LARGER PLANET RADII INFERRRED FROM STELLAR “FLICKER” BRIGHTNESS VARIATIONS OF BRIGHT PLANET-HOST STARS

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ABSTRACT

Most extrasolar planets have been detected by their influence on their parent star, typically either gravitationally (the Doppler method) or by the small dip in brightness as the planet blocks a portion of the star (the transit method). Therefore, the accuracy with which we know the masses and radii of extrasolar planets depends directly on how well we know those of the stars, the latter usually determined from the measured stellar surface gravity, log g. Recent work has demonstrated that the short-timescale brightness variations (“flicker”) of stars can be used to measure log g to a high accuracy of ∼0.1–0.2 dex. Here, we use flicker measurements of 289 bright (Kepmag < 13) candidate planet-hosting stars with $T_{\text{eff}} = 4500–6650$ K to re-assess the stellar parameters and determine the resulting impact on derived planet properties. This re-assessment reveals that for the brightest planet-host stars, Malmquist bias contaminates the stellar sample with evolved stars: nearly 50% of the bright planet-host stars are subgiants. As a result, the stellar radii, and hence the radii of the planets orbiting these stars, are on average 20%–30% larger than previous measurements had suggested.

Key words: planets and satellites: fundamental parameters – stars: fundamental parameters – techniques: photometric

Online-only material: color figures, machine-readable table

1. INTRODUCTION

NASA’s Kepler mission (Borucki et al. 2010), which monitored the brightnesses of >150,000 stars, has uncovered >3000 transiting planetary candidates (Batalha et al. 2013; Burke et al. 2014). In order to measure the effective temperatures ($T_{\text{eff}}$) and surface gravities (log g) of this large number of stars—with the core purpose of quickly identifying as many likely dwarf stars as possible and to screen out as many evolved stars as possible to achieve the primary mission goals—the mission has of necessity relied on broadband photometry. This is the most efficient method for estimating stellar parameters, but with uncertainties in log g of 0.35–0.6 dex (Brown et al. 2011). Through community follow-up observations, a number of the Kepler targets have been observed spectroscopically, typically reducing the reported uncertainty in log g to ∼0.1–0.2 dex (though with the possibility of systematic offsets up to ∼0.4 dex; Torres et al. 2012).

Because such uncertainties in log g translate into similarly large uncertainties in the derived planet radii, many previous analyses have attempted to mitigate stellar parameter uncertainties by imposing priors based on theoretical stellar evolutionary tracks. This results in a better match of the inferred $T_{\text{eff}}$ and log g to the theoretical main sequence, but also results in an underestimate of subgiant frequency in e.g., the Kepler Input Catalog (KIC; Brown et al. 2011; Huber et al. 2014; Everett et al. 2013).

Planets orbiting bright stars are of particular interest as these offer the most opportunities for follow-up investigation such as radial-velocity studies and in-depth spectroscopic analysis. However, magnitude-limited samples are generally not representative of the Galaxy’s underlying stellar population, one of several biases (Gaidos & Mann 2013) that affect the Kepler transiting planet candidates. In particular, magnitude-limited samples can be strongly biased toward stars that are intrinsically more luminous (i.e., physically larger) than the main-sequence dwarfs that comprise ∼85% of stars in the Galaxy. Hence, it is imperative to ascertain the true log g of the stellar hosts, the bright ones especially, as accurately as possible.

Bastien et al. (2013) demonstrated that the 8 hr “flicker” ($F_8$) in the Kepler light curves can be used to measure stellar log g with an accuracy of ∼0.1–0.2 dex from its correlation with granulation power (Mathur et al. 2011; Kjeldsen & Bedding 2011; Cranmer et al. 2014). Thus, log g determined from $F_8$ for planet-host stars can potentially significantly improve the inferred parameters of the planets. Here, we use $F_8$ to refine the stellar log g for the bright Kepler Objects of Interest (KOIs, which include both candidate and confirmed planets) with magnitudes of Kepmag < 13, and we re-examine the planet radii resulting from these revised stellar log g.

2. DATA AND ANALYSIS

2.1. KOI Target Selection

We draw our bright KOI sample from the NASA Exoplanet Archive (NEA; Akeson et al. 2013) accessed on 2014 January 7. We restrict the sample to stars with 6650 K > $T_{\text{eff}}$ > 4500 K, the $T_{\text{eff}}$ range for which $F_8$ is calibrated. We exclude 28 stars with overall range of photometric variability >10 ppt (parts per thousand), as phenomena in the light curves of such chromospherically active stars can boost the measured $F_8$ and thus result in an erroneous $F_8$-based log g. These excluded stars (10% of the sample) are cooler than average for the overall sample, as expected given their large variability. Our sample after applying these cuts contains 289 stars (407 KOIs).

We compare the $F_8$-based log g with values from the recently published Kepler Stellar Properties catalog (Huber et al. 2014). Many of these values were obtained from the original KIC, whose core purpose was to ensure that as many dwarfs as
possible were included among the Kepler targets at the risk of suffering contamination from some more evolved stars.

In Figure 1, we represent (Burger et al. 2013) these 289 planet-host stars on the photometric variability evolutionary diagram introduced by Bastien et al. (2013). This diagram traces the evolution of Sun-like stars with three simple measures of their brightness variations (Basri et al. 2011): range (Rvar), number of zero crossings (X0), and root mean square (rms) on timescales shorter than 8 hr (8 hr “flicker” or F8; see Section 2.2). Most of the KOIs orbit stars with Rvar < 1 ppt, reflecting the preference for searches around magnetically quiet stars, and F8-based log g greater than 3.5 (indicative of dwarfs or subgiants). Some of the stars lie on the “flicker floor” and have log g as low as ~2.7, making them evolved giants.

2.2. Measurement of Stellar Surface Gravity

To derive the F8-based log g of a star, we take all of the available PDC-MAP Kepler light curves and remove all known planet candidate transits using publicly available (NEA) orbital parameters. To remove remaining outlying points (flares, data artifacts, etc.), we apply a 2.5σ clipping to the resultant light curves. We then calculate F8-based log g for all light curves of the star following the methodology of Bastien et al. (2013) and take the median of the quarter-by-quarter F8 as our robust estimate of the F8-based log g.

In general, the quarter-to-quarter variations in the F8-based log g are <0.1 dex. However, the true accuracy of the F8-based log g is a mild function of Rvar (Bastien et al. 2013). Stars with Rvar < 1 ppt show a constant scatter relative to the asteroseismic calibration sample of ~0.1 dex in log g, whereas stars with Rvar > 1 ppt show a slightly increased scatter of ~0.15 dex. Therefore, we assign an uncertainty of either 0.1 or 0.15 dex to the F8-based log g depending on whether the total Rvar is less than or greater than 1 ppt.

Additionally, the asteroseismic calibration sample used in Bastien et al. (2013) only included stars brighter than Kepmag = 12; the asteroseismic set in Huber et al. (2014) extends to Kepmag ~ 13 and reveals that the uncertainty in F8-based log g increases to ~0.2 dex for stars fainter than Kepmag = 12 (Figure 1(c)). We therefore increase the assigned F8-based log g uncertainty to 0.2 dex for Kepmag = 12–13. Note that the comparison to the asteroseismic sample indicates that the F8-based log g start to become unreliable for highly evolved giants with log g ~ 2.7 (Bastien et al. 2013); thus in addition to restricting our analysis to the T eff range of 4500–6650 K for which F8 is calibrated, we also disregard stars with log g < 2.7.

2.3. Determination of Planet Properties

To determine the planetary radius for each KOI, we begin with the NEA-reported planet-to-star radius ratios. For the stellar radii, we use the empirical relationship between stellar radius, T eff, log g, and metallicity (Torres et al. 2010), where we use NEA metallicities and T eff (Huber et al. 2014) together with our newly determined F8-based log g values. Huber et al. (2014) used isochrone fitting to derive the NEA stellar radii from T eff, metallicity, and log g. Torres et al. (2010) showed that stellar masses and radii resulting from the empirical relations agree with those of model isochrones to within ~5%. This difference in method for determining stellar radii, therefore, does not change the core results of this work.

When multiple parameter estimates are available for a given star, we favor asteroseismic parameters, followed in priority by broad-band photometry and spectroscopy. If F8 is calibrated, we also disregard stars with log g < 2.7.
order by spectroscopy, transit analyses, and lastly broadband photometry which often includes original KIC values (note that the resulting sample contains no objects with transit-derived properties).

The result is a sample of stellar parameters that is necessarily heterogeneous but whose average accuracy in $\log g$ we expect surpasses the original KIC. We also note that the spectroscopic sample is itself heterogeneous in quality and signal-to-noise. An assessment of the individual spectra and their analysis is beyond the scope of this Letter, and we consider the spectroscopic results together as an ensemble. We provide the final stellar parameters that we use, including our $F_8$-based $\log g$ and the NEA parameters, in Table 1.

3. RESULTS

Comparing the $\log g$ previously estimated from broadband photometry/spectroscopy versus that newly measured via $F_8$ (Figure 1(c)), we find the $F_8$-based $\log g$ to be systematically lower (i.e., more subgiant-like), with a median difference of $\sim 0.2$ dex (rms of 0.3 dex for spectroscopy, 0.4 dex for photometry). In contrast, the subset of the stars with $\log g$ determined asteroseismically agrees with the $F_8$-based $\log g$ to 0.02 dex in the median (rms of 0.15 dex), consistent with the expected accuracy of the $F_8$-based $\log g$ (Section 2.2). While the scatter of 0.3–0.4 dex in the spectroscopic/photometric $\log g$ is consistent with the expected precision of photometry, it is large compared to that expected of spectroscopy. The asteroseismic and $F_8$-based $\log g$ together appear to indicate a significant overestimate of the NEA $\log g$ for the bright KOI stars (the overestimate increasing to fainter magnitudes; Figure 1(c)). We stress that we also find this overestimate for a number of stars whose NEA $\log g$ is spectroscopically derived. This result has also been reported in asteroseismic studies, and may be due to biases in spectroscopic analyses that impact the $\log g$ determined for giants and subgiants (see, e.g., Huber et al. 2013 for a discussion).

The key effect of including $F_8$-derived $\log g$ is to significantly increase the median radius of the bright KOIs (Figure 2). We find that the median KOI radius is larger by 20%–30% compared to that inferred using the $\log g$ previously estimated from broadband photometry or spectroscopy, though a number of objects show a more modest or even negative change in radius (Figure 2(b)).

To compare our results with those expected based on the underlying stellar population, given the magnitude-limited nature of the sample, we simulated the Kepler field using the TRILEGAL Galactic population synthesis model (Girardi et al. 2005).

We used the default TRILEGAL model parameters, for a $1 \deg^2$ line-of-sight toward the center of the Kepler field, and we include only simulated stars down to Kepmag $< 13$ and with $6650 \, K < T_{\text{eff}} < 4500 \, K$, as for the KOI sample.

Figure 3(a) shows the H-R diagram of the simulated population compared with the actual KOI sample using $F_8$-based (Figure 3(b)) and NEA (Figure 3(c)) $\log g$ values. We retain the full set of $\sim 1200$ stars produced by the TRILEGAL simulation to visually preserve the detail of the parameters; the actual sample with $\sim 300$ stars necessarily appears sparser. By construction, the simulated sample closely traces the theoretical evolutionary tracks, with both a tight main-sequence population along the bottom and a large red giant population at upper right being most prominent, as expected for a magnitude-limited population including a mix of stellar masses and ages. For stellar masses $\gtrsim 1 \, M_\odot$, the simulated sample also includes a large population of modestly evolved subgiants with masses $\sim 1$–$2 \, M_\odot$, forming a thick but well defined horizontal band with $3.5 < \log g < 4.1$.

By comparison, the observed H-R diagram (middle or bottom panel) lacks the highly evolved red giants ($\log g < 3$) present in the simulated sample, the result of their systematic removal by the Kepler mission (Batalha et al. 2010). Additionally, there is a noticeable dearth of mid-F type stars with $T_{\text{eff}} \gtrsim 6500 \, K$, as well as late-K type stars with $T_{\text{eff}} \lesssim 4700 \, K$, among the observed KOI sample, likely the result of the Kepler target selection process that strongly favored late-F to early-K type dwarfs for Kepmag $< 13$ (Batalha et al. 2010). For stars with $6500 \, K > T_{\text{eff}} > 4700 \, K$ and Kepmag $< 13$, the Kepler target sample should be representative of the field for all but evolved giants with $\log g < 3.5$ (Batalha et al. 2010).
More importantly, in the H-R diagram using log \( g \) previously estimated from broadband photometry/spectroscopy (bottom panel) the KOI sample overall follows the main sequence very closely, with few apparent subgiants with \( \log g < 4.1 \). With the exception of a few cool stars beginning their ascent up the red giant branch (at \( T_{\text{eff}} \approx 5000 \text{ K} \) and \( \log g \approx 3.5 \)), there are apparently very few of the warmer, \( \sim 1–2 \, M_\odot \) subgiants with \( \log g \) as low as 3.5 that are expected from the simulated sample.

In contrast, the H-R diagram using the F8-based log \( g \) matches the simulated stellar population more closely. In particular, the subgiant population predicted by the simulated sample is more clearly present. Indeed, the F8-based log \( g \) values extend down to, but cleanly truncate at, \( \log g \approx 3.5 \) for \( T_{\text{eff}} \gtrsim 5200 \text{ K} \), just as in the simulated population. At higher \( \log g \), the F8-based log \( g \) also trace the slope of the main sequence, with a scatter generally within \( \sim 1\sigma \) of that expected for the F8-based log \( g \) (0.1–0.2 dex). Note that the F8-based log \( g \) are not forced to match isochrones and more generally have no priors applied to the resulting log \( g \)'s.

At the same time, the F8-based H-R diagram does not perfectly match the simulated sample. For example, for stellar masses \( \lesssim 1 \, M_\odot \), the F8-based H-R diagram includes a few stars that appear elevated by \( 1\sigma–2\sigma \) relative to the main sequence (e.g., at \( T_{\text{eff}} \approx 4800 \text{ K} \) and \( \log g \approx 4.3 \)). Since stars less massive than \( \sim 0.9 \, M_\odot \) cannot be evolved, these stars should be firmly on the main sequence. The NEA log \( g \) values in this region of the H-R diagram appear better behaved, a consequence of the prior that is imposed in most photometric/spectroscopic log \( g \) analyses to force the stellar parameters to match theoretical isochrones (e.g., Huber et al. 2014). The F8 method imposes no prior on the log \( g \) values, and so it is not surprising that for some stars the inferred log \( g \) may scatter by \( 1\sigma–2\sigma \) into “forbidden” regions of the H-R diagram. This may also be partially a result of the fact that F8 is fundamentally calibrated to the Kepler asteroseismic sample and to the Sun (Bastien et al. 2013), such that F8-based log \( g \gtrsim 4.5 \) constitute an extrapolation from that calibration. However, we also cannot rule out the possibility that the true radii of the low-mass stars are in fact larger than predicted by theoretical main-sequence models, as recent interferometric observations of low-mass planet-host stars have found the stellar radii to frequently be larger than previously thought (see von Braun et al. 2011, 2012, 2014; Boyajian et al. 2012). For example, of the six stars with masses \( \sim 0.8–0.9 \, M_\odot \) included in these studies, four of them (55 Cnc, 61 Vir, rho CrB, HD 1461) are similarly elevated above the theoretically expected main sequence (von Braun et al. 2014) for reasons that are not yet clear but which may include the effects of magnetic activity (e.g., Stassun et al. 2012). In any event, for the bright KOIs considered here with very few such low-mass stars, this issue affects 1%–2% of the sample.

Figure 4 shows these log \( g \) comparisons directly. Here we limit the \( T_{\text{eff}} \) range to 4700–6500 K for which the observed Kepler targets should be representative of the field and therefore most directly comparable to the simulated population (see above). Again, the very large population of red giants with \( \log g < 3.5 \) seen in the simulated sample is conspicuously missing in the actual planet-host-star sample. Thus we compare the distributions only for \( \log g > 3.5 \), and we normalize the histogram of the simulated sample by the number of observed stars with \( \log g > 3.5 \). A two-sided K-S test gives a probability of 0.01% that the NEA log \( g \) and the log \( g \) from the simulated stellar population are drawn from the same parent sample, whereas a K-S test gives a probability of 16% that the simulated and F8-based log \( g \) samples are drawn from the same parent sample. The F8-based log \( g \) show the poorest match to the simulated distribution at the highest log \( g \), corresponding to the

![Figure 3](image3.png)

**Figure 3.** H-R diagram of KOI host stars with log \( g \) derived from F8 (middle) and broadband photometry/spectroscopy (bottom), and as predicted by a TRILEGAL (Girardi et al. 2005) simulation (top). Colored curves represent the theoretical evolutionary tracks (masses labeled in \( M_\odot \)). Vertical lines demarcate the range of stellar \( T_{\text{eff}} \) considered in this study. The horizontal lines demarcate the range of log \( g \) for subgiants (3.5 < log \( g \) < 4.1). A representative error bar on log \( g \) for each stellar sample is in the upper right of each panel. We find that the F8-based log \( g \) distribution more closely matches expectation than previous log \( g \) measurements, particularly in the subgiant domain, perhaps because F8 involves no main-sequence prior on the F8-based log \( g \) values (see text).

(A color version of this figure is available in the online journal.)

![Figure 4](image4.png)

**Figure 4.** Distributions of log \( g \) for simulated (black) and KOI host stars with F8-based log \( g \) (red) and broadband photometry/spectroscopy-based log \( g \) (cyan). We limit the \( T_{\text{eff}} \) range here to 4700–6500 K, for which the Kepler targets should be representative of the field (Batalha et al. 2010). Vertical lines indicate the range of log \( g \) corresponding to subgiants.

(A color version of this figure is available in the online journal.)
low-mass main-sequence dwarfs that the simulation assumes to be unevolved but for which the $F_8$-based log $g$ indicate larger radii in some cases (see above). However, the $F_8$-based log $g$ are a better match overall to the simulated sample, in particular in reproducing the expected population of subgiants. Specifically, 48% of the stars have $F_8$-based log $g$ values indicative of modestly evolved subgiants ($3.5 < \log g < 4.1$), whereas previously estimated log $g$ values had indicated that only 27% are subgiants. In comparison, 44% of the simulated sample are subgiants, in good agreement with the 48% inferred from the $F_8$ analysis.

4. CONCLUSIONS

In this work, we used the granulation “flicker” ($F_8$) of bright Kepler planet candidate host stars to measure improved stellar log $g$ and to thereby redetermine the planet radii. Comparing the $F_8$-based log $g$ values with those previously published in the NEA, the latter representing a heterogeneous mix of broadband photometric, spectroscopic, and asteroseismic methods, indicates that the stellar, and hence planetary, radii are on average 20%–30% larger than suggested by the previous estimates.

The H-R diagram positions of the stars according to the $F_8$-based log $g$ in general appear better matched to the distribution from the simulated Galactic population of bright stars (Kepmag < 13) in the Kepler field, especially the presence of a significant population of subgiants. However, for the few very low-mass stars ($\leq 0.9 \, M_\odot$) in the sample, the log $g$ values from photometry/spectroscopy appear to better match expectations as these are generally forced to match the main sequence. Whether this is a failing of the extrapolation of the $F_8$–log $g$ relation to log $g \gtrsim 4.5$, or a manifestation of larger-than-predicted stellar radii for low-mass K and M stars as observed interferometrically (e.g., von Braun et al. 2014; Boyajian et al. 2012), remains to be determined. The performance of $F_8$-based log $g$ for very low-mass stars will be an important area for continued refinement of the $F_8$ technique, including its application in contexts such as asteroseismic profiling (Kipping et al. 2014).

Most importantly, for a magnitude-limited sample such as that considered here, modestly evolved subgiants represent a large fraction of the population. Methods that apply a strong prior favoring main-sequence dwarf log $g$ will systematically overestimate log $g$ for such a sample, and in turn systematically underestimate the planet radii, particularly among the brightest stellar hosts. Our finding that broadband photometric and spectroscopic methods yield systematically larger stellar log $g$ than asteroseismic or $F_8$-based methods—especially among subgiants—is consistent with previous reports (Huber et al. 2013; Plavchan et al. 2014) but now demonstrated for a much larger sample. This bias directly impacts our understanding of the true distribution of exoplanetary radii, especially for the scientifically valuable bright systems. The results reported herein also demonstrate that one cannot ignore the magnitude-limited nature of the stellar samples when inferring their ensemble properties.

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