, doi: 10.3847/0004-637X/831/2/180
Choi, J., Dotter, A., Conroy, C., et al. 2016, ApJ, 823, 102, doi: 10.3847/0004-637X/823/2/102
Christiansen, J. L., Clarke, B. D., Burke, C. J., et al. 2015, ApJ, 810, 95, doi: 10.1088/0004-637X/810/2/95
—. 2016, ApJ, 828, 99, doi: 10.3847/0004-637X/828/2/99
Christiansen, J. L., Vanderburg, A., Burt, J., et al. 2017, AJ, 154, 122, doi: 10.3847/1538-3881/aa832d
Cloutier, R. 2019, AJ, 158, 81, doi: 10.3847/1538-3881/ab27be
Crossfield, I. J. M., Ciardi, D. R., Petigura, E. A., et al. 2016, ApJS, 226, 7, doi: 10.3847/0067-0049/226/1/7
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, 2MASS All Sky Catalog of point sources.
Dressing, C. D., & Charbonneau, D. 2013, ApJ, 767, 95, doi: 10.1088/0004-637X/767/1/95
—. 2015, ApJ, 807, 45, doi: 10.1088/0004-637X/807/1/45
Dressing, C. D., Charbonneau, D., Dumusque, X., et al. 2015, ApJ, 800, 135, doi: 10.1088/0004-637X/800/2/135
Dressing, C. D., Vanderburg, A., Schlieder, J. E., et al. 2017, AJ, 154, 207, doi: 10.3847/1538-3881/aa89f2
Fressin, F., Torres, G., Charbonneau, D., et al. 2013, ApJ, 766, 81, doi: 10.1088/0004-637X/766/2/81
Fulton, B. J., & Petigura, E. A. 2018, AJ, 156, 264, doi: 10.3847/1538-3881/aae828
Fulton, B. J., Petigura, E. A., Howard, A. W., et al. 2017, AJ, 154, 109, doi: 10.3847/1538-3881/aa80eb
Gaidos, E., Mann, A. W., Kraus, A. L., & Ireland, M. 2016, MNRAS, 457, 2877, doi: 10.1093/mnras/stw097
Ginzburg, S., Schlichting, H. E., & Sari, R. 2018, MNRAS, 476, 759, doi: 10.1093/mnras/sty290
Gupta, A., & Schlichting, H. E. 2019a, MNRAS, 487, 24, doi: 10.1093/mnras/stz1230
—. 2019b, arXiv e-prints. https://arxiv.org/abs/1907.03732
Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJS, 201, 15, doi: 10.1088/0067-0049/201/2/15
Huber, D., Zinn, J., Bojsen-Hansen, M., et al. 2017, ApJ, 844, 102, doi: 10.3847/1538-4357/aa75ca
Jenkins, J. M., Chandrasekaran, H., McCauliff, S. D., et al. 2010, in SPIE, Vol. 7740, Software and Cyberinfrastructure for Astronomy, 77400D
Jin, S., & Mordasini, C. 2018, ApJ, 853, 163, doi: 10.3847/1538-4357/aa9f1e
Jin, S., Mordasini, C., Parmentier, V., et al. 2014, ApJ, 795, 65, doi: 10.1088/0004-637X/795/1/65
Kruse, E., Agol, E., Luger, R., & Foreman-Mackey, D. 2019, ApJS, 244, 11, doi: 10.3847/1538-4365/ab346b
Lee, E. J., & Chiang, E. 2016, ApJ, 817, 90, doi: 10.3847/0004-637X/817/2/90
Lee, E. J., Chiang, E., & Ormel, C. W. 2014, ApJ, 797, 95, doi: 10.1088/0004-637X/797/2/95

Lindegren, L., Hernández, J., Bombrun, A., et al. 2018, A&A, 616, A2, doi: 10.1051/0004-6361/201832727

Livingston, J. H., Endl, M., Dai, F., et al. 2018, AJ, 156, 78, doi: 10.3847/1538-3881/aaccde

Lopez, E. D., & Fortney, J. J. 2014, ApJ, 792, 1, doi: 10.1088/0004-637X/792/1/1

Lopez, E. D., & Rice, K. 2016, ArXiv e-prints. https://arxiv.org/abs/1610.09390

Luger, R., Agol, E., Kruse, E., et al. 2016, AJ, 152, 100, doi: 10.3847/0004-6256/152/4/100

Luger, R., Kruse, E., Foreman-Mackey, D., Agol, E., & Saunders, N. 2018, AJ, 156, 99, doi: 10.3847/1538-3881/aad230

Mann, A. W., Feiden, G. A., Gaidos, E., Boyajian, T., & von Braun, K. 2015, ApJ, 804, 64, doi: 10.1088/0004-637X/804/1/64

Martinez, C. F., Cunha, K., Ghezzi, L., & Smith, V. V. 2019, ApJ, 875, 29, doi: 10.3847/1538-4357/ab0d93

Mathur, S., Huber, D., Batalha, N. M., et al. 2017, ApJS, 229, 30, doi: 10.3847/1538-4365/229/2/30

Mayo, A. W., Vanderburg, A., Latham, D. W., et al. 2018, AJ, 155, 136, doi: 10.3847/1538-3881/aaadff

Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20

Morton, T. D. 2012, ApJ, 761, 6, doi: 10.1088/0004-637X/761/1/6

—. 2015, VESPA: False positive probabilities calculator, Astrophysics Source Code Library. http://ascl.net/1503.011

Morton, T. D., & Swift, J. 2014, ApJ, 791, 10, doi: 10.1088/0004-637X/791/1/10

Owen, J. E., & Wu, Y. 2013, ApJ, 775, 105, doi: 10.1088/0004-637X/775/2/105

—. 2017, ApJ, 847, 29, doi: 10.3847/1538-4357/aa890a

Pecaut, M. J., & Mamajek, E. E. 2013, ApJs, 208, 9, doi: 10.1088/0067-0049/208/1/9

Petigura, E. A., Howard, A. W., & Marcy, G. W. 2013, Proceedings of the National Academy of Science, 110, 19273, doi: 10.1073/pnas.1319909110

Petigura, E. A., Howard, A. W., Marcy, G. W., et al. 2017, AJ, 154, 107, doi: 10.3847/1538-3881/aa80de

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003, doi: 10.1117/1.JATIS.1.1.014003

Rogers, L. A. 2015, ApJ, 801, 41, doi: 10.1088/0004-637X/801/1/41

Van Eylen, V., Agentoft, C., Lundkvist, M. S., et al. 2018, MNRAS, 479, 4786, doi: 10.1093/mnras/sty1783

Weiss, L. M., & Marcy, G. W. 2014, ApJL, 783, L6, doi: 10.1088/2041-8205/783/1/L6

Wu, Y. 2019, ApJ, 874, 91, doi: 10.3847/1538-4357/ab06f8

Youdin, A. N. 2011, ApJ, 742, 38, doi: 10.1088/0004-637X/742/1/38