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MEASUREMENT OF THE SURFACE GRAVITY OF η BOOTIS

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ABSTRACT

Direct angular size measurements of the G0 IV subgiant η Boo from the Palomar Testbed Interferometer are presented, with a limb-darkened angular size of $\theta_{\rm LD} = 2.1894^{+0.0055}_{-0.0140}$ mas, which indicates a linear radius of $R = 2.672 \pm 0.028\ R_{\odot}$. A bolometric flux estimate of $F_{\rm bol} = (22.1 \pm 0.28) \times 10^{-7}$ ergs cm^{-2} s^{-1} is computed, which indicates an effective temperature of $T_{\rm eff} = 6100 \pm 28$ K and a luminosity of $L = 8.89 \pm 0.16\ L_{\odot}$ for this object. Similar data are established for a check star, HD 121860. The η Boo results are compared to, and confirm, similar parameters established by the *MOST* asteroseismology satellite. In conjunction with the mass estimate from the *MOST* investigation, a surface gravity of $\log g = 3.817 \pm 0.016$ [cm s^{-2}] is established for η Boo.

Subject headings: infrared: stars — stars: fundamental parameters — stars: individual (η Bootis) — techniques: interferometric

1. INTRODUCTION

The bright G0 IV star η Bootis (8 Boo, HR 5235, HD 121370) is an interesting target to study, given its place on the H-R diagram and its implications for stellar modeling. Solar-like oscillations were detected for η Boo by Kjeldsen et al. (1995, 2003). η Boo was recently observed with the *Microvariability and Oscillations of Stars* (*MOST*) satellite (Guenther et al. 2005), a 15 cm aperture satellite observatory put into orbit in 2003 June by the Canadian Space Agency (Walker et al. 2003). Given that the convective envelope of η Boo is expected to be very thin, containing less than 1% of the total mass of the star, observations by *MOST* were motivated by the possibility of detecting g-modes, along with the p-modes indicative of turbulent convection. In detecting eight consecutive low-frequency radial p-modes for this G0 IV star, the *MOST* team was able to estimate many stellar parameters, including its temperature, age, and mass. In addition, new models examined by Straka et al. (2006) are able to simultaneously match the space- and ground-based pulsation data for η Boo through the inclusion of turbulence in the stellar models.

Using interferometry to obtain a *direct*, absolute measurement of this object's linear size and effective temperature, in conjunction with the mass estimate from the models fitted to the *MOST* data, we may also infer its surface gravity, $\log g$. Values of $\log g$ are frequently used in stellar modeling and spectroscopy, and a direct characterization of $\log g$ for this slightly evolved object is of significant utility. We show that the high-precision photometry of *MOST* and the high spatial resolution observations of the Palomar Testbed Interferometer (PTI) make for a potent combination with which to uniquely interpret a star's astrophysical parameters.

2. INTERFEROMETRIC OBSERVATIONS AND DATA REDUCTION

The Palomar Testbed Interferometer is a three-element long-baseline interferometer that combines two of its three 40 cm apertures to make measurements of fringe visibility, V^2, for astronomical sources. These measurements are made at either the H (1.6 μm) or K band (2.2 μm); for this particular investigation, the K band was employed, being spectrally dispersed into five "narrow" bands across the K band that were centered at 2.009, 2.106, 2.203, 2.299, and 2.396 μm. For all of these observations, PTI's 109.8 m north-south baseline was used; details on PTI can be found in Colavita et al. (1999).

η Boo was observed, along with the unresolved calibration sources HD 117176 (70 Vir), HD 120136 (τ Boo), HD 121107, and HD 121560, on 18 nights between 2000 and 2005. In addition to η Boo, a resolved check star, HD 121860, was observed as a means to monitor system performance. None of the calibrators exceeded PTI's pointlike calibrator angular size criterion of $\theta_{\rm est} < 1.0$ mas (van Belle & van Belle 2005) for absolute measurement calibration. A previous interferometric measure of η Boo's size was made by Thévenin et al. (2005), but resolved calibration sources used in this study (due to sensitivity limitations) make the resulting η Boo diameter estimate subject to potential systematic errors. Two of the four calibrators, 70 Vir and τ Boo, are associated with radial velocity (RV) planets (Marcy & Butler 1996; Butler et al. 1997), but no evidence has been found for V^2 variations indicative of face-on binary stars that could supplant the RV planet interpretation for these objects. The relevant observing parameters are found in Table 1, along with parameters to be derived in § 3.1.

The calibration of the η Boo V^2 data is performed by estimating the interferometer system visibility ($V^2_{\rm sys}$) using the calibration source with a model angular diameter and then normalizing the raw η Boo visibility by $V^2_{\rm sys}$ to estimate the V^2 measured by an ideal interferometer at that epoch (Mozurkewich et al. 1991; Boden et al. 1998; van Belle & van Belle 2005). Uncertainties in the system visibility and the calibrated target visibility are inferred from internal scatter among the data in an observation by using standard error propagation calculations (Colavita 1999). Calibrating our pointlike calibration objects against each other produced no evidence of systematics, with all objects delivering a reduced $V^2 = 1$. The observation dates, calibrated visibilities for each wavelength bin, (u, v) coordinates, and hour angles of the observations are presented in Table 2 for η Boo and in Table 3 for HD 121860. Plots of the absolute visibility data for η Boo are found in Figure 1. PTI's limiting night-to-night measurement error is $\sigma_{V^2_{\rm sys}} \approx 1.5\%$–$1.8\%$, the source of which is most likely a combination of effects: uncharacterized atmospheric seeing (in

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TABLE 1

Results from SED Fittings, Including Reddening, Estimated Angular Size, and Bolometric Flux at Source

Source Name	R.A. (J2000.0)	Decl. (J2000.0)	V (mag)	K (mag)	Spectral Template	A_V (mag)	θ_{est} (mas)	F_{bol} (ergs cm^{-2} s^{-1})
η Boo:								
HD 121370	13 54 41.002	+18 23 55.30	2.68	1.485	G0 IV	0.000 ± 0.011	2.320 ± 0.072	(221 ± 2.8) × 10^{-8}
Resolved check star:								
HD 121860	13 58 01.602	+07 27 48.40	7.5	2.448	M2 III	0.927 ± 0.043	2.010 ± 0.109	(25.4 ± 1.3) × 10^{-8}
Calibrators:								
HD 117176.....................	13 28 25.809	+13 46 43.63	5.000	3.500	G5 V	0.117 ± 0.015	0.986 ± 0.020	(31.5 ± 0.6) × 10^{-8}
HD 120136	13 47 15.743	+17 27 24.86	4.5	3.507	F5 IV	0.214 ± 0.017	0.892 ± 0.042	(49.2 ± 1.2) × 10^{-8}
HD 121107.....................	13 53 12.931	+17 55 58.33	5.711	4.077	G5 III	0.002 ± 0.043	0.837 ± 0.052	(16.6 ± 0.8) × 10^{-8}
HD 121560	13 55 49.994	+14 03 23.41	6.1	4.843	F6 V	0.105 ± 0.016	0.442 ± 0.010	(10.1 ± 0.1) × 10^{-8}

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

TABLE 2

Calibrated Visibility Data Obtained by PTI for η Bootis

		V^2							
Date	UT	2.009 μm	2.106 μm	2.203 μm	2.299 μm	2.396 μm	u (m)	v (m)	H.A.
2000 Apr 9.........	7.73	0.391 ± 0.017	0.529 ± 0.033	0.479 ± 0.015	0.510 ± 0.025	0.454 ± 0.023	−48.46	−96.13	−0.78
	7.98	0.402 ± 0.022	0.551 ± 0.033	0.493 ± 0.020	0.529 ± 0.028	0.465 ± 0.029	−44.96	−97.12	−0.53
	9.14	0.579 ± 0.050	0.556 ± 0.023	0.537 ± 0.026	0.510 ± 0.039	0.499 ± 0.020	−26.82	−100.58	0.63
2000 Apr 28.......	5.93	0.526 ± 0.020	0.441 ± 0.017	0.507 ± 0.020	0.406 ± 0.013	0.480 ± 0.023	−55.30	−93.75	−1.34
2000 May 2........	6.44	0.566 ± 0.011	0.518 ± 0.009	0.487 ± 0.011	0.457 ± 0.011	0.558 ± 0.011	−45.54	−96.96	−0.57
	6.70	0.566 ± 0.010	0.514 ± 0.008	0.481 ± 0.011	0.546 ± 0.010	0.462 ± 0.012	−41.77	−97.91	−0.31
	7.53	0.589 ± 0.008	0.502 ± 0.010	0.567 ± 0.010	0.472 ± 0.012	0.542 ± 0.008	−28.50	−100.35	0.53
	7.71	0.589 ± 0.010	0.506 ± 0.012	0.569 ± 0.012	0.475 ± 0.013	0.549 ± 0.009	−25.46	−100.75	0.71
2000 May 4........	6.96	0.558 ± 0.026	0.475 ± 0.024	0.550 ± 0.029	0.521 ± 0.022	0.453 ± 0.021	−35.70	−99.18	0.09
	8.14	0.577 ± 0.042	0.564 ± 0.035	0.537 ± 0.036	0.504 ± 0.040	0.478 ± 0.049	−15.66	−101.70	1.27
2000 May 14......	5.85	0.504 ± 0.012	0.566 ± 0.014	0.475 ± 0.015	0.557 ± 0.016	0.460 ± 0.015	−42.62	−97.71	−0.36
	7.47	0.449 ± 0.045	0.546 ± 0.031	0.486 ± 0.034	0.528 ± 0.035	0.588 ± 0.042	−15.85	−101.69	1.26
2000 May 30......	5.58	0.494 ± 0.016	0.558 ± 0.017	0.591 ± 0.013	0.537 ± 0.017	0.484 ± 0.018	−30.41	−100.07	0.42
	6.52	0.495 ± 0.015	0.587 ± 0.015	0.574 ± 0.017	0.544 ± 0.018	0.482 ± 0.018	−14.07	−101.81	1.36
	7.68	0.461 ± 0.034	0.598 ± 0.018	0.515 ± 0.014	0.552 ± 0.014	0.588 ± 0.013	7.23	−102.14	2.52
2000 Jun 12	3.70	0.566 ± 0.016	0.481 ± 0.020	0.548 ± 0.018	0.527 ± 0.019	0.461 ± 0.024	−46.17	−96.79	−0.61
	4.58	0.566 ± 0.023	0.544 ± 0.026	0.481 ± 0.025	0.521 ± 0.025	0.455 ± 0.031	−32.89	−99.68	0.27
	5.34	0.561 ± 0.016	0.511 ± 0.027	0.541 ± 0.025	0.483 ± 0.030	0.455 ± 0.028	−19.93	−101.35	1.03
	6.11	0.572 ± 0.018	0.601 ± 0.009	0.545 ± 0.021	0.482 ± 0.023	0.518 ± 0.022	−6.02	−102.18	1.80
2000 Jun 14	5.03	0.588 ± 0.018	0.501 ± 0.015	0.538 ± 0.018	0.573 ± 0.019	0.488 ± 0.020	−23.03	−101.03	0.85
2001 Mar 16	10.65	0.560 ± 0.036	0.542 ± 0.029	0.447 ± 0.019	0.483 ± 0.023	0.527 ± 0.023	−28.07	−100.41	0.56
	11.20	0.448 ± 0.019	0.575 ± 0.039	0.498 ± 0.023	0.560 ± 0.027	0.545 ± 0.014	−18.57	−101.47	1.11
2001 Mar 17	10.65	0.453 ± 0.051	0.597 ± 0.040	0.571 ± 0.028	0.512 ± 0.037	0.545 ± 0.025	−27.09	−100.54	0.62
	11.14	0.450 ± 0.053	0.504 ± 0.040	0.537 ± 0.040	0.597 ± 0.042	0.573 ± 0.041	−18.51	−101.47	1.11
	12.08	0.459 ± 0.042	0.566 ± 0.034	0.630 ± 0.035	0.542 ± 0.037	0.612 ± 0.028	−1.41	−102.25	2.05
	12.29	0.421 ± 0.046	0.510 ± 0.038	0.488 ± 0.037	0.582 ± 0.045	0.557 ± 0.036	2.37	−102.24	2.26
2001 Mar 19	8.91	0.537 ± 0.023	0.515 ± 0.017	0.486 ± 0.018	0.457 ± 0.015	0.424 ± 0.024	−51.21	−95.25	−1.00
	9.76	0.550 ± 0.031	0.523 ± 0.025	0.501 ± 0.023	0.470 ± 0.018	0.450 ± 0.030	−39.36	−98.44	−0.15
	10.57	0.560 ± 0.019	0.482 ± 0.015	0.545 ± 0.023	0.521 ± 0.020	0.462 ± 0.024	−26.11	−100.66	0.67
2001 Mar 22	9.88	0.468 ± 0.021	0.440 ± 0.021	0.542 ± 0.026	0.519 ± 0.029	0.587 ± 0.026	−34.34	−99.42	0.18
2001 Mar 23	9.72	0.519 ± 0.023	0.468 ± 0.021	0.500 ± 0.024	0.446 ± 0.022	0.427 ± 0.024	−35.92	−99.14	0.08
	10.62	0.594 ± 0.014	0.540 ± 0.006	0.509 ± 0.012	0.576 ± 0.011	0.484 ± 0.014	−20.83	−101.26	0.98
2001 Mar 24	9.57	0.580 ± 0.013	0.490 ± 0.012	0.554 ± 0.012	0.528 ± 0.013	0.475 ± 0.012	−37.14	−98.90	0.00
2003 Apr 28.......	6.41	0.562 ± 0.020	0.535 ± 0.014	0.511 ± 0.015	0.479 ± 0.016	0.451 ± 0.020	−50.08	−95.62	−0.91
	6.70	0.554 ± 0.020	0.530 ± 0.018	0.470 ± 0.018	0.504 ± 0.018	0.443 ± 0.020	−46.26	−96.76	−0.62
	7.00	0.570 ± 0.017	0.543 ± 0.015	0.483 ± 0.016	0.520 ± 0.015	0.459 ± 0.022	−41.97	−97.85	−0.32
2005 Apr 3.........	8.80	0.590 ± 0.029	0.517 ± 0.027	0.585 ± 0.024	0.556 ± 0.022	0.522 ± 0.041	−38.93	−98.52	−0.12
	9.19	0.562 ± 0.021	0.500 ± 0.013	0.565 ± 0.020	0.544 ± 0.014	0.489 ± 0.017	−32.86	−99.66	0.27
	9.50	0.592 ± 0.021	0.548 ± 0.021	0.579 ± 0.021	0.517 ± 0.022	0.501 ± 0.019	−27.74	−100.44	0.58
	9.79	0.576 ± 0.036	0.495 ± 0.027	0.530 ± 0.037	0.561 ± 0.039	0.486 ± 0.022	−22.63	−101.06	0.88
2005 Apr 5.........	8.30	0.560 ± 0.018	0.503 ± 0.017	0.539 ± 0.019	0.479 ± 0.018	0.457 ± 0.022	−44.44	−97.24	−0.49
	8.67	0.499 ± 0.012	0.560 ± 0.015	0.470 ± 0.015	0.535 ± 0.016	0.454 ± 0.021	−39.01	−98.51	−0.12
	8.95	0.471 ± 0.032	0.441 ± 0.030	0.539 ± 0.033	0.515 ± 0.033	0.430 ± 0.031	−34.50	−99.38	0.17
	9.25	0.550 ± 0.028	0.495 ± 0.025	0.534 ± 0.034	0.476 ± 0.025	0.454 ± 0.034	−29.68	−100.16	0.46
	9.55	0.589 ± 0.015	0.537 ± 0.013	0.506 ± 0.018	0.573 ± 0.015	0.484 ± 0.022	−24.63	−100.83	0.76
	9.86	0.582 ± 0.015	0.494 ± 0.020	0.527 ± 0.016	0.567 ± 0.017	0.469 ± 0.024	−19.08	−101.41	1.08

TABLE 3

Calibrated Visibility Data Obtained by PTI for HD 121860

Date	UT	V^2					u	v	
		2.009 μm	2.106 μm	2.203 μm	2.299 μm	2.396 μm	(m)	(m)	H.A.
2000 Apr 9............	7.83	0.479 ± 0.026	0.563 ± 0.035	0.593 ± 0.017	0.620 ± 0.037	0.621 ± 0.046	−47.91	−90.37	−0.74
	8.08	0.524 ± 0.028	0.568 ± 0.034	0.592 ± 0.018	0.605 ± 0.032	0.620 ± 0.043	−44.39	−90.77	−0.49
2000 May 2............	6.53	0.534 ± 0.018	0.575 ± 0.014	0.602 ± 0.012	0.641 ± 0.014	0.647 ± 0.015	−44.99	−90.71	−0.53
	6.80	0.522 ± 0.018	0.565 ± 0.014	0.592 ± 0.008	0.623 ± 0.013	0.630 ± 0.012	−41.11	−91.10	−0.26
2000 May 4............	7.06	0.556 ± 0.036	0.585 ± 0.040	0.621 ± 0.030	0.643 ± 0.040	0.640 ± 0.034	−35.04	−91.61	0.13
2000 Jun 12	3.53	0.562 ± 0.040	0.580 ± 0.030	0.613 ± 0.032	0.634 ± 0.029	0.637 ± 0.026	−49.23	−90.21	−0.84
	4.41	0.570 ± 0.049	0.597 ± 0.039	0.626 ± 0.038	0.646 ± 0.036	0.651 ± 0.032	−36.50	−91.50	0.04
2001 Mar 17	9.81	0.507 ± 0.078	0.538 ± 0.081	0.550 ± 0.082	0.587 ± 0.072	0.594 ± 0.063	−41.43	−91.06	−0.28
2001 Mar 19	9.01	0.506 ± 0.035	0.542 ± 0.022	0.569 ± 0.028	0.595 ± 0.026	0.612 ± 0.036	−50.66	−90.01	−0.95
2003 Apr 28...........	6.51	0.516 ± 0.030	0.546 ± 0.023	0.577 ± 0.021	0.599 ± 0.019	0.610 ± 0.028	−49.50	−90.16	−0.86
	6.79	0.508 ± 0.035	0.529 ± 0.030	0.558 ± 0.026	0.579 ± 0.024	0.601 ± 0.032	−45.74	−90.61	−0.58
	7.11	0.521 ± 0.037	0.559 ± 0.029	0.596 ± 0.027	0.617 ± 0.024	0.633 ± 0.031	−41.16	−91.08	−0.26

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).

3. EFFECTIVE TEMPERATURE AND RADIUS DETERMINATIONS

3.1. *Bolometric Flux Estimates*

For each of the target and calibrator stars observed in this investigation, a spectral energy distribution (SED) fit was performed. This fit was accomplished using photometry available in the literature as the input values, with template spectra appropriate for the spectral types indicated for the stars in question. The template spectra, from Pickles (1998), were adjusted to account for overall flux level and wavelength-dependent reddening, resulting in an estimate of the angular size. Reddening corrections were based on the empirical reddening determination described by Cardelli et al. (1989), which differs little from van de Hulst's theoretical reddening curve No. 15 (Johnson 1968; Dyck et al. 1996). Both narrowband and wideband photometry in the range from 0.3 μm to 30 μm were used where available, including Johnson *UBV* (see, for example, Eggen 1963, 1972; Moreno 1971), Strömgren $uvby\beta$ (Piirola 1976), Geneva $UBVB_1B_2V_1G$ (Rufener 1976), 2MASS JHK_s (Cutri et al. 2003), and Vilnius *UPXYZVTS* (Zdanavicius et al. 1972). Zero-magnitude flux density calibrations were based on the values given in Cox (2000).

Starting with a reference spectral type and luminosity class as cited by SIMBAD, template spectra were fitted to the photometric data. Templates in adjacent locations in spectral type and luminosity class were also tested for best fit, with the fit with the best χ^2 being selected in the end for use in this study. For example, a star indicated by SIMBAD to be of type G0 IV would have its photometry fitted to the nine templates of spectral types F9, G0, and G1 and luminosity classes III, IV, and V. Metallicities for these fits were assumed to be roughly solar, which is consistent with the values found for these objects in the references listed in Cayrel de Strobel et al. (1997) and Cayrel de Strobel et al. (2001).

From the best SED fit, estimates were obtained for each star for their reddening (A_V) and bolometric flux ($F_{\rm bol}$); since the effective temperature was fixed for each of the Pickles (1998) library spectra, an estimate of angular size ($\theta_{\rm est}$) was also obtained. The results of the fitting are given in Table 1. As an example, the SED fitting plot for η Boo is given in Figure 2.

For our calibration sources, a priori estimates of their sizes are necessary to account for residual resolution that may be afforded by an interferometer's long baselines. With an expected limb-darkened size of $\theta_{\rm est} \leq 1.00$ mas from the SED fit, calibrators have predicted values of V^2 of >86% for a 110 m baseline used

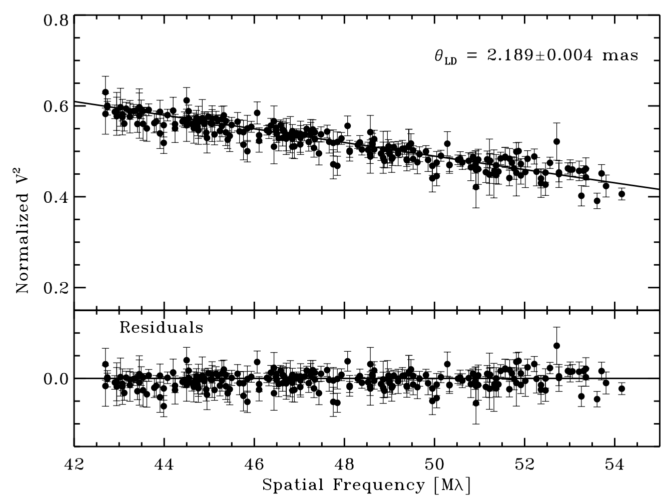

Fig. 1.—Absolute visibility data for η Boo, as discussed in § 2. The line fitted to the data is the visibility function corresponding to a 2.1894 ± 0.0038 mas limb-darkened angular disk diameter. See §§ 3.2 and 4 for a discussion of our final uncertainty estimate for the η Boo angular size.

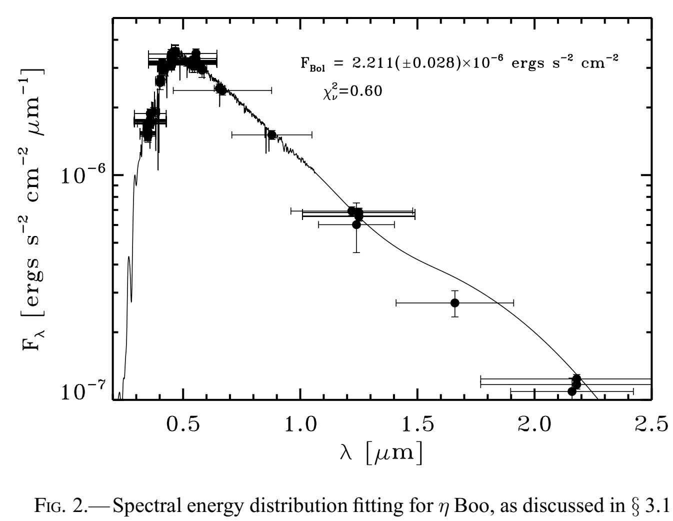

Fig. 2.—Spectral energy distribution fitting for η Boo, as discussed in § 3.1. Vertical bars on the data points represent the photometric errors, and horizontal bars correspond to the bandpass of the photometric filter being used.

TABLE 4

Summary of Stellar Fundamental Parameters Measured for η Bootis and HD 121860

Star	θ_{LD} (mas)	F_{bol} (10^{-8} ergs cm^{-2} s^{-1})	π[a] (mas)	T_{eff} (K)	R ($R_\odot$)	L ($L_\odot$)	log g (log [cm s^{-2}])
η Boo	$2.1894^{+0.0055}_{-0.0140}$	221 ± 2.82	88.17 ± 0.75	6100 ± 28	2.672 ± 0.028	8.89 ± 0.16	3.817 ± 0.016
HD 121860	2.100 ± 0.009	25.4 ± 1.26	1.54 ± 0.97	3627 ± 46	147 ± 92	3350 ± 2989	0.184 ± 0.288

Note.—The error on θ_{LD} includes the uncertainty discussed in § 4; subsequent columns propagate the larger of the two error bars where appropriate.
[a] Perryman et al. (1997).

at $\lambda = 2.2$ μm (with $V^2 > 96\%$ expected for our smallest calibrator, HD 121560). We consider this size effectively identical to its uniform disk size, since for most of our potential calibration sources, their effective temperatures are in excess of ~5000 K. The difference between the uniform disk and limb-darkened sizes is at the level of a few percent (Davis et al. 2000; Claret & Hauschildt 2003), which is far less than our size estimate error or, in particular, its impact on the system visibility estimate derived from observations of our calibrators. A $\leq$5% uncertainty in angular size will contribute, at most, less than $\leq$1.3% uncertainty to the system visibility V^2_{sys} for PTI. The night-to-night limiting measurement error of PTI is $\sigma_{V^2_{sys}} \approx 1.5\%-1.8\%$ (Boden et al. 1999), and so any measures of V^2 using our calibrators will be free from any potential bias in its angular size measurement at the $\sigma_\theta/\theta \approx 7\%$ level for our largest calibrator, HD 117176, and at better levels of insensitivity for our smaller calibrators.

3.2. *Angular Sizes of η Boo and HD 121860*

We may fit our observed visibility data to a uniform disk approximation to get an initial estimate of the angular sizes of η Boo and HD 121860. From the expression $V^2 = [2J_1(x)/x]^2$, where $x = \pi B \theta_{UD} \lambda^{-1}$, we get angular sizes θ_{UD} of 2.1528 ± 0.0037 mas and 2.035 ± 0.009 mas for η Boo and HD 121860, respectively, with reduced χ^2 values of 0.90 and 0.48. Given η Boo's low rotation value of 13.5 km s^{-1} (Reiners 2006), rotational oblateness did not need to be considered in the fit (van Belle et al. 2001).

For limb-darkened fits, we used the visibility function for a limb-darkened stellar disk as parameterized with a linear limb-darkening coefficient, μ_λ (Hanbury Brown et al. 1974):

$$V^2 = \left(\frac{1-\mu_\lambda}{2} + \frac{\mu_\lambda}{3}\right)^{-2} \left[(1-\mu_\lambda)\frac{J_1(x)}{x} + \mu_\lambda \frac{j_1(x)}{x}\right]^2, \quad (1)$$

where $x = \pi B \theta_{LD} \lambda^{-1}$. For these fits we used the 2.2 μm coefficients of $\mu_\lambda = 0.22$ and 0.38 for η Boo and HD 121860, respectively (Claret et al. 1995). Examination of the linear limb-darkening coefficients from Claret et al. (1995) indicates that the value of $\mu_\lambda = 0.22 \pm 0.02$ is sufficient to account for the five narrowband channels of the PTI data (e.g., μ_λ varies by less than $\Delta\mu_\lambda = 0.04$ between 2.0 μm and 2.4 μm). Fitting our data, we get limb-darkened angular sizes of $\theta_{LD} = 2.1894 \pm 0.0038$ mas and 2.100 ± 0.009 mas for η Boo and HD 121860, respectively, with no appreciable change in the reduced χ^2 values as compared to the uniform disk fits. A previous limb-darkened angular size of 2.25 ± 0.25 mas for η Boo was measured by Mozurkewich et al. (2003) and is consistent with our measurement.

These errors are sufficiently small that additional sources of error need to be considered. First, PTI's operational wavelength has a limit of $\sigma_\lambda \approx 0.01$ μm; second, the limb-darkening coefficient μ_λ is estimated to be accurate to only $\sigma_\mu \approx 0.02$. Incorporating these effects into our limb-darkening fit for η Boo, we find an additional uncertainty contribution of 0.0040 mas, resulting in $\theta_{LD} = 2.1894 \pm 0.0055$ mas, with no appreciable increase in error for HD 121860, where the measurement error dominates the uncertainty due to the smaller number of measurements. We will return to the estimate of uncertainty on η Boo's angular size in § 4, where the limitations of our knowledge of η Boo's possible binarity in fact ultimately limits the lower bound on our knowledge of the star's angular size.

The absolute value of θ_{LD} is in agreement with that of the Very Large Telescope Interferometer (VLTI) measurement in Thévenin et al. (2005), who quote $\theta_{LD} = 2.200 \pm 0.027 \pm 0.016$ mas (statistical and systematic errors are cited separately). This previous measurement is based on limited data (only three V^2 data points) and is anchored to the angular size estimates of Cohen et al. (1999). Tracing back through the calibration history outlined in their paper, we find that this is an indication that the SED angular size estimates from Cohen et al. (1999) of the resolved calibrators α Crt and μ Vir that they used to calibrate the system were accurate at the stated uncertainties, although this is uncertain—no values were quoted in the manuscript—and that Thévenin et al.'s measurement process preserved that SED accuracy. In addition, no evaluation of the impact of possible binarity was considered by Thévenin et al. (2005), possibly due to the limits of their relatively small sample. Our result, since it is anchored to unresolved calibration sources, avoids the danger of being susceptible to any potential significant systematic error from SED modeling.

3.3. *T_{eff} and R*

The effective temperature can be directly derived from the bolometric flux and the limb-darkening angular size:

$$T_{eff} = 2341 \left(\frac{F_{bol}}{\theta^2_{LD}}\right)^{1/4}, \quad (2)$$

where F_{bol} is in units of 10^{-8} ergs cm^{-2} s^{-1} and θ_{LD} is in units of mas (van Belle et al. 1999). Stellar radius is given by $R = 0.1076\theta_{LD} d$, where R is in units of $R_\odot$, d is in units of pc, and θ_{LD} is used as a proxy for the Rosseland mean diameter. The luminosity can be derived directly from the radius and effective temperature, $L = 4\pi R^2 \sigma T^4_{eff}$, and is wholly independent of PTI's measure of θ, depending only on d and our estimate of F_{bol} (and, by extension, A_V). These derived values are summarized in Table 4. Our value of $L = 8.89 \pm 0.16$ $L_\odot$ is statistically consistent with the independent Guenther et al. (2005) value, indicating that our F_{bol} value discussed in § 3.1 is accurate.

The measured effective temperature for HD 121860 is $T_{eff} = 3627 \pm 46$ K, which differs only slightly from the expected $T_{eff} = 3750 \pm 22$ K (van Belle et al. 1999) for a M2 III spectral type that was derived from the described fitting in § 3.1. Its radius of 147 ± 92 $R_\odot$ exceeds the expected value of ~60 $R_\odot$, but the error on the radius is sufficiently large (due to the large error on the parallax) that it is not inconsistent with the smaller expected radius. The agreement of HD 121860's value of T_{eff} with the expected value is an indication to us that our confidence in PTI's data and its error estimates are reasonable.

4. NONDETECTION OF BINARITY OF η BOO

η Boo has historically been listed as a possible spectroscopic binary (Bertiau 1957; Vansina & de Greve 1982), with an orbital confirmation being cited by Abt & Levy (1976). However, speckle interferometry observations (McAlister 1978; Bonneau et al. 1980; Hartkopf & McAlister 1984; McAlister et al. 1992) showed no evidence for detection of a possible companion to η Boo, despite an expected angular separation of 0.170″ (Halbwachs 1981), and particularly given an quoted luminosity ratio of $\approx$0.75 (Vansina & de Greve 1982). However, the original discovery paper for η Boo's binary nature (Bertiau 1957) suggests a late K- or M-type dwarf companion to the G0 IV subgiant primary, which would indicate a brightness difference of at least $\Delta K \approx 4.5$, a substantially greater value than that indicated by Vansina & de Greve (1982), and one consistent with the speckle nondetections. Abt & Levy (1976) also cite an earlier astrometric detection (Daniel & Burns 1939), although this seems unlikely, given both the expected separation and the brightness ratio. The spectroscopy of Brown et al. (1997) indicates that η Boo's barycentric velocity is being influenced by binarity, which Christensen-Dalsgaard et al. (1995) have suggested is indeed due to a M dwarf.

Nevertheless, given the higher resolution of PTI, a possible close-separation secondary companion may affect our measures of η Boo's V^2 and thereby complicate our interpretation. As such, it was prudent for us to examine our data for evidence of ΔV^2 excursions that would be indicative of binarity. As seen in Figure 1 and the data contained in Table 2, the η Boo V^2 data are consistent with a single-star hypothesis, incorporating a wide range of (u, v) coverage and dates.

To explore to what extent a secondary star could be hidden within our data points, we examined in detail the residuals found in our single-star fit, as seen in the bottom panel of Figure 1. We began by creating a synthetic V^2 data set corresponding to a single star observed by PTI with $\theta_{\rm LD} = 2.2$ mas, to which we added varying amounts of measurement noise. We then characterized the V^2 residuals through use of a histogram created through averaging two dozen runs of this synthesis, stepping through the residual values in increments of $\Delta\sigma_{V^2} = 0.01$, and comparing that histogram to that of our actual data. We found that the best fit was for measurement noise at the $\sigma_{V^2} = 0.018$ level, with a reduced χ^2 fit value of $\chi^2_\nu = 1.66$, consistent with our expectation for PTI data as discussed in § 3.1.

We then repeated this process, including measurement noise at the $\sigma_{V^2} = 0.018$ level but also adding a main-sequence stellar companion of varying spectral type, using standard values of luminosity and color from Cox (2000), and constraining the orbital parameters to match the reported period of $P = 494$ days. The reduced χ^2 fit value increased as expected as the mass of the putative companion increased, but we could not exclude a possible companion of spectral type M7 and lower in a statistically meaningful way. The net result of any potential V^2 bias of a M7 companion with $\Delta K \approx 5.5$ would be to decrease the actual size of the η Boo primary by 0.014 mas. As such, we are including an additional, negative error in our calculations for the absolute parameters of η Boo to account for our uncertainty regarding this possible companion.

Given the long time baseline of V^2 measures that are present in our full data set, it seems unlikely that chance geometric alignment would persist in making a secondary companion not appear in the form of ΔV^2 excursions. It is still entirely possible that a secondary companion is present, but at a brightness ratio that makes it not a factor in determining η Boo's size ($L_2/L_1 < 0.005$), which is consistent with the original Bertiau (1957) result.

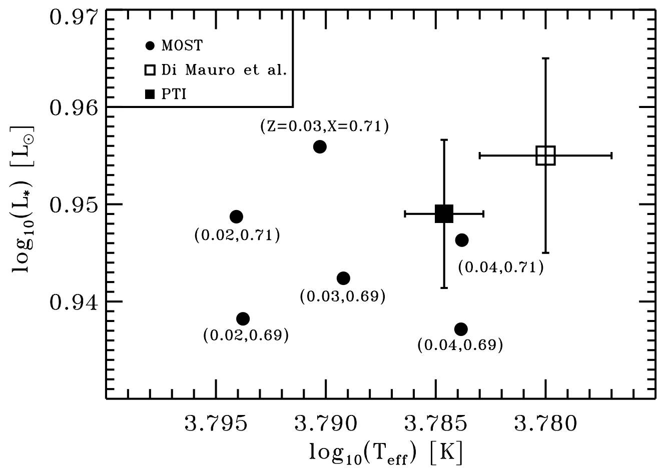

FIG. 3.—Comparison of *MOST* fits to luminosity and effective temperature values determined in this study ("PTI") and those of Di Mauro et al. (2003). The *MOST* fit corresponding to a model composition of ($X = 0.71$, $Z = 0.04$) was within the error ellipse of this study's ($\log L = 0.9490 \pm 0.0076$, $\log T = 3.7853 \pm 0.0020$) coordinates and was ultimately favored in Guenther et al. (2005) as the best fit to their data.

5. DISCUSSION OF THE ASTROPHYSICAL PARAMETERS OF η BOO

Placing η Boo on a H-R diagram, just as was done in Guenther et al. (2005; see their Fig. 6), we may compare our values for the star's luminosity and effective temperature to those best fitted to the *MOST* data. We have highlighted this region of interest in Figure 3. We find that our ($\log L = 0.9490 \pm 0.0076$, $\log T = 3.7853 \pm 0.0020$) coordinates fall within the locus of points defined by the models of the *MOST* team. The error ellipse of our ($\log L$, $\log T$) derived from the PTI data encompasses the *MOST* ($X = 0.71, Z = 0.04$)-composition model point, which ultimately was favored by Guenther et al. as the best fit to their *MOST* data.

The ($\log L$, $\log T$) coordinates defined by Di Mauro et al. (2003) were sufficiently displaced from all of the possible *MOST* coordinates that Guenther et al. suggested that the Di Mauro et al. (2003) coordinates were incorrect. Our η Boo data and analysis are clearly consistent with this suggestion by Guenther et al. (2005).

5.1. *Surface Gravity of η Boo*

With the mass for η Boo established from the asteroseismic constraints of *MOST*, and the radius determined from interferometric observations, we may directly establish the surface gravity for η Boo:

$$g = \frac{GM}{R^2}. \tag{3}$$

Using the *MOST*-derived mass of $M = 1.71 \pm 0.05\ M_\odot$ and the PTI-derived radius of $R = 2.672 \pm 0.024\ R_\odot$, we derive a surface gravity of $\log g = 3.817 \pm 0.015$ [cm s^{-2}].

The PTI $\log g$ result for η Boo is in significant disagreement with the "trigonometric" gravities found in Allende Prieto et al. (1999), who found a value of $\log g = 3.47 \pm 0.10$ [cm s^{-2}]. Malagnini & Morossi (1990) quote a value of $\log g = 3.8 \pm 0.15$ [cm s^{-2}] from stellar evolution theories, although the angular size, radius, and mass values on which their theories were based are divergent from the PTI and *MOST* results at the 10%–20%

level. The study by Laird (1985) using photometric and spectrophotometric data for $T_{\rm eff}$ and Strömgren photometry plus intermediate-dispersion spectra for log g is in reasonable agreement with our values, quoting values of $T_{\rm eff} = 5930 \pm 70$ K and $\log g = 3.71 \pm 0.15$ [cm s^{-2}]. Similarly, Morossi et al. (2002) find a value of $\log g = 3.71 \pm 0.13$ [cm s^{-2}] using ultraviolet-visual spectrophotometry. In all of these cases, indirect measures of log g and other astrophysical parameters are overshadowed by the more direct, empirical methods afforded by the unique capabilities of PTI and *MOST*.

6. CONCLUSIONS

While considerably more accurate, our angular diameter determination is statistically consistent with the earlier measurement from Thévenin et al. (2005), an apparent indication that these results are free from systematic errors at their stated level of uncertainty. Our angular diameter and bolometric flux values have led to an effective temperature and luminosity for the evolved star η Boo that is in direct agreement with those established by the *MOST* asteroseismology mission. Furthermore, in conjunction with the *MOST* value for its stellar mass, a measure of its stellar surface gravity may be made.

The combination of the precise mass estimate from *MOST* and the accurate radius measure of PTI has allowed us to derive a precise value of the surface gravity for η Boo. The measurement of the surface gravity for η Boo, independent of spectroscopy, is a significant demonstration of the astrophysical investigative value of combining high spatial resolution interferometry with high temporal resolution photometry. Of the determinations of log g for η Boo in the literature, we find that our value has a claimed precision that is an order of magnitude greater than previous measures.

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REFERENCES

Abt, H. A., & Levy, S. G. 1976, ApJS, 30, 273
Allende Prieto, C., García López, R. J., Lambert, D. L., & Gustafsson, B. 1999, ApJ, 527, 879
Bertiau, F. C. 1957, ApJ, 125, 696
Boden, A. F., Colavita, M. M., van Belle, G. T., & Shao, M. 1998, Proc. SPIE, 3350, 872
Boden, A. F., et al. 1999, ApJ, 515, 356
Bonneau, D., Blazit, A., Foy, R., & Labeyrie, A. 1980, A&AS, 42, 185
Brown, T. M., Kennelly, E. J., Korzennik, S. G., Nisenson, P., Noyes, R. W., & Horner, S. D. 1997, ApJ, 475, 322
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cayrel de Strobel, G., Soubiran, C., Friel, E. D., Ralite, N., & Francois, P. 1997, A&AS, 124, 299
Cayrel de Strobel, G., Soubiran, C., & Ralite, N. 2001, A&A, 373, 159
Christensen-Dalsgaard, J., Bedding, T. R., & Kjeldsen, H. 1995, ApJ, 443, L29
Claret, A., Diaz-Cordoves, J., & Gimenez, A. 1995, A&AS, 114, 247
Claret, A., & Hauschildt, P. H. 2003, A&A, 412, 241
Cohen, M., Walker, R. G., Carter, B., Hammersley, P., Kidger, M., & Noguchi, K. 1999, AJ, 117, 1864
Colavita, M. M. 1999, PASP, 111, 111
Colavita, M. M., et al. 1999, ApJ, 510, 505
Cox, A. N., ed. 2000, Allen's Astrophysical Quantities (4th ed.; New York: AIP)
Cutri, R. M., et al. 2003, 2MASS All Sky Catalog of Point Sources (Pasadena: IPAC)
Daniel, Z., & Burns, K. 1939, Pub. AAS, 9, 146
Davis, J., Tango, W. J., & Booth, A. J. 2000, MNRAS, 318, 387
Di Mauro, M. P., Christensen-Dalsgaard, J., Kjeldsen, H., Bedding, T. R., & Patern, L. 2003, A&A, 404, 341
Dyck, H. M., Benson, J. A., van Belle, G. T., & Ridgway, S. T. 1996, AJ, 111, 1705
Eggen, O. J. 1963, AJ, 68, 483
———. 1972, ApJ, 175, 787
Guenther, D. B., et al. 2005, ApJ, 635, 547
Halbwachs, J. L. 1981, A&AS, 44, 47
Hanbury Brown, R., Davis, J., Lake, R. J. W., & Thompson, R. J. 1974, MNRAS, 167, 475
Hartkopf, W. I., & McAlister, H. A. 1984, PASP, 96, 105
Johnson, H. L. 1968, in Stars and Stellar Systems 7, Nebulae and Interstellar Matter, ed. B. M. Middlehurst & L. H. Aller (Chicago: Univ. Chicago Press), 167
Kjeldsen, H., Bedding, T. R., Viskum, M., & Frandsen, S. 1995, AJ, 109, 1313
Kjeldsen, H., et al. 2003, AJ, 126, 1483
Laird, J. B. 1985, ApJS, 57, 389
Malagnini, M. L., & Morossi, C. 1990, A&AS, 85, 1015
Marcy, G. W., & Butler, R. P. 1996, ApJ, 464, L147
McAlister, H. A. 1978, PASP, 90, 288
McAlister, H. A., Hartkopf, W. I., & Mason, B. D. 1992, AJ, 104, 1961
Moreno, H. 1971, A&A, 12, 442
Morossi, C., Di Marcantonio, P., Franchini, M., Malagnini, M. L., & Chavez, M. 2002, ApJ, 577, 377
Mozurkewich, D., et al. 1991, AJ, 101, 2207
———. 2003, AJ, 126, 2502
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Pickles, A. J. 1998, PASP, 110, 863
Piirola, V. 1976, Obs. Astrophys. Lab. Univ. Helsinki Rep., 1
Reiners, A. 2006, A&A, 446, 267
Rufener, F. 1976, A&AS, 26, 275
Straka, C. W., Demarque, P., Guenther, D. B., Li, L., & Robinson, F. J. 2006, ApJ, 636, 1078
Thévenin, F., Kervella, P., Pichon, B., Morel, P., di Folco, E., & Lebreton, Y. 2005, A&A, 436, 253
van Belle, G. T., Ciardi, D. R., Thompson, R. R., Akeson, R. L., & Lada, E. A. 2001, ApJ, 559, 1155
van Belle, G. T., & van Belle, G. 2005, PASP, 117, 1263
van Belle, G. T., et al. 1999, AJ, 117, 521
Vansina, F., & de Greve, J. P. 1982, Ap&SS, 87, 377
Walker, G., et al. 2003, PASP, 115, 1023
Zdanavicius, K., et al. 1972, Vilnius Astron. Obs. Biuletenis, 34, 3