MEASURED DIAMETERS OF TWO F STARS IN THE β PIC MOVING GROUP

M. SIMON[1] AND G. H. SCHAEFER[2]

[1] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA; michal.simon@stonybrook.edu
[2] The CHARA Array of Georgia State University, Mount Wilson Observatory, Mount Wilson, CA 91023, USA; schaefer@chara-array.org

ABSTRACT

We report angular diameters of HIP 560 and HIP 21547, two F spectral-type pre-main-sequence members of the β Pic Moving Group. We used the east–west 314 m long baseline of the CHARA Array. The measured limb-darkened angular diameters of HIP 560 and HIP 21547 are 0.492 ± 0.032 and 0.518 ± 0.009 mas, respectively. The corresponding stellar radii are 2.1 and 1.6 $R_\odot$ for HIP 560 and HIP 21547, respectively. These values indicate that the stars are truly young. Analyses using the evolutionary tracks calculated by Siess, Dufour, and Forestini and the tracks of the Yonsei–Yale group yield consistent results. Analyzing the measurements on an angular diameter versus color diagram we find that the ages of the two stars are indistinguishable; their average value is 13 ± 2 Myr. The masses of HIP 560 and HIP 21547 are 1.65 ± 0.02 and 1.75 ± 0.05 $M_\odot$, respectively. However, analysis of the stellar parameters on a Hertzsprung–Russell diagram yields ages at least 5 Myr older. Both stars are rapid rotators. The discrepancy between the two types of analyses has a natural explanation in gravitational darkening. Stellar oblateness, however, does not affect our measurements of angular diameters.

Key words: stars: fundamental parameters – stars: pre-main sequence – techniques: interferometric

Online-only material: color figure

1. INTRODUCTION

The age and mass of a pre-main-sequence (PMS) star are usually estimated from its location in the Hertzsprung–Russell diagram (HRD) relative to theoretical calculations of stellar evolution. Unfortunately, differences among the theoretical calculations can produce mass and age estimates discrepant by factors of two to three (Hillenbrand & White 2004; Simon 2006). The consequences are that the mass spectrum of stars produced in a star-forming region, the region's star-forming history, and the chronology of planet formation are imprecisely known. The latter point has taken on a pressing importance as astronomers are poised to detect exoplanets associated with young stars.

Measurement of the diameters of young stars as they contract to the main sequence can provide their ages and a new independent test of the theoretical PMS evolutionary tracks (Simon 2006). Once a reliable set of evolutionary tracks is established, measurement of the diameters of PMS stars will yield measurements of their absolute ages. Remarkably, members of the β Pic Moving Group (BPMG) are young enough (10–20 Myr) and near enough (<50 pc; e.g., Torres et al. 2006) that some are resolvable with the optical/IR interferometric array of the Center for High Angular Resolution Astronomy (CHARA). The brighter members of the BPMG have parallaxes measured by *Hipparcos*. The ages of individual stars in the BPMG are determined by HRD fitting and the strength of the Li line. An age for the group as a whole may be estimated dynamically by tracing the group's motion back to a common origin. The age estimates range from 11.2 ± 0.3 to 22 ± 12 Myr (see Table 2 in Fernández et al. 2008; Yee & Jensen 2010). Whether the spread represents uncertainties of the dating methods or a range in individual formation times is unknown. Astronomers already have evidence of planet formation associated with the members of the BPMG. Lagrange et al. (2010) imaged the exoplanet of β Pic, an A star. Debris disks are understood as indicators of planet formation (Quillen et al. 2007); β Pic and AU Mic, a BPMG member of M1 spectral type, are known to have debris disks (Smith & Terrile 1984; Lagrange et al. 2010; Liu 2004).

We measured the angular diameters of two stars in the BPMG, HIP 560 and HIP 21547, using the CHARA Array. Section 2 describes our observations and Section 3 presents our analysis and discussion of the diameter measurements. We summarize our results in Section 4.

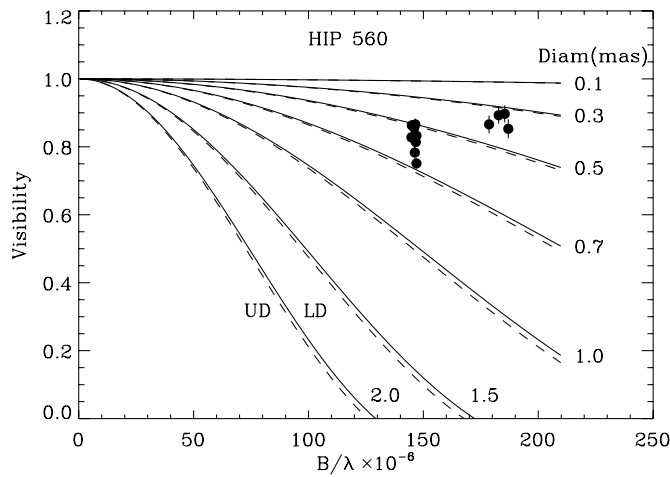## 2. INTERFEROMETRIC MEASUREMENTS OF HIP 560 AND HIP 21547

We observed at the CHARA Array located on Mt. Wilson, CA, on the nights of UT 2010 September 11–13. Our observing assignment was made through an allotment made available competitively to the astronomical community by CHARA and administered by the National Optical Astronomical Observatory through its observing time application process. The array consists of six 1 m telescopes in a Y configuration on baselines from 34 to 331 m (ten Brummelaar et al. 2005). We used the CLASSIC beam combiner operating in the H and K' bands to observe with the two telescopes on the 314 m E1–W1 baseline. At the CHARA Array these bands are centered at 1.673 and 2.133 μm wavelengths, with bandwidths 0.285 and 0.349 μm, respectively.

Table 1 lists the properties of HIP 560 and HIP 21547 we need for this paper; the parallactic distances are van Leeuwen et al.'s (1997) revised *Hipparcos* values. Neither star is known to be a spectroscopic binary. HIP 21547 is one component of a common proper motion binary; its companion, GJ 3305, is at about $1'$ angular separation. We checked the near-IR and thermal-IR fluxes of the stars as given by Two Micron All Sky Survey (2MASS) and *WISE*.[3] Neither shows evidence of excess emission in the near-IR. HIP 560 is not included in the *WISE* Preliminary Data Release. For HIP 21547, the *WISE* magnitudes at 3.6, 12, and 22 μm are consistent with the 2MASS K-band magnitude, $\sim$4.5 (Table 1). HIP 21547 is $\sim$0.5 mag brighter in *WISE* band 2 at 4.5 μm; on a color–color diagram this still places the star in the region of normal stars without a debris

---

[3] http://irsa.ipac.caltech.edu

Table 1
Properties of HIP 560 and HIP 21547

	HIP 560	HIP 21547
Alternate name	HD 203	HD 29391
Spectral type	F3V	F0V
V (mag)	6.19	5.22
K (mag)	5.24	4.54
$v \sin i$ (km s^{-1})	170.7	95.0
Distance (pc)	39.4 ± 0.4	29.4 ± 0.3
X, Y, Z (pc)	$4.5, 5.8, -38.4$	$-24.3, -8.2, -15.2$
U, V, W (km s^{-1})	$-10.4, -14.5, -13.3$	$-14.0, -16.2, -10.1$
Calibrators:		
	HD 268	HD 26794
ϕ_{LD}(mas)	0.27	0.25
	HD 223884	
ϕ_{LD}(mas)	0.26	

Data for β Pic targets from Torres et al. (2006)

Figure 2. Same as Figure 1 but for HIP 21547.

Table 2
Calibrated Visibilities

Object	λ	MJD	B (m)	P.A. (deg)	V_{cal}	$\sigma_{V_{cal}}$
HIP 560	K	55450.286	308.62	69.69	0.828	0.018
HIP 560	K	55450.300	311.91	71.87	0.783	0.016
HIP 560	K	55450.314	313.44	73.94	0.751	0.015
HIP 560	K	55450.332	312.66	76.38	0.866	0.017
HIP 560	K	55450.347	309.38	78.47	0.863	0.016
HIP 560	K	55452.314	313.51	74.74	0.839	0.015
HIP 560	K	55452.324	312.91	76.10	0.814	0.015
HIP 560	K	55452.334	311.39	77.39	0.856	0.015
HIP 560	H	55451.328	312.81	76.22	0.853	0.028
HIP 560	H	55451.342	310.18	78.08	0.897	0.025
HIP 560	H	55451.355	305.80	79.82	0.893	0.025
HIP 560	H	55451.370	298.79	81.72	0.866	0.026
HIP 21547	K	55450.515	313.26	75.68	0.849	0.013
HIP 21547	K	55450.525	313.44	75.86	0.819	0.012
HIP 21547	K	55450.535	312.45	75.96	0.860	0.014
HIP 21547	H	55451.501	311.41	75.40	0.769	0.021
HIP 21547	H	55451.515	313.41	75.73	0.776	0.022
HIP 21547	H	55451.533	312.20	75.97	0.766	0.021
HIP 21547	H	55451.544	310.15	76.02	0.775	0.021
HIP 21547	H	55452.496	311.11	75.37	0.773	0.022
HIP 21547	H	55452.513	313.43	75.73	0.719	0.020
HIP 21547	H	55452.521	313.31	75.88	0.791	0.022
HIP 21547	H	55452.533	311.69	75.99	0.729	0.020

Figure 1. Calibrated visibilities of HIP 560 at H and K vs. spatial frequency, the projected baseline divided by the wavelength. The dashed curves are for uniform disk (UD) models with the diameters indicated and the solid curves are limb-darkened models.

disk. Both stars are rapid rotators with values of $v \sin i$ in the range typical of F stars (Abt & Hunter 1962).

The essential observational datum of an interferometer measurement is the fringe contrast or visibility, V, of the target or calibrator. An observation of a program star or its calibrators took about 10 minutes each and consisted of a series of data scans through the central interferometer fringe and a sequence of shutters. Each program star observation was bracketed by observations of one or two stellar calibrators with angular diameters smaller than 0.3 mas and located within $10°$ of the target (Table 1). An observation of HIP 560 or HIP 21547 and their calibrators required about 2 hr to obtain good signal-to-noise ratio.

The calibrators were chosen to be unresolved by the interferometer, but their diameters are nonetheless finite (Table 1). S. Ridgway (2010, private communication) kindly estimated the limb-darkened diameters, ϕ_{LD}, of the calibrators, using Kervella et al.'s (2004) angular diameter fits for main-sequence stars as a function of their $V - K$ color, K-band magnitude, the parallactic distance of the star, and an estimate of its extinction (always small, $A_V \leqslant 0.07$). We scaled the observed calibrator visibilities to those of a point-like star. We then calibrated the target visibilities by ratioing them to the scaled calibrator visibilities. Table 2 lists the wavelength, MJD time of observation, projected

baseline in meters, its position angle on the sky, measured eastward from north, the calibrated visibilities V_{cal} of the targets, and their uncertainties $\sigma_{V_{cal}}$. The $\sigma_{V_{cal}}$ include the uncertainties of the measured visibilities of target and calibrators and an assumed $\pm 10\%$ uncertainty in the calculated diameters of the calibrators.

Figures 1 and 2 show the calibrated visibilities at H and K versus spatial frequency (projected baseline/wavelength). Figure 1 for HIP 560 indicates a systematic difference in angular diameters measured at H and K. We do not think this can be attributed to a property of the star because HIP 21547, also an F spectral-type star, does not show the effect. The difference is probably measurement error. At angular diameters as small as those of HIP 560 and HIP 21547 the curves for a uniform disk and limb-darkened disk are nearly indistinguishable.[4] Nonetheless, we did analyze the visibilities with respect to

---

[4] This would not be true for stars more strongly limb darkened than F stars (van Belle et al. 2001).
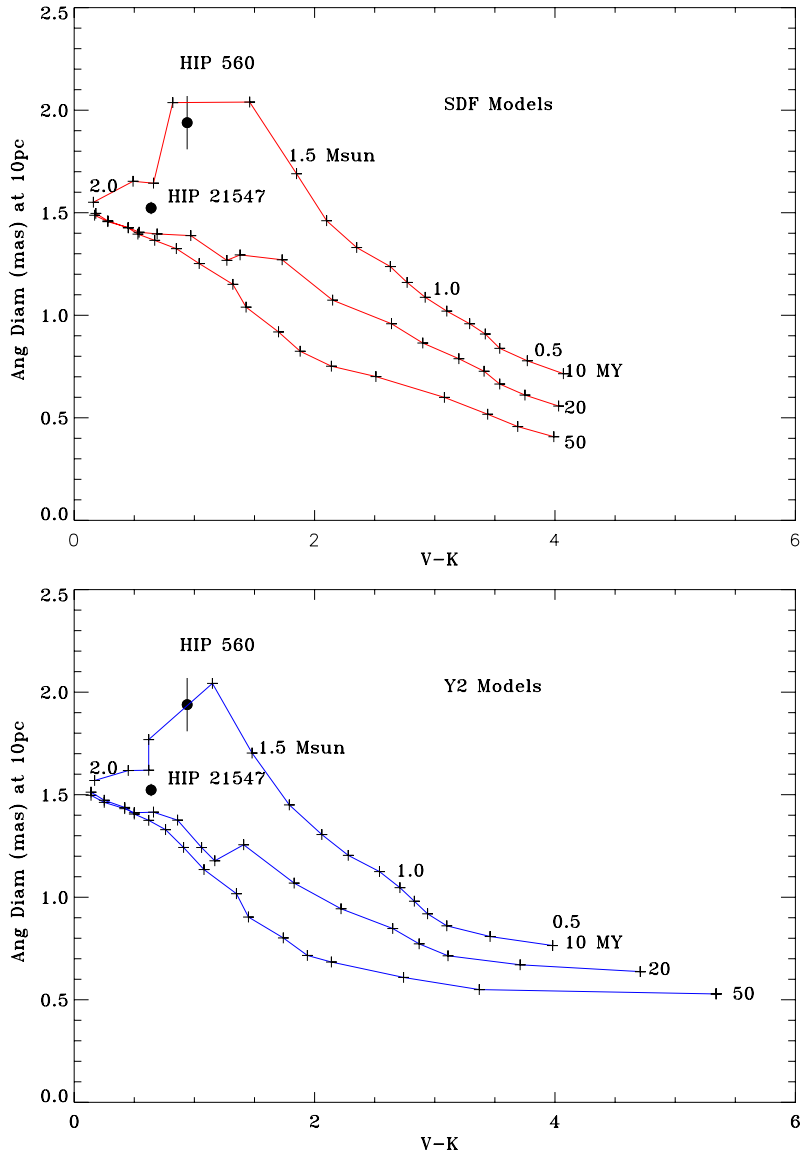
Figure 3. HIP 560 and HIP 21547 angular diameters scaled to 10 pc distance vs. $(V − K)$ compared to isochrones at 10, 20, and 50 Myr calculated by SDF (top) and Y2 (bottom). The crosses indicate masses 0.4–2.0 $M_\odot$ at 0.1 $M_\odot$ intervals for the SDF isochrones and 0.5–2.0 $M_\odot$ for the Y2 isochrones.
(A color version of this figure is available in the online journal.)

limb-darkened models following Hanbury-Brown et al.'s (1974) analysis. Their expression for the visibility of a limb-darkened star can be written as

$$V_{LD}(x) = \left[\frac{1 - u_\lambda}{2} + \frac{u_\lambda}{3} \right]^{-1} \left[\frac{1}{2}(1 - u_\lambda)V_{UD} \right. $$
$$\left. + \frac{u_\lambda}{x^2}\left(\frac{\sin x}{x} - \cos x \right) \right],$$

where V_{UD} is the visibility of a uniform stellar disk, $V_{UD} = 2\frac{J_1(x)}{x}$, in which J_1 is the Bessel function of order 1, and $x = \frac{\pi \phi B}{\lambda}$ with ϕ the star's angular diameter, B the projected baseline during the scan, and λ the wavelength of observation. We used values of the limb-darkening parameter, u_λ, derived by Claret et al. (1995) appropriate to stars that have effective temperatures of 1.5–1.7 $M_\odot$ stars 10–20 Myr old, $u_\lambda = 0.24$ and 0.20, at H and K, respectively. We included a ±10% uncertainty in the values

of u_λ in the calculation of the uncertainties of the measured stellar diameters.

We fit each calibrated visibility to a limb-darkened diameter, average the individual values, and present the results, $\overline{\phi}_{Diam}$(mas), for HIP 560 and HIP 21547 in Table 3. The uncertainties are standard deviations of the mean. The uncertainties are dominated by the scatter of the individual visibility measurements. Table 3 also lists the "absolute" angular diameter $\overline{\Phi}_{Diam}$, the value of ϕ scaled to a common distance of 10 pc, and the corresponding stellar radii. The uncertainties in $\overline{\Phi}_{Diam}$ include the uncertainties in the *Hipparcos* distances (van Leeuwen 2007).

3. ANALYSIS AND DISCUSSION

3.1. Analysis in the Φ versus $(V − K)$ and the H-R Diagrams

Figure 3 shows $\overline{\Phi}_{Diam}$ compared with diameters predicted by PMS evolution models calculated by Siess et al. (2000, hereafter SDF) and the Yonsei–Yale (Y2) models calculated by Yi
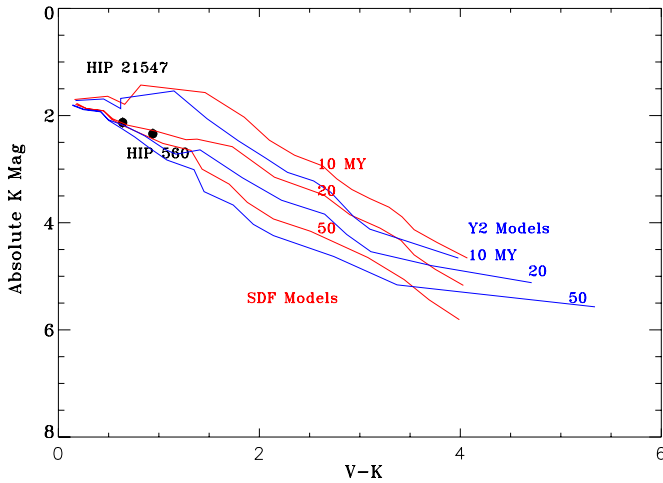
Figure 4. HIP 560 and HIP 21547 on a conventional Hertzsprung–Russell diagram here presented as M_K vs. $(V - K)$. The isochrones are calculated by SDF and Y2 as in Figure 3.

Table 3
Measured Sizes

	HIP 560	HIP 21547
$\overline{\phi}$(mas)	0.492 ± 0.032	0.518 ± 0.009
$\overline{\Phi}$(mas)	1.94 ± 0.13	1.52 ± 0.03
$R/R_\odot$	2.08 ± 0.14	1.63 ± 0.03

et al. (2003). The Y2 calculations[5] provide the luminosity, L, and effective temperature, T_{eff}, at 5 Myr intervals during the contraction; we calculated the corresponding radii through the defining relation $L = 4\pi R^2 \sigma T_{eff}^4$, where σ is the Stefan–Boltzmann constant. The SDF Web site provides the photospheric radii directly[6] and connects T_{eff} to magnitudes using Kenyon & Hartmann's (1995) Table A5. To present the Y2 results with $(V - K)$ as the independent variable, we interpolated their T_{eff} to the Kenyon and Hartmann scale. The diameter measurements indicate, for both stars, ages in the range 10–15 Myr and masses 1.6–1.8 $M_\odot$. The left-hand portion of Table 4 lists more precise values obtained by placing the observed diameters on a finer mesh in the Φ versus $(V - K)$ color diagram (henceforth the ΦCD); the values lie in the columns designated Φ_{SDF} and Φ_{Y2}. The age difference between HIP 560 and HIP 21547 is not statistically significant and the SDF and Y2 tracks yield values that are in good agreement. The average age of the two stars is 13 ± 2 Myr. The masses determined using the SDF and Y2 tracks are also consistent. The average mass of HIP 560 is $1.65 \pm 0.02 M_\odot$ and that of HIP 21547 is $1.75 \pm 0.05 M_\odot$.

If we did not have angular diameter measurement of HIP 560 and HIP 21547, the only way to estimate their age and mass would be by their positions on HRD relative theoretical isochrones. Figure 4 shows such an analysis, here on an HRD plotted as M_K versus $(V - K)$. It is seen that both the SDF and Y2 tracks indicate ages at least 5 Myr older and masses ~0.2 $M_\odot$ smaller than those indicated by the ΦCD (the columns designated HRD$_{SDF}$ and HRD$_{Y2}$ in Table 4).

The observational inputs, angular diameters, distances, and photometry, and hence the stellar radii, luminosities, and effective temperatures give essentially the same ages and masses

---

[5] www.astro.yale.edu/demarque/yystar.html
[6] www-astro.ulb.ac.be/~siess/

Table 4
Measured Ages and Masses

Star	Φ_{SDF}	Φ_{Y2}	HRD$_{SDF}$	HRD$_{Y2}$
		Age (Myr)		
HIP 560	12.0 ± 3.0	10 ± 2	25^{+25}_{-8}	18 ± 2
HIP 21547	15.0 ± 2.0	15 ± 2	20^{+30}_{-2}	18 ± 2
		Mass ($M_\odot$)		
HIP 560	1.68 ± 0.03	1.63 ± 0.02	1.49 ± 0.05	1.45 ± 0.10
HIP 21547	1.75 ± 0.05	1.75 ± 0.05	1.56 ± 0.05	1.55 ± 0.10

whether the SDF or Y2 models are used. The results are however consistently discrepant when interpreted on the ΦCD or the HRD. This suggests that the source of the discrepancy lies in the application of theoretical calculations of non-rotating stars to stars that rotate with high angular velocities.

3.2. The Effects of Stellar Rotation

The rotation of stars less massive than ~2 $M_\odot$ slows over their lifetimes because stellar winds powered by the convective outer layers carry away their angular momentum. The convective zone in main-sequence F spectral-type stars disappears toward the earlier F spectral-type sub-classes and energy transport becomes entirely radiative. This explains the rapid decrease of $v \sin i$ from F0V to F9V (e.g., Abt & Hunter 1962; Kraft 1967). The observation and theoretical analysis of stellar rotation have a rich history (e.g., Tassoul 2000) and its effects are revealed beautifully now that stars can be imaged interferometrically (e.g., Peterson et al. 2006a, 2006b; Monnier et al. 2007; Zhao et al. 2009; Che et al. 2011).

The effective surface gravity, g_{eff} in a rotating star decreases from the pole to the equator. This produces oblateness and a brightness variation with latitude known as gravity darkening. The oblateness of a rotating star in radiative equilibrium is given by

$$o = \frac{R_e - R_p}{R_e} = 0.77 \frac{\omega^2}{2\pi G \rho_m},$$

where R_e and R_p are the equatorial and polar radii, ω is the angular velocity, and ρ_m is the mean density (von Zeipel 1924; Chandrasekhar 1933). Inserting numerical values,

$$o = 0.0261 \left(\frac{R_p}{R_\odot}\right)\left(\frac{M_\odot}{M_*}\right)\left(\frac{V_{eq}}{100 \, \text{km s}^{-1}}\right)^2,$$

where R_p is the polar radius of the star, and M_* and V_{eq} are its mass and equatorial velocity. Sackmann (1970) showed that the decrease of R_p from its non-rotating value is only a few percent even when the star is rotating nearly at breakup. At breakup, $R_{eq} = 3/2 R_p$, $o = 0.33$, and $V^2_{eq,bk} = 2GM_*/3R_p$ (e.g., Collins 1963). It is safe to apply these results to HIP 560 and HIP 21547 because Demarque & Roeder (1967) showed that the outer convective layers disappear at F early spectral type.

To make numerical estimates of the expected oblateness for HIP 560 and HIP 21547, we use values from SDF for the radius and mass of an early F spectral-type star at age 13 Myr, $R_* = 1.7 R_\odot$, $M_* = 1.7 M_\odot$. We use these values because, in principle, our measured values could be affected by oblateness. We also use the $v \sin i$ values, 171 and 95 km s^{-1}, measured for HIP 560 and HIP 21547, respectively (Table 1). Since the inclinations are not known we cannot calculate the equatorial

velocities. We can, however, estimate them by calculating the expectation values $\langle v \sin i \rangle$. The upper bound on the inclination is $i = \pi/2$. If the lower bound on i were 0, $\langle v \sin i \rangle = V_{eq}\pi/4$. Here, however, a lower bound, i_{crit}, is set by the value at which $v \sin i_{crit}$ would imply rotation at the breakup velocity. For the adopted radius and mass, $V_{eq,bk} = 357$ km s^{-1}. Hence, $\sin i_{crit} = $ (observed $v \sin i$)/357 and $i_{crit} = 8\overset{\circ}{.}6$ and $15\overset{\circ}{.}4$ for HIP 560 and HIP 21547, respectively. Using these values as a lower bound on the inclination, the expectation values of the equatorial velocities are 202 and 118 km s^{-1}, and of the oblateness, 0.104 and 0.036, for HIP 560 and HIP 21547, respectively. These values could be measured only if the stars' rotation axes were positioned for best resolution of the oblateness with the east–west baseline of the CHARA Array. The measured oblateness values are therefore likely to be smaller. In the case of HIP 21547 our observations probably would not have measured $o \leqslant 0.036$ because the precision of the diameter measurement is ∼2% (Table 3). For HIP 560, in the unlikely case that a ∼10% oblateness accounts for the measured value of its angular diameter, a 10% smaller value of Φ would still place it between the 10 and 20 Myr isochrones. We conclude that stellar oblateness probably does not enter into the interpretation of our results.[7]

In a rotating star in radiative equilibrium, the radiative flux at a point on the photosphere is proportional to g_{eff} (von Zeipel 1924). Since g_{eff} decreases from the pole to the equator, the corresponding decrease in radiative flux can be characterized as a decrease in the local effective temperature and is called gravity darkening. In the A spectral-type stars that have been imaged (Peterson et al. 2006a, 2006b; Monnier et al. 2007; Zhao et al. 2009), the temperature difference is large, ∼2000 K. Thus, relative to a non-rotating star, a rotating star seen pole-on ($i = 0$) will appear brighter and its photometric color will be hotter than one seen equator-on ($i = \pi/2$). Observed values for a given star depend, of course, on its inclination. Maeder & Peytremann (1970) have calculated the photometric effects for stars of mass 1.4, 2, and 5 $M_\odot$ at various values of V_{eq} and i. Typically, the values of M_V vary by a few tenths of a mag and of $(B - V)$ by a few hundredths. Details depend on the stellar mass and inclination; Maeder and Peytremann's calculations show that for $i \gtrsim 54°$ the rotating star appears less bright and redder than a non-rotating star.

The effects of gravity darkening suggest that the discrepancies summarized in Table 4 are attributable to rotation of HIP 560 and HIP 21547. If their rotational velocities and inclinations are such that their absolute magnitudes at K are depressed by a few tenths relative to a non-rotating star and their $(V - K)$ are slightly redder, the ages and masses deduced from the ΦCD and HRD could be in agreement. A detailed test of this hypothesis will be possible when the inclinations of these stars are measured. This can be accomplished by either measuring their light fluctuations and thus rotational periods or by mapping the interferometric imaging of the photospheric emission of these stars. The first approach is possible now as Garcia-Alvarez et al. (2011) demonstrated by measuring the periods and inclinations of two other stars in the BPMG.

3.3. Implications for the BPMG

If we accept the results of the ΦCD analysis and attribute the discrepancy of results from the HRD to stellar rotation,

we conclude that HIP 560 and HIP 21547 are roughly coeval at an average age of about 13 Myr. Their galactic (X, Y, Z) coordinates (Table 1) place them about 49 pc apart with each moving at speed ∼22 km s^{-1} given by their (U, V, W) velocity components. It is too soon to attribute the results for this pair to all the stars in the BPMG but our results suggest that the members were born together about 13 Myr ago, and thus are at the younger end of the age span described in Section 2.

4. SUMMARY AND FUTURE DIRECTIONS

1. The measured angular diameters of HIP 560 and HIP 21547 in the H and K bands are 0.492 ± 0.032 and 0.518 ± 0.009 mas, respectively. Scaled to a common distance of 10 pc, their angular diameters are $\Phi = 1.94 \pm 0.13$ and 1.52 ± 0.03 mas, respectively.

2. Analyzing these results in the Φ versus $(V - K)$ diagram with SDF and Y2 isochrones calculated yields ages of the two stars that are not different at a statistically significant level. Their average age is 13 ± 2 Myr. The masses determined according to the two sets of isochrones also do not differ at a statistically different level. The average values are 1.65 ± 0.02 $M_\odot$ for HIP 560 and 1.75 ± 0.05 $M_\odot$ for HIP 21547.

3. Analyzing the stellar parameters with the SDF and Y2 isochrones in a conventional HRD yields ages at least 5 Myr older and masses ∼0.2 $M_\odot$ smaller.

4. HIP 560 and HIP 21547 are rapid rotators (Table 1). The discrepancy in ages and masses can be accounted for by gravitational darkening of rotating stars in radiative equilibrium. A detailed test of this hypothesis will be possible when their inclinations are determined either by measuring their rotational periods or by interferometric images of their photospheres.

5. Taken together, our results suggest that HIP 560 and HIP 21547 formed coevally about 13 Myr ago.

The most pressing task is to determine whether the 13 Myr age applies to the BPMG as a whole. Although most BPMGs are in the southern hemisphere, at least three other F and G spectral-type stars are bright and near enough for measurement with the CHARA Array. Stars of later spectral type are too faint for observation at the present time unless, by good luck, they are close to the Sun. Many more of the BPMG members will be observable when the planned sensitivity improvements at the CHARA Array are realized.

---

[7] Also, the on-sky angle of the projected baseline was essentially the same throughout our observations (Table 2). Thus baseline rotation during our observations is not an issue.

also used the SIMBAD database operated at CDS, Strasbourg, France.

REFERENCES

Abt, H. A., & Hunter, J. H., Jr. 1962, ApJ, 136, 381
Chandrasekhar, S. 1933, MNRAS, 93, 390
Che, X., Monnier, J. D., Zhao, M., et al. 2011, ApJ, 732, 68
Claret, A., Diaz-Cordoves, J., & Gimenez, A. 1995, A&AS, 114, 247
Collins, G. W. 1963, ApJ, 138, 1134
Demarque, P., & Roeder, R. 1967, ApJ, 147, 1188
Fernández, D., Figueras, F., & Torra, J. 2008, A&A, 480, 735
Garcia-Alvarez, D., Lanza, A. F., Messina, S., et al. 2011, A&A, 533, A30
Hanbury-Brown, R., Davis, J., Lake, R. J. W., & Thompson, R. J. 1974, MNRAS, 167, 475
Hillenbrand, L., & White, R. 2004, ApJ, 604, 741
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Kervella, P., Thvenin, F., Di Folco, E., & Sgransan, D. 2004, A&A, 426, 297
Kraft, R. 1967, ApJ, 150, 551
Lagrange, A.-M., Bonnefoy, M., Chauvin, G., et al. 2010, Science, 329, 57
Liu, M. 2004, Science, 305, 1442
Maeder, A., & Peytremann, E. 1970, A&A, 7, 120
Monnier, J. D., Zhao, M., Pedretti, E., et al. 2007, Science, 317, 342
Peterson, D. M., Hummel, C. A., Pauls, T. A., et al. 2006a, Nature, 440, 896
Peterson, D. M., Hummel, C. A., Pauls, T. A., et al. 2006b, ApJ, 636, 1087
Quillen, A. C., Morbidelli, A., & Moore, A. 2007, MNRAS, 380, 1642
Sackmann, I.-J. 1970, A&A, 8, 76
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593 (SDF)
Simon, M. 2006, in The Power of Optical/IR Interferometry, ed. A. Richichi, F. Delplancke, F. Paresce, & A. Chelli (Berlin: Springer), 227
Smith, B. A., & Terrile, R. J. 1984, Science, 226, 1421
Tassoul, J.-L. 2000, Stellar Rotation (Cambridge: Cambridge Univ. Press)
ten Brummelaar, T. A., McAlister, H. A., Ridgway, S. T., et al. 2005, ApJ, 628, 453
Torres, C. A. O., Quast, G. R., da Silva, L., et al. 2006, A&A, 460, 695
van Belle, G., Ciardi, D. R., Thompson, R. R., et al. 2001, ApJ, 559, 1155
van Leeuwen, F. 2007, A&A, 474, 653
van Leeuwen, F., Evans, D. W., Grenon, M., et al. 1997, A&A, 323, L61
von Zeipel, H. 1924, MNRAS, 84, 684
Yee, J. C., & Jensen, E. L. N. 2010, ApJ, 711, 303
Yi, S., Kim, Y.-C., & Demarque, P. 2003, ApJS, 144, 259
Zhao, M., Monnier, J. D., Pedretti, E., et al. 2009, ApJ, 701, 209