TESTING STELLAR MODELS WITH AN IMPROVED PHYSICAL ORBIT FOR 12 BOOTIS

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Received 2004 November 30; accepted 2005 February 8

ABSTRACT

In a previous paper we reported on the binary system 12 Bootis and its evolutionary state. In particular, the 12 Boo primary component is in a rapid phase of evolution; hence accurate measurement of its physical parameters makes it an interesting test case for stellar evolution models. Here we report on a significantly improved determination of the physical orbit of the double-lined spectroscopic binary system 12 Boo. We have a 12 Boo interferometry data set spanning 6 yr with the Palomar Testbed Interferometer, a smaller amount of data from the Navy Prototype Optical Interferometer, and a radial velocity data set spanning 14 yr from the Harvard-Smithsonian Center for Astrophysics. We have updated the 12 Boo physical orbit model with our expanded interferometric and radial velocity data sets. The revised orbit is in good agreement with previous results, and the physical parameters implied by a combined fit to our visibility and radial velocity data result in precise component masses and luminosities. In particular, the orbital parallax of the system is determined to be 27.72 ± 0.15 mas, and masses of the two components are determined to be 1.4160 ± 0.0049 and 1.3740 ± 0.0045 $M_\odot$, respectively. These mass determinations are more precise than those in the previous report by a factor of 4–5. As indicated in the previous publication, even though the two components are nearly equal in mass, the system exhibits a significant brightness difference between the components in the near-infrared and visible. We attribute this brightness difference to evolutionary differences between the two components in their transition between main-sequence and giant evolutionary phases, and based on theoretical models, we can estimate a system age of approximately 3.2 Gyr. Comparisons with stellar models suggest that the 12 Boo primary may be just entering the Hertzsprung gap, but that conclusion is highly dependent on details of the models. Such a dynamic evolutionary state makes the 12 Boo system unique and important test for stellar models.

Subject headings: binaries: spectroscopic — binaries: visual — stars: evolution — stars: individual (12 Bootis)

Online material: machine-readable tables

1. INTRODUCTION

12 Bootis (d Bootis, HR 5304, HD 123999, HIP 69226) is a short-period (9.6 days) binary system with nearly equal mass ($q \sim 0.97$) components. The system was first detected as a radial velocity variable over 100 years ago (Campbell & Wright 1900), and the first “good” double-lined orbit was calculated by Abt & Levy (1976). The Abt & Levy (1976) orbit has been confirmed by an independent CORAVEL radial velocity orbit by De Medeiros & Udry (1999, hereafter DU99, data from which was used in Boden et al. 2000). The composite system has been consistently assigned the spectral type F8 IV–F9 IVw, the latter by Barry (1970), with the “w” indicating weak ultraviolet metallic features. All studies seem to confirm that 12 Boo has heavy-element abundances near solar proportions (Duncan 1981; Balachandran 1990; Lébre et al. 1999; Nordström et al. 2004).

Previously we reported a physical orbit model for the 12 Boo system (Boden et al. 2000, hereafter Paper I). Paper I discussed the interesting evolutionary state of the 12 Boo component; despite the nearly equal mass ratio, the 12 Boo components exhibit an unusual intensity ratio because of their positions on the Hertzsprung-Russel diagram. However, the orbit model of Paper I relied on rather limited radial velocity data. Given this shortcoming and the favorable geometry of the 12 Boo system for high-precision study, we decided to refine the orbit model in order to fully exploit the 12 Boo components as a test of stellar models. Consequently, herein we report on a significantly improved determination of the 12 Boo physical orbit from an expanded set of near-infrared, long-baseline interferometric measurements taken with the Palomar Testbed Interferometer (PTI) and Navy Prototype Optical Interferometer (NPOI), and a large set of new spectroscopic radial velocity measurements obtained at the Harvard-Smithsonian Center for Astrophysics (CfA).

In the following we discuss the new observations (§ 2) and the orbit model (§ 3) and physical properties (§ 4) derived from them, and we compare the component properties with stellar models (§ 5). We summarize our findings in § 6.

2. OBSERVATIONS

2.1. Interferometry

As in Paper I, the interferometric observable used for these measurements is the fringe contrast or visibility (squared) of an observed brightness distribution on the sky. PTI was used to make the interferometric measurements presented here; PTI is a long-baseline $H$- ($1.6 \mu m$) and $K$-band ($2.2 \mu m$) interferometer located at Palomar Observatory and described in detail elsewhere (Colavita et al. 1999). The analysis of such data in the context of a binary system is discussed in detail in Paper I and elsewhere (e.g., Hummel et al. 2001) and is not repeated here.

12 Boo was observed in conjunction with objects in our calibrator list by PTI in $K$ band ($\lambda \sim 2.2 \mu m$) on 67 nights between 1998 June 21 and 2004 June 18, a data set covering roughly 6 yr and 228 orbital periods. In addition, 12 Boo was observed by PTI in $H$ band ($\lambda \sim 1.6 \mu m$) on 12 nights between 1999 May 28 and 2001 June 15. 12 Boo, along with calibration objects, was
usually observed multiple times during each of these nights, and each observation, or scan, was approximately 130 s long. For each scan we computed a mean \( V^2 \) value from the scan data, and the error in the \( V^2 \) estimate from the rms internal scatter (Colavita 1999). 12 Boo was always observed in combination with one or more calibration sources within \( \sim 10^\circ \) on the sky. As in Paper I, here we have used three stars as calibration objects: HD 121107 (G5 III), HD 128167 (F2 V), and HD 123612 (K5 III). Table 1 lists the relevant physical parameters for the calibration objects.

The calibration of 12 Boo \( V^2 \) data is performed by estimating the interferometer system visibility \( V^2_{\text{sys}} \) using calibration sources with model angular diameters and then normalizing the raw 12 Boo visibility by \( V^2_{\text{sys}} \) to estimate the \( V^2 \) measured by an ideal interferometer at that epoch (Mozurkewich et al. 1991; Boden et al. 1998). Calibrating our 12 Boo data set with respect to the three calibration objects listed in Table 1 results in a total of 303 calibrated scans (258 in \( K \), 46 in \( H \)) on 12 Boo over 78 nights, roughly quadrupling the visibility data set from Paper I. Our calibrated synthetic wide-band \( V^2 \) measurements are summarized in Table 2. In particular, all \( V^2 \) data from Paper I are also contained in Table 2 and used in this analysis. Table 2 gives \( V^2 \) measurements and times, measurement errors, residuals, between our data and orbit model (Table 4) predictions, the photon-weighted average wavelength, \( u-v \) coordinates, and on-target hour angle for each of our calibrated PTI 12 Boo \( V^2 \) observations.

In addition to the PTI visibility data, we have obtained new visibility and closure-phase data on 12 Boo with the NPOI (Armstrong et al. 1998; Hummel et al. 2003). NPOI observed 12 Boo and calibrator HD 128167 (Table 1) on 13 nights from 2001 April 9 through 2001 June 28 inclusive. On five nights, the NPOI C, E, and W stations were used with a maximum baseline of 38 m, and on all other nights the W7, E, and W stations with a maximum baseline of 64 m were used. The data were taken in 10 narrowband channels spanning a passband between 650 and 850 nm. Unlike the single-baseline PTI \( V^2 \) data, NPOI data were all taken simultaneously using three NPOI baselines; in addition to visibility amplitude, such data provide phase-closure information. In particular, the NPOI phase-closure data break the \( \Omega \) inversion degeneracy inherent in the PTI \( V^2 \) (see §3). The NPOI data were reduced and calibrated according to the standard procedures outlined by Hummel et al. (1998).

### 2.2. Spectroscopy

The largest shortcoming in the orbit model from Paper I was the limited and inhomogeneous radial velocity (RV) data. To improve this situation we have obtained 49 new high-resolution spectra of the 12 Boo system at CfA, with an échelle spectrograph mounted at the Cassegrain focus of the 1.5 m Wyeth reflector at the Oak Ridge Observatory (Harvard, Massachusetts). The resolving power of this instrument is \( \lambda/\Delta \lambda \approx 35,000 \). A single échelle order spanning 45 Å was recorded with a photon-counting Reticon detector, at a central wavelength of 5188.5 Å, near the Mg \( i \) triple.

12 Boo observations were carried out between 1987 June and 2001 April, spanning nearly 14 yr and 526 system periods.

Component velocities were determined from the spectra using the TODCOR two-dimensional cross-correlation technique (Zucker & Mazeh 1994), with synthetic templates for each star based on Kurucz model atmospheres.5 The optimal parameters for the templates (mainly effective temperature and rotational

### TABLE 2

**12 Boo PTI \( V^2 \) Data Set and Residuals with Full-Fit Orbit Model**

| Cal Date (UTC) | Measured \( V^2 \) | Error | Residual | \( \alpha \) | \( \delta \) | HA (hr) |
|---------------|-----------------|-------|----------|----------|--------|-------|
| MJD 50985.1681| 2.201           | 0.300 | 0.022    | 0.006    | -36.90 | -101.78| 0.014 |
| MJD 50985.1847| 2.201           | 0.436 | 0.027    | 0.021    | -30.47 | -103.27| 0.413 |
| MJD 51007.1544| 2.202           | 0.745 | 0.039    | 0.029    | -18.13 | -105.21| 1.131 |
| MJD 51007.1652| 2.201           | 0.750 | 0.037    | -0.013   | -13.49 | -105.67| 1.390 |
| MJD 51008.1611| 2.198           | 0.940 | 0.100    | 0.076    | -14.06 | -105.62| 1.359 |
| MJD 51008.1747| 2.200           | 0.972 | 0.093    | 0.062    | -8.15  | -106.02| 1.684 |
| MJD 51009.1677| 2.192           | 0.509 | 0.044    | 0.070    | -10.01 | -105.92| 1.582 |
| MJD 51009.1871| 2.190           | 0.734 | 0.080    | 0.145    | -1.44  | -106.22| 2.050 |
| MJD 51009.1888| 2.189           | 0.647 | 0.062    | 0.045    | -0.73  | -106.22| 2.089 |
| MJD 51237.4622| 2.199           | 0.758 | 0.137    | 0.062    | -42.40 | -100.17| -0.349|

Notes.— Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Residuals are quoted as data minus model.
velocity were determined by seeking the best match to the observed spectra as judged from the peak cross-correlation value averaged over all exposures. We obtained $\sin i$ values of 14 and 12 km s$^{-1}$ for the primary (more massive star) and secondary, respectively, with estimated errors of 1 km s$^{-1}$. The effective temperatures are sensitive to the adopted surface gravity and chemical composition. For estimated log $g$ values of 3.8 and 4.0 (see §4), we obtained by interpolation temperatures of 6130 and 6230 K for the primary and secondary with adopted uncertainties of 100 and 150 K, respectively. These are in good agreement with photometric estimates for 12 Boo ($\sin i$ uncertainties of 100 and 150 K, respectively). The final radial velocities are given in Table 3, which gives measured primary and secondary velocities and associated uncertainties, residuals between the measurements and predictions from our orbit model (Table 4), and model phase.

### Table 3

| MJD (day) | Primary RV (km s$^{-1}$) | Primary Error (km s$^{-1}$) | Secondary RV (km s$^{-1}$) | Secondary Error (km s$^{-1}$) | Primary Residual | Secondary Residual | Orbit Phase |
|-----------|--------------------------|----------------------------|-----------------------------|-------------------------------|-----------------|-------------------|-------------|
| 46966.200 | 64.62                    | 0.47                       | -47.95                      | 0.54                          | -0.27           | -0.47             | 0.255       |
| 47642.344 | -43.04                   | 0.47                       | 62.81                       | 0.54                          | -0.37           | -0.56             | 0.654       |
| 47665.226 | 52.78                    | 0.47                       | 35.11                       | 0.54                          | -0.04           | -0.06             | 0.036       |
| 47688.202 | 15.68                    | 0.47                       | 3.92                        | 0.54                          | 0.87            | -0.21             | 0.428       |
| 47730.096 | -53.18                   | 0.47                       | 74.29                       | 0.54                          | 0.04            | 0.05              | 0.790       |
| 47778.994 | -33.13                   | 0.47                       | 54.41                       | 0.54                          | 0.30            | 0.56              | 0.881       |
| 47894.466 | -23.75                   | 0.47                       | 43.51                       | 0.54                          | -0.04           | -0.32             | 0.904       |
| 47922.433 | -50.83                   | 0.47                       | 71.48                       | 0.54                          | -0.28           | -0.01             | 0.816       |
| 47953.389 | 54.18                    | 0.47                       | -35.64                      | 0.54                          | -0.07           | 0.87              | 0.039       |
| 47989.272 | -53.67                   | 0.47                       | 74.92                       | 0.54                          | 0.24            | -0.03             | 0.775       |

Note.—Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Residuals are quoted as data minus model.

### Table 4

| Orbital Parameter | DU99 | Paper I Full Fit | K-band $V^2$ Only | RV Only | Full Fit |
|-------------------|------|-----------------|-----------------|---------|---------|
| Period (days)      | 9.6046 ± 1×10$^{-4}$ | 9.604565 ± 1.0×10$^{-5}$ | 9.604638 ± 5.9×10$^{-5}$ | 9.6045518 ± 8.6×10$^{-6}$ | 9.6045492 ± 7.6×10$^{-6}$ |
| $T_0$ (MJD)        | 48990.29 ± 0.03 | 51237.779 ± 0.024 | 51237.759 ± 0.0086 | 51237.779 ± 0.0090 | 51237.7729 ± 0.0051 |
| $e$                | 0.193 ± 0.004  | 0.1884 ± 0.0022 | 0.1895 ± 0.0022 | 0.19256 ± 0.00099 | 0.19233 ± 0.00086 |
| $K_1$ (km s$^{-1}$) | 67.11 ± 0.41  | 67.84 ± 0.31 | ... | 67.320 ± 0.090 | 67.302 ± 0.087 |
| $K_2$ (km s$^{-1}$) | 70.02 ± 0.48  | 69.12 ± 0.48 | ... | 69.38 ± 0.10 | 69.36 ± 0.10 |
| $\gamma$ (km s$^{-1}$) | 9.29 ± 0.19  | 9.11 ± 0.13 | ... | 9.550 ± 0.051 | 9.551 ± 0.051 |
| $\omega_0$ (deg)   | 286.19 ± 1.31 | 287.03 ± 0.75 | 286.85 ± 0.35 | 286.92 ± 0.35 | 286.67 ± 0.19 |
| $\Omega$ (deg)     | ... | 79.83 ± 0.45 | 80.49 ± 0.12 | ... | 80.291 ± 0.079 |
| $i$ (deg)          | ... | 108.58 ± 0.36 | 108.15 ± 0.12 | ... | 107.990 ± 0.077 |
| $a$ (mas)          | ... | 3.392 ± 0.050 | 3.449 ± 0.018 | ... | 3.451 ± 0.018 |
| $M_{J20}$ (mag)    | ... | 0.618 ± 0.022 | 0.593 ± 0.006 | ... | 0.589 ± 0.005 |
| $H_{J20}$ (mag)    | ... | 0.566 ± 0.066 | ... | ... | 0.560 ± 0.020 |
| $\Delta K_{CTT}$ (mag) | ... | ... | ... | ... | ... |
| $\Delta H_{CTT}$ (mag) | ... | ... | ... | ... | ... |
| $M_{J20}$ (mag)    | ... | ... | ... | ... | ... |
| $\chi^2$/DOF       | 0.5 ± 0.1 | 0.82 | 1.0 | ... | 0.85 |
| $\frac{RV_1}{RV_2}$ | 0.023 | 0.017/0.027 | 0.017/0.027 | ... | ... |
| $R_{RV}/\sigma_RV$ (km s$^{-1}$) | 0.90 | 1.7 | 0.39/0.49 | 0.40/0.49 | ... |

Notes.—Summarized here are the apparent orbital parameters for the 12 Boo system as determined by DU99, Paper I, and present results. We give three separate fits to our data: $K$-band $V^2$ only, RV only, and integrated (full fit). Note that $\omega_0$ refers to the argument of periastron of the primary component, and (unlike Paper I) $A$ values are the position angle of the ascending node.
diameters here were held fixed at photometrically estimated values; see § 4). Given the well-established 12 Boo model from Paper I, the additional data presented here are straightforwardly used to refine the previous orbit model.

In general, the NPOI data were found to agree well with the orbit estimated from the PTI \( V^2 \) and RV data. However, with the exception of the closure phases these data did little to further constrain the orbit parameters. Therefore, we have adopted the general orbit orientation (i.e., \( \Omega \)) indicated by the NPOI closure phases, but the high-precision orbital parameters are derived solely from the PTI \( V^2 \) (Table 2) and RV (Table 3) data.

Figure 1 depicts the relative visual orbit of the 12 Boo system, with the primary component rendered at the origin, and the secondary component rendered at periastron. We have indicated the phase coverage of our \( V^2 \) data on the relative orbit with heavy lines; our data cover essentially all phases of the orbit, leading to a reliable orbit determination. Note that relative to Paper I the orbit is inverted around the origin; the \( V^2 \) data used in Paper I and here are invariant under a mirror reflection of the component relative positions and thus do not distinguish between the two orbit orientations. The \( V^2 \) observable degeneracy was noted in Paper I (in particular, see the notes to Paper I, Table 5) and is broken by the addition of the closure phase data from NPOI. Figure 1 thus depicts the 12 Boo orbit as it appears on the sky.

Tables 2 and 3 list the constituent set of \( V^2 \) and RV measurements in our 12 Boo data set, and residuals (in a datum minus model sense) between the observables and predictions based on the best-fit integrated orbit model (our “full-fit” model; Table 4) for 12 Boo. Figures 2 and 3 illustrate the results of our orbit modeling for 12 Boo. Figure 2 depicts phased RV measurements and the primary and secondary radial velocity orbits from our integrated model. Inset in the lower frame are phased velocity residuals (datum minus model). Figure 3 depicts the phase coverage of our visibility and radial velocity data and the statistics of our modeling residuals. The agreement between our various data and our orbit model is excellent; our full-fit solution results in a total \( \chi^2 \) per degree of freedom in our fit of 0.85 (suggesting that we may have overestimated our measurement errors). The resulting rms \( V^2 \) and RV measurement residuals from our model are 0.027 and 0.49 km s\(^{-1}\), respectively.

Orbit models for 12 Boo are summarized in Table 4, including spectroscopic orbit parameters from DU99, the integrated model from Paper I, and our present visual, spectroscopic, and integrated orbit models. In particular, we list the results of separate fits to only our \( K \)-band \( V^2 \) data (our “\( V^2 \) Only” solution), our double-lined radial velocity data (our “RV Only” solution), and...
a simultaneous fit to our $V^2$ and RV data (our full-fit solution)—all with component diameters constrained as noted above. For the orbit parameters that we have estimated from our visibility data we list a total 1σ error in the parameter estimate, including errors in the parameter estimates from statistical (measurement uncertainty) and systematic error sources. In our analysis the dominant forms of systematic error are (1) uncertainties in the calibrator angular diameters (Table 1), (2) uncertainty in the center-band operating wavelength ($\lambda_0 \approx 2.2 \mu m$), taken to be 10 nm (∼0.5%), (3) the geometrical uncertainty in our interferometric baseline (<0.01%), and (4) uncertainties in ancillary parameters constrained in our orbit-fitting procedure (i.e., the angular diameters in all solutions involving interferometry data). For example, our angular semimajor axis error is completely dominated by the operating wavelength uncertainty; the statistical error is a factor of 5 smaller.

In addition to the overall orientation, the NPOI data have been used to estimate the component in-band intensity ratio, constraining to the relevant orbital parameters from the Full Fit solution. The 750 nm intensity ratio is constrained by the NPOI

Fig. 3.——Orbit fit residuals for 12 Boo. (a) Orbit phase plots of $K$ and $H$-band $V^2$ fit residuals, and residual histograms for the full-fit orbit model. (b) Orbit phase plots of radial velocity fit residuals, and residual histograms for the full-fit orbit model (Table 4).
4. PHYSICAL PARAMETERS

Physical parameters derived from our 12 Boo full-fit integrated visual/spectroscopic orbit are summarized in Table 5. Notable among these is the high-precision determination of the component masses for the system, a virtue of the favorable geometry of the orbit and the quality of the visibility and radial velocity data sets. We estimate the masses of the primary and secondary components as $1.4160 \pm 0.0049$ and $1.3740 \pm 0.0045 \ M_\odot$, respectively. These are in good agreement (approximately 1.0 and 1.7 $\sigma$ for the primary and secondary, respectively) with the component mass estimates given in Paper I.

The *Hipparcos* catalog lists the parallax of 12 Boo as 27.27 $\pm$ 0.78 mas (ESA 1997). The distance determination to 12 Boo based on our orbital solution is 36.08 $\pm$ 0.19 pc, corresponding to an orbital parallax of 27.72 $\pm$ 0.15 mas, consistent with the *Hipparcos* result at 1.7% and 0.6 $\sigma$.

A number of metallicity estimates for 12 Boo exist in the literature that appear to indicate a composition near solar. Photometric estimates by Duncan (1981), Balachandran (1990), and Nordström et al. (2004) give [Fe/H] values of $-0.03 \pm 0.12$, $-0.06$, and $-0.12$, respectively, and are based on Strömgren $ubvy\beta$ or $\delta (U-B)_{0.2}$ indices. Although the object was recognized as a binary in these investigations, no corrections for this were made. The effect is expected to be small in any case, as the two components have very similar temperatures. Spectroscopic determinations of the metallicity have been reported by Balachandran (1990) and Lébre et al. (1999) as $[Fe/H] = -0.03 \pm 0.09$ and $-0.1 \pm 0.1$, respectively. Once again, the binary nature of 12 Boo was known to these investigators, although Balachandran (1990) reported not detecting the secondary in their spectra. The effect would be to make the spectral lines appear somewhat weaker, since the secondary ($L_{sec}/L_{prim} = 0.64$) would tend to fill in the lines of the primary. Overall there is good agreement in that all these studies place the metallicity of 12 Boo within 0.1 dex of solar. This metallicity range is an important constraint we use below in the comparison with stellar evolution models.

4.1. Component Diameters, Effective Temperatures, and Radii

The “effective” angular diameter of the 12 Boo system has been estimated using the infrared flux method by Blackwell and collaborators (Blackwell et al. 1990; Blackwell & Lysa-Gray 1994) at approximately 0.8 mas. At this size, neither of the 12 Boo components are resolved by PTI, and we must resort to model diameters for the component stars. Following Blackwell, we estimate 12 Boo component diameters through bolometric flux and effective temperature ($T_{eff}$) arguments. Blackwell & Lysa-Gray (1994) list the bolometric flux of the 12 Boo system at $3.11 \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$, and $T_{eff}$ as 6204 K, both quoted without error estimates. Similarly, we have analyzed archival photometry available from SIMBAD, 2MASS, and Paper I using an empirical model atmosphere for a solar-metallicity F8 IV star taken from Pickles (1998). Figure 4 depicts the results of this spectral energy distribution (SED) modeling, resulting in a bolometric flux estimate of $(3.074 \pm 0.021) \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$ in reasonable agreement with the Blackwell & Lysa-Gray (1994) result—and providing a plausible error estimate.

As a check on our spectroscopic effective temperature estimates we have made additional estimates of the 12 Boo component effective temperatures from the component colors. The interferometric and spectroscopic observations provide $V - K$ color indices for the components individually (Table 5). With these color indices we have used effective temperature/color calibrations published by Blackwell & Lysa-Gray (1994) and Alonso et al. (1996; with the component $K$ magnitudes transformed to the Johnson system). The resulting component effective temperature estimates are in excellent agreement with our adopted spectroscopic values (§ 2, Table 5).
Estimating the bolometric flux ratio from the observed $K$-band flux ratio and component effective temperatures provide bolometric flux estimates for the two components individually (Table 5), and these along with the effective temperatures allow us to estimate angular diameters of $0.638 \pm 0.025$ and $0.480 \pm 0.039$ mas for the primary and secondary components, respectively. At the distance estimate to 12 Boo these model angular diameters correspond to model component linear radii of $2.474 \pm 0.095$ and $1.86 \pm 0.15 R_\odot$ for the primary and secondary components, respectively. Finally, coupled with our component masses we find (log) surface gravities of $3.802 \pm 0.033$ and $4.036 \pm 0.070$ dex. All these estimates are in good agreement with (and more precise than) the results from Paper I. These linear radii estimates are roughly a factor of 2 smaller than the putative Roche lobe radii for these two stars (Iben 1991, eq. [1]), making significant mass transfer unlikely at this stage of system evolution.

4.2. Component Rotation

Tidal interaction theory predicts that in short-period binary systems the components gravitationally interact so as to circularize the orbit and synchronize the component rotations to the orbital period (Zahn 1977; Hut 1981). These predictions are borne out in observation (e.g., Duquennoy & Mayor 1991). The circularization and synchronization phenomena necessarily require an energy dissipation mechanism, generally thought to be associated with convection in the outer envelopes of cool stars such as giants (Verbunt & Phinney 1995).

Paper I noted that 12 Boo is interesting from a tidal interaction perspective; despite the relatively short orbital period the system orbit is modestly eccentric (Table 4). The component masses indicate both components were around F1–F3 at their initial appearance on the main sequence; the putative reason for the remnant orbital eccentricity is the lack of strong convection in the atmospheres during the components’ main-sequence lives. However, as the 12 Boo components evolve off the main sequence, their atmospheres become much more convective, and tidal circularization and synchronization should begin. Once the component atmospheres become fully convective, the timescale for rotation synchronization will be short (~1 Myr for the primary; Paper I).

Several recent measurements of the rotation $v \sin i$ of 12 Boo components exist, offering the possibility of assessing whether the two components are currently synchronously rotating. These 12 Boo component rotation measurements are summarized in Table 6. As in Paper I, the consensus remains that both 12 Boo components appear to be rotating in a manner consistent with

| Reference                  | Primary $v \sin i$ (km s$^{-1}$) | Secondary $v \sin i$ (km s$^{-1}$) |
|----------------------------|---------------------------------|-----------------------------------|
| Balachandran (1990)         | 10 ± 3                          | …                                 |
| De Medeiros et al. (1997)   | 12.7 ± 1                        | …                                 |
| DU99                       | 12.5 (± 1)                      | 9.5 (± 1)                         |
| Paper I                    | 13.1 ± 0.3                      | 10.4 ± 0.3                        |
| Shorlin et al. (2002)       | 14.0 ± 3.0                      | 12.0 ± 3.0                        |
| Reiners & Schmitt (2003)    | 15.0 ± 1.0                      | …                                 |
| This work                  | 14.0 ± 1.0                      | 12.0 ± 1.0                        |
| Model synth rotation       | 12.4 (± 1.1)                    | 9.3 (± 0.8)                       |
| Model pseudo-synch rotation | 15.2 (± 1.4)                    | 11.4 (± 1.0)                      |

Notes.—Summarized here are recent $v \sin i$ measurements for the 12 Boo system components, including this work. For references where a single $v \sin i$ measurement is listed we have assumed this pertains to the primary component. DU99 does not list errors for their component $v \sin i$ estimates; we have arbitrarily taken 1 km s$^{-1}$ so as to be consistent with the characteristic accuracies of earlier CORAVEL determinations (see discussions in De Medeiros et al. 1996, 1997). For comparison, we give model estimates of $v \sin i$ for synchronous and pseudosynchronous rotation of the two components given the physical sizes discussed in § 4. Both 12 Boo components would appear to be rotating at rates consistent with synchronous rotation.
synchronous rates. Within the errors and the scatter of the measurements, the secondary $v \sin i$ is also consistent with the pseudo-synchronous rate (synchronous with the orbital motion at periastron; Hut 1981), while the primary appears to be rotating marginally slower than the pseudosynchronous rate.

5. COMPARISONS WITH STELLAR MODELS

With our estimates of the component masses, absolute magnitudes, color indices, and effective temperatures derived from our measurements and orbital solution (Table 5), we proceed in this section to examine the 12 Boo components in the context of recent stellar evolution models.

In Paper I we compared the measurements for the 12 Boo components with models from the Padova series by Bertelli et al. (1994). Since then, the input physics of these particular models has been updated mainly by incorporating improvements in the equation of state and in the opacities, as described by Girardi et al. (2000, hereafter G2000). In Figure 5 the observed properties of the 12 Boo components are shown against four isochrones for solar metallicity from G2000, in various planes. The panels on the left show the $V$ and $K$ absolute magnitudes versus mass (diagrams for $H$ are similar and are not shown here). (For purposes of model comparisons, the component infrared magnitudes have been transformed from the CIT to the Johnson system using color conversions from Bessell & Brett 1988). No single isochrone appears to fit the observations within the error bars. The diagrams on the right suggest that an isochrone between 2.5 and 2.8 Gyr might provide a good fit in the color-magnitude plane.

Fig. 5.—Comparison of the 12 Boo component parameters with the G2000 stellar models. Comparisons between our observed 12 Boo component parameters and G2000 models are shown in observable mass-magnitude and color-magnitude spaces.
with both stars located near the end of their hydrogen-burning phase. Paper I reached a similar conclusion on the system age estimate based on Padova models. However, as indicated by the left-hand panels the model masses for such an age would not agree with the measured component parameters.

Figure 6 compares the observed quantities to models from the Yonsei-Yale (Y2) collaboration (Yi et al. 2001; Demarque et al. 2004). The Y2 models use physics similar to those of G2000 but differ in a number of details, including the radiative opacities, the equation of state, the treatment of convective core overshooting, and the implementation of helium and heavy element diffusion (not accounted for in G2000). In this case we show evolutionary tracks for the exact component masses determined from the physical orbit (Table 5), using an interpolation routine described by Yi et al. (2003). Absolute magnitudes in $V$ and $K$ are displayed against both $V - K$ and effective temperature as estimated from our spectra, so that each panel displays the constraint from three observables at the same time (shown with their uncertainties) rather than two as in the previous figure. The 1 $\sigma$ mass uncertainties are indicated by the dotted lines bracketing the tracks. To show the constraint on coevality, which we assume to hold for this binary, an isochrone from the same series of models is also represented in each panel. An age of 3.2 Gyr provides the best overall fit to the observations; this is significantly older than the system age estimate from Paper I based on Bertelli models. As mentioned in § 4, the metallicity determinations in the literature suggest a near-solar composition for 12 Boo. The Y2 models seem to agree with that assessment; in surveying a range of metallicities allowed by previous studies we found the best agreement between our observational parameters and the model predictions at solar abundance (+0.0 dex/$Z = 0.01812$ in Y2 models). While our estimates of the surface gravities and absolute radii for the
stars rely not on the physical orbit but on other radiative properties, they do enter weakly into the orbital solution (through the component angular diameters), as well as our spectroscopic estimate of the effective temperatures (§2). The comparison of our inferred log \( g \) and radius (Table 5) values with the Yi et al. (2003) models is shown in Figure 7.

Figure 6 suggests that the secondary of 12 Boo is comfortably in the main-sequence stage, while the primary would appear to be near the beginning of the rapid phase of evolution during which it burns hydrogen in a shell—the so-called Hertzsprung gap. The duration of this phase is only about 4% of the main-sequence lifetime for a star of this mass. Although it is a priori unlikely that we would find a star in this state, the possibility certainly can not be excluded (e.g., see Andersen et al. 1990; Fekel et al. 2001; Parsons 2004). However, we note that a minor increase in the amount of convective core overshooting (a free parameter in the models) could easily extend the main sequence enough to bring the star at the end of the hydrogen-burning phase rather than in the Hertzsprung gap. The treatment of overshooting in these models is shown in Figure 7.

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The apparent agreement between the \( Y^2 \) model predictions and our measurements is in contrast to the apparent disagreement of our results with the Padova/G2000 model series. The differences between the \( Y^2 \) and Padova models are more directly appreciated in Figure 9, where we show 2.82 Gyr (log age = 9.45) isochrones from both series for the same (solar) metallicity. From top to bottom, we depict the isochrones from the purely theoretical plane (luminosity vs. \( T_e \)) to the purely observational plane (absolute magnitude vs. \( V - K \) color). While there is excellent agreement for unevolved stars in the top two diagrams (lower main sequence), the end of the main-sequence region highlights the subtle differences that have to do with the details in the input physics. In the lower panel the discrepancies extend also to the unevolved stars; this is due to differences in the color-temperature calibrations between the models. Over the temperature range shown in the figure, the Padova isochrone relies on color and bolometric correction tables based on theoretical model atmospheres (see Bertelli et al. 1994), while the \( Y^2 \) model relies on semiempirical tables by Lejeune et al. (1998).

6. SUMMARY AND DISCUSSION

By virtue of our interferometric resolution and the precision of the radial velocity data we are able to determine an accurate physical orbit for 12 Boo, resulting in accurate physical parameters for the 12 Boo constituents and an accurate system distance. Our 12 Boo distance estimate is in excellent agreement with the Hipparcos determination. Our finding of unexpectedly large relative \( K_1, H_1, \) and \( V \)-magnitude differences in the two nearly equal mass 12 Boo components is understood in the context that the system is in a unique evolutionary state, with the primary component apparently making its transition off the main sequence. 12 Boo component rotation measurements are consistent...
with synchronous rotation for the system components, and at least the primary is less consistent with pseudosynchronous rotation.

The results of comparing the 12 Boo components with stellar models are mixed. While we see relatively good agreement between the component physical parameters and the Y2 evolutionary (mass) tracks, the agreement with the G2000 isochrones is not nearly as good. Furthermore, the discrepancy seems to be intrinsic; Figure 9 illustrates that fundamental differences exist between the Y2 and G2000 models in both theoretical and observational spaces near the end of the main sequence. Our measured 12 Boo component parameters are clearly in much better agreement with the Y2 model predictions for intermediate-mass stars near the end of the main sequence.

Further, it is interesting to note that the agreement between our observations and the Y2 mass tracks is significantly better than the agreement with the best-fit Y2 isochrone at 3.2 Gyr. Presumably, the 12 Boo components must be coeval, so the larger mismatch in the isochrone prediction must be indicative of a remaining discrepancy between the observations and Y2 models. This discrepancy is illustrated in Figure 10, which depicts the 12 Boo components and their mass tracks in the same observational color-absolute magnitude spaces given in Figure 6. The left panels in Figure 10 focus on the observed component parameters and Y2 mass tracks and in particular indicate that the ages on the mass tracks that best match the component parameters. We find that the Y2 tracks would indicate best-match ages of 3.25 and 2.91 Gyr for the primary and secondary components,
respectively. The right panels in Figure 10 show these same spaces with Y2 isochrones computed for the specific best-match component ages. Presumably, this apparent discrepancy in the component ages cannot be physical. It seems likely that the unique evolutionary state of 12 Boo could provide important observational constraints on the physical evolution of intermediate-mass stars making their transition off the main sequence.

Finally, Figures 6, 7, and 10 lead to the tempting inference that the 12 Boo primary is early in its first transition across the Hertzsprung gap to the base of the red giant branch. However, as discussed in § 5, Figure 8 shows that at the apparent evolutionary state of the 12 Boo primary, relatively small changes in the physics of the stellar models can make significant changes in the model predictions. Particularly coupled with the apparent age discrepancy in the 12 Boo components indicated by the models, caution suggests that a Hertzsprung-gap interpretation for the 12 Boo primary should be provisional only.

Work done with the Palomar Testbed Interferometer was performed at the Michelson Science Center, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Interferometer data were obtained at Palomar Observatory using the NASA PTI, supported by NASA contracts to the Jet Propulsion Laboratory. Science operations with PTI are conducted through the efforts of the PTI Collaboration (http://huey.jpl.nasa.gov/palomar/ptimembers.html), and we acknowledge the invaluable contributions of our PTI colleagues. We particularly thank Kevin Rykoski for his professional operation of PTI. We thank Joe Caruso, Bob Davis, David Latham,
Robert Stefanik, and Joe Zajac for obtaining many of the spectroscopic observations used here. G. T. acknowledges partial support from NASA's MASSIF SIM Key Project (BLF57-04) and NSF grant AST 04-06183. Work done with the NPOI interferometer was performed through a collaboration between the Naval Research Lab and the US Naval Observatory in association with Lowell Observatory and was funded by the Office of Naval Research and the Oceanographer of the Navy. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France; NASA's Astrophysics Data System Abstract Service; and services from the Michelson Science Center, California Institute of Technology, http://msc.caltech.edu.

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