Direct Measurements of Giant Star Effective Temperatures and Linear Radii: Calibration against Spectral Types and $V - K$ Color

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Abstract

We calculate directly determined values for effective temperature (T_{eff}) and radius (R) for 191 giant stars based upon high-resolution angular size measurements from optical interferometry at the Palomar Testbed Interferometer. Narrow- to wideband photometry data for the giants are used to establish bolometric fluxes and luminosities through spectral energy distribution fitting, which allows for homogeneously establishing an assessment of spectral type and dereddened $V_0 - K_0$ color; these two parameters are used as calibration indices for establishing trends in T_{eff} and R . Spectral types range from G0III to M7.75III, $V_0 - K_0$ from 1.9 to 8.5. For the $V_0 - K_0 = \{1.9, 6.5\}$ range, median T_{eff} uncertainties in the fit of effective temperature versus color are found to be less than 50 K; over this range, T_{eff} drops from 5050 to 3225 K. Linear sizes are found to be largely constant at $11 R_{\odot}$ from G0III to K0III, increasing linearly with subtype to $50 R_{\odot}$ at K5III, and then further increasing linearly to $150 R_{\odot}$ by M8III. Three examples of the utility of this data set are presented: first, a fully empirical Hertzsprung–Russell diagram is constructed and examined against stellar evolution models; second, values for stellar mass are inferred based on measures of R and literature values for $\log g$; finally, an improved calibration of an angular size prediction tool, based upon V and K values for a star, is presented.

Unified Astronomy Thesaurus concepts: Fundamental parameters of stars (555); Red giant stars (1372); Stellar properties (1624); Stellar radii (1626); Calibration (2179); Long baseline interferometers (931); Optical interferometry (1168); Stellar masses (1614); Interferometry (808); High angular resolution (2167); Stellar effective temperatures (1597); Flux calibration (544)

Supporting material: machine-readable tables

1. Introduction

One of the key contributions of long-baseline optical interferometry to date has been the empirical determination of fundamental stellar parameters. The range of values for parameters such as radius and temperature can be simply inferred from blackbody assumptions about stars or with greater precision through using stellar models such as PHOENIX (Husser et al. 2013), but they ultimately are most accurate when directly measured. Their utility is consequently extended by calibrating stellar models.

Calibration of “canonical” values for temperature and radius has wide-ranging utility in astrophysics. Evaluation of X-ray transient host stars (Skopal 2015; McCollum et al. 2018), interpretation of protoplanetary environments (Arulanantham et al. 2017), establishing the temperature of a galactic runaway giant (Massey et al. 2018), and modeling of galactic long-period variables (Barthès & Luri 2001) are a few examples of the use of our earlier calibration of effective temperature (van Belle et al. 1999, hereafter vB99). Improved temperature calibrations can have wide-ranging effects, particularly when they refine calibrations used in large surveys (e.g., the symbiotic star survey of Akra et al. 2019). General values

for such calibrations appear in references such as Cox (2000) and facilitate a myriad of back-of-the-envelope calculations.

The Palomar Testbed Interferometer (PTI; Colavita et al. 1999), whose technical details are discussed in Section 3, was a particularly productive long-baseline optical interferometer (LBOI) that operated from 1996 until 2008. Its highly efficient, semirobotic operations enabled the collection of large amounts of stellar fringe visibility data on any given night; these visibility data can be used to establish a direct measure of source angular size for resolved stellar sources greater in size than ~ 0.75 mas. Given the sensitivity limit of the facility ($m_K < 5$) and its angular resolving power, PTI was particularly well suited for large surveys of evolved stars; main-sequence stars on the faint end of this sensitivity range tended to be too small to resolve.

Our first investigation of the calibration of surface temperatures of giant stars, in vB99, was published early in the operation of the instrument. Subsequent to that investigation, notable improvements were made that motivate this larger follow-up study. Considerable effort was invested in increasing our understanding of the operations of PTI and the implications for its data products (Colavita 1999), the night-to-night repeatability of the data (Boden et al. 1998b, 1999), the atmospheric conditions of the site (Linfield et al. 2001), the

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Table 1

Long-baseline Optical Interferometry Diameter Surveys of Five or More Stars

Facility	Survey Size	References
Giants		
Mark III	24 giants	Hutter et al. (1989)
Mark III	12 giants	Mozurkewich et al. (1991)
IOTA	37 giants	Dyck et al. (1996a)
IOTA	74 giants	Dyck et al. (1998)
PTI	69 giants/supergiants	van Belle et al. (1999)
NPOI	50 giants	Nordgren et al. (1999)
NPOI	41 giants	Nordgren et al. (2001)
Mark III	85 giants	Mozurkewich et al. (2003)
CHARA	25 K giants	Baines et al. (2010)
NPOI	69 giants, 18 additional stars	Baines et al. (2018)
PTI	191 giants	This work
Other Evolved Stars		
IOTA	15 carbon stars	Dyck et al. (1996b)
IOTA	18 O-rich Miras	van Belle et al. (1996)
IOTA	9 carbon/S-type Miras, 4 non-Mira S-types	van Belle et al. (1997)
IOTA	22 O-rich Miras	van Belle et al. (2002)
VLTI-VINCI	14 Miras	Richichi & Wittkowski (2003)
VLTI-VINCI	7 Cepheids	Kervella et al. (2004)
PTI	74 supergiants	van Belle et al. (2009)
PTI	5 carbon stars	Paladini et al. (2011)
PTI	41 carbon stars	van Belle et al. (2013)
VLTI-PIONIER	9 Cepheids	Breitfelder et al. (2016)
VLTI-PIONIER	23 post-AGB disks	Kluska et al. (2019)
Main-sequence Stars		
PTI	5 main-sequence stars	Lane et al. (2001)
VLTI-VINCI	5 Vega-like stars	Di Folco et al. (2004)
VLTI-VINCI/ AMBER	7 low-mass stars	Demory et al. (2009)
PTI	40 stars (incl. 12 exoplanet hosts)	van Belle & von Braun (2009)
CHARA	44 AFG MS stars	Boyajian et al. (2012a)
CHARA	22 KM stars	Boyajian et al. (2012b)
CHARA	23 A–K stars, 5 exoplanet hosts	Boyajian et al. (2013)
CHARA	11 exoplanet hosts	von Braun et al. (2014)
CHARA	7 A-type stars	Jones et al. (2015)
Young Stellar Objects		
VLTI-PIONIER	92 debris disk stars	Ertel et al. (2014)
VLTI-PIONIER	21 T Tauri stars	Anthonioz et al. (2015)
VLTI-PIONIER	7 debris disk stars	Ertel et al. (2016)
VLTI-PIONIER	51 Herbig AeBe disks	Lazareff et al. (2017)
VLTI-GRAVITY	27 Herbig AeBe disks	GRAVITY Collaboration et al. (2019)

Note. See Table 3.1 in von Braun & Boyajian (2017) for a detailed list of stars with interferometrically determined radii. See Section 2 for details.

nature of the absolute calibration of the fringe visibility data (van Belle & van Belle 2005), and a strictly vetted set of on-sky calibration sources (van Belle et al. 2008). In addition to those improvements, the instrument during its decade of operation was used to conduct a wide range of scientific investigations, including a broad survey to measure the angular sizes of giant stars.

Table 2

Number of Targets per Angular Size Bin

Angular Size Bin	Number of Stars
0.75	1
1.00	2
1.25	9
1.50	17
1.75	29
2.00	36
2.25	23
2.50	29
2.75	16
3.00	10
3.25	15
3.50	7
3.75	5
4.00	3
4.25	3
4.50	1
4.75	2

Note. For more information, see Section 3.1 and Figure 1.

The development of the `sedFit` code subsequent to our initial `vB99` investigation has provided a superior means of calculating bolometric fluxes through spectral energy distribution (SED) fitting, which is necessary for robust determination of temperature. Utilization of `sedFit` is furthered by the availability of modern stellar spectral templates such as PHOENIX (Husser et al. 2013), as well as empirical spectral templates such as the INGS library,¹⁰ a substantial improvement over the earlier Pickles Flux Library (Pickles 1998). Additionally, given the availability of `sedFit`, considerable effort was invested in the collection of ancillary photometric data through both observation and examination of archival sources and improving our zero-point calibrations of those data (Bohlin et al. 2014; Mann & von Braun 2015). Finally, for each individual science target reported upon herein, data from a larger number of observing nights and baseline configurations were typically collected, allowing for better control of occasional spurious data points. Our intent with this investigation was to establish the definitive effective temperature scale for giant stars, and as such, great care was taken in having each of these steps be as empirical as possible, with the greatest accuracy and precision available.

The previous surveys of PTI and other notable LBOI facilities are presented in Section 2. Details on the PTI facility are given in Section 3, as well as the particulars of the target selection (Section 3.1). Bolometric flux determination using `sedFit` is detailed in Section 4, derived effective temperatures are given in Section 5, and distances and their determinations are discussed in Section 6. With the establishment of these fundamental parameters, relationships between T_{eff} and R and indicator indices $V_0 - K_0$ (dereddened) color and spectral type are explored in Section 7. An intriguing gap in the otherwise smooth continuum of points in the T_{eff} versus $V_0 - K_0$ is examined statistically for significance in Section 7.1. A serendipitous result from the steps taken in this investigation, the calibration of spectral type versus $V_0 - K_0$, is presented in

¹⁰ IUE, NGSL, SpeX/IRTF library, <https://lco.global/~apickles/INGS/>.

Figure 1. Histogram of the measured angular sizes for bins centered at intervals of 0.25 mas (blue columns, left vertical axis), along with the minimum fractional error for each of those bins (red line, right vertical axis). For more information, see Section 3.1 and Tables 2 and 3.

Section 7.2.3. We then take a broader look at some of the possible applications of these data with the examples in Section 8. First, we compare our results to stellar evolutionary tracks (Section 8.1); second, we demonstrate that these measures of R , when combined with $\log g$, can be used to infer evolved star masses (Section 8.2). Finally, a new calibration of a predictive tool for stellar angular diameters is presented in Section 9.

2. Previous Large Surveys

Measures of stellar angular diameters are particularly useful when conducted in surveys covering multiple targets. A summary of the surveys by LBOI facilities is presented in Table 1. Given the intersection of sensitivity and angular resolution of earlier facilities that typically had baselines only up to ~ 100 m, a focus on evolved stars is seen in those surveys from roughly before 2005. More modern facilities have baselines in excess of $\gtrsim 100$ (VLTI), $\gtrsim 300$ (CHARA), and $\gtrsim 400$ (NPOI) m, enabling studies of smaller ($< \lesssim 1.0$ mas) objects such as main-sequence stars. However, the most highly automated facilities—PTI and the Mark III, which could hop star-to-star in times of $\lesssim 5$ minutes—are now in the past, meaning the largest surveys are more difficult and time-consuming observationally.

Although use of the lunar occultation (LO) technique is not a focus of this investigation, it is worth noting that the very earliest surveys at milliarcsecond scales, from the 1970s onward, were carried out with the LO technique. These include the extensive work of the Kitt Peak group (Ridgway et al. 1977, 1979, 1980a, 1982; Schmidtke et al. 1986), as well as the UT-Austin group (see Papers I–XVI of the series that concludes with Evans et al. 1986). A summary of 348 measures on 124 stars is presented in White & Feigman (1987). There continue to be LO measures carried out with

Table 3
Minimum Possible Fractional Error for Measured Angular Sizes, Based upon PTI’s Night-to-night Limiting V^2 Repeatability of 1.5%, as Discussed in Section 3

Angular Size Bin (mas)	Minimum Fractional Error
0.75	10%
1.00	6.0%
1.25	4.1%
1.50	3.1%
1.75	2.4%
2.00	2.1%
2.25	1.9%
2.50	1.8%
2.75	1.7%
3.00	1.8%
3.25	2.0%
3.50	2.2%
3.75	2.6%
4.00	3.1%
4.25	4.1%
4.50	5.5%
4.75	8.0%

Note. For more information, see Section 3.1 and Figure 1.

more modern equipment (Tej & Chandrasekhar 2000; Mondal & Chandrasekhar 2005; Baug & Chandrasekhar 2013; Ertel et al. 2014), though the principal body of high-resolution work in the last 15 yr has been with LBOI facilities.

In relation to these previous surveys, the intent of this particular investigation is twofold. First, the homogeneous data set presented herein is twice as large as the next-largest survey and benefits from advances in the understanding of atmospheric

Table 4
Computed Bolometric Fluxes for the Program Stars

Star ID	Primary ST	Primary Reference	Secondary ST	Secondary Reference	Model T_{eff}	Model $\log g$	Fit ST	Flux ^a F_{bol}	Err.	Reddening A_V	Fit χ^2/dof	Fit dof
HD 178	M5/6III	Houk (1982)	M6III	Jones (1972)	3200	1.0	M6III	30.4 ± 0.9	3.0%	0.43 ± 0.03	4.9	6
HD 598	M4III	Wilson & Joy (1952)	M7	Lee et al. (1943)	3400	1.0	M5III	36.0 ± 0.7	1.8%	0.00 ± 0.03	21.5	8
HD 672	M5III	Jones (1972)			3300	1.0	M5.5III	25.6 ± 0.8	3.2%	0.18 ± 0.03	5.1	5
HD 787	K5III	Roman (1952)	K5III	Adams et al. (1935)	3900	1.5	K5III	51.9 ± 1.1	2.2%	0.00 ± 0.03	3.2	16
HD 1522	K1+III	Keenan & McNeil (1989)	K1.5III	Morgan & Keenan (1973)	4600	2.0	K1.3III	141.0 ± 1.5	1.0%	0.01 ± 0.01	0.9	54
HD 1632	K5III	S. (1932)			3900	1.5	K5III	43.0 ± 1.3	3.0%	0.31 ± 0.03	2.3	14
HD 2436	K5III	Adams et al. (1935)			3900	1.5	K5III	29.8 ± 0.8	2.6%	0.24 ± 0.02	4.3	26
HD 3346	K6IIIa	Keenan & McNeil (1989)	M0III	Henry et al. (2000)	3900	1.5	K5III	76.9 ± 1.2	1.6%	0.29 ± 0.02	3.2	24
HD 3546	G7III	Keenan & McNeil (1989)	G8III	Roman (1955)	5400	2.5	G1III	68.8 ± 1.2	1.7%	0.31 ± 0.01	0.4	87
HD 3574	K4III	Abt (1985)	K7III	Bakos (1974)	3800	1.5	M0III	50.4 ± 0.6	1.2%	0.09 ± 0.01	13.0	20
HD 3627	K3III-IIIb	Keenan & McNeil (1989)	K3III	Gray et al. (2003)	4500	2.0	K1.5III	216.0 ± 2.1	1.0%	0.14 ± 0.01	1.6	62
HD 5006	K8III	Gaze & Shajn (1952)			3400	1.0	M5III	22.5 ± 1.0	4.4%	0.01 ± 0.04	12.8	12
HD 5575	G6III	Adams et al. (1935)			4800	2.5	G9III	23.9 ± 0.3	1.4%	0.07 ± 0.01	0.7	24
HD 6186	G9IIIb	Keenan & McNeil (1989)	G9	Hossack (1954)	5000	2.5	G5III	67.1 ± 0.8	1.2%	0.07 ± 0.01	0.3	84
HD 6262	M3III	Moore & Paddock (1950)	M5	Lee et al. (1943)	3600	1.5	M3III	25.3 ± 0.8	3.1%	0.31 ± 0.03	7.3	9
HD 6409	M5	Lee et al. (1943)			3500	1.0	M4III	19.2 ± 0.3	1.4%	0.01 ± 0.02	8.9	10
HD 7000	M4	Lee et al. (1943)			3400	1.0	M5III	14.7 ± 0.6	4.2%	0.19 ± 0.04	8.4	8
HD 7087	G8.5III	Keenan & McNeil (1989)	K0III	Sato & Kuji (1990)	4900	2.5	G7III	46.0 ± 0.6	1.2%	0.06 ± 0.01	0.8	48
HD 7318	G8III	Abt (1985)	G8III-IV	Yoss (1961)	4900	2.5	G7III	46.7 ± 0.8	1.6%	0.08 ± 0.02	1.4	57
HD 8126	K5III	Adams et al. (1935)			4200	2.0	K3.III	46.6 ± 0.8	1.7%	0.20 ± 0.02	2.1	20
HD 9500	M3III	Wilson & Joy (1952)	M4III	Moore & Paddock (1950)	3500	1.0	M4III	29.4 ± 0.5	1.7%	0.03 ± 0.02	4.5	17
HD 9927	K3III	Keenan & McNeil (1989)	K3	Hossack (1954)	4500	2.0	K1.5III	168.0 ± 1.8	1.0%	0.16 ± 0.01	1.2	53
IRC+30095	M8 D	Color fitting			2900	0.5	M7.7III	26.7 ± 1.4	5.2%	0.24 ± 0.04	52.9	7

Notes. For more details, see Section 4.3.

^a Flux units are $10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$.

References. Color fitting is used when no literature spectral type is found. Parkhurst (1912), Adams et al. (1926), S. (1932), Moore (1932), Adams et al. (1935), Hoffleit & Shapley (1937), Keenan (1942), Joy (1942), Hoffleit (1942), Lee et al. (1943), Cannon & Mayall (1949), Wilson & Joy (1950), Moore & Paddock (1950), Wilson & Joy (1952), Roman (1952), Gaze & Shajn (1952), Keenan & Keller (1953), Swings et al. (1953), Westerlund (1953), Hossack (1954), Nassau & Blanco (1954), Gyldenkerne (1955), Halliday (1955), McCuskey (1955), Roman (1955), Heard (1956), Bidelman (1957), Neckel (1958), van de Kamp (1958), Stephenson (1960), Herbig (1960), Malmquist (1960), Yoss (1961), Fehrenbach et al. (1961), Perraud (1961), Pedoussaut (1962), Morgan & Hiltner (1965), Ljunggren & Oja (1966), Ljunggren (1966), Barbier & Maiocchi (1966), Fehrenbach (1966), McCuskey (1967), Appenzeller (1967), Yamashita (1967), Wing (1967), Stephenson & Sanwal (1969), Harlan (1969), Barbier (1971), Schmitt (1971), Jones (1972), Schild (1973), Morgan & Keenan (1973), Bakos (1974), Garrison & Kormendy (1976), Yoss (1977), Uranova (1977), Keenan & Wilson (1977), Iijima & Ishida (1978), Levato & Abt (1978), Cowley & Bidelman (1979), Turnshek et al. (1980), Yamashita & Norimoto (1981), Abt (1981), Houk (1982), Bopp (1984), Abt (1985), Bidelman (1985), Shaw & Guinan (1989), Keenan & McNeil (1989), Strassmeier & Fekel (1990), Sato & Kuji (1990), Lu (1991), Cannon & Pickering (1993), Garrison & Gray (1994), Ginestet et al. (1994), Abt & Morrell (1995), Parsons & Ake (1998), Henry et al. (2000), Ginestet & Carquillat (2002), Gray et al. (2003), Medhi et al. (2007), Abt (2008), Zorec et al. (2009), Skiff (2014).

(This table is available in its entirety in machine-readable form.)

and instrumental effects. Second, the ancillary data sets and supporting modeling have improved substantially. Together, these advances build on the experience from those surveys but make for a substantially improved characterization of stellar fundamental parameters for giant stars.

3. Angular Size Measurements with PTI

The PTI was an 85–110 m baseline H - and K -band (1.6 and 2.2 μm) interferometer located at Palomar Observatory in San Diego County, California, and is described in detail in Colavita et al. (1999). It had three 40 cm apertures used in pairwise combination for measurement of stellar fringe visibility on sources that range in angular size from 0.05 to 5.0 mas, being able to resolve individual sources with angular sizes $\theta > 0.75$ mas in size. It was in nightly operation between 1997 and 2008, with minimum downtime throughout the intervening years. The data from PTI considered herein cover the range from the beginning of 1998 (when the standardized data collection and pipeline reduction went into place) until the beginning of 2008 (when operations at PTI concluded). In addition to the giant stars discussed herein, appropriate calibration sources were observed and can be found in van Belle et al. (2008).

The calibration of the giant star visibility (V^2) data was performed by estimating the interferometer system visibility (V_{sys}^2) using the calibration sources with model angular diameters and then normalizing the raw giant visibility by V_{sys}^2 to estimate the V^2 measured by an ideal interferometer at that epoch (Mozurkewich et al. 1991; Boden et al. 1998a; van Belle & van Belle 2005). Uncertainties in the system visibility and calibrated target visibility are inferred from internal scatter among the data in an observation using standard error-propagation calculations (Colavita 1999). Calibrating our pointlike calibration objects against each other produced no evidence of systematics, with all objects delivering reduced $V^2 = 1$.

The PTI’s limiting night-to-night measurement error is $\sigma_{V_{\text{sys}}^2} \approx 1.5\%$, the source of which is most likely a combination of effects: uncharacterized atmospheric seeing (in particular, scintillation), detector noise, and other instrumental effects. This measurement error limit is an empirically established floor from the previous study of Boden et al. (1999).

From the relationship between visibility and uniform disk (UD) angular size (θ_{UD}), $V^2 = [2J_1(x)/x]^2$ (Airy 1835; Born & Wolf 1980), where J_1 is the first Bessel function and spatial frequency $x = \pi B \theta_{\text{UD}} \lambda^{-1}$, we established UD angular sizes (θ) for the giants observed by PTI, since the accompanying parameters (projected telescope-to-telescope separation, or baseline, B and wavelength of observation λ) are well characterized during the observation. This UD angular size will be connected to a more physical limb-darkened (LD) angular size (θ_{LD}) in Section 5.1; these UD angular sizes are presented in Table 20.

3.1. Target Selection for PTI

Given the highly efficient queue-scheduled nature of observing with PTI, a large program of observing as many evolved stars as possible was undertaken at the facility. These were targets of opportunity, available for observing when the facility was not tasked with other observing. The scope of this manuscript will focus on the field giant stars. This leaves objects such as S-type stars and Miras for forthcoming papers,

Table 5
Sources of Photometry for Our Program Stars with $N \geq 20$ Data Points

Reference	System	N_{points}
Smith et al. (2004)	COBE DIRBE	1038
This work	Farnham-HB	822
Johnson & Mitchell (1995)	Johnson 13-color	748
Kornilov et al. (1991)	WBVR	707
Ducati (2002)	Johnson-IR	509
McClure & Forrester (1981)	DDO	507
Häggkvist & Oja (1970)	Oja	436
Johnson et al. (1966)	Johnson-IR	396
Golay (1972)	Geneva	378
Mermilliod (1986)	Johnson-visible	325
Neugebauer & Leighton (1969)	Johnson-IR	241
Kazlauskas et al. (2005)	Vilnius	157
Häggkvist & Oja (1966)	Johnson-visible	150
Argue (1966)	Johnson-visible	149
Argue (1963)	Johnson-visible	144
Jennens & Helfer (1975)	Johnson-visible	105
Hauck & Mermilliod (1998)	Stromgren	104
Zdanavicius et al. (1969)	Vilnius	102
Zdanavicius et al. (1972)	Vilnius	88
Shenavrin et al. (2011)	Johnson-IR	80
Johnson (1964)	Johnson-IR	79
L. Häggkvist & T. Oja (1970, private communication)	Johnson-visible	73
Mermilliod & Nitschelm (1989)	DDO	67
Oja (1993)	Stromgren	60
Alonso et al. (1998)	Johnson-IR	55
Jasevicius et al. (1990)	Vilnius	50
Straizys et al. (1989a)	Vilnius	49
Gutierrez-Moreno et al. (1966)	Johnson-visible	40
Crawford & Barnes (1970)	Stromgren	40
Nicolet (1978)	Johnson-visible	35
Johnson & Morgan (1953)	Johnson-visible	34
Bartkevicius et al. (1973)	Vilnius	34
Roman (1955)	Johnson-visible	32
Fernie (1983)	Johnson-visible	32
Glass (1974)	Johnson-IR	29
Sudzius et al. (1970)	Vilnius	28
Ljunggren & Oja (1965)	Johnson-visible	26
Lee (1970)	Johnson-IR	26
Voelcker (1975)	Johnson-IR	24
McWilliam & Lambert (1984)	Johnson-IR	24
Gray & Olsen (1991)	Stromgren	24
Neckel (1974)	Johnson-visible	22
Straizys & Meistas (1989)	Vilnius	22
Oja (1991)	Johnson-visible	22
McClure (1970)	Johnson-visible	21
Oja (1986)	Johnson-visible	21
Selby et al. (1988)	Johnson-IR	21
Forbes et al. (1993)	Vilnius	21
Laney et al. (2012)	Johnson-IR	21
Moffett & Barnes (1979)	Johnson-visible	20
Oja (1983)	Stromgren	20
Oja (1984)	Johnson-visible	20

Note. In the system column, “Johnson-visible” is used to denote any passbands from *UBVR*, and “Johnson-IR” denotes passbands from *JHKLM*. Additional sources are listed on a star-by-star basis in Table 6. For more details, see Section 4.2.

and objects such as supergiants (van Belle et al. 2009) and carbon stars (van Belle et al. 2013) have already been published. This broad sweep meant target selection was largely limited by the “sweet spot” of PTI sensitivity for both target brightness and angular size.

Figure 2. PHOENIX fitting of INGS spectra by luminosity class as a Kiel diagram. For more details, see Section 4.1.

Angular size range. Angular sizes at PTI for robust size determination, noting the night-to-night precision cited above, were typically intended to be in the range of 1.5–4.0 mas. This range is consistent with K -band operation of a 109 m baseline, resulting in a V^2 contrast below roughly 90% (to ensure target resolution) and above roughly 10% (to avoid degenerate diameter solutions). A priori estimators, such as the $V-K$ technique found in van Belle (1999), allowed reasonable expectations of the gross size of a given target prior to observing. The number of resulting targets over the range of angular sizes is found in Table 2 and plotted in Figure 1. Some angular sizes in excess of 4.0 mas are seen from large objects observed with PTI’s shorter 85 m baseline. Based on the minimum expected night-to-night V^2 repeatability discussed above, the limiting fractional error expected for various angular sizes is presented in Table 3.

Brightness range. The PTI’s limiting magnitude of $K < 5$ primarily limited the available pointlike calibrator observations interleaved with resolved target star observations. Generally speaking, targets that satisfied the angular size range constraints for resolvability above were quite bright, with $K < 3$. The bigger impacts on operations were those targets that were extremely red (corresponding to the targets with the lowest effective temperature); a lack of visible-light photons made it difficult for the facility’s tip-tilt tracker to follow atmospheric turbulence. However, this was more of a concern for studies that targeted even redder targets than this particular investigation, such as carbon stars (van Belle et al. 2013).

Spectral types. Spectral types were initially taken from various literature references (e.g., see Skiff 2014, and references therein); care was taken to select those that had been previously typed as luminosity class III or were otherwise indicated to be off the main sequence (e.g., based on parallax

values). As will be presented below in Section 4, these types were taken as starting points for our own solutions for fitting spectral types. These initial spectral types are presented in Table 4, as well as our best-fit values.

Completeness. A cursory examination of the Two Micron All Sky Survey (2MASS) and Skiff catalogs (Cutri et al. 2003a; Skiff 2014) can give an indication of the completeness of our giant star sample. First, the 2MASS catalog was sampled for all objects brighter than $K < 3.5$, resulting in approximately 13,000 objects. For stars in this brightness range, 2MASS photometry is saturated and increasingly unreliable, although for this assessment, it is more than sufficient. Second, from the B and K magnitudes in 2MASS, all such objects were selected for angular sizes in the range of $\theta = \{1.0, 4.75\}$ mas using the $B-K$ size estimator in van Belle (1999). Finally, those $\sim 11,600$ objects were compared against the Skiff catalog for objects previously typed to be luminosity class III objects, resulting in ~ 4500 targets, of which 1723 are northern hemisphere objects. As such, our sample herein constitutes a sample of $\sim 10\%$ of all possible giant stars that PTI could have observed.

This is an ex post facto assessment and could not have guided target selection at the time. The Skiff catalog was not available at the time of the PTI target selection, and 2MASS was available only for the latter portion of PTI operations. During PTI operations, our guideposts were the Bright Star Catalog (Hoffleit & Jaschek 1982), the recently released (for that era) Hipparcos catalog (Perryman et al. 1997), and the Catalog of Infrared Observations (CIO; Gezari et al. 1993). During that era, luminosity classification was somewhat less clearly defined during PTI operations, even if, in the course of this investigation, our targets will be diligently sorted for luminosity class III objects.

Figure 3. Bolometric flux F_{bol} (in units of $10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$) vs. angular size θ (milliarcseconds) for our program stars. Canonical fit lines for fixed values of T_{eff} from Equation (1) are shown as dotted lines.

4. Bolometric Fluxes

For the program stars, measurements of the stellar bolometric fluxes (F_{bol}) were needed in order to compute the stellar effective temperature, T_{eff} . A direct determination of T_{eff} can be made from a stellar angular diameter (θ), in conjunction with a measurement of F_{bol} (Equation (1)). The F_{bol} is calculated by integrating a stellar spectrum (stellar model, spectral template, or spectrophotometric data product) over frequency or wavelength after shifting this spectrum in flux units to fit calibrated photometry or spectrophotometry. For this study, these photometry data are a combination of literature photometry and data we obtained ourselves in support of this particular survey.

The stellar bolometric flux is the total integrated flux from a star, as if there were no intervening obscuration between us and the object of interest. Any attempts at measuring F_{bol} need to be careful to account for two problems that can limit our attempts to characterize the flux from the star. First, phenomena that attenuate the apparent flux of a star at the location of the observer need to be accounted for. This includes interstellar extinction, extinction local to the source (such as circumstellar material), and effects local to the observer, such as atmospheric extinction. Second, photometric measures of stellar flux are rarely (if ever) done in a comprehensively multiwavelength fashion; hence, gaps in the wavelength coverage of flux observations need to be interpolated or extrapolated in a plausible manner using appropriate spectral type templates (Section 4.1). We discuss the literature photometry products in Section 4.2 and Table 5, as well as the photometry obtained ourselves in support of this project. An approach to the determination of F_{bol} in a robust manner that accommodates these complications and delivers $\sim 2\%$ levels of accuracy for F_{bol} seen in Section 4.3 follows these steps.

1. Photometry is collected for the target of interest. Ground-based photometry must be extinction-corrected for atmospheric extinction (Johnson & Morgan 1953; Hardie 1964; Johnson 1965a; Linnell 1982; Cousins 1985).
2. The instrument response, and in particular, the filter function, must be known in detail; the zero-point calibration needs to be known to $\sim 1\%$ – 2% or better. Ideally, zero-point calibrations are directly traceable to

Figure 4. Same as Figure 3 but a zoom on the central region. For more details, see Section 4.3.

National Institute of Standards and Technology standards or similar absolute standards. See, for example, the ACCESS experiment (Kaiser & Kruk 2008; Kaiser et al. 2010) or the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph Next Generation Spectral Library (NGSL; Gregg et al. 2004; Heap & Lindler 2010).

3. Generalized broadband photometry is the easiest to collect due to its high photon throughput and ready filter availability. However, narrowband or specialized broadband photometry is of great utility in disentangling degeneracies between spectral type, luminosity class, and interstellar or circumstellar extinction; such photometry has been used for stellar classification since the advent of high-precision phototubes (e.g., Canterna 1976; Johnson & Mitchell 1995). Our fitting approach can utilize both broad- and narrowband photometry from multiple sources, which provides an element of cross-checking data points from multiple heterogeneous sources.
4. Photometry is ideally on both the long- and short-wavelength sides of the “blackbody” peak. These data help to break the degeneracy between gross flux levels and interstellar or circumstellar extinction.
5. Once the photometry is in hand, a spectral template is fit to these data. The necessity of this step is to interpolate or extrapolate over the unsampled wavelength regimes; a secondary purpose of this step is to fit for interstellar/circumstellar extinction. In this step, a grid of templates is typically searched to determine the most appropriate one for use with the star being examined.

4.1. Spectral Templates and Spectral Types

A significant question that we frequently encountered during this study was whether to fit our photometric data with empirical spectral templates such as the INGS library or work with model spectral templates based on models such as the PHOENIX. The INGS (IUE/NGSL/SpeX) library¹¹ is a refinement of the empirical templates originally found in Pickles (1998) by the same author; it has the virtue of being a model-independent approach to providing a stellar spectral

¹¹ <https://lco.global/user/apickles/dev/INGS/>

Table 6
Photometry for the Program Stars

Star ID	System/Wavelength (nm)	Band/Bandpass	Value	References
HD 178	Johnson	<i>V</i>	9.26 ± 0.02	This work
HD 178	1250	310	138.80 ± 11.20	Smith et al. (2004)
HD 178	Johnson	<i>H</i>	1.95 ± 0.05	Ducati (2002)
HD 178	Johnson	<i>H</i>	1.96 ± 0.05	Feast et al. (1990)
HD 178	Johnson	<i>H</i>	2.09 ± 0.05	Kerschbaum & Hron (1994)
HD 178	2200	361	158.30 ± 8.60	Smith et al. (2004)
HD 178	Johnson	<i>K</i>	1.63 ± 0.04	Neugebauer & Leighton (1969)
HD 178	Johnson	<i>K</i>	1.66 ± 0.05	Ducati (2002)
HD 178	Johnson	<i>L</i>	1.43 ± 0.05	Ducati (2002)
HD 178	3500	898	84.10 ± 6.30	Smith et al. (2004)
HD 178	4900	712	39.20 ± 6.00	Smith et al. (2004)
HD 178	12000	6384	10.20 ± 18.20	Smith et al. (2004)

References. This work, Sharpless (1952), Johnson & Morgan (1953), Johnson (1953), Giclas (1954), Miczaika (1954), Johnson & Harris (1954), Roman (1955), Johnson & Knuckles (1955), Johnson & Knuckles (1957), de Vaucouleurs (1958), Hogg (1958), Bouigue (1959), Popper (1959), Grant (1959), de Vaucouleurs (1959), Oosterhoff (1960), Bouigue et al. (1961), Irwin (1961), Kraft & Hiltner (1961), Serkowski (1961), Westerlund (1962), Cousins (1962a), Cousins (1962b), Cousins & Stoy (1962), Eggen (1963), Oja (1963), Argue (1963), Cousins (1963a), Cousins (1963c), Cousins (1963b), Gehrels et al. (1964), Shao (1964), Smak (1964), Tolbert (1964), Low & Johnson (1964), Johnson (1964), Cousins (1964a), Cousins (1964b), O’Connell (1964), Eggen (1965), Johnson (1965b), Johnson et al. (1965c), Johnson et al. (1965a), Ljunggren & Oja (1965), Johnson (1965c), Johnson et al. (1965b), Johnson (1965d), Cousins (1965), Crawford & Perry (1966), Williams (1966), Crawford et al. (1966), Ljunggren (1966), Häggkvist & Oja (1966), Häggkvist (1966), Johnson et al. (1966), Cameron (1966), Argue (1966), Gutierrez-Moreno et al. (1966), Appenzeller (1966), Landolt (1967), Cowley et al. (1967), Wisniewski et al. (1967), Johnson (1967), Mendoza (1967), Bakos (1968), Landolt (1968), Kakaras et al. (1968), Rybka (1969), Hyland et al. (1969), Häggkvist & Oja (1969b), Häggkvist & Oja (1969a), Fernie (1969), Bartkevicius & Metik (1969), Zdanavicius et al. (1969), Neugebauer & Leighton (1969), Helfer & Sturch (1970), Crawford & Barnes (1970), McClure (1970), Low et al. (1970), Lee (1970), Johansen & Gyldenkerne (1970), Häggkvist & Oja (1970), Iriarte (1970), L. Häggkvist & T. Oja (1970, private communication), T. Oja (1970, private communication), Sudzius et al. (1970), Moreno (1971), Walker (1971), Sturch & Helfer (1972), Hyland et al. (1972), Swings & Allen (1972), Golay (1972), Zdanavicius et al. (1972), Warren (1973), Cuffey (1973), Schild (1973), Philip & Philip (1973), Häggkvist & Oja (1973), Sanwal et al. (1973), Bartkevicius et al. (1973), Grasdalen (1974), Olson (1974), Neckel (1974), Glass (1974), Bartkevicius & Sperauskas (1974), Voelcker (1975), Glass (1975), Jennens & Helfer (1975), Landolt (1975), Grønbech et al. (1976), Piirola (1976), Garrison & Kormendy (1976), Meistas & Zitkevicius (1976), Lutz & Lutz (1977), Yoss (1977), Szabados (1977), Mendoza et al. (1978), Frogel et al. (1978), Nicolet (1978), Barnes et al. (1978), Iijima & Ishida (1978), Pilachowski (1978), Janes (1979), Strecker et al. (1979), Persi et al. (1979), Jameson & Akinci (1979), Blackwell et al. (1979), Moffett & Barnes (1979), Clark & McClure (1979), Ney & Merrill (1980), Moffett & Barnes (1980), Ridgway et al. (1980b), Bergeat & Lunel (1980), Harmanec et al. (1980), Phillips et al. (1980), Guetter (1980), Slutsikij et al. (1980), Engels et al. (1981), Bergeat et al. (1981), Dzervitis & Paupers (1981), Noguchi et al. (1981), McClure & Forrester (1981), Dean (1981), Gnedin et al. (1981), Bartasute (1981), Sperauskas et al. (1981), Coleman (1982), Olsen (1982), Chen et al. (1982), Gnedin et al. (1982), Rydgren & Vrba (1983), Carney (1983), Kenyon & Gallagher (1983), Lu et al. (1983), Fernie (1983), Castor & Simon (1983), Oja (1983), Oja (1983), Kodaira & Lenzen (1983), Alexander et al. (1983), Oja (1984), Leitherer & Wolf (1984), Ghosh et al. (1984), Guetter & Hewitt (1984), McWilliam & Lambert (1984), Cousins (1984), Campins et al. (1985), Oja (1985b), Oja (1985a), Wu & Wang (1985), Zdanavicius & Cerniene (1985), Sleivyte (1985), Oja (1986), Mermilliod (1986), Janulis (1986), Arribas & Martínez Roger (1987), Reglero et al. (1987), Oja (1987), Sleivyte (1987), Kenyon (1988), Selby et al. (1988), Beichman (1988), Mermilliod & Nitschelm (1989), Straizys et al. (1989a), Eggen (1989), Straizys et al. (1989b), Straizys & Meistas (1989), Cernis et al. (1989), Fabregat & Reglero (1990), Arellano Ferro et al. (1990), Blackwell et al. (1990), Carter (1990), Feast et al. (1990), Jasevicius et al. (1990), Gray & Olsen (1991), Oja (1991), Kornilov et al. (1991), Oja (1993), Straizys et al. (1993), Forbes et al. (1993), Peña et al. (1993), Kerschbaum & Hron (1994), Alonso et al. (1994), Bergner et al. (1995), Kerschbaum (1995), Ito et al. (1995), Johnson & Mitchell (1995), Kerschbaum et al. (1996), Cousins & Caldwell (1996), Yoss & Griffin (1997), Hauck & Mermilliod (1998), Alonso et al. (1998), Chen et al. (1998), Ducati (2002), Cutri et al. (2003b), Smith et al. (2004), Kazlauskas et al. (2005), Clariá et al. (2008), Shenavrin et al. (2011), Laney et al. (2012).

(This table is available in its entirety in machine-readable form.)

template. Unfortunately, the drawback of the INGS templates is that they are, relative to model grids such as the PHOENIX models, less densely available in a grid of stellar spectral type versus luminosity class.

In contrast to the INGS empirical templates, a dense grid of PHOENIX model templates is available (Husser et al. 2013)¹² that offers a significantly denser sampling in T_{eff} (i.e., spectral type) versus surface gravity (i.e., luminosity class) and also sidesteps any potential concerns about uncorrected interstellar extinction in the INGS empirical templates.

Our solution to get the best of these complementary approaches to stellar spectral templates was to utilize a set of PHOENIX models that had been calibrated against the INGS spectral data. Using the INGS data as input spectrophotometry into our *sedFit* code (described in Section 4.3, with the reddening option for *sedFit* disabled), the best-fit PHOENIX model spectra

from a grid of PHOENIX models were matched to each INGS empirical template. The results in $\log(g)$ – T_{eff} space of fitting of INGS spectra against PHOENIX models can be seen as a Kiel diagram (see Fuhrmann 1998) in Figure 2. Comparing the PHOENIX T_{eff} model values against the Pickles T_{eff} values, we find an average T_{eff} difference of -12 K (-0.2%) with no particular evident trend against spectral type of those differences. Overall, this approach allows us the density of the PHOENIX grid while still being based on the empirical INGS grid. Table 7 outlines the INGS-to-PHOENIX mapping and indicates where spectral types not present in the INGS are mapped onto PHOENIX.

4.2. Photometry

Execution of the *sedFit* code, and its ability to provide meaningful results on our program stars, was wholly dependent upon providing the code with meaningful photometry. A large number of archival sources were researched for narrow- to

¹² <http://phoenix.astro.physik.uni-goettingen.de/>

Figure 5. Effective temperature T_{eff} vs. dereddened $V - K$ color, $V_0 - K_0$. The corresponding data are shown in Table 11.

Figure 6. Effective temperature vs. dereddened $V - K$ color, $V_0 - K_0$, zoomed into the principal range of our colors, $V_0 - K_0 = \{2.0, 6.5\}$. The corresponding data are shown in Table 11. Notable gaps are seen at $V_0 - K_0 = 3.0$ and 4.6 and are discussed in Section 7.1.1.

broadband photometry. Meta-references such as SIMBAD,¹³ the General Catalogue of Photometric Data¹⁴ (GCPD; Mermilliod et al. 1997), and the CIO (Gezari et al. 1993) were useful in locating primary data sources; the sources that provided the largest number of points are noted in Table 5, with the individual data points called out explicitly in Table 6. The meta-references are uniquely empowering in collecting a large number of archival data points; thus, for the sake of traceability

and proper attribution credit, we were scrupulous in Table 6 in providing the original source reference.

In addition to the archival sources, we engaged in an extensive program of photometric observing at the Lowell 31 inch telescope located at Anderson Mesa. These visible data included broadband Johnson *UBVRI*, as well as narrowband photometry taken in the Hale–Bopp (HB) system of Farnham et al. (2000). The telescope and CCD characteristics for this observing are described in Schleicher & Bair (2011) and Knight & Schleicher (2015), with HB system filters that isolate emission bands in OH, NH, CN, C_3 , and C_2 , as well as narrowband continuum points in the UV, blue, and green.

¹³ <http://simbad.u-strasbg.fr/simbad/>

¹⁴ <http://obswww.unige.ch/gcpd/>

Table 7
PHOENIX Model Parameters Fit to INGS Spectral Templates

Spectral Type	T_{eff}	$\log(g)$	χ^2_{dof}
B9III	12,000	3.0	0.34
	11,800	3.0	
	11,600	3.0	
	11,400	3.0	
	11,200	3.0	
	11,000	3.0	
	10,800	3.0	
	10,600	3.0	
	10,400	3.0	
	10,200	3.0	
	10,000	3.0	
	9800	3.0	
A0III	9600	3.0	0.48
	9400	3.0	
	9200	3.0	
	9000	3.0	
{A1III}	8800	3.0	
	8600	3.0	
{A2III}	8400	3.0	
	8200	3.0	
A3III	8000	3.0	0.46
	7800	3.0	
A5III	7600	3.0	0.16
A7III	7400	3.0	0.56
{A8III}	7200	3.0	
{A9III}	7000	3.0	
F0III	6900	3.0	0.51
	6800	3.0	
{F1III}	6700	3.0	
	6600	3.0	
F2III	6500	3.0	0.55
	6400	3.0	
{F3III}	6300	3.0	
	6200	3.0	
{F4III}	6100	3.0	
{F5III}	6000	3.0	
{F6III}	5900	3.0	
{F7III}	5800	3.0	
{F8III}	5700	2.5	
{F9III}	5600	2.5	
{G0III}	5500	2.5	
{G1III}	5400	2.5	
{G2III}	5300	2.5	
{G3III}	5200	2.5	
{G4III}	5100	2.5	
G5III	5000	2.5	0.96
{G6III}	5000	2.5	
{G7III}	4900	2.5	
G8III	4900	2.5	0.85
{G9III}	4800	2.5	
K0III	4800	2.5	1.21
{K0.5III}	4700	2.5	
K1III	4700	2.5	0.71
	4600	2.0	
{K1.5III}	4500	2.0	
K2III	4400	2.0	0.93
{K2.5III}	4400	2.0	
K3III	4300	2.0	1.16
	4200	2.0	
{K3.5III}	4100	2.0	
K4III	4000	2.0	3.13
{K4.5III}	3900	1.5	
K5III	3900	1.5	2.21
{K6III}	3900	1.5	
{K7III}	3900	1.5	

Table 7
(Continued)

Spectral Type	T_{eff}	$\log(g)$	χ^2_{dof}
M0III	3800	1.5	2.49
{M0.5III}	3800	1.5	
M1III	3800	1.5	3.19
{M1.5III}	3800	1.5	
M2III	3700	1.5	2.43
{M2.5III}	3700	1.5	
M3III	3600	1.5	2.77
{M3.5III}	3500	1.0	
M4III	3500	1.0	5.54
{M4.5III}	3400	1.0	
M5III	3400	1.0	4.06
{M5.5III}	3300	1.0	
M6III	3200	1.0	8.44
{M6.5III}	3200	1.0	
M7III	3100	0.5	11.28
{M7.5III}	3000	0.5	
M8III	2900	0.5	16.57
	2800	0.5	
{M8.5III}	2700	0.5	
M9III	2600	0.0	26.35
{M9.5III}	2500	0.0	
M10III	2400	0.0	229.16
	2300	0.0	

Note. Spectral types in brackets do not have INGS spectral templates and are linearly inferred interpolations associated with the corresponding PHOENIX models. For more details, see Section 4.1.

For best results with the `sedFit` code, we found that three elements were needed in the photometric input data. First, visible data were necessary to broadly characterize the Wien short-wavelength side of the SED. Second, near-infrared data were essential for characterizing the Rayleigh–Jeans long-wavelength side of the SED. Since most of our targets’ spectral peaks are located between 3000 and 6000 K, data bracketing the peak at $\lambda \sim 1 \mu\text{m}$ were necessary. Third, for the resolution of the degeneracies between interstellar extinction, spectral types, and luminosity classes, narrowband ($\Delta\lambda \sim 60\text{--}100 \text{ \AA}$) photometric data were particularly helpful and motivated our observing program at the 31 inch.

A note on V- and K-band magnitudes. Given the extensive use of V and K magnitudes (and their dereddened counterparts, V_0 and K_0) in the analyses of Sections 7 and 9, it is worthwhile to note in detail the nature of these parameters. Both symbols are intended to denote the standard Johnson bandpasses and zero-points; for the visible V band (Johnson & Morgan 1951; Arp 1958; Bessell 1990), this is to be expected, but for the near-infrared K band (Mendoza v 1963; Bessell & Brett 1988), a likely alternative would be K_s found in 2MASS (Cutri et al. 2003a). Unfortunately, for the majority of our stars—which, particularly in the near-infrared, were rather bright—we found that the K_s data was saturated, and that use of the K_s data in our `sedFit` process led to poor fits. Since most of our program stars had Johnson K-band data present in the CIO, which did not make for problematic `sedFit` fits, we elected to use this variant of the K band in our study.

4.3. `sedFit` Process

We have previously used the `sedFit` code in similar investigations (van Belle et al. 2007, 2009, 2013, 2016; van

Table 8
Multiplicative Correction for Converting 2.2 μm UD Angular Sizes to
Rosseland LD Angular Sizes

T_{eff} (K)	DTB00 (Plane)	NL13 (Plane)	NL13 (Spherical)	NL13 Fit (Spherical)
3000	...	1.025	1.061	1.065
3100	...	1.022	1.066	1.060
3200	...	1.024	1.050	1.057
3400	...	1.022	1.055	1.050
3500	1.030	1.021	1.056	1.047
3600	1.030	1.021	1.043	1.045
3700	1.029	1.020	1.043	1.042
3800	1.029	1.021	1.036	1.040
3900	1.029	1.019	1.035	1.038
4000	1.028	1.019	1.035	1.037
4100	1.027	1.019	1.035	1.035
4200	1.027	1.018	1.034	1.034
4300	1.026	1.018	1.034	1.033
4400	1.025	1.018	1.033	1.032
4500	1.025	1.017	1.033	1.031
4600	1.024	1.017	1.028	1.030
4700	1.024	1.017	1.028	1.029
4800	1.023	1.017	1.028	1.029
4900	1.023	1.016	1.027	1.028
5000	1.022	1.016	1.027	1.027
5100	1.021	1.015	1.027	1.027
5200	1.020	1.015	1.027	1.026
5300	1.020	1.015	1.027	1.026
5400	1.019	1.015	1.027	1.026
5500	1.019	1.014	1.027	1.025
5600	1.019	1.014	1.027	1.025
5700	1.019	1.013	1.027	1.024
5800	1.019	1.013	1.023	1.024
5900	1.019	1.013	1.023	1.024
6000	1.019	1.013	1.022	1.023
6100	...	1.012	1.022	1.023
6200	...	1.012	1.022	1.022
6300	...	1.012	1.021	1.022
6400	...	1.012	1.021	1.022
6800	...	1.010	1.020	1.020
7400	...	1.009	1.019	1.019
7500	...	1.009	1.020	1.019
7600	...	1.009	1.020	1.019
7700	...	1.009	1.020	1.019
7800	...	1.009	1.020	1.019
7900	...	1.009	1.020	1.020
8000	...	1.009	1.020	1.020

Note. Based upon the spherically symmetric model atmosphere analysis in NL13; comparable values for plane-parallel atmosphere analyses in DTB00 and NL13 are also given. For more details, see Section 5.1.

Belle & von Braun 2009) for determinations of F_{bol} and A_V . The process is rather straightforward: input photometry is matched against an input spectral template via amplitude scaling of that template, optimized through a Marquardt–Levenberg (M-L) least-squares technique. As an option, the overall spectral template can also be optimized for reddening A_V . Reddening corrections are based upon the empirical determination by Cardelli et al. (1989), which is only marginally different from van de Hulst’s theoretical reddening curve No. 15 (Johnson 1968; Dyck et al. 1996a).

If the input spectral template has an assigned effective temperature estimate, then an angular size prediction can also

be produced.¹⁵ A multithreaded wrapper script enables many ($\sim$ dozens) of input spectral templates to be tested against the same input photometry for establishing which template is most appropriate for that photometry. An important recent improvement to the `sedFit` code has been the ability to incorporate detailed spectral profiles and optimized zero-points for individual filters of the photometric systems; a number of specific filters have significantly skewed and/or side-weighted profiles (e.g., Johnson R band) that benefit significantly from this improvement. As a result, the detailed empirical characterization of those filters based upon HST NGSL data computed by Mann & von Braun (2015) were included as part of the SED fitting.

The `sedFit` code works as follows. Input photometry (consisting of values and their uncertainties) is read in, matched to its photometric system, and converted, if necessary, from astronomical magnitudes to flux values using standard values for its photometric system. These points are then scaled in amplitude for comparison against a reference spectral template (e.g., an INGS-linked PHOENIX model). That spectral template can be reddened as noted above, and the whole process converges to an optimum solution using an M-L least-squares technique. Once optimized, the code explores the relevant reduced χ^2 space to establish uncertainties on template amplitude and reddening. Finally, the code computes the indicated bolometric flux via a sum across the wavelength of the spectral template. This process can be automatically repeated to explore a grid of templates for the best-fit template against a set of photometry, as indicated by the reduced χ^2 values for each template.

A significant element of the `sedFit` process is establishing the correct input spectral template for SED fitting. Our technique for arriving at the optimal template began with a literature search for previously published spectral types for a given star; ideally, this was reported from at least two sources. These spectral types and original references are given in Table 4.

Following the mapping of that spectral type to PHOENIX models from our analysis in Section 4.1, a grid of spectral templates in T_{eff} and $\log g$ about that location was examined for the optimum spectral template. The best fit in $\{T_{\text{eff}}, \log g\}$, and the corresponding spectral type, is also given in Table 4, along with the resultant estimates for F_{bol} and A_V . While the range of A_V estimates is small—typically a few tenths of a magnitude—corrections at this level are important in attempting to achieve F_{bol} measurements and derived T_{eff} values at our optimum levels of accuracy and precision. Estimation of the appropriate reddening A_V for a given object also allowed us to establish dereddened photometric values for V and K , as well as the dereddened color $V_0 - K_0$.

The resulting values for F_{bol} are evenly distributed as a function of source angular size, as seen in Figures 3 and 4; we have used Equation (1) to show “standard” F_{bol} versus θ curves for given values of T_{eff} .

The F_{bol} estimation process has the following sources of error. First, the observables—the photometry—have inherent measurement errors, as well as errors in the corrections applied for Earth’s atmospheric extinction. Next, we interpret those observables radiometrically, using zero-point values, which

¹⁵ Although this is a fine way to produce an angular size estimate, such a process does not replace the significant value of actually making an angular size measurement, if possible.

Table 9
Angular Sizes, UD Sizes, Limb-darkening Corrections, Unreddened $V_0 - K_0$ Color, and Computed Effective Temperatures for the Program Stars

Star ID	UD Size (mas)	Initial T_{eff} (K)	UD-to-LD	LD Size (mas)	$V_0 - K_0$ (mag)	T_{eff} (K)
HD 598	$2.591 \pm 0.021 \pm 0.043$	3562	1.046	2.709 ± 0.045	5.53 ± 0.05	3484 ± 34
HD 1632	$2.281 \pm 0.014 \pm 0.043$	3969	1.037	2.366 ± 0.045	4.06 ± 0.08	3897 ± 47
HD 3346	$3.102 \pm 0.007 \pm 0.058$	3936	1.038	3.219 ± 0.060	4.00 ± 0.07	3864 ± 39
HD 3546	$1.689 \pm 0.011 \pm 0.043$	5188	1.026	1.734 ± 0.045	2.12 ± 0.07	5120 ± 69
HD 3574	$2.270 \pm 0.040 \pm 0.043$	4140	1.035	2.349 ± 0.045	3.82 ± 0.06	4070 ± 41
HD 3627	$3.968 \pm 0.005 \pm 0.120$	4505	1.031	4.090 ± 0.124	2.76 ± 0.07	4438 ± 68
HD 5006	$2.152 \pm 0.031 \pm 0.043$	3476	1.048	2.255 ± 0.045	5.17 ± 0.11	3395 ± 51
HD 6186	$1.879 \pm 0.041 \pm 0.043$	4888	1.028	1.932 ± 0.045	2.25 ± 0.07	4821 ± 58
HD 6409	$1.937 \pm 0.014 \pm 0.039$	3521	1.047	2.027 ± 0.040	5.16 ± 0.10	3442 ± 36
HD 7000	$1.835 \pm 0.049 \pm 0.043$	3384	1.051	1.928 ± 0.051	5.87 ± 0.11	3301 ± 56
HD 7087	$1.578 \pm 0.030 \pm 0.043$	4853	1.028	1.623 ± 0.045	2.27 ± 0.11	4786 ± 68
HD 8126	$2.038 \pm 0.027 \pm 0.039$	4284	1.033	2.105 ± 0.040	3.31 ± 0.08	4216 ± 44
HD 9500	$2.313 \pm 0.012 \pm 0.043$	3584	1.045	2.417 ± 0.045	5.11 ± 0.09	3506 ± 36
HD 9927	$3.354 \pm 0.008 \pm 0.067$	4602	1.030	3.454 ± 0.069	2.77 ± 0.07	4535 ± 47
IRC+30095	$2.673 \pm 0.020 \pm 0.048$	3255	1.055	2.819 ± 0.051	8.21 ± 0.08	3169 ± 51

Note. For more information, see Section 5.2.

(This table is available in its entirety in machine-readable form.)

themselves have uncertainty. Finally, we model those radiometric points with a model SED—the PHOENIX models—while applying interstellar extinction corrections. Once the `sedFit` process has determined the optimum template for a given star, the median 1σ uncertainty reported by the code after exploration of the reduced χ^2 space for that optimum template in our F_{bol} values is 2.1%. This level of uncertainty is consistent with (a) a limiting photometric (observable) accuracy of 1%–2%, as seen in Table 6; (b) zero-point errors, which, as seen in Mann & von Braun (2015), have a median error of 0.5%; and (c) the SED modeling with its interstellar extinction corrections. On that latter point, the overall flux levels are set by the agreement between the SED models, with the notable caveat that application of interstellar extinction could potentially lead to spurious results when a mismatched spectral template is overly reddened. To break this degeneracy, we found that narrowband photometry was particularly useful in ensuring that the correct template was utilized for a given star. Specifically, when using narrowband photometry, we found that the reduced χ^2 values for spectral templates offset from the optimum template increased, on average, by a value of $\Delta\chi^2_{\text{red}} = 1.4$; for wideband photometry alone, this value was less than half (i.e., not statistically significant).

Taking these elements into account, the SED fitting process established the estimates of uncertainty for F_{bol} and A_V simultaneously through the appropriate exploration of χ^2 space; the median uncertainty in A_V of 2% is consistent with our median F_{bol} uncertainty. Finally, one minor potential source of systematic error could result from our spectral type mapping exercise of Section 4.1, with disagreement between the Pickles templates and PHOENIX models. However, the matched Pickles–PHOENIX pairs showed disagreement in overall bolometric flux at only the $\sim 0.1\%$ level, well below the general level of uncertainty in the F_{bol} estimates.

5. Effective Temperatures

5.1. Limb-darkening Corrections

To convert the wavelength-specific UD angular size measurements from PTI into more general LD Rosseland

mean angular diameters, we applied the standard procedure of estimating a multiplicative factor for converting the K -band UD diameters to LD diameters. One advantage of the K -band PTI data is that this correction is small (on the order of 2%–6%) relative to corrections for observations at shorter wavelengths; systematic uncertainties, if any, that exist in these corrections will therefore have a smaller impact on the results. For example, the visible-light study of Mozurkewich et al. (2003) had UD-to-LD factors that averaged $\sim 9\%$ and went as high as $\sim 20\%$.

Previous estimates of such conversion factors by Davis et al. (2000, hereafter DTB00) are now superseded by those in Neilson & Lester (2013, hereafter NL13), the latter of which we used in our investigation. The principal improvement between these two investigations is a transition from plane-parallel to spherically symmetric model atmospheres. Also, NL13 reported results from a plane-parallel evaluation, which is similar to DTB00, with a slight decrease in the magnitude of the correction. The spherically symmetric results for the stars hotter than >4000 K remain similar to the two plane-parallel results; but for stars cooler than 4000 K, the UD-to-LD correction trends upward from ~ 1.03 to ~ 1.06 . This is consistent with the expectation that, for these cooler extended atmospheres, the spherically symmetric model atmospheres start to deviate from plane-parallel models and improve predictions of the wavelength dependence of the structure (Scholz & Takeda 1987; Hofmann & Scholz 1998). Values taken from NL13 were for 2.5 $M_{\odot}$ stars (out of a choice of 1.0, 2.5, and 5.0 $M_{\odot}$ stars) and interpolated between NL13 temperature data point spacing of 100 K for use in our study; see the last column of Table 8. As demonstrated in Section 8.2, this mass range is a reasonable choice for our program stars.

To quantify the numerical impact of these corrections if we were to not utilize them, we impose a uniform UD-to-LD conversion value of 1.026 (the average of the DTB00 values in Table 8 for our typical program star T_{eff} range of 3000–5200 K), resulting in a shift downward in T_{eff} for the hottest stars in the range by -4 K and the cooler stars by -60 K relative to our final adopted answer using the NL13-fit values. To quantify the impact of uncertainties in this

Table 10
Luminosities L and Radii R for the Program Stars

Star ID	$V_0 - K_0$ (mag)	Sp. Type	π (mas)	Source	R ($R_\odot$)	L ($L_\odot$)
HD 598	5.53 ± 0.05	M5III	3.10 ± 0.11	GaiaDR2	94.16 ± 3.66	1171.91 ± 85.08
HD 1632	4.06 ± 0.08	K5III	4.37 ± 0.14	GaiaDR2	58.20 ± 2.15	701.15 ± 48.93
HD 3346	4.00 ± 0.07	K5III	4.95 ± 0.19	GaiaDR2	69.98 ± 2.98	979.20 ± 76.65
HD 3546	2.12 ± 0.07	G1III	19.91 ± 0.19	HIP	9.37 ± 0.26	54.17 ± 1.37
HD 3574	3.82 ± 0.06	M1III	2.40 ± 0.14	GaiaDR2	105.52 ± 6.59	2740.58 ± 327.59
HD 3627	2.76 ± 0.07	K1.5III	30.91 ± 0.15	HIP	14.24 ± 0.44	70.56 ± 0.96
HD 5006	5.17 ± 0.11	M5III	3.93 ± 0.09	GaiaDR2	61.71 ± 1.84	454.02 ± 28.13
HD 6186	2.25 ± 0.07	G5III	17.94 ± 0.21	HIP	11.59 ± 0.30	65.07 ± 1.72
HD 6409	5.16 ± 0.10	M4III	2.48 ± 0.08	GaiaDR2	87.85 ± 3.41	971.52 ± 66.10
HD 7000	5.87 ± 0.11	M5III	1.45 ± 0.08	GaiaDR2	142.90 ± 8.29	2176.61 ± 242.46
HD 7087	2.27 ± 0.11	G8III	8.50 ± 0.21	HIP	20.54 ± 0.76	198.70 ± 10.12
HD 8126	3.31 ± 0.08	K3.25III	8.14 ± 0.16	GaiaDR2	27.82 ± 0.77	219.27 ± 9.62
HD 9500	5.11 ± 0.09	M4III	2.70 ± 0.18	GaiaDR2	96.47 ± 6.78	1261.80 ± 172.36
HD 9927	2.77 ± 0.07	K1.5III	18.41 ± 0.18	HIP	20.19 ± 0.45	154.70 ± 3.43
IRC+30095	8.21 ± 0.08	M7.75III	1.02 ± 0.14	GaiaDR2	296.93 ± 41.26	7980.99 ± 2237.84

Note. We discuss dereddened colors in Section 4.3, spectral typing in Sections 4.1 and 4.3, distances and radii in Section 6, and luminosities in Section 8.1.

(This table is available in its entirety in machine-readable form.)

correction factor, we assume that the correction factors presented in Table 8 have an uncertainty of ± 0.01 and the final T_{eff} values presented in Table 9 would be impacted by ± 20 K, well below the errors in those values from other sources.

5.2. Effective Temperature Computations

Incorporating the limb-darkening corrections of the previous subsection, the final values for effective temperature can be computed, as seen in Table 9. The UD angular sizes as measured by PTI are given with their formal and systematic errors (as noted in Table 3). An initial estimate of T_{eff} is then computed using angular sizes and the computed bolometric fluxes (Table 4) in the standard relationship,

$$T_{\text{eff}} = 2341 \times \left[\frac{F_{\text{bol}}}{\theta^2} \right]^{1/4}, \quad (1)$$

where the units of F_{bol} are $10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$, and θ is in milliarcseconds. Equation (1) is used with θ_{UD} for an initial estimate of T_{eff} to select the UD-to-LD correction, which is consequently applied to θ_{UD} to obtain the LD Rosseland mean diameter θ_{R} . Additional iterations on the T_{eff} -to-correction step are not necessary, since this would have the effect of revising T_{eff} further by 10^{-4} , which is far below our measurement error. With θ_{R} and F_{bol} in Equation (1), a final value for T_{eff} is then computed and presented in the last column of Table 9.

The median uncertainty of our T_{eff} values is 49 K (1.25%). Of this error, the principal contribution is error in θ_{UD} ; if there were no uncertainty in F_{bol} , the total random error in T_{eff} values is still 42 K (1.00%). Conversely, if θ_{UD} uncertainty were eliminated, the total random error in T_{eff} values would be 22 K (0.55%).

6. Distances and Linear Radii

The combination of measured angular diameter with measured trigonometric parallax value trivially yields an

empirical estimate of linear stellar radius R ,

$$R = \frac{\theta}{0.009292 \times \pi} R_\odot, \quad (2)$$

where π is parallax and θ is angular size, both in milliarcseconds, and R is given in units of solar radius, calibrated to $R_\odot = 6.957 \times 10^8 \text{ m}$ (Brown & Christensen-Dalsgaard 1998; Haberreiter et al. 2008). A significant number of our targets have Gaia magnitudes of brighter than 6, for which calibration issues exist in the astrometry in Data Release 2 of 2018 April (Lindgren et al. 2018). To calculate the distances and, consequently, linear radii of our targets, we thus preferentially utilize Hipparcos parallax values (van Leeuwen 2007) instead, resorting to Gaia DR2 for dimmer objects and those not present in the Hipparcos catalog. The parallax values we employed, source, and resulting R values are in Table 10.

Regardless of the source of the distance data, a significant fraction of the targets are sufficiently far away for distance estimates to carry very large associated uncertainties. By and large, the influence of distance uncertainties on the error budget for linear diameter estimates is greater than that of the measured angular diameters for the stars in our sample, quite unlike for effective temperatures (Section 5.2). We list target distances and calculated linear radii in Table 10, along with the associated uncertainties. The parallax zero-point effects reported for Gaia DR2 at $\varpi_0 = -48 \pm 1 \mu\text{as}$ (Chan & Bovy 2020) are below the noise threshold for our stars. (Applying this offset to the parallaxes for our program stars that utilize DR2 has the net effect of reducing their sizes by an average of $\sim 1.1\%$.)

It is also worth noting that, while these stars are not as severely affected by spotting phenomenology as Mira variables, they will suffer similarly in ways that affect distance measures, particularly on the red end. These reddest, coolest stars in our sample are expected to have increasingly large convection cells (Chiavassa 2018), up to $>10\%$ – 20% of the radius of the star. Coincidentally, for a given angular size, the characteristic distance of such stars in our instrumentation is

Table 11
 T_{eff} vs. $V_0 - K_0$, Binned

Bin Center	Bin Width	Bin Bounds	N	$V_0 - K_0$ (mag)	T_{eff} (K)
2.0	0.1	{1.95, 2.05}	4	2.013 ± 0.032	5043 ± 73
2.1	0.1	{2.05, 2.15}	12	2.105 ± 0.026	5007 ± 57
2.2	0.1	{2.15, 2.25}	10	2.210 ± 0.033	4896 ± 115
2.3	0.1	{2.25, 2.35}	4	2.281 ± 0.022	4762 ± 62
2.4	0.1	{2.35, 2.45}	7	2.400 ± 0.031	4776 ± 88
2.5	0.1	{2.45, 2.55}	5	2.490 ± 0.010	4695 ± 81
2.6	0.1	{2.55, 2.65}	5	2.575 ± 0.016	4580 ± 61
2.7	0.1	{2.65, 2.75}	3	2.686 ± 0.023	4490 ± 17
2.8	0.1	{2.75, 2.85}	4	2.770 ± 0.010	4492 ± 44
2.9	0.1	{2.85, 2.95}	7	2.882 ± 0.023	4408 ± 64
3.0	0.1	{2.95, 3.05}	2	3.025 ± 0.020	4438 ± 37
3.1	0.1	{3.05, 3.15}	3	3.125 ± 0.019	4183 ± 40
3.2	0.1	{3.15, 3.25}	5	3.199 ± 0.036	4197 ± 115
3.3	0.1	{3.25, 3.35}	6	3.304 ± 0.030	4162 ± 64
3.4	0.1	{3.35, 3.45}	5	3.433 ± 0.009	4040 ± 68
3.5	0.1	{3.45, 3.55}	7	3.505 ± 0.025	3959 ± 56
3.6	0.1	{3.55, 3.65}	4	3.623 ± 0.030	3951 ± 57
3.7	0.1	{3.65, 3.75}	3	3.704 ± 0.030	3887 ± 45
3.8	0.1	{3.75, 3.85}	5	3.804 ± 0.025	3941 ± 102
3.9	0.1	{3.85, 3.95}	4	3.876 ± 0.014	3852 ± 52
4.0	0.1	{3.95, 4.05}	3	3.984 ± 0.038	3840 ± 49
4.1	0.1	{4.05, 4.15}	3	4.091 ± 0.044	3751 ± 131
4.2	0.1	{4.15, 4.25}	2	4.183 ± 0.019	3809 ± 129
4.3	0.1	{4.25, 4.35}	6	4.279 ± 0.019	3728 ± 69
4.4	0.1	{4.35, 4.45}	7	4.399 ± 0.024	3707 ± 98
4.5	0.1	{4.45, 4.55}	2	4.462 ± 0.012	3685 ± 233
4.6	0.1	{4.55, 4.65}	0		
4.7	0.1	{4.65, 4.75}	4	4.699 ± 0.037	3547 ± 68
4.8	0.1	{4.75, 4.85}	3	4.818 ± 0.027	3540 ± 140
4.9	0.1	{4.85, 4.95}	6	4.911 ± 0.039	3565 ± 113
5.0	0.1	{4.95, 5.05}	6	4.988 ± 0.034	3486 ± 35
5.1	0.1	{5.05, 5.15}	4	5.111 ± 0.045	3493 ± 20
5.2	0.1	{5.15, 5.25}	5	5.202 ± 0.029	3447 ± 69
5.3	0.1	{5.25, 5.35}	4	5.289 ± 0.035	3411 ± 45
5.4	0.1	{5.35, 5.45}	4	5.406 ± 0.034	3439 ± 68
5.5	0.15	{5.45, 5.60}	4	5.490 ± 0.033	3469 ± 18
5.7	0.2	{5.60, 5.80}	3	5.650 ± 0.025	3414 ± 53
5.9	0.2	{5.80, 6.00}	4	5.858 ± 0.024	3241 ± 117
6.1	0.2	{6.00, 6.20}	4	6.113 ± 0.042	3363 ± 46
6.3	0.2	{6.20, 6.40}	2	6.213 ± 0.005	3296 ± 67
6.6	0.35	{6.40, 6.75}	2	6.460 ± 0.051	3225 ± 162
7.0	0.5	{6.75, 7.25}	1		
7.5	0.5	{7.25, 7.75}	2	7.656 ± 0.030	3117 ± 4
8.0	0.5	{7.75, 8.25}	2	8.062 ± 0.219	3110 ± 70
8.5	0.5	{8.25, 8.75}	2	8.565 ± 0.013	3090 ± 66

Note. For more details, see Section 7.1 and Figures 5 and 6.

such that the magnitude of the parallactic shift can be on the order of the size of the stellar disk (e.g., compare the values in Tables 9 and 10). Given that the stellar photocenter—the principal observable for parallax measures—is shifting by such spots by a significant fraction of disk on timescales similar to parallax measurement epochs, the impact here is in an unfortunate confluence of factors that operate in a correlated fashion to degrade parallax measures. This effect is more pronounced in the visible (where Hipparcos and Gaia work) than in the near-infrared. (See the detailed discussion in Section 3.5 of van Belle et al. 2002.)

Overall, the median uncertainty in linear radius for our program stars is 3.7%, of which the greater contribution is

Table 12
Spectral Type as a Function of Effective Temperature for Our Program Stars

Sp. Type	Sp. Type Num.	N	T_{eff}	σ_T	T_{fit}	χ^2/dof
G0III	50	1	4963	0	0	0.00
G1III	51	1	5120	0	5166	...
G3III	53	2	5062	24	5061	...
G4III	54	6	5023	46	5008	0.11
G5III	55	13	4963	71	4955	0.01
G8III	58	11	4781	122	4797	0.02
K0III	60	8	4715	43	4692	0.30
K1III	61	4	4634	107	4639	...
K1.25III	61.25	5	4528	47	4537	0.03
K1.5III	61.5	9	4424	80	4487	0.62
K2III	62	4	4387	32	4387	...
K3III	63	1	4452	0	4188	...
K3.25III	63.25	10	4183	59	4138	0.61
K3.5III	63.5	8	4063	98	4088	0.06
K4III	64	8	3951	63	3988	0.35
K5III	65	18	3911	54	3902	0.03
M0III	66				3816	
M1III	67	13	3777	102	3730	0.21
M2III	68	10	3617	92	3644	0.09
M3III	69	8	3559	120	3558	...
M4III	70	27	3466	114	3472	...
M5III	71	14	3381	69	3386	0.01
M5.5III	71.5	4	3301	147	3343	0.08
M6III	72	2	3112	29	3134	0.60
M7III	73	1	3114	0	3134	...
M7.5III	73.5	1	3121	0	3134	...
M7.75III	73.75	2	3145	22	3134	0.27

Note. Spectral types of our program stars as determined by our SED fitting approach as a function of effective temperatures for our program stars, with italicized values for where interpolation provided a T_{eff} value. For more details, see Section 7.2.

parallax error. If the uncertainty from the parallaxes for our program stars were zero, the average uncertainty in linear radius for our program stars would drop to 2.0%; likewise, if the angular size uncertainty were zero, the linear radius uncertainty would drop to 2.5%.

7. Temperature and Radius versus $V_0 - K_0$ and Spectral Type

We shall first present the directly measured fundamental stellar parameters of stellar effective temperature (T_{eff}) and linear radius (R) as functions of $V_0 - K_0$ and spectral type indices. Examples of expanded analyses enabled by these measurements follow in Section 8.

7.1. T_{eff} versus $V_0 - K_0$

Our T_{eff} results as indexed by $V_0 - K_0$ color are seen in Figure 5, with a zoom on the central results in the range of $V_0 - K_0 = \{2, 6\}$ in Figure 6. Unsurprisingly, T_{eff} is tightly correlated with this color. The general progression of T_{eff} with $V_0 - K_0$ is summarized in Table 11, wherein we step through our sample in steps of $\Delta V_0 - K_0 = 0.1$, increasing the bin sizes on the red end to account for the increasing sparsity of data. For this table, we estimate the unbiased sample variance, taking into account the varying weights $\{\sigma_{V_0-K_0}, \sigma_{T_{\text{eff}}}\}$ for the

Figure 7. Effective temperature T_{eff} vs. spectral type. For more details, see Section 7.2.

Table 13

Linear Fits of T_{eff} vs. Spectral Type for Specific Spectral Type Ranges

Spectral Type Range	Slope a	Intercept b	χ^2	Median ΔT (K)
51–61	−52.74	7856	0.44	52
61–64	−199.41	16751	1.68	53
64–71.5	−85.98	9491	0.77	52
72–74	0.00	3134	0.87	28

Note. These fits are plotted in Figure 8. Spectral type indices range from G0 = 50, K0 = 60 and M0 = 66. Median ΔT is the median average difference between the linear fit and the individual data points in the spectral type range. For more details, see Section 7.2.

parameters $\{V_0 - K_0, T_{\text{eff}}\}$,

$$s^2 = \frac{\sum_{i=1}^N w_i (x_i - \mu^*)^2}{V_1 - (V_2/V_1)}, \quad (3)$$

where μ^* is the weighted mean for each of these parameters, $w_i = 1/\sigma^2$, $V_1 = \sum_{i=1}^N w_i$, and $V_2 = \sum_{i=1}^N w_i^2$. Given the occasional large spread in measurement error of T_{eff} for a given star, as seen in Table 9, an approach such as this was necessary to give proper consideration to the varying weights of each pair of data points in determining the bin weight (Kendall et al. 1987). For the data in Table 11, the median T_{eff} uncertainty is 66 K bin^{-1} .

7.1.1. Gap Analysis: T_{eff} versus $V_0 - K_0$

A striking characteristic of the T_{eff} versus $V_0 - K_0$ plots (Figures 5 and 6) that merited further investigation was the apparent gaps in the continuum of data points in the region of densest sampling of $V_0 - K_0$ color space, $V_0 - K_0 = \{1.9, 6.5\}$. Two such gaps are apparent to visual inspection, located at $\{T_{\text{eff}}, V_0 - K_0\} = \{4350 \text{ K}, 3.10 \text{ mag}\}$ and $\{3600 \text{ K}, 4.55 \text{ mag}\}$.

However, to test our intuition in this regard, we developed a Monte Carlo test to examine the likelihood that these gaps in our data were simply the product of random fluctuation.

The initial step in this analysis was to collect the observational data in the region of interest, $V_0 - K_0 = \{1.9, 6.5\}$, which encompasses a subsample of $N = 183$ of our stars. A polynomial fit of T_{eff} versus $V_0 - K_0$ gave the following result:

$$T_{\text{eff}} = -9.301 \times (V_0 - K_0)^3 + 212.4 \times (V_0 - K_0)^2 - 1648 \times (V_0 - K_0) + 7602. \quad (4)$$

For our subsample in this range of interest, the median individual measurement errors of our observational data are $\sigma_{T_{\text{eff}}} = 49 \text{ K}$ and $\sigma_{V_0 - K_0} = 0.07 \text{ mag}$; the median absolute difference between the individual T_{eff} measurements and the fit in Equation (4) is 50 K, which agrees well with our measurement error.

Given these data, we were able to construct synthetic populations of observational data points in $\{T_{\text{eff}}, V_0 - K_0\}$ space. Each population consisted of the same number of observations ($N = 183$), and randomly generated values for $V_0 - K_0$ were generated in the range of $\{1.9, 6.5\}$ from a uniform distribution, with a corresponding T_{eff} value determined from Equation (4). Each synthetic data point was then scattered by a typical measurement error by random generation of a $\sigma_{T_{\text{eff}}}$ from a normal distribution of width equal to the median error of the true observational data (49 K), which was then added to the synthetic data point. An identical step added a measurement error to the synthetic data point's $V_0 - K_0$ value. Each of the synthetic data points was then assigned values for their measurement error equal to the median errors in our true observational data.

Once constructed, these synthetic populations could be “gap tested” by scanning a test particle along the Equation (4) fit line in steps of $\Delta V_0 - K_0 = 0.01 \text{ mag}$ in the range of interest, $\{1.9,$

Figure 8. Effective temperature T_{eff} vs. spectral type, binned by spectral type with weighted averages and variance. For more details, see Section 7.2.

6.5}. At each step, a region around the test particle would be examined for the presence of data points from the test population; if at any point along the scan region, a test particle’s examination region was found to be free of data points, that population would be considered to have a gap. For sufficiently small scan regions, nearly all populations would be found to have gaps; for sufficiently large regions, all populations would fail that test. (It is worthwhile to note that this test broadly seeks gaps anywhere along the population’s $V_0 - K_0$ sequence, not just at specific locations.) The statistics of gap likelihood for various region sizes can then be built by running a large number of synthetic populations; for our investigation, we found $N_{\text{pop}} = 1000$ was a reasonable size for each test run.

Gap 1 testing. Examination of the first gap that we noted in our data at $\{T_{\text{eff}}, V_0 - K_0\} = \{4350 \text{ K}, 3.10 \text{ mag}\}$ shows a gap of size $\Delta T_{\text{eff}} = \pm 88 \text{ K}$ and $\Delta V_0 - K_0 = \pm 0.15 \text{ mag}$. Taking that as our scan region envelope, we find that a run of $N_{\text{pop}} = 1000$ synthetic populations turns up only 53 as having gaps of this size anywhere along the range of $V_0 - K_0$ values.

Gap 2 testing. Examination of the second gap that we noted in our data at $\{T_{\text{eff}}, V_0 - K_0\} = \{3500 \text{ K}, 4.55 \text{ mag}\}$ shows a gap of size $\Delta T_{\text{eff}} = \pm 400 \text{ K}$ and $\Delta V_0 - K_0 = \pm 0.10 \text{ mag}$. For this sample, we find that an $N_{\text{pop}} = 1000$ synthetic population run indicates only 70 as having gaps of this size.

“Control” run. Finally, as a check on the overall likelihood of being able to conceal a data point of “typical” size in the sample, we tested our process against a gap matched in size to the median errors in both T_{eff} and $V_0 - K_0$, namely, $\Delta T_{\text{eff}} = \pm 49 \text{ K}$ and $\Delta V_0 - K_0 = \pm 0.07 \text{ mag}$. Interestingly, in this only slightly smaller scan region, only one of the 1000 synthetic populations has no gaps.

Overall, we took these results from our first and second gap analyses as motivating evidence that one or more astrophysical phenomena are quite likely causing these overall discontinuities in what would otherwise be a continuum of points in $\{T_{\text{eff}}, V_0 - K_0\}$ space.

Gaps being noted in photometric color sequences are not a new phenomenon. Böhm-Vitense (1970a, 1970b, 1981, 1982) noted that the onset of surface convection in hotter stars ($T_{\text{eff}} \sim 7250 \text{ K}$) would result in a discontinuity in M_V versus $B - V$ data, given how the temperature differences between convective and radiative layers were expected to affect B -band filters. Evidence for detection of these gaps was initially sparse (Böhm-Vitense & Canterna 1974; Rachford & Canterna 2000), and their existence was disputed (Mazzei & Pigatto 1988; Newberg & Yanny 1998) until gaps in Hipparcos M_V versus $B - V$ data were noted by de Bruijne et al. (2000, 2001). Böhm-Vitense (1995a, 1995b) further predicted a second gap at $T_{\text{eff}} \sim 6400 \text{ K}$, associated with “a sudden increase in convection zone depths,” for which evidence was found in the de Bruijne et al. (2001) investigation.

Recently, the detection of a possible gap in Gaia data for M_G versus $G_{\text{BP}} - G_{\text{RP}}$ for cooler stars was noted by Jao et al. (2018), who attributed it to the luminosity–temperature regime where M dwarf stars transition from partially to fully convective (roughly M3.0V). This detection is particularly relevant to our finding here, in that the second of our gaps—at $\{T_{\text{eff}}, V_0 - K_0\} = \{3500 \text{ K}, 4.55 \text{ mag}\}$ —corresponds well with the gap detected by Jao et al.

7.2. T_{eff} versus Spectral Type

For examining the relationship between T_{eff} and spectral type, we took two approaches to arranging the data. First, we sorted by straight spectral type, and second, we sorted by $V_0 - K_0$ color, with an analysis of the resulting relationship seen between T_{eff} and spectral type in each approach.

7.2.1. Sorted into Spectral Type Bins

Although stellar spectral typing may at times be considered to be subjective (e.g., different practitioners can arrive at different spectral types of individual stars, as discussed in Section 4.3 and seen in the range of results for individual stars

Table 14
 T_{eff} vs. Spectral Type

$V_0 - K_0$	Sp. Type Num.	T_{eff}
1.974 ± 0.031	53.20 ± 0.54	5060 ± 62
2.081 ± 0.032	54.60 ± 0.79	5011 ± 43
2.111 ± 0.029	54.00 ± 0.58	5016 ± 60
2.167 ± 0.028	55.40 ± 0.62	4901 ± 126
2.223 ± 0.033	57.40 ± 0.65	4870 ± 124
2.258 ± 0.030	57.00 ± 0.45	4867 ± 134
2.369 ± 0.029	58.40 ± 0.46	4773 ± 111
2.454 ± 0.025	60.00 ± 0.71	4721 ± 75
2.524 ± 0.033	60.05 ± 0.68	4668 ± 100
2.622 ± 0.031	61.65 ± 0.79	4513 ± 52
2.745 ± 0.028	61.05 ± 0.57	4488 ± 41
2.874 ± 0.028	61.45 ± 2.24	4410 ± 67
2.983 ± 0.031	61.80 ± 1.29	4396 ± 90
3.166 ± 0.030	63.10 ± 0.95	4178 ± 95
3.269 ± 0.035	63.30 ± 2.24	4179 ± 93
3.360 ± 0.039	63.40 ± 1.83	4110 ± 115
3.456 ± 0.032	63.95 ± 0.93	4033 ± 66
3.520 ± 0.040	64.40 ± 0.91	3947 ± 76
3.627 ± 0.035	64.80 ± 1.12	3929 ± 67
3.759 ± 0.032	65.00 ± 0.25	3916 ± 46
3.849 ± 0.029	65.00 ± 0.71	3921 ± 114
3.981 ± 0.032	65.80 ± 0.65	3842 ± 47
4.181 ± 0.035	66.60 ± 0.79	3744 ± 85
4.285 ± 0.028	67.20 ± 1.12	3723 ± 77
4.390 ± 0.029	67.80 ± 0.79	3725 ± 91
4.510 ± 0.033	67.50 ± 0.50	3603 ± 117
4.772 ± 0.039	68.80 ± 0.79	3558 ± 132
4.867 ± 0.033	69.20 ± 0.79	3549 ± 93
4.952 ± 0.028	69.80 ± 1.12	3530 ± 94
5.045 ± 0.036	69.60 ± 0.79	3484 ± 40
5.159 ± 0.036	70.20 ± 1.12	3453 ± 32
5.257 ± 0.030	70.00 ± 0.25	3426 ± 87
5.397 ± 0.037	69.60 ± 0.79	3442 ± 68
5.523 ± 0.024	70.60 ± 0.91	3440 ± 54
5.786 ± 0.033	70.80 ± 1.12	3340 ± 144
6.113 ± 0.028	71.10 ± 1.58	3356 ± 54
6.542 ± 0.032	71.40 ± 1.12	3242 ± 117
8.109 ± 0.029	73.20 ± 0.85	3116 ± 33

Note. The T_{eff} results are sorted by $V_0 - K_0$ and then collected into bins of $N = 5$. Spectral type indices range from G0 = 50, K0 = 60, M0 = 66. For more details, see Section 7.2 and Figure 9.

in Skiff 2014), it remains a useful shorthand for quickly referencing stellar properties. We have collected the general T_{eff} properties using the spectral type values assigned during the *sedFit* process in Section 4.3. The raw T_{eff} versus spectral type values, and general trends, can be seen in Figure 7.

For each spectral subtype, the weighted average T_{eff} and weighted variance σ_T (as described in Section 7.1) were computed; these values are seen in Table 12 and Figure 8. A simple linear fit ($T_{\text{eff}} = a \times ST + b$) was applied to the data seen in Figure 7 and can be seen as well in Figure 8; the fit values are presented in Table 13. Minimization of the χ^2 metric was used not only to optimize the line fits but also to correctly select when to bracket spectral type ranges. A continuity requirement was enforced at spectral type values that joined two linear fit regions.

7.2.2. Sorted by $V_0 - K_0$ Color into Bins of Five

As a secondary check against the possible subjectivity of spectral typing in exploring the T_{eff} versus spectral type trends seen in Figures 7 and 8, we explored arranging our spectral type data in the following alternative way. First, we sorted the stars by $V_0 - K_0$ color and then binned the data into bins of five. Once done, we then determined the average spectral type and weighted average T_{eff} values for each bin of five stars. These data can be seen in Table 14 and Figure 9 and qualitatively duplicate the results seen in Figures 7 and 8. The principal difference between the latter figure and the first two is a measure of spectral type “smearing” in each of the $V_0 - K_0$ bins (e.g., the bin widths in spectral type are one to two subtypes), illustrating that spectral type, T_{eff} , and $V_0 - K_0$ color do not uniquely map in 3D space for these stars.

7.2.3. Calibration of Spectral Type versus $V_0 - K_0$

One useful tangential result from the analyses performed in support of this investigation is that a calibration of $V_0 - K_0$ versus spectral type can be explored. “Intrinsic” values for giant stars of this color were presented in Bessell & Brett (1988, hereafter BB88), who provided a comparison basis for our own values, presented in Table 15 and Figure 10. Interestingly, our calibration of this relationship shows a consistently redward trend; the difference between our $V_0 - K_0$ colors for a given spectral subclass and those of BB88 is that our values are redder by a median value of $\Delta V_0 - K_0 = +0.11$.

7.3. R versus $V_0 - K_0$

In contrast to the tight correlations seen in T_{eff} versus $V_0 - K_0$ in Section 7.1, we find that values for stellar radius R show considerably more scatter. As discussed in Section 6, there are uncertainties in our targets’ distance determinations and, consequently, significant intrinsic scatter for R as a function of $V_0 - K_0$; the raw data are seen in Figure 11.

In order to assess any possible general trend in the relation between stellar radius and dereddened color, we binned the data into sections of width $\Delta V_0 - K_0 = 0.5$. The first and final bins ($\Delta V_0 - K_0 = \{1.5, 2.5\}$ and $\Delta V_0 - K_0 = \{6.0, 9.0\}$) are wider to capture the color outliers. For each one of the bins, a weighted average radius for all of the stars in that given bin was computed. To assess the impact of significant outliers, a second step was taken; the data for a given bin were assessed with a linear fit ($R = a \times (V_0 - K_0) + b$), and the 10σ outliers were excluded from a second weighted average computation of mean R for that bin. In most bins, this did not result in a significant change in the expected R value for that bin. These results are presented in Table 16.

The general trend shows a relatively flat size distribution for the bluest $\Delta V_0 - K_0 = \{1.5, 2.5\}$ stars at $\sim 11 R_\odot$ and then a steady increase in linear size as the $V_0 - K_0$ color becomes redder. This becomes more gradual as the stellar linear sizes exceed $100 R_\odot$ but still trends upward with increasing $V_0 - K_0$ as the expectation for the stellar linear size hits $\sim 150 R_\odot$ for the reddest stars. Overall, $V_0 - K_0$ is indicative of stellar linear size at only the $\sim 30\%$ level.

Figure 9. Effective temperature T_{eff} vs. spectral type, with our T_{eff} results sorted by $V_0 - K_0$ and then collected into bins of $N = 5$. For more details, see Section 7.2 and Table 14.

Table 15
 $V_0 - K_0$ by Spectral Type from Our SED Fitting

Spectral Type	Sp. Type Num.	N	$V_0 - K_0$ (BB88)	$V_0 - K_0$ (This Work)
G0III	50	1	1.75	2.024 ± 0.073
G1III	51	1	1.83	2.121 ± 0.072
G2III	52		1.90	2.078 ± 0.088
G3III	53	2	1.98	2.035 ± 0.051
G4III	54	6	2.05	2.156 ± 0.024
G5III	55	13	2.10	2.126 ± 0.019
G6III	56		2.15	2.207 ± 0.028
G7III	57		2.16	2.288 ± 0.028
G8III	58	11	2.16	2.369 ± 0.021
G9III	59		2.24	2.393 ± 0.032
K0III	60	8	2.31	2.416 ± 0.025
K1III	61	4	2.50	2.519 ± 0.027
K1.25III	61.25	5	2.55	2.694 ± 0.030
K1.5III	61.5	9	2.60	2.865 ± 0.022
K2III	62	4	2.70	2.990 ± 0.034
K3III	63	1	3.00	2.753 ± 0.101
K3.25III	63.25	10	3.07	3.194 ± 0.023
K3.5III	63.5	8	3.13	3.373 ± 0.028
K4III	64	8	3.26	3.612 ± 0.026
K5III	65	18	3.60	3.785 ± 0.019
M0III	66		3.85	3.974 ± 0.026
M1III	67	13	4.05	4.163 ± 0.018
M2III	68	10	4.30	4.603 ± 0.024
M3III	69	8	4.64	4.718 ± 0.024
M4III	70	27	5.10	5.222 ± 0.013
M5III	71	14	5.96	5.842 ± 0.019
M5.5III	71.5	4	6.40	6.527 ± 0.034
M6III	72	2	6.84	7.435 ± 0.068
M7III	73	1	7.80	7.632 ± 0.073
M7.5III	73.5	1	...	7.674 ± 0.064
M7.75III	73.75	2	...	8.473 ± 0.040

Note. For comparison, the values from BB88 are also presented. Our values are in the last column, with italicized values for where interpolation provided $V_0 - K_0$ values. These data are plotted in Figure 10. For more details, see Section 7.2.3.

7.4. R versus Spectral Type

Similar to Section 7.2, we examined R versus spectral type by arranging the data by spectral type and then by $V_0 - K_0$ color.

7.4.1. Sorted into Spectral Type Bins

As in Sections 7.2 and 7.3, the linear radius R shows a considerable amount of scatter versus spectral type, although there are some interesting trends. Specifically, the linear size of the giants appears to be roughly constant between G0III and K0III, at $\sim 12 R_\odot$; this is consistent with the flat linear size (Section 7.3) for the bluer stars (Table 17).

7.4.2. Sorted by $V_0 - K_0$ Color into Bins of Five

Similar to the second part of Section 7.2, to check against the possible subjectivity of spectral typing in exploring the R versus spectral type trends seen in Figure 12, we again arranged our spectral type data into bins of five. We then determined the average spectral type and weighted average R values; these data are presented in Table 18 and Figure 13.

It is apparent in the figure that arranging our data in this fashion results in qualitatively “cleaner” data, exhibiting clear trends in R versus the binned spectral type values. For each of the GKM spectral types in this data set, we performed a linear fit to assess the R trend as a function of binned spectral type; the linear fit parameters are presented in Table 19. A continuity constraint was enforced for the fitting procedure so that there were no “jumps” in R at the boundaries of the linear fit regimes. The results in this table are consistent with the previous sections: the G-type giants show an almost flat linear radius across all subtypes at $\sim 11 R_\odot$; the K-types present a trend of increasing size with subtype, hitting a maximum of $\sim 50 R_\odot$ at K5III; and the M-types have an increased slope in their size–subtype relationship, hitting a size of $\sim 150 R_\odot$ for the reddest in this group. The average

Figure 10. The $V_0 - K_0$ vs. spectral type. The solid line is the value from Bessell & Brett (1988); data points are from this study. For more details, see Section 7.2.3 and Table 15.

Figure 11. Radius R vs. $V_0 - K_0$. The dotted red line is for the linear fits noted in Table 16. For more details, see Section 7.3.

deviation of the data with respect to these linear fits across the GKM range is 11%.

8. Discussion: Luminosities, Masses, and Evolutionary Tracks

The principal intent of this investigation is to provide reference values for giant star angular sizes, effective temperatures, and, to the extent possible by current distance measurements, radii, all calibrated against the indices of $V_0 - K_0$ and spectral type. These data present a launchpad for further investigations of interest. We illustrate below how the

stellar fundamental parameters presented in this investigation can be used to establish giant star luminosities, build a Hertzsprung–Russell (HR) diagram (Hertzsprung 1909, 1911; Russell 1914), and explore the determination of stellar masses.

8.1. Luminosities and Evolutionary Tracks

Given the values of stellar F_{bol} and distance, stellar luminosity L can be calculated. Note that, as discussed in detail in the Appendix, L is not dependent upon our determinations of R and T_{eff} but rather F_{bol} and π ; see

Table 16
R vs. Binned $V_0 - K_0$

$V_0 - K_0$ Bin (mag)	All Data				10 σ Removed	
	<i>N</i>	<i>R</i> ($R_\odot$)	<i>a</i>	<i>b</i>	<i>N</i>	<i>R</i> ($R_\odot$)
1.5–2.5	42	12.1 $\pm$ 2.7	1.3	7.3	32	10.7 $\pm$ 1.1
2.5–3.0	20	24.3 $\pm$ 9.3	26.5	–56.2	14	25.7 $\pm$ 9.2
3.0–3.5	24	42.6 $\pm$ 15.9	20.4	–37.6	20	39.9 $\pm$ 12.8
3.5–4.0	22	61.5 $\pm$ 20.8	53.5	–156.0	20	61.3 $\pm$ 20.2
4.0–4.5	21	71.6 $\pm$ 12.7	44.4	–125.0	19	74.4 $\pm$ 11.4
4.5–5.0	16	93.6 $\pm$ 25.4	17.9	–13.0	14	92.5 $\pm$ 22.6
5.0–5.5	23	94.3 $\pm$ 16.3	29.2	–69.0	22	95.9 $\pm$ 16.0
5.5–6.0	8	112.7 $\pm$ 22.0	7.0	57.9	7	104.3 $\pm$ 14.6
6.0–9.0	15	170.4 $\pm$ 37.9	20.1	–0.1	15	170.4 $\pm$ 37.9

Note. Details of the fitting are presented in Section 7.3 and shown in Figure 11.

Table 17
Weighted Average *R* vs. Weighted Average Spectral Type

Spectral Type	Sp. Type Num.	<i>N</i>	<i>R</i> ($R_\odot$)
G0III	50	1	9.78 $\pm$...
G1III	51	1	9.37 $\pm$...
G3III	53	2	8.18 $\pm$ 2.90
G4III	54	6	9.70 $\pm$ 1.14
G5III	55	13	11.76 $\pm$ 2.40
G8III	58	11	11.97 $\pm$ 2.69
K0III	60	8	9.96 $\pm$ 1.72
K1III	61	4	12.87 $\pm$ 2.62
K1.25III	61.25	5	19.41 $\pm$ 1.90
K1.5III	61.5	9	16.08 $\pm$ 5.53
K2III	62	4	23.50 $\pm$ 5.49
K3III	63	1	52.06 $\pm$...
K3.25III	63.25	10	33.82 $\pm$ 7.51
K3.5III	63.5	8	28.22 $\pm$ 8.37
K4III	64	8	41.28 $\pm$ 8.54
K5III	65	18	43.60 $\pm$ 14.16
M0III	66		53.6
M1III	67	13	63.76 $\pm$ 11.09
M2III	68	10	79.30 $\pm$ 14.15
M3III	69	8	75.87 $\pm$ 20.28
M4III	70	27	92.42 $\pm$ 15.58
M5III	71	14	97.83 $\pm$ 30.41
M5.5III	71.5	4	145.59 $\pm$ 35.54
M6III	72	2	162.74 $\pm$ 24.84
M7III	73	1	173.31 $\pm$...
M7.5III	73.5	1	208.23 $\pm$...
M7.75III	73.75	2	155.09 $\pm$ 23.67

Note. Data are shown in Figure 12, with italicized values for where interpolation provided an *R* value. For more details, see Section 7.4.

Equation (A3). Our target luminosity values are seen in Table 10 and Figure 14.

For further illustration, we took stellar evolutionary tracks in *L* versus T_{eff} from the BaSTI models¹⁶ in Pietrinferni et al. (2006), using the solar abundance tracks ([M/H] = 0.058, Z = 0.0198, Y = 0.273) for two representative mass tracks, $M = 1.2$ and $2.4 M_\odot$. Our choice of solar abundance was rather perfunctory and motivated only by there being no significant impetus to choose any other track. The mass values were

chosen to represent values expected to be characteristic of the lowest-mass giants at $M = 1.2 M_\odot$, with twice that to explore the impact of mass on the track path. Additionally, we cross-referenced our target list against those stars called out in Gontcharov (2008) as red giant clump stars. Clump giants are post-helium flash giants undergoing core helium burning, with an inert hydrogen envelope surrounding the core (Gontcharov 2017). These tracks, along with our program stars, are shown in Figure 14. Along the evolutionary tracks, time intervals of $\Delta t = 10$ Myr are indicated, and there is a pileup of those interval ticks in the lower left corner of the plot, characteristic of red giant clump stars.

Interestingly, when identified as clump giants, it is qualitatively apparent that there is an overdensity of our program stars in that region of our HR diagram, which is consistent with the increased loiter time of the evolutionary tracks in that area of the plot. Overall, the BaSTI evolutionary tracks bracket our program stars well, with most outliers coming to the upper left of the $M = 2.4 M_\odot$ stars, indicative of higher-mass objects.

8.2. Masses

A precision measurement of stellar linear radius enables the calculation of stellar mass, provided a value for a given star’s surface gravity $\log g$ is available. For that purpose, we utilized the most recent version of the PASTEL catalog of Soubiran et al. (2016), using the 2020 January 30 version, which features an inventory of such values from the literature. Ninety-one of our program stars can be found in this catalog; the values we used from PASTEL are seen in Table 21, along with their respective primary references.

For stars that have *R* and $\log g$, ($g = GM/R^2$) can be trivially rearranged to solve for *M*, minding the usual conversion factors and error propagation, so long as errors are provided for $\log g$. For the PASTEL catalog measurements that had no value for the uncertainty in $\log g$, a value of 0.25 was assigned as a placeholder.

Overall, this approach is quite crude, and limited as well. On the former point, our average mass error was typically 50%; this improved only slightly, by about 10%, if the measures were restricted to those that reported formal errors. For this approach’s limitations, it is worth noting that few of our program stars have $\log g$ measures if they are below $T_{\text{eff}} < 4000$ K, which is indicative of the difficulty currently found in determining $\log g$ for these lower-temperature stars.

Nevertheless, this approach is at least qualitatively illustrative of mass effects on our results. If we replot our Figure 14 with the corresponding mass information, in Figure 15, we can see that the points that lie above and to the left of the BaSTI evolutionary tracks are, as expected, the stars that indicate higher masses. Quantitatively, the values in Table 21 are consistent with expectations. The median value of our program stars for which we can calculate a value for mass is $M = 1.9 M_\odot$; these program stars are bracketed well by the $M = \{1.2, 2.4\} M_\odot$ evolutionary tracks in Figure 14.

If stellar $\log g$ measures can be (a) improved to better than 0.05 dex and (b) extended to the lower-temperature ranges, the community will have a useful tool for $\sim 10\%$ or better mass determinations of stars in this region of the HR diagram. In so doing, the $\log g$ measures will approach the current noise floor on the uncertainty in *M* that is contributed by the linear radius measures, which is approximately 8.5%.

¹⁶ “Bag of Stellar Tracks and Isochrones,” <http://basti.oa-teramo.inaf.it/index.html>.

Figure 12. Radius R vs. spectral type. The yellow boxes are the weighted averages for each spectral type, as presented in Table 17. For more details, see Section 7.4.

9. Prediction of Angular Diameters

Stellar angular diameter prediction is a useful tool for various observational endeavors, particularly small solar system body occultation events and microlensing events. Previous calibrations of evolved star angular sizes can be found in van Belle (1999) and Di Benedetto (2005); main-sequence predictions have followed more recently with significant data sets on such stars from the CHARA Array (Boyajian et al. 2014; Adams et al. 2018).

Implementing an analysis similar to van Belle (1999), we can use our results to produce a robust predictive tool for stellar angular size, based upon $V_0 - K_0$ color, improving substantially upon that prior investigation. The utility of this tool lies in that it is strictly empirical and sidesteps considerations of spectral type, distance, and atmospheric modeling. To begin, we scale all of our angular sizes to a common $V=0$ zero-magnitude basis ($\theta_{V=0} = \theta \times 10^{V/5}$). Minimization of the two-axis χ^2 (e.g., see Equation (15.3.2) in Bevington & Robinson 1992) gives a fit of

$$\log(\theta_{V=0}) = 0.2292 \pm 0.0016 \times (V_0 - K_0) + 0.6164 \pm 0.0067, \quad (5)$$

with the data and fit plotted in Figure 16; the reduced χ^2_ν is 0.87. The resulting median absolute scatter in predicted versus measured $\theta_{V=0}$ values is 2.9%, indicating a factor of 4 improvement over the calibration in van Belle (1999).

10. Conclusions

This study is the intersection of multiple, significant lines of investigation. First, it is the product of considerable effort in data collection, both with optical interferometry and photometry. Second, literature data and metadatabases, such as distances from Hipparcos and Gaia, photometry in the GCPD (Mermilliod et al. 1997), and spectral types from Skiff (Skiff 2014) and the INGS Library of A. Pickles, have all played major supporting roles. Third, advances in modeling,

including the PHOENIX models (Husser et al. 2013) and our *sedFit* package, have allowed us to take the data to build a large, precise set of fundamental parameters for giant stars. Our intent has been to provide a meticulously calibrated reference data set of giant star T_{eff} and R . Our main findings are as follows.

1. When indexed against $V_0 - K_0$, T_{eff} can be predicted to a precision of 50 K (Equation (4)) over the range $V_0 - K_0 = \{1.9, 6.5\}$. Within that range, there appear to be two statistically significant gaps, as discussed in Section 7.1.1.
2. When indexed against the spectral type, T_{eff} can be linearly fit against the spectral subtype with a median absolute difference of fit versus our data points of 52–53 K for most stars (Section 7.2 and Table 13).
3. For R , the color index $V_0 - K_0$ is indicative of the linear radius at only an $\sim 30\%$ level (Section 7.3).
4. Using the spectral type as a guide, the linear radius can be predicted to $\sim 11\%$ (Section 7.4 and Table 19).
5. Luminosities are dependent upon our bolometric fluxes and published parallax measures and, with our values for T_{eff} , can be used to directly build an empirical HR diagram, which qualitatively agrees well with theoretical evolutionary tracks. Masses can be inferred from our values for R and literature $\log g$ values and are also qualitatively in agreement with those tracks (Section 8).
6. An improved calibration of $V_0 - K_0$ as a predictor of stellar angular size is presented, with a median absolute scatter of 2.9% (Section 9).

Additionally, we present a serendipitous calibration of $V_0 - K_0$ versus spectral type, exhibiting colors slightly redder at the 0.11 mag level for a given spectral subtype than Bessell & Brett (1988; Section 7.2.3).

For future work, improvement in parallax measurements is the most obvious avenue for extending the data herein for both linear radii and luminosities. More subtly, subpercent absolute photometry would also improve the luminosities, but the

Table 18*R* vs. Spectral Type Sorted by $V_0 - K_0$ and Collected into Bins of $N = 5$

Sp. Type Num.	$V_0 - K_0$	R	R_{fit}
53.2 ± 0.5	1.97 ± 0.03	9.2 ± 1.8	9.8
54.6 ± 0.8	2.08 ± 0.03	11.1 ± 2.6	10.1
54.0 ± 0.6	2.11 ± 0.03	10.0 ± 2.0	10.0
55.4 ± 0.6	2.17 ± 0.03	11.4 ± 5.1	10.2
57.4 ± 0.6	2.22 ± 0.03	12.0 ± 3.0	10.5
57.0 ± 0.4	2.26 ± 0.03	11.1 ± 3.4	10.4
58.4 ± 0.5	2.37 ± 0.03	9.8 ± 1.9	10.7
60.0 ± 0.7	2.45 ± 0.03	11.5 ± 2.1	10.7
60.1 ± 0.7	2.52 ± 0.03	11.5 ± 3.0	11.0
61.7 ± 0.8	2.62 ± 0.03	14.2 ± 4.1	22.9
61.1 ± 0.6	2.74 ± 0.03	16.5 ± 5.5	18.4
61.5 ± 2.2	2.87 ± 0.03	22.2 ± 4.8	21.4
61.8 ± 1.3	2.98 ± 0.03	24.4 ± 7.7	24.0
63.1 ± 1.0	3.17 ± 0.03	30.2 ± 12.5	33.6
63.3 ± 2.2	3.27 ± 0.04	34.6 ± 7.0	35.1
63.4 ± 1.8	3.36 ± 0.04	26.0 ± 8.5	35.8
64.0 ± 0.9	3.46 ± 0.03	43.3 ± 10.7	39.9
64.4 ± 0.9	3.52 ± 0.04	37.6 ± 8.4	43.2
64.8 ± 1.1	3.63 ± 0.04	37.2 ± 12.6	46.2
65.0 ± 0.3	3.76 ± 0.03	43.2 ± 10.9	47.6
65.0 ± 0.7	3.85 ± 0.03	52.3 ± 23.0	47.6
65.8 ± 0.6	3.98 ± 0.03	65.5 ± 6.2	53.6
66.6 ± 0.8	4.18 ± 0.03	61.2 ± 12.0	61.6
67.2 ± 1.1	4.28 ± 0.03	62.5 ± 13.6	68.3
67.8 ± 0.8	4.39 ± 0.03	82.3 ± 8.6	75.0
67.5 ± 0.5	4.51 ± 0.03	76.9 ± 22.8	71.6
68.8 ± 0.8	4.77 ± 0.04	75.4 ± 33.5	86.1
69.2 ± 0.8	4.87 ± 0.03	67.4 ± 12.1	90.5
69.8 ± 1.1	4.95 ± 0.03	103.2 ± 13.5	97.2
69.6 ± 0.8	5.04 ± 0.04	102.0 ± 12.2	95.0
70.2 ± 1.1	5.16 ± 0.04	75.1 ± 19.7	101.6
70.0 ± 0.3	5.26 ± 0.03	90.1 ± 11.8	99.4
69.6 ± 0.8	5.40 ± 0.04	90.8 ± 18.7	95.0
70.6 ± 0.9	5.52 ± 0.02	104.2 ± 13.9	106.1
70.8 ± 1.1	5.79 ± 0.03	100.6 ± 33.3	108.3
71.1 ± 1.6	6.11 ± 0.03	124.8 ± 4.6	111.6
71.4 ± 1.1	6.54 ± 0.03	138.8 ± 40.7	115.0
73.2 ± 0.8	8.11 ± 0.03	172.0 ± 37.4	135.0

Note. The fit values in the last column are from the linear fits noted in Table 19. Spectral type indices range from G0 = 50, K0 = 60 and M0 = 66. Data are shown in Figure 13. For more details, see Section 7.4.

angular size precision would have to be improved by a factor of 2–3 to realize a substantive improvement in effective temperatures. As noted in Section 8, improvements in the measurement of giant star $\log g$ could mean significant insights into the nature of giant star masses. As an increasing number of asteroseismic results from TESS are released, possibly on our very program stars, the combination of constraints from those studies and ours could provide even sharper insights into the nature of post-main-sequence stellar evolution.

10.1. Data Release

All data produced for this investigation will be made available at the NASA Exoplanet Science Institute (NExSci) PTI archive.¹⁷ This includes all tables in this paper and *sedFit* figures for each of our program stars.

Table 19Linear Fits for R vs. the Spectral Type Numbers in Table 18 and shown Figure 13

Sp. Type Range	a	b	χ^2
G	0.16	1.41	0.85
K	7.39	−432.90	5.41
M	11.11	−678.55	7.05

Note. For more details, see Section 7.4.

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Facilities: PO:PTI, LO:0.8m.

Appendix

The Relationship between L , R , T —and θ , π , F_{bol}

A common misconception that we have encountered frequently during the last 30 yr of carrying out these sorts of angular size measurements is the perceived value of measurements of stellar luminosity L . This is understandable, given that L is defined as

$$\begin{aligned}
 L &= \text{stellar surface area} \times \text{emitted flux at stellar surface} \\
 &= 4\pi R^2 \sigma_{\text{SB}} T^4,
 \end{aligned}
 \tag{A1}$$

where π is the usual 3.14159... and σ_{SB} is the Stefan–Boltzmann constant, $5.6704... \times 10^5 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ K}^{-4}$. On the face of it, since our measurements of angular size provide new information on stellar R and T , the expectation is that additional information has also been derived for L . This, unfortunately, is not true and can be revealed if the underlying measurements that establish L from R and T are examined further. Expanding

¹⁷ <https://nexsci.caltech.edu/software/PTISupport/>

Figure 13. Effective temperature R vs. spectral type, with our R results sorted by $V_0 - K_0$ and then collected into bins of $N = 5$. The linear fit parameters can be found in Table 19 and are discussed in Section 7.4.

Figure 14. Shown is L vs. T_{eff} for our program stars. The upper and lower lines are the $M = 1.2$ and $2.4 M_{\odot}$ stellar evolutionary tracks from Pietrinferni et al. (2006), with red/yellow triangles at 10 Myr intervals. Our program stars are blue diamonds and yellow squares; the latter are those stars that are also identified in Gontcharov (2008) as red giant clump stars. See discussion in Section 8.1.

Figure 15. Shown is L vs. T_{eff} vs. M for our program stars. The evolutionary tracks are those seen in Figure 14. See Section 8.2 for more information.

Figure 16. Zero-magnitude angular size $\theta_{V=0}$ vs. $V_0 - K_0$ color.

Table 20
Broadband *H*- and *K*-band Angular Sizes for the Program Stars

Star ID	$N_{\text{pts},H}$	θ_H	$N_{\text{pts},K}$	θ_K	Avg. Res.	χ^2/dof
HD 598	...	...	30	$2.591 \pm 0.021 \pm 0.046$	0.033	0.28
HD 1632	10	$2.251 \pm 0.009 \pm 0.042$	22	$2.281 \pm 0.014 \pm 0.042$	0.029	1.51
HD 1795	...	...	15	$2.024 \pm 0.049 \pm 0.042$	0.120	1.80
HD 3346	...	...	11	$3.102 \pm 0.007 \pm 0.055$	0.005	4.43
HD 3546	...	...	75	$1.689 \pm 0.011 \pm 0.042$	0.029	0.69
HD 3574	...	...	20	$2.270 \pm 0.040 \pm 0.042$	0.037	0.55
HD 3627	...	...	82	$3.968 \pm 0.005 \pm 0.120$	0.011	1.13
HD 5006	...	...	18	$2.152 \pm 0.031 \pm 0.042$	0.054	1.49
HD 5575	...	...	25	$3.019 \pm 0.012 \pm 0.055$	0.035	3.03
HD 6186	...	...	29	$1.879 \pm 0.041 \pm 0.042$	0.074	0.40
HD 6409	...	...	75	$1.937 \pm 0.014 \pm 0.042$	0.031	0.44
HD 7000	...	...	5	$1.835 \pm 0.049 \pm 0.042$	0.037	0.57
HD 7087	...	...	35	$1.578 \pm 0.030 \pm 0.042$	0.037	0.43
HD 8126	...	...	3	$2.038 \pm 0.027 \pm 0.042$	0.009	0.15
HD 9500	...	...	16	$2.313 \pm 0.012 \pm 0.042$	0.010	0.80
HD 9927	...	...	121	$3.354 \pm 0.008 \pm 0.069$	0.027	0.69
IRC+30095	...	...	38	$2.673 \pm 0.020 \pm 0.046$	0.057	2.16

Note. Errors cited are (in order) the formal error and the systematic error based upon a limiting σ_V of 1.5%.

(This table is available in its entirety in machine-readable form.)

Table 21
Reported $\log g$ Values for the Program Stars Found in the PASTEL Catalog of Soubiran et al. (2016) along with Resulting Mass Determinations M

Star ID	$\log g$	References	R ($R_\odot$)	M ($M_\odot$)
HD 3546	2.83 ± 0.19	da Silva et al. (2015)	9.37 ± 0.26	1.20 ± 0.53
HD 3574	1.44	McWilliam (1990)	105.52 ± 6.59	6.21 ± 3.66
HD 3627	2.56	Zhao et al. (2001)	14.24 ± 0.44	1.49 ± 0.86
HD 6186	2.99	McWilliam (1990)	11.59 ± 0.30	2.66 ± 1.54
HD 7087	2.77	McWilliam (1990)	20.54 ± 0.76	5.03 ± 2.92
HD 8126	1.93	McWilliam (1990)	27.82 ± 0.77	1.33 ± 0.77
HD 9927	2.17 ± 0.14	Maldonado & Villaver (2016)	20.19 ± 0.45	1.22 ± 0.40

Note. For references that did not report a formal error in $\log g$, a value of 0.25 dex was assumed (and the resulting error in M is italicized). For more details, see Section 8.2.

References. Kyrolainen et al. (1986), Smith & Lambert (1986), Smith & Lambert (1990), McWilliam (1990), Mallik (1998), Zhao et al. (2001), Hekker & Meléndez (2007), Thygesen et al. (2012), Mortier et al. (2013), Matrozis et al. (2013), Ramírez et al. (2013), Adamczak & Lambert (2014), Luck (2015), Jofré et al. (2015), da Silva et al. (2015), Heiter et al. (2015), Maldonado & Villaver (2016), Deka-Szymankiewicz et al. (2018), Lomaeva et al. (2019).

(This table is available in its entirety in machine-readable form.)

Equation (A1) with Equations (1) and (2), it can be shown how θ cancels out:

$$L = 4\pi \left[\frac{\theta}{0.009292 \times \pi} \right]^2 \sigma_{\text{SB}} \left[2341 \times \left[\frac{F_{\text{bol}}}{\theta^2} \right]^{1/4} \right]^4 \quad (\text{A2})$$

$$= 312.1 \times \frac{F_{\text{bol}}}{\pi^2} L_\odot \quad (\text{A3})$$

(carrying only the first four significant figures for the various constants and noting some symbol collision between π for the constant in Equation (A1) and for parallax in Equation (2); as before, units for F_{bol} are $10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$, units are milliseconds for π , and L is in units of solar luminosity $L_\odot$, based on 2015 IAU Resolution B3's $L_\odot \equiv 3.828 \times 10^{33} \text{ erg s}^{-1}$).

From this, we can see

$$\sigma_L = L \left[\left(\frac{\sigma_F}{F_{\text{bol}}} \right)^2 + 4 \times \left(\frac{\sigma_\pi}{\pi} \right)^2 \right]^{1/2}. \quad (\text{A4})$$

It is true that our efforts in determining new values for stellar F_{bol} in Section 4 constitute “new” information on L , and as such, we have included discussion of this parameter in Section 8. Why is this important?¹⁸ The most significant element of realizing the underlying nature of Equation (A3) in the determination of L is for error propagation. If one were to simply propagate errors from Equation (A1), calculations of σ_L would unnecessarily be carrying additional uncertainty from σ_θ . In practice, we find that with the data set presented herein,

¹⁸ And will the editor allow a rhetorical question in our manuscript?

this makes for uncertainties in L that are roughly 30% greater than necessary.

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