ANGULAR DIAMETERS AND EFFECTIVE TEMPERATURES OF 25 K GIANT STARS FROM THE CHARA ARRAY

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ABSTRACT

Using Georgia State University’s Center for High Angular Resolution Astronomy Array interferometer, we measured angular diameters for 25 giant stars, six of which host exoplanets. The combination of these measurements and Hipparcos parallaxes produces physical linear radii for the sample. Except for two outliers, our values match angular diameters and physical radii estimated using photometric methods to within the associated errors with the advantage that our uncertainties are significantly lower. We also calculated the effective temperatures for the stars using the newly measured diameters. Our values do not match those derived from spectroscopic observations as well, perhaps due to the inherent properties of the methods used or because of a missing source of extinction in the stellar models that would affect the spectroscopic temperatures.

Key words: infrared: stars – planetary systems – stars: fundamental parameters – techniques: interferometric – techniques: spectroscopic

1. INTRODUCTION

Giant star radii have been measured in the past using various interferometers, including the Mark III (85 giants and supergiants; Mozurkewich et al. 2003), the Palomar Testbed Interferometer (69 giants and supergiants; van Belle et al. 1999), the Navy Prototype Optical Interferometer (50 giants and supergiants; Nordgren et al. 1999), and the Center for High Angular Resolution Astronomy (CHARA) Array (four Hyades giants; Boyajian et al. 2009). These measurements are valuable because these are the stars populating the coolest, most luminous part of the Hertzsprung–Russell (H–R) diagram (van Belle et al. 1999). What makes the sample of giant stars under consideration here particularly interesting is that they are potential exoplanet hosts, and planetary candidates have been discovered around six of the stars already.

Two important characteristics of a star are its mass and radius. For giant stars, the determination of these parameters is indirect and heavily model dependent. In practice, spectroscopic observations to measure the surface gravities (log g), effective temperatures (Teff), and iron abundances ([Fe/H]) can be combined with a distance measurement to derive the stellar radius. Fitting evolutionary tracks to the position of the star in the H–R diagram then yields the mass. The reliability of these measurements depends both on the validity of the model atmospheres and the stellar evolution code. Unfortunately this is an uncertain process because the evolutionary tracks of stars with a wide range of masses all converge to near the same region of the H–R diagram as they evolve up the giant branch. In particular, the

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pressure is the restoring force. Thus, giant stars are an ideal class of objects for deriving fundamental stellar parameters. They are abundant, they have large angular diameters suitable for interferometric measurements, and they exhibit stellar oscillations with radial velocity amplitudes of a few to several tens of m s\(^{-1}\), which are easily measurable by state-of-the-art techniques. The observed oscillation frequencies constrain the internal structure of the star (Bedding et al. 2006) and interferometry measures the star’s size, and the combination leads to the mass of the star. Once stellar isochrones have been refined and calibrated for these evolved stars, they can be used to determine the masses of all planet-hosting giant stars. Because collecting data on the oscillation frequencies requires considerable telescope resources and can only be done for relatively few stars, we first present our results on interferometric measurements on a larger sample of giant stars.

The advantage interferometry provides is the ability to directly measure stellar angular diameters. Once the angular diameters are known for these giant stars, physical radii and effective temperatures can be calculated when combined with other parameters, such as the parallax, bolometric flux, interstellar absorption, and bolometric corrections (BCs). The radii and effective temperatures are important values that characterize the parent star as well as the environment in which the exoplanet resides for those stars hosting planets. Section 2 describes the spectroscopic measurements of \( T_{\text{eff}} \) and \( \log g \) for the sample, Section 3 discusses the interferometric observations, Section 4 explains how the angular diameters, linear radii, and \( T_{\text{eff}} \) were determined, and Section 5 explores the physical implications of the interferometric observations.

## 2. SPECTROSCOPIC OBSERVATIONS

Our sample of K giant stars were obtained from the planet search survey of Döllinger et al. (2007). As part of this program the \( T_{\text{eff}} \) and \( \log g \) were measured, which allowed us to estimate the stellar radii and masses. Table 1 lists the 25 stars observed here, and planets have already been found orbiting HD 73108 (Döllinger et al. 2007), HD 139357 and HD 170693 (Döllinger et al. 2009a), HD 32518 and HD 136726 (Döllinger et al. 2009b), and HD 167042 (Johnson et al. 2008; Sato et al. 2008; M. P. Döllinger et al. 2010a, in preparation). Three additional stars show long-period variations in their radial velocity measurements: HD 106574, HD 157681, and HD 200205 (M. P. Döllinger et al. 2010b, in preparation). The targets chosen for our observing list are bright (\( V < 6.5 \)) giant stars that showed significant short-term variability indicative of stellar pulsations, which made them excellent candidates for both stellar oscillation observations and interferometric measurements.

The spectroscopic observations were carried out using the Coudé Échelle spectrograph of the 2 m Alfred Jensch telescope of the Thüringer Landessternwarte Tautenburg. The spectrograph has a resolving power of \( \Delta \lambda/\lambda = 67,000 \) and the wavelength range used was 4700–7400 Å. Standard IRAF routines were used for subtracting the bias offset, flat-fielding,
subtracts the scattered light, extracting the spectra, and for
the wavelength calibration.\footnote{IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.}

In order to determine the stellar parameters from the spectra, a grid of model atmospheres from Gustafsson et al. (1975) was used in which a plane-parallel atmosphere in local thermodynamic equilibrium was assumed. We selected 144 unblended Fe i and eight Fe ii lines in the wavelength range 5806 and 6858 Å using the line list of Pasquini et al. (2004). The iron abundance [Fe/H] was determined by assuming that Fe i lines of different equivalent widths have to give the same relative abundance of iron. For the effective temperature, an excitation equilibrium was assumed, and the surface gravity was determined from the ionization balance of Fe i, assuming that Fe i lines are used, and Fe ii lines in the wavelength range 5806 and 6858 Å using the line list of Pasquini et al. (2004). The resulting [Fe/H], \(T_{\text{eff}}\), and log \(g\) values are listed in Table 1.

### Table 2

Observing Log and Calibrator Stars’ Basic Parameters

| Target HD | Calibrator HD | Baseline\(^a\) (max. length) | Date (UT) | Obs | \(T_{\text{eff}}\)\(^b\) (K) | log \(g\)\(^b\) (cm s\(^{-2}\)) | \(\theta_{\text{LD}}\)\(^c\) (mas) |
|-----------|---------------|-------------------------------|-----------|-----|-------------------------|-----------------------------|--------------------------|
| 32518     | 31675         | S1–E1 (331 m)                 | 2007 Nov 14 | 9   | 6310 4.39               | 0.401 ± 0.015               |
| 60294     | 63332         | S1–E1 (331 m)                 | 2009 Apr 23 | 5   | 6310 4.19               | 0.431 ± 0.014               |
| 73108     | 69548         | E2–W2 (156 m)                 | 2008 May 9  | 5   | 6761 4.31               | 0.402 ± 0.018               |
| 102328    | 98673         | S1–E1 (331 m)                 | 2009 Apr 23 | 3   | 8128 4.21               | 0.220 ± 0.010               |
| 103605    | 108954        | S1–E1 (331 m)                 | 2009 Apr 24 | 2   | 6026 4.34               | 0.452 ± 0.021               |
| 106574    | 107193        | E2–W2 (156 m)                 | 2008 Jun 29 | 6   | 8710 3.93               | 0.315 ± 0.030               |
| 113049    | 107193        | S1–E1 (331 m)                 | 2009 Apr 23 | 8   | 8710 3.93               | 0.315 ± 0.030               |
| 124063    |               |                               | 2008 Jun 29 | 5   | 7740 4.29               | 0.232 ± 0.010               |
| 118904    | 108954        |                               | 2008 May 1  | 3   | 9772 4.13               | 0.268 ± 0.015               |
| 137443    | 138265        |                               | 2008 May 29 | 4   | 9772 4.13               | 0.268 ± 0.015               |
| 136726    | 139357        |                               | 2008 May 29 | 4   | 9772 4.13               | 0.268 ± 0.015               |
| 149681    | 149303        |                               | 2008 Jul 1  | 4   | 8511 4.10               | 0.288 ± 0.011               |
| 151044    | 150010        |                               | 2008 Jul 1  | 3   | 7586 4.23               | 0.368 ± 0.012               |
| 157681    | 152812        |                               | 2008 Jul 2  | 4   | 9000 4.19               | 0.295 ± 0.012               |
| 161693    | 160290        |                               | 2008 Jul 2  | 3   | 8000 4.24               | 0.295 ± 0.012               |
| 167042    | 167278        |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |
| 170693    | 175823        |                               | 2008 Jul 2  | 3   | 7413 3.98               | 0.309 ± 0.013               |
| 178207    |               |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |
| 176408    | 172728        |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |
| 186815    | 188760        |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |
| 188793    |               |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |
| 192781    | 184960        |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |
| 200205    | 197950        |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |
| 214868    | 211211        |                               | 2008 Jul 2  | 3   | 9790 4.14               | 0.236 ± 0.020               |

Notes.

\(^a\) The three arms of the array are denoted by their cardinal directions: “S” is south, “E” is east, and “W” is west. Each arm bears two telescopes, numbered “1” for the telescope farthest from the beam combining laboratory and “2” for the telescope closer to the lab.

\(^b\) All \(T_{\text{eff}}\) and log \(g\) values are from Allende Prieto & Lambert (1999) except for HD 124063, HD 158414, HD 158460, HD 161693, HD 172728, HD 178207, and HD 188793, which are from Cox (2000) and were based on their spectral types as listed in the SIMBAD Astronomical Database.

\(^c\) In calculating \(\theta_{\text{LD}}\) as described in Section 3, the \(UBV\) values were from Mermilliod (1991) except for HD 149303 (ESA 1997), and HD 151044 and HD 184960 (Morel & Magnenat 1978); all \(RI\) values were from Monet et al. (2003) except for HD 151044 and HD 184960 (Morel & Magnenat 1978); and all \(JHK\) values were from Cutri et al. (2003).
| Target HD | Calibrator HD | MJD | $B$ (m) | $\Theta$ (deg) | $V_c$ | $\sigma_{V_c}$ |
|----------|--------------|-----|-------|---------------|------|---------------|
| 32518    | 31675        | 54418.238 | 230.84 | 200.1 | 0.755 | 0.067 |
| 60294    | 63332        | 54944.176 | 319.48 | 94.9  | 0.444 | 0.045 |
| 73108    | 69548        | 54955.215 | 264.89 | 228.2 | 0.456 | 0.061 |
| 102328   | 98673        | 54945.239 | 314.63 | 268.9 | 0.860 | 0.011 |
| 106574   | 107193       | 54646.187 | 155.91 | 241.7 | 0.699 | 0.099 |
| 113049   | 107193       | 54944.362 | 272.32 | 265.1 | 0.655 | 0.059 |
| 118904   | 124063       | 54646.251 | 155.81 | 244.4 | 0.574 | 0.074 |

| Target HD | Calibrator HD | MJD | $B$ (m) | $\Theta$ (deg) | $V_c$ | $\sigma_{V_c}$ |
|----------|--------------|-----|-------|---------------|------|---------------|
| 5495.166 | 214.66      | 206.9 | 75.1  | 0.061 |
| 5495.178 | 244.20      | 208.6 | 74.3  | 0.053 |
| 5495.200 | 249.36      | 212.0 | 74.1  | 0.065 |
| 5495.213 | 251.81      | 213.8 | 73.2  | 0.053 |
| 5495.230 | 319.72      | 91.0  | 526.5 | 0.057 |
| 5495.252 | 316.18      | 252.0 | 0.088 | 0.009 |
| 5495.255 | 314.17      | 261.0 | 0.073 | 0.011 |
| 5495.267 | 315.40      | 253.8 | 0.465 | 0.069 |
| 5495.280 | 316.51      | 256.9 | 0.446 | 0.062 |
| 5495.280 | 316.51      | 256.9 | 0.489 | 0.054 |
| 5495.293 | 317.37      | 260.2 | 0.449 | 0.044 |
| 5495.375 | 317.53      | 99.7  | 0.437 | 0.027 |
| 5495.382 | 317.18      | 100.6 | 0.442 | 0.032 |
| 5495.388 | 316.77      | 102.2 | 0.457 | 0.038 |
| 5495.394 | 316.37      | 103.5 | 0.409 | 0.029 |
| 5495.394 | 316.37      | 103.5 | 0.409 | 0.029 |
| 5495.411 | 271.80      | 99.0  | 0.630 | 0.076 |
| 5495.437 | 272.47      | 267.4 | 0.630 | 0.051 |
| 5495.438 | 272.53      | 269.5 | 0.692 | 0.070 |
| 5495.438 | 272.50      | 91.9  | 0.670 | 0.052 |
| 5495.439 | 272.37      | 94.4  | 0.587 | 0.049 |
| 5495.440 | 272.12      | 96.8  | 0.605 | 0.049 |
| 5495.441 | 271.80      | 101.3 | 0.696 | 0.071 |
| 5495.442 | 271.38      | 101.3 | 0.696 | 0.071 |
| 5495.450 | 272.32      | 265.1 | 0.655 | 0.059 |
| 5495.450 | 272.32      | 265.1 | 0.655 | 0.059 |
| 5495.451 | 272.38      | 101.3 | 0.656 | 0.058 |
| 5495.451 | 272.38      | 101.3 | 0.656 | 0.058 |

(Continued)
### Table 3 (Continued)

| Target HD | Calibrator HD | MJD  | $B$  (m) | $\Theta$ (deg) | $V_c$ | $\sigma_{V_c}$ |
|-----------|---------------|------|--------|---------------|-------|--------------|
| 170693    | 172569        | 54355.267 | 319.05 | 105.9 | 0.591 | 0.041 |
| 178207    | 172728        | 54444.471 | 297.24 | 232.9 | 0.499 | 0.044 |
| 176408    | 172728        | 54444.473 | 296.67 | 223.9 | 0.409 | 0.043 |
| 186815    | 186760        | 54445.396 | 248.69 | 209.6 | 0.792 | 0.082 |
| 192781    | 186760        | 54450.400 | 231.04 | 202.6 | 0.225 | 0.027 |

Note. The projected baseline position angle (\(\Theta\)) is calculated to be east of north.

### 3. INTERFEROMETRIC OBSERVATIONS

Interferometric observations were obtained using the CHARA Array, a six element optical-infrared interferometer located on Mount Wilson, California (ten Brummelaar et al. 2005). All observations used the pupil-plane “CHARA Classic” beam combiner in the $K'$ band at 2.15 $\mu$m, while visible wavelengths (470–800 nm) were used for tracking and tip/tilt corrections. The observing procedure and data reduction process employed here are described in McAlister et al. (2005).

We interleaved calibrator and target star observations so that every target was flanked by calibrator observations made as close in time as possible, which allowed us to convert instrumental target and calibrator visibilities to calibrated visibilities for the target. Reliable calibrators were chosen to be single stars with expected visibility amplitudes >85% so they were nearly unresolved on the baselines used, which meant uncertainties in the calibrator’s diameter did not affect the target’s diameter calculation as much as if the calibrator star had a significant angular size. In a few cases, a calibrator had a stellar companion but at such a distance that light from the secondary star would not contaminate our interferometric measurements and the calibrator could therefore be treated as a single star.

To check for possible unseen close companions that would contaminate our observations, we created spectral energy distribution (SED) fits based on published $UBVRIJHK$ photometric values obtained from the literature for each calibrator to establish diameter estimates. This also allowed us to see if there was any excess emission associated with a low-mass stellar companion or circumstellar disk. Calibration candidates displaying variable radial velocities or any other indication of companions were discarded.

We used Kurucz model atmospheres based on $T_{\text{eff}}$ and $\log g$ values to calculate limb-darkened angular diameters for the calibrators. The stellar models were fit to observed photometry after converting magnitudes to fluxes using Colina et al. (1996) for $UBVRI$ values and Cohen et al. (2003) for $JHK$ values. See Table 2 for the $T_{\text{eff}}$ and $\log g$ used and the resulting limb-darkened angular diameters.

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8 Available to download at [http://kurucz.cfa.harvard.edu](http://kurucz.cfa.harvard.edu).
Figure 1. LD disk diameter fits for all the stars observed with one calibrator except HD 214868. The solid line represents the theoretical visibility curve for a star with the best-fit $\theta_{LD}$, the dashed lines are the $1\sigma$ error limits of the diameter fit, the solid symbols are the calibrated visibilities, and the vertical lines are the measured errors. Some of the stars' visibilities were shifted as indicated by “(V ± #)” so they would not overlap other data points.

4. DETERMINATION OF ANGULAR DIAMETER AND $T_{\text{eff}}$

The observed quantity of an interferometer is defined as the visibility ($V$), which is fit to a model of a uniformly illuminated disk (UD) that represents the observed face of the star. Diameter fits to $V$ were based upon the UD approximation given by $V = [2J_1(x)]/x$, where $J_1$ is the first-order Bessel function and $x = \pi B \theta_{UD} \lambda^{-1}$, where $B$ is the projected baseline at the star's position, $\theta_{UD}$ is the apparent UD angular diameter of the star, and $\lambda$ is the effective wavelength of the observation (Shao & Colavita 1992). A more realistic model of a star's disk involves limb-darkening (LD), and relationship incorporating the linear LD coefficient $\mu \lambda$ (Hanbury-Brown et al. 1974) is

$$V = \left(1 - \frac{1}{3} \mu \lambda + \frac{1}{2} \mu \lambda \right)^{-1} \times \left(1 - \mu \lambda \right) J_1(x) + \mu \lambda \left(\frac{\pi}{2} \right)^{1/2} J_{3/2}(x) \frac{\lambda^{3/2}}{x^{3/2}}.$$ (1)

Table 3 lists the modified Julian Date (MJD), projected baseline ($B$) at the time of observation, projected baseline position angle ($\Theta$), calibrated visibility ($V_c$), and error in $V_c$ ($\sigma V_c$) for each giant star observed. Figures 1–3 show the LD diameter fits for all the stars. The LD coefficient was obtained from Claret et al. (1995) after adopting the $T_{\text{eff}}$ and log $g$ values required for each star observed. The resulting LD angular diameters are listed in Table 4. The average difference between the UD and LD diameters are on the order of a few percent, and the final angular diameters are little affected by the choice of $\mu \lambda$. All but four stars have $\theta_{LD}$ errors of 2% or less, three of the four have errors of only 3%, and the final star has a 5% error. Additionally, the combination of the interferometric measurement of the star's angular diameter plus the Hipparcos parallax (van Leeuwen 2007a, 2007b) allowed us to determine the star's physical radius. The results are also listed in Table 4. In principle, one can calculate the mass of each star from the physical radius and log $g$ values. However, the formal errors in log $g$ lead to errors in such mass estimates near the 50% level, thereby significantly decreasing their usefulness to this analysis.

For each $\theta_{LD}$ fit, the errors were derived via the reduced $\chi^2$ minimization method (Wall & Jenkins 2003; Press et al. 1992): the diameter fit with the lowest $\chi^2$ was found and the corresponding diameter was the final $\theta_{LD}$ for the star. The errors were calculated by finding the diameter at $\chi^2 + 1$ on either side of the minimum $\chi^2$ and determining the difference between the $\chi^2$ diameter and $\chi^2 + 1$ diameter. In calculating the diameter errors in Table 4, we adjusted the estimated visibility errors to force the reduced $\chi^2$ to unity because when this is omitted, the reduced $\chi^2$ is well under 1.0, indicating we are overestimating the errors in our calibrated visibilities.

Limb-darkened angular diameters were estimated using the relationship described in Kervella et al. (2004) between the $(V-K)$ color and log $\theta_{LD}$ (see $\theta_{estimate}$ in Table 1). The table also lists $R_{estimate}$, which were derived using $\theta_{estimate}$ and the stars’ parallaxes. The major weakness of this method lies...
in the uncertainties surrounding the $K$-magnitudes, which were taken from two sources: the Two-Micron Sky Survey (TMSS; Neugebauer & Leighton 1969, errors $\sim 2\% - 5\%$) and the 2MASS All-sky Catalog of Point Sources (2MASS; Cutri et al. 2003, errors $\sim 6\% - 12\%$). Preference was given to the former because 2MASS measurements saturate at magnitudes brighter than $\sim 3.5$ in the $K$ band even when using the shortest exposure time. The large errors associated with 2MASS magnitudes for these bright stars led to large errors in angular diameter and physical radii estimates.

Once $\theta_{LD}$ was determined interferometrically, the $T_{\text{eff}}$ was calculated using the relation

$$F_{\text{BOL}} = \frac{1}{4} \theta_{LD}^2 \sigma T_{\text{eff}}^4,$$

where $F_{\text{BOL}}$ is the bolometric flux and $\sigma$ is the Stefan–Boltzmann constant. The stars’ $V$ and $K$ magnitudes were dereddened using the extinction curve described in Cardelli et al. (1989) and interstellar absorption ($A_V$) values were from Famaey et al. (2005) except for HD 113049 and HD 176408, which had no $A_V$ in the literature. $A_V$ values for these two stars were estimated through a nonlinear, least squares fit and a reddening prescription from Fitzpatrick (1999), who presented a wavelength-dependent extinction curve. The intrinsic broadband color ($V - K$) was calculated and BCs were determined by interpolating between the $\text{[Fe/H]} = +0.2, 0.0, \text{and} -1.0$ tables found in Alonso et al. (1999). They point out that in the range of $6000 \text{K} \geq T_{\text{eff}} \geq 4000 \text{K}$, their BC calibration is symmetrically distributed around a $\pm 0.10$ mag band when compared to other calibrations. The average BC used here is 0.55, and because 0.10 is 18% of 0.55, we assigned a 18% error bar to our BC values. The bolometric flux was determined by applying the BC for each star and the $T_{\text{eff}}$ was calculated (see Table 4). All $T_{\text{eff}}$ errors are $\leq 4\%$, 11 stars have errors of $\leq 2\%$, and the major source of error in calculating $T_{\text{eff}}$ stemmed, again, from uncertainties in $K$ magnitudes.

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**Figure 2.** LD disk diameter fits for all the stars observed with two calibrators except HD 150010. The symbols are the same as listed in Figure 1. For the sake of clarity, the data points for one calibrator only are shown.
Giant star masses were estimated using the PARAM stellar model\textsuperscript{10} from Girardi et al. (2000) with a modified version of the method described in da Silva et al. (2006). The input parameters for each star were its interferometrically measured $T_{\text{eff}}$, its spectroscopically derived $[\text{Fe}/\text{H}]$, its $V$ magnitude from Mermilliod (1991), and its Hipparcos parallax (van Leeuwen 2007a, 2007b) along with the corresponding error for each value. The model used these inputs to estimate each star’s age, mass, radius, $(B - V)_0$, and $\log g$ using the isochrones and a Bayesian estimating method, calculating the probability density function separately for each property in question. da Silva et al. qualify mass estimates as “more uncertain” than other properties, so the resulting masses listed in Table 1 should be viewed as rough estimates only.

\textsuperscript{10} http://stev.oapd.inaf.it/cgi-bin/param_1.0

5. RESULTS AND DISCUSSION

In order to check how well the estimated and measured angular diameters agreed, we plotted photometrically estimated versus interferometrically measured angular diameters in Figure 4, and Figure 5 shows a similar plot for physical radii. The angular diameters determined using $K$-band photometry from 2MASS show generally higher errors in Figure 4 than the diameters determined using TMSS photometry. This plot clearly shows the advantage of measuring angular diameters interferometrically, as the errors are significantly smaller than the photometric estimates in all cases. There is an even scatter around the 1:1 ratio line, and all but two stars are within 1$\sigma$ of the line.

The outliers in both Figures 4 and 5 are HD 118904 and HD 157681. Neither star shows any sign of binarity in the literature, and the SEDs created using the $T_{\text{eff}}$ and $\log g$ based on their spectral type and Cox (2000) do not show any excess in the infrared wavelengths that would suggest a low-mass stellar companion or a circumstellar disk. In both cases, the problem may lie with the calibrator stars chosen. HD 157681 was observed using the calibrator HD 158460, and though the latter has a small estimated diameter (0.268 ± 0.016 mas) and its SED shows no excess flux in the infrared that would indicate a low-mass stellar companion or circumstellar disk, HD 157681 was the only star observed with that calibrator and there could be an unseen companion that is not taken into account when estimating the star’s diameter. Future observations of HD 157681 with different calibrators will make the situation clearer.

HD 118904 was observed using HD 124063 as a calibrator, and the same calibrator was used to observe the target star HD 113049 along with the second calibrator HD 107193. When
the data were calibrated separately for HD 113049, the diameters differed by 0.08 mas difference, which is on the order of an 8% change. If HD 118904’s diameter is reduced by 8%, the data point is within errors on the 1:1 ratio line for both plots in Figures 4 and 5. Because this is the case, only HD 107193 was used in the calibration of HD 113049’s data, and the angular diameter, radius, and $T_{\text{eff}}$ listed in Table 4 are based on those data alone.

Figure 5 shows that while a fair number of photometric and interferometric radii agree very well, there are some that show slight discrepancies, notwithstanding the error bars. This could...
be due to a few different effects. First, the photometrically
determined radii depend on temperature estimates that may not
be correct. If the star is highly active or there is a very faint
companion, these could affect the temperature and therefore
radii estimates. Second, the LD law used to determine in-
ferferometric diameters and radii may not take certain stellar
features into account, such as starspots or extremely active
regions. This would not be a large effect because even altering the
LD coefficient \( \mu_{\lambda} \) by 20% changes the limb-darkened angular
diameter by an average of 0.7%. Third, the differences may be
due to changes in the stars’ convections zones, because as the
star evolves the convection zone gets deeper. Convection is not
well modeled, which may lead to errors in the photometric radii
estimates.

We also plotted the interferometrically measured \( T_{\text{eff}} \) versus
those derived spectroscopically in Figure 6. There is some
correlation off the 1:1 ratio line, particularly for the cooler stars.
The errors in \( T_{\text{eff}} \) do not show a trend with log \( g \), diameter,
radius, \((V - K)\) color, distance, spectral type, metallicity, or
BC. The discrepancies may be due to the inherent properties
of the methods used to measure \( T_{\text{eff}} \). Spectroscopic values are
based on Fe\( \text{i} \) and Fe\( \text{ii} \) lines and measure the \( T_{\text{eff}} \) in the
part of the atmosphere where those lines are present, while
interferometry calculates the overall \( T_{\text{eff}} \) of the star using the
measured diameter. It has been surmised that atmospheric
models of K giant stars in the near-ultraviolet band are missing
a source of thermal extinction, which would also affect the \( T_{\text{eff}} \) measurements (Short & Hauschildt 2009).

Our next step will be to determine the oscillation frequencies
of these stars so that we can compare the true masses of these
stars with those estimated using evolutionary models.

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\(^{11}\) If a second star is present and is more than \( \sim 2.5 \) mag fainter than the host
star, the effects of the secondary star will be not seen in interferometric
observations and would therefore have no effect on the angular diameter or
physical radii measurements.