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NEW PRECISION ORBITS OF BRIGHT DOUBLE-LINED SPECTROSCOPIC BINARIES. I. RR LYNCIS, 12 BOOTIS, AND HR 6169

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ABSTRACT

Radial velocities from the 2.1 m telescope at McDonald Observatory supplemented with radial velocities from the coudé feed telescope at Kitt Peak National Observatory provide new precise orbits for the double-lined spectroscopic binaries RR Lyn (A3/A8/A6), 12 Boo (F8 IV), and HR 6169 (A2 V). We derive orbital dimensions ($a_1 \sin i$ and $a_2 \sin i$) and minimum masses ($m_1 \sin^3 i$ and $m_2 \sin^3 i$) with accuracies of 0.06%–0.9%. The three systems, which have V magnitudes of 5.53, 4.82, and 6.42, respectively, are all sufficiently bright that they are easily within the grasp of modern optical interferometers and so afford the prospect, when our spectroscopic observations are complemented by interferometric observations, of fully determined orbits, precise masses, and distances. In the case of RR Lyn, which is also a detached eclipsing binary with a well-determined orbital inclination ($i = 87\overset{\circ}{.}45 \pm 0\overset{\circ}{.}11$), we are able to determine the semimajor axis of the relative orbit, $a = 29.32 \pm 0.04\ R_\odot$; primary and secondary radii of 2.57 ± 0.02 and $1.59 \pm 0.03\ R_\odot$, respectively; and primary and secondary masses of 1.927 ± 0.008 and $1.507 \pm 0.004\ M_\odot$, respectively. Comparison of our new systemic velocity determination, $\gamma = -12.03 \pm 0.04$ km s^{-1}, with the earlier one of Kondo, $\gamma = -11.61 \pm 0.30$ km s^{-1}, shows no evidence of any change in the systemic velocity in the 40 yr separating the two measurements, a null result that neither confirms nor contradicts the presence of the low-mass third component proposed by Khaliullin & Khaliullina. Our spectroscopic orbit of 12 Boo is more precise than that of Boden et al. but confirms their results about this system. Our analysis of HR 6169 has produced a major improvement in its orbital elements. The minimum masses of the primary and secondary are 2.20 ± 0.01 and $1.64 \pm 0.02\ M_\odot$, respectively. Although all three systems have eccentric orbits, the six components of the systems are either pseudo-synchronously rotating or very nearly so.

Key words: binaries: eclipsing — binaries: spectroscopic

1. INTRODUCTION

The current generation of ground-based interferometers, such as the Palomar Testbed Interferometer (PTI; Colavita et al. 1999), the Naval Prototype Optical Interferometer (Hummel et al. 2003), the Infrared Optical Telescope Array (Traub et al. 2003), and the Center for High Angular Resolution in Astronomy array (ten Brummelaar et al. 2003), is advancing stellar astronomy in a number of ways. Quirrenbach (2001), for example, reviewed the state of optical and infrared interferometry. One direction of progress is the increasing number of spectroscopic binaries that are being resolved as visual binaries. This allows the determination of their three-dimensional orbits and the derivation of accurate masses for the component stars and distances to the systems, distances that in many cases are more accurate than those from *Hipparcos*.

In recognition of this development we have started a program to determine substantially improved spectroscopic orbits for bright, field spectroscopic binaries. The program has two benefits: the provision of new radial velocities and spectroscopic orbits of a quality that matches or exceeds the prospective interferometric observations and, for some binaries, the detection of the secondary spectrum and measurement of secondary radial velocities for the first time. We now briefly consider these two points in turn.

While some interferometric studies, such as that of 12 Boo (Boden et al. 2005), include complementary new radial velocities, the usual practice is to take the radial velocities for the binary concerned from the literature. The precision of such velocities often falls short of that needed to match the interferometric observations. For example, in their recent determination of the three-dimensional orbit of the bright spectroscopic binary σ Psc, Konacki & Lane (2004) had to complement their interferometric measurements with radial velocities observed in 1944 and 1945 (Belserene 1947). Their resulting best-fit solution for the three-dimensional orbit has rms velocity residuals of 4.8 and 3.6 km s^{-1} for the primary and secondary, respectively. Orbits with large velocity residuals are not exceptional because of the generally lower resolution and low signal-to-noise ratio of spectra obtained in the first roughly three-quarters of the 20th century. For example, of the first 100 systems in the Eighth Catalogue (Batten et al. 1989), 63 have orbits that were published in 1980 or earlier and 24 have orbits that were published in 1950 or earlier, long before the advent of radial velocity spectrometers and charge-coupled device detectors, which can produce spectra with very high signal-to-noise ratios. Similar proportions must apply for all 1469 systems in the Catalogue[2] While these proportions have improved as a

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[2] One would like to cite the Ninth Catalogue (Pourbaix et al. 2004) here, but at present it is incomplete with respect to orbits published since 1989 and so is unsuitable for the point we are making.

TABLE 1
Basic Properties of the Program Stars

Name	HR	HD	Spectral Type	V[a]	$B-V$[a]	Parallax[a] (mas)	Period (days)	Eccentricity
RR Lyn	2291	44691	A3/A8/A6	5.53	0.238	12.01	9.95	0.08
12 Boo	5304	123999	F8 IV	4.82	0.541	27.27	9.60	0.19
. . .	6169	149632	A2 V	6.42	0.062	06.17	10.56	0.41

[a] Perryman et al. (1997).

result of the substantial number of new spectroscopic binary orbits that have been published since 1989 (Pourbaix et al. 2004), most such orbits are for newly discovered binaries.

With respect to the detection of the secondary spectrum, we note that without secondary radial velocities and a determination of the secondary's spectroscopic orbit, the linear separation between the binary components is unknown and the determination of the three-dimensional orbit is incomplete. Increasing the pool of double-lined spectroscopic binaries (SB2s) thus increases the number of spectroscopic binaries available for fruitful interferometric observation. In addition, binary systems with components of significantly different masses provide the greatest constraints on evolutionary models. Considering that the majority of spectroscopic binaries are single-lined spectroscopic binaries (SB1s), there is ample opportunity here. Pourbaix et al. (2004), for example, found that two-thirds of the spectroscopic binaries in their catalog are SB1s. (There is no reason to think the catalog's incompleteness affects this statistic much.)

Our program uses new, high-resolution, red-wavelength spectra obtained with the 2.1 m telescope at McDonald Observatory of the University of Texas and the coudé feed telescope at Kitt Peak National Observatory (KPNO). Fekel & Tomkin (2004) provided a preliminary description of our program and an initial list of observed stars, which has now been expanded to over 40 systems. These come primarily from a sample of 130 candidate systems obtained by searching Batten et al. (1989) for SB2 systems that could profit from renewed spectroscopic observation and SB1 systems with large enough mass functions to suggest that high signal-to-noise ratio spectra might transform them into SB2 systems (e.g., Stockton & Fekel 1992). The stars are north of -40° in declination and generally brighter than $V = 7.5$ mag.

Others have also seen the need for improved radial velocities for spectroscopic binaries. For example, Konacki (2005) has successfully applied the iodine absorption cell method for determining very precise radial velocities to the measurement of radial velocities of *both* components in SB2s. Hitherto, this technique, which uses an iodine absorption cell to impose a reference spectrum on the stellar spectrum and is notable for its use in the discovery of extrasolar planets, has been restricted to the radial velocities of single stars or stars with companions of insignificant relative brightness. Konacki's pioneering investigation, which was carried out on the Keck I telescope with the HIRES spectrograph, was limited to five objects, including a radial velocity standard and two SB2s. Among the latter was 64 Psc (HD 4676), a well-known, bright spectroscopic binary (F8 V, $P =$ 13.8 days) with a three-dimensional orbit determined by Boden et al. (1999), using their own interferometric observations made with PTI and radial velocities from Duquennoy & Mayor (1991). Konacki's combined fit of his new radial velocities and the Boden et al. (1999) interferometric data leads to better-determined orbital and physical parameters for 64 Psc. In particular, the rms velocity residual of 24 m s^{-1}, determined from his new fit, is a striking improvement compared to the rms residual of 810 m s^{-1} (average $|O - C| = 650$ m s^{-1}) given by Duquennoy & Mayor (1991) for their radial velocity solution. Our new velocities are not as precise as the iodine cell velocities from the Keck I telescope—we see that for 12 Boo, which has a similar spectral type to 64 Psc, the rms residual for our velocities is 110 m s^{-1}—but their quality is still a good match with that of current interferometric observations. There is thus ample opportunity for radial velocities from small and medium-sized telescopes, measured by traditional methods, to make a worthwhile contribution.

Here we report new orbit determinations for three bright spectroscopic binaries, RR Lyn, 12 Boo, and HR 6169. Analysis of our new velocities provides significant improvements in the orbital elements of the systems. Indeed, in the case of HR 6169, some of the revisions are substantial. Table 1 gives basic data for the systems; all three are known SB2s and have orbital periods near 10 days and eccentric orbits. We now briefly look at each system individually.

1.1. *RR Lyn*

RR Lyn has long been known as both an eclipsing and a spectroscopic binary. Its orbit has a period of 9.95 days and a modest eccentricity, $e = 0.08$. The star's peculiar abundances are indicated in its metallic-line spectral classification, which reflects primarily the spectral type of the primary. Abt & Morrell (1995) classified it as A3/A8/A6, based on its Ca II K line, hydrogen Balmer lines, and metallic lines, respectively, while Roman (1949) called the hydrogen lines A7 and the metallic lines F0. Khaliullin et al. (2001) compared the two components with evolutionary tracks and also used their photoelectric photometry on the *WBVR* system (Khaliullin et al. 1985) to place the components of RR Lyn in a $(B - V,\ V - R)$ diagram. From those results they estimated individual spectral types of A6 IV for the primary and F0 V for the secondary. Thus, the primary has already begun to leave the main sequence, while the secondary is still ensconced within it. The metallic-line status of the primary is not in doubt (Popper 1971; Kondo 1976; Lyubimkov & Rachkovskaya 1995), while that of the secondary remains uncertain, although the abundances of Lyubimkov & Rachkovskaya (1995) indicate possible metallicism.

Harper (1915) published the first spectroscopic orbit. More recent, but now quite old, orbits were published by Popper (1971) and Kondo (1976). Kondo's orbit has the advantages that it sampled the primary and secondary radial velocity curves more fully than Popper's and that it has a single systemic velocity, while Popper determined different systemic velocities for the primary and secondary.

Photoelectric light curves of RR Lyn have been reported by Huffer (1931), Magalashvili & Kumsishvili (1959), Botsula (1960), Linnell (1966), Lavrov et al. (1988), and Khaliullin et al. (2001). The last of these studies used precise photometry in the *W*, *B*, *V*, and *R* bandpasses (Khaliullin et al. 1985), which are based on but somewhat different from the Johnson *U*, *B*, *V*, and *R* photometric bandpasses. Khaliullin et al. (2001) showed that

TABLE 2

Recent and New Spectroscopic Investigations of 12 Boo

Investigation	Years of Observation	Number of Observations	Mean $\|O - C\|$ (km s^{-1})
Abt & Levy (1976)	1966–1971	20	1.3
De Medeiros & Udry (1999)	1987–1992	12	0.90
Boden et al. (2005)	1987–2001	49	0.39
This paper (McDonald and KPNO)	2002–2005	24	0.14

the primary and secondary eclipse depths in V are $\sim$0.37 and $\sim$0.25, respectively; the fractional luminosities, also in V, are $L_1 = 0.7835 \pm 0.0039$ and $L_2 = 1 - L_1$; and the orbital inclination is $87.^{\circ}45 \pm 0.^{\circ}11$. Both Linnell (1966) and Budding (1974) needed the addition of third light to solve the light curves, while Kondo (1976), who also did a photometric analysis, found no requirement for third light. This last result is supported by Khaliullin et al. (2001), who demonstrated that their observations in all filters are fitted by the same geometry and that their model matches the observations without any need to invoke third light. In a later paper, however, Khaliullin & Khaliullina (2002) presented new evidence for a third body, based not on an analysis of the light curve but on the times of the eclipse minima.

The presence of the third star, which Khaliullin & Khaliullina (2002) suggested is a very low-mass, low-luminosity object that contributes an insignificant amount of light to the system, is inferred from quasi-periodic oscillations in the times of primary and secondary minima. They proposed an extremely eccentric orbit ($e = 0.96 \pm 0.02$) with a rather long orbital period of 39.7 ± 4.2 yr. The 64 yr time span of the published photoelectric minima amounts to only 1.5 orbital periods, however, so the case for the third body cannot yet be regarded as conclusive.

1.2. *12 Boo*

The SB2 system 12 Boo is the only one in our trio that already has a determination of its three-dimensional orbit (Boden et al. 2005). The two components have an orbital period of 9.60 days and are of very similar mass, having a secondary-to-primary mass ratio of 0.97. The system's combined spectral type is F8 IV (Roman 1950) or F8 V (Gray et al. 2001). Boden et al. (2005) found that the primary is leaving the main sequence, and with $T_{\rm eff} = 6130 \pm 100$ K it is now marginally *cooler* than the secondary ($T_{\rm eff} = 6230 \pm 150$ K).

Harper (1914) was the first to determine its spectroscopic orbit. Newer orbital elements have been published by Abt & Levy (1976) and De Medeiros & Udry (1999). Boden et al. (2005) presented the newest set of radial velocities, as well as interferometric observations. Details for these more recent spectroscopic orbits, including the present investigation, are summarized in Table 2. Prior to its publication, we were unaware of the new investigation of 12 Boo by Boden et al. (2005). Thus, in spite of the element of (unintentional) redundancy here, our own study of 12 Boo, based on radial velocities acquired from 2002 to 2005, is still of interest because our velocities turn out to be significantly more precise, allowing us to determine improved spectroscopic orbital elements.

1.3. *HR 6169*

Compared to RR Lyn and 12 Boo, the previous work on HR 6169 has been quite modest. This binary has a combined spectral type of A2 V (Cowley et al. 1969) or A1 IV (Abt & Morrell 1995). The first and, to date, only spectroscopic orbit is that of Young (1920), which was based on radial velocities from blue photographic spectrograms obtained at the Cassegrain focus of the 1.8 m telescope at the Dominion Astrophysical Observatory (DAO). This SB2 system has an orbit with a period of 10.56 days and a moderate eccentricity, $e = 0.41$.

2. OBSERVATIONS AND SPECTRUM REDUCTION

Our observations were collected from 2002 April through 2005 October at the McDonald Observatory and KPNO, with the majority of spectra of all three program stars obtained at McDonald. The McDonald observations were acquired with the 2.1 m telescope, the Sandiford Cassegrain echelle spectrograph (McCarthy et al. 1993), and a Reticon CCD with 27 μm^2 pixels arranged in a 1200×400 pixel format. The spectrograms cover the wavelength range 5700–7000 Å and have a resolving power of 60,000. The collapsed one-dimensional stellar spectra have a representative signal-to-noise ratio of $\sim$300. Each stellar observation was followed by an observation of a thorium-argon comparison spectrum.

The observations at KPNO were obtained with the coudé feed telescope, the coudé spectrograph, and a TI CCD detector. All the spectrograms were centered at 6430 Å, cover a wavelength range of about 80 Å, and have a resolution of 0.21 Å or a resolving power of just over 30,000. The spectrograms typically have signal-to-noise ratios of 200–250. The McDonald and KPNO data were processed and wavelength-calibrated in a conventional manner with the IRAF[3] package of programs.

3. RADIAL VELOCITY MEASUREMENT

The spectra of the three systems are double-lined, and at most orbital phases the secondary lines are well separated from their primary counterparts. In RR Lyn there are numerous lines of both the primary and secondary with the secondary lines being distinctly weaker, while in 12 Boo the primary and secondary lines are also numerous and are of roughly similar strength. In HR 6169 the primary is represented by only a few lines from ionized species, while the secondary has numerous lines, mostly from neutral species, which are also sharper than those of the primary. In this system, therefore, at the yellow and red wavelengths covered by our observations the secondary lines are much better for velocity measurement than those of the primary. We now outline the procedures used to measure the McDonald and KPNO radial velocities.

For the McDonald velocities we proceeded as follows: the wavelengths of well-defined primary and secondary lines were measured by fitting Gaussian profiles with the *splot* routine of IRAF, the wavelength differences between the measured wavelengths and rest wavelengths (Moore et al. 1966) of the lines

[3] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

provided the topocentric radial velocities, telluric O_2 lines near 6300 Å (α band) and 6900 Å (*B* band) were measured in the same way so as to determine the offset between the stellar spectrum and its associated thorium-argon comparison spectrum, the stellar topocentric velocities were then corrected by subtracting from them the telluric line offset in velocity form, and, finally, the heliocentric correction led to the heliocentric radial velocities. The McDonald velocities are, thus, absolute velocities.

The KPNO radial velocities were determined with the IRAF cross-correlation program *fxcor* (Fitzpatrick 1993). The IAU radial velocity standard stars β Vir, HR 5694, and HR 7560, which have late-F spectral classes, were used as cross-correlation reference stars. Their velocities of 4.4, 54.4, and 0.0 km s^{-1}, respectively, were adopted from Scarfe et al. (1990). In the KPNO spectra, lines in the wavelength region redward of 6445 Å are not particularly suitable for measurement because most features are blends, and there are a number of modest strength water vapor lines. Thus, the radial velocities were determined from lines in the region 6385–6445 Å. Unfortunately, this 60 Å portion of the spectrum is so small that a mismatch, caused by the varying strength of line blends, between the spectral type of the program star and that of the cross-correlation standard can significantly affect the measured velocity. Thus, instead of cross-correlating this entire 60 Å wavelength region, only the wavelength regions around the strongest and least-blended lines were cross-correlated. For our stars with components of late-A or F spectral type the list includes five lines, the Fe I lines at 6394, 6412, 6421, and 6431 Å plus the Ca I line at 6439 Å. The weakness of those neutral lines in the spectra of early-A stars means that the only measurable lines in their KPNO spectrograms are the two Fe II lines at 6417 and 6433 Å, which can provide good velocities if the lines are narrow enough. Each cross-correlation profile was fitted with a Gaussian function.

Because different techniques were used to measure the McDonald and KPNO radial velocities, the two velocity systems may have slightly different zero points. We examine this possibility in § 6. Table 3 gives the calendar dates, Heliocentric Julian Dates, and heliocentric radial velocities for the McDonald and KPNO observations.

4. SPECTRAL AND LUMINOSITY CLASSES

Strassmeier & Fekel (1990) identified several luminosity-sensitive and temperature-sensitive line ratios in the 6430–6465 Å region. They employed those critical line ratios and the general appearance of the spectrum as spectral-type criteria. However, for stars that are hotter than early-G spectral class, the line ratios in that wavelength region have little sensitivity to luminosity. Thus, for the A and F stars of our three systems, we have used the entire 80 Å spectral region of our KPNO observations to estimate just the spectral classes of the individual components. In the 6430 Å region most of the strongest features are Fe I lines with the addition of three Fe II and three Ca I lines. The luminosity class may be determined by computing the absolute visual magnitude with the *Hipparcos* parallax and comparing that magnitude to evolutionary tracks or a table of canonical values for giants and dwarfs.

Spectra of our three binaries were compared with the spectra of a number of A- and F-type stars primarily from the lists of Abt & Morrell (1995) and Fekel (1997). The reference star spectra were obtained at KPNO with the same telescope, spectrograph, and detector as our binary star spectra. To facilitate a comparison, the spectra of the reference stars were rotationally broadened and shifted in radial velocity with a computer program developed by Huenemoerder & Barden (1984) and Barden (1985).

This spectrum addition enables us to determine a continuum intensity ratio of the binary components at 6430 Å, a wavelength that is about 0.6 of the way between the central wavelengths of the Johnson *V* and *R* bandpasses. If the two stars have very similar spectral types, this intensity ratio is also the luminosity ratio and, thus, can be converted directly into a magnitude difference. However, if the lines of the secondary are intrinsically stronger than those of the primary, as would be the case, for example, if the components were main-sequence stars of rather different spectral types, then the continuum intensity ratio results in a minimum magnitude difference.

5. PROJECTED ROTATIONAL VELOCITIES

We have determined projected rotational velocities from our red-wavelength KPNO spectra with the procedure of Fekel (1997). For each star the full width at half-maximum of several metal lines in the 6430 Å region was measured and the results averaged. An instrumental broadening of 0.21 Å was removed from the measured broadening by taking the square root of the difference between the squares of measurements of the stellar and comparison lines, resulting in the intrinsic broadening. The calibration polynomial of Fekel (1997) was used to convert this broadening in angstroms into a total line broadening in kilometers per second. For A-type stars this line broadening corresponds to the $v \sin i$ value. For F-type stars macroturbulent broadening has been taken into account. Following Fekel (1997), for early-F stars a macroturbulence of 5 km s^{-1} was adopted and removed, while for mid-F and late-F stars values of 4 and 3 km s^{-1}, respectively, were used.

6. ORBIT DETERMINATION AND RESULTS

All three systems have eccentric orbits, so we obtained simultaneous solutions of the primary and secondary radial velocities by the Lehmann-Filhes method to determine the orbits. A preliminary to the orbit calculation was the assignment of suitable weights for the various velocities. Typically, the primary and secondary spectra are of different quality because the components can differ, sometimes markedly, as to strength of lines, line width, and number of available lines, resulting in primary and secondary velocities that are of different weight. Also, the McDonald velocities, because of the higher resolution by a factor of 2 and the substantially greater wavelength coverage of the McDonald spectra, resulting in a larger number of available lines, are somewhat more precise than the KPNO velocities and therefore have higher weight. For each system there are, thus, four different sets of velocity, each with its own weight. These weights, which are given in Table 3, were chosen so as to approximately equalize the products of the weights and the mean square velocity residuals for the different sets of velocity. Once the weights were assigned, the velocities were then solved to determine the spectroscopic orbits.

The velocity residuals (Table 3) for the orbital solutions, given to two decimal places to facilitate our examination, allow a straightforward check on the consistency of the radial velocities from the two observatories. Any systematic difference between the McDonald and KPNO velocities will manifest itself as a corresponding difference between the average residuals, calculated with regard to sign, for the two types of velocity, while if they are consistent, then their average residuals, apart from statistical fluctuations, will be identical and equal to zero. A comparison of the residuals for the McDonald and KPNO radial velocities is given in Table 4.

Although the differences are all smaller than or similar to their estimated errors, they all have the same sign, thus suggesting an

TABLE 3

Radial Velocities of the Program Stars

Date (UT)	Telescope	HJD−2,400,000	Phase	Velocity Primary (km s^{-1})	Velocity Secondary (km s^{-1})	Weight Primary	Weight Secondary	O − C Primary (km s^{-1})	O − C Secondary (km s^{-1})
				RR Lyn					
2003 Apr 22	McD	52,751.635	0.3781	33.9	−70.8	1.000	0.100	−0.17	0.16
2004 Feb 7	McD	53,042.843	0.6598	25.3	−59.9	1.000	0.100	0.03	−0.19
2004 Feb 8	McD	53,043.803	0.7563	−10.2	. . .	0.000	. . .	−1.44	. . .
2004 Feb 9	McD	53,044.812	0.8577	−50.6	36.5	1.000	0.100	0.11	−0.92
2004 Mar 10	McD	53,074.760	0.8691	−55.0	43.0	1.000	0.100	0.03	0.06
2004 Mar 11	McD	53,075.734	0.9670	−80.9	75.4	1.000	0.100	−0.12	−0.46
2004 Apr 13	McD	53,108.648	0.2766	2.9	−31.8	1.000	0.100	0.12	−0.84
2004 Apr 15	McD	53,110.647	0.4776	47.8	−89.5	1.000	0.100	−0.06	−0.92
2004 Apr 24	KPNO	53,119.647	0.3826	35.5	−72.3	0.500	0.050	0.44	−0.07
2004 Sep 25	KPNO	53,274.019	0.9050	−67.4	58.8	0.500	0.050	−0.13	0.21
2004 Sep 28	KPNO	53,276.991	0.2039	−26.9	6.3	0.500	0.050	−0.20	−0.43
2004 Nov 25	McD	53,334.893	0.0260	−81.7	76.6	1.000	0.100	0.10	−0.57
2004 Dec 3	McD	53,342.913	0.8325	−40.8	24.6	1.000	0.100	−0.24	0.15
2005 Jan 29	McD	53,399.846	0.5572	45.6	−85.2	1.000	0.100	0.07	0.40
2005 Apr 28	McD	53,488.717	0.4934	48.3	−89.2	1.000	0.100	−0.05	0.01
2005 Apr 29	McD	53,489.670	0.5892	41.1	−79.8	1.000	0.100	−0.13	0.31
2005 Apr 30	KPNO	53,490.636	0.6863	17.7	−48.7	0.500	0.050	0.58	0.59
2005 Sep 21	KPNO	53,634.874	0.1898	−32.9	13.6	0.500	0.050	−0.28	−0.69
2005 Oct 18	McD	53,662.011	0.9185	−71.0	64.1	1.000	0.100	0.13	0.58
2005 Oct 20	McD	53,663.896	0.1080	−64.0	54.9	1.000	0.100	0.10	0.38
2005 Oct 20	McD	53,663.990	0.1175	−60.9	51.1	1.000	0.100	0.04	0.61
				12 Boo					
2002 Apr 28	McD	52,392.711	0.1964	76.7	−59.7	1.000	0.500	−0.01	−0.13
2002 Apr 29	McD	52,393.750	0.3046	51.3	−33.9	1.000	0.500	−0.24	−0.26
2003 Mar 21	McD	52,719.792	0.2512	65.6	−48.5	1.000	0.500	−0.16	−0.21
2003 Apr 20	McD	52,749.700	0.3651	33.7	−15.1	1.000	0.500	0.06	0.10
2003 Apr 20	McD	52,749.892	0.3851	27.6	−8.8	1.000	0.500	0.00	0.18
2003 Apr 21	McD	52,750.903	0.4904	−3.6	23.3	1.000	0.500	−0.11	0.27
2003 Sep 6	McD	52,888.618	0.8289	−48.3	69.2	1.000	0.500	−0.11	0.12
2003 Sep 7	McD	52,889.586	0.9297	−10.0	29.8	1.000	0.500	0.10	−0.04
2003 Sep 8	McD	52,890.584	0.0336	52.0	−34.2	1.000	0.500	0.09	−0.17
2004 Feb 8	McD	53,043.967	0.0034	35.0	−16.4	1.000	0.500	0.07	0.14
2004 Feb 9	McD	53,044.932	0.1039	76.7	−59.5	1.000	0.500	−0.10	0.16
2004 Apr 13	McD	53,108.880	0.7620	−54.1	75.0	1.000	0.500	−0.16	0.00
2004 Apr 14	McD	53,109.858	0.8638	−39.2	59.9	1.000	0.500	0.15	−0.07
2004 Apr 26	KPNO	53,121.792	0.1063	77.4	−59.9	0.500	0.250	0.16	0.21
2004 Jun 12	KPNO	53,168.659	0.9860	24.0	−4.8	0.500	0.250	−0.20	0.69
2004 Jun 13	KPNO	53,169.752	0.0998	76.0	−58.5	0.500	0.250	−0.01	0.34
2004 Sep 12	McD	53,260.584	0.5570	−21.4	41.6	1.000	0.500	0.01	0.11
2004 Sep 13	McD	53,261.583	0.6610	−43.9	64.7	1.000	0.500	0.11	−0.07
2005 Apr 27	McD	53,487.876	0.2220	72.3	−54.8	1.000	0.500	0.07	0.16
2005 Apr 28	McD	53,488.844	0.3228	46.3	−28.1	1.000	0.500	0.03	0.11
2005 Apr 29	McD	53,489.708	0.4128	20.0	0.3	0.000	0.000	0.74	0.69
2005 May 1	KPNO	53,491.692	0.6193	−35.9	56.3	0.500	0.250	0.09	−0.21
2005 May 2	KPNO	53,492.672	0.7214	−52.2	72.9	0.500	0.250	−0.20	−0.10
2005 Jun 11	KPNO	53,532.796	0.8990	−25.6	46.3	0.500	0.250	0.13	0.36
				HR 6169					
2002 Apr 28	McD	52,392.790	0.2518	−46.5	20.1	0.100	1.000	0.67	−0.14
2002 Apr 29	McD	52,393.881	0.3551	−59.4	35.1	0.100	1.000	−0.88	−0.33
2003 Mar 21	McD	52,719.891	0.2289	−43.3	14.3	0.100	1.000	−0.67	0.13
2003 Apr 20	McD	52,749.868	0.0678	35.7	−91.3	0.100	1.000	−0.58	0.10
2003 Apr 21	McD	52,750.881	0.1637	. . .	−14.2	. . .	0.000	. . .	−1.99
2003 Sep 6	McD	52,888.661	0.2118	. . .	8.8	. . .	1.000	. . .	0.11
2003 Sep 7	McD	52,889.664	0.3068	. . .	30.1	. . .	1.000	. . .	−0.26
2004 Feb 9	McD	53,044.975	0.0150	75.0	−143.9	0.100	1.000	−0.38	−0.18
2004 Mar 10	McD	53,074.983	0.8569	14.3	−59.9	0.100	1.000	1.96	−0.53
2004 Apr 10	McD	53,105.944	0.7889	. . .	−20.6	. . .	0.000	. . .	0.76
2004 Apr 24	KPNO	53,119.942	0.1146	0.6	−46.1	0.025	0.500	−1.38	−0.58

TABLE 3—*Continued*

				Velocity		Weight		O − C	
Date (UT)	Telescope	HJD−2,400,000	Phase	Primary (km s^{-1})	Secondary (km s^{-1})	Primary	Secondary	Primary (km s^{-1})	Secondary (km s^{-1})
2004 Apr 26	KPNO	53,121.925	0.3024	−53.8	29.6	0.025	0.500	0.47	−0.14
2004 Jun 14	KPNO	53,170.838	0.9345	62.4	−122.9	0.025	0.500	2.09	0.66
2004 Jun 15	KPNO	53,171.771	0.0229	74.0	−138.3	0.025	0.500	2.95	−0.37
2004 Sep 11	McD	53,259.654	0.3456	−58.0	34.2	0.100	1.000	−0.06	−0.46
2004 Sep 12	McD	53,260.625	0.4375	−59.4	38.2	0.100	1.000	1.26	−0.09
2004 Sep 13	McD	53,261.620	0.5318	−56.7	34.8	0.100	1.000	1.23	0.16
2004 Sep 13	McD	53,261.685	0.5379	−55.5	34.3	0.100	1.000	2.07	0.14
2005 Jan 29	McD	53,400.003	0.6369	−48.5	21.6	0.100	1.000	−0.03	−0.38
2005 Apr 27	McD	53,487.910	0.9619	75.7	−144.2	0.100	1.000	0.00	−0.06
2005 Apr 28	McD	53,488.899	0.0556	48.0	−104.8	0.100	1.000	1.56	0.20
2005 Jun 10	KPNO	53,531.732	0.1119	6.2	−47.5	0.025	0.500	2.55	0.25
2005 Jun 13	KPNO	53,534.900	0.4119	−56.7	38.4	0.025	0.500	3.79	0.34
2005 Jun 14	KPNO	53,535.789	0.4961	−58.0	37.6	0.025	0.500	1.56	0.77
2005 Jun 15	KPNO	53,536.754	0.5875	−53.8	29.6	0.025	0.500	0.04	0.43

offset of order 0.1–0.2 km s^{-1} between the McDonald and KPNO velocities. We attach the most importance, however, to the primaries of RR Lyn and 12 Boo because, of the six stars in our three systems, these two have the most well-determined radial velocities, and in both cases there is no evidence of an offset. This simple check, therefore, indicates the possible presence of an offset of 0.1–0.2 km s^{-1} between the McDonald and KPNO velocities, but the results are inconclusive. In the absence of clear evidence of an offset, we decided not to adjust either set of velocities. We now look at the results for the individual systems.

6.1. *RR Lyn*

Table 5 gives the spectroscopic orbital elements of RR Lyn obtained from the solution of our radial velocities. For comparison, the elements of Kondo (1976) and the photometrically based elements of Khaliullin et al. (2001) are also listed. Figure 1 shows our radial velocities along with the calculated radial velocity curves for our orbital elements. Although the photometrically determined orbital period is more precise than our spectroscopically measured value, the difference between the two 10 day periods corresponds to less than 1 s. We have retained the spectroscopic period for the determination of our spectroscopic orbit, since adopting the photometric period does not change the orbital elements. Examining the solutions in Table 5, one sees that to within the uncertainties all three investigations give the same eccentricity of 0.08. This agreement is especially pleasing in the case of Khaliullin et al. (2001) because their photometric determination of the eccentricity is completely independent of our spectroscopic one. We note that our determination of ω (179.°4 ± 0.°6) is the first accurate measurement of this element and that to within its uncertainty it is 180°, which means that the major axis of the true orbit and the line of nodes coincide. Also of interest, we find that our and Kondo's determinations of K_1 and K_2 are the same to within the uncertainties. We compare the two γ-velocity determinations shortly. The minimum masses are also in agreement, with our uncertainties being about 10 times smaller than Kondo's.

As we have seen, RR Lyn is also a detached eclipsing binary, so the photometric and spectroscopic orbital elements can be combined to provide the sizes and masses of the components, as well as the linear separation between the primary and secondary. This is done in Table 6. The new mass determinations of $m_1 = 1.927 \pm 0.008$ and $m_2 = 1.507 \pm 0.004\ M_\odot$ are extremely precise, having uncertainties of only 0.4% and 0.3%, respectively. Although our new determinations of the masses and radii of the primary and secondary are more precise than those of Khaliullin et al. (2001), our values differ only slightly from theirs. The new primary and secondary masses are just 0.037 and 0.017 $M_\odot$ larger, respectively, than theirs, while the new primary and secondary radii differ from theirs by 0.00 and 0.01 $R_\odot$, respectively. We do not rediscuss, therefore, the evolutionary state of RR Lyn because our new results would have little impact on the conclusions of Khaliullin et al. (2001) in this regard. Instead, we note that insofar as our new masses and radii confirm theirs, we support their determinations of other derived quantities. In particular, we confirm their

TABLE 4
Average Velocity Residuals Comparison

		Average Residual (km s^{-1})		Difference
System	Component	McDonald	KPNO	(km s^{-1})
RR Lyn	Primary	−0.003 ± 0.031 (15)	0.082 ± 0.178 (5)	−0.085 ± 0.181
	Secondary	−0.083 ± 0.139 (15)	−0.078 ± 0.227 (5)	(−0.005 ± 0.266)
12 Boo	Primary	−0.012 ± 0.028 (17)	−0.005 ± 0.066 (6)	−0.007 ± 0.072
	Secondary	0.024 ± 0.038 (17)	0.215 ± 0.134 (6)	−0.191 ± 0.139
HR 6169	Primary	0.473 ± 0.288 (13)	1.509 ± 0.602 (8)	(−1.036 ± 0.667)
	Secondary	−0.106 ± 0.063 (15)	0.170 ± 0.172 (8)	−0.276 ± 0.183

Notes.—The quoted errors are the standard deviations of the averages with the number of residuals in parentheses. The differences for the secondary of RR Lyn and the primary of HR 6169 are in parentheses because of the relatively low quality of their velocities.

TABLE 5

Orbital Elements of RR Lyn

Parameter	Kondo (1976)	Khaliullin et al. (2001) (Light Curve)	This Study
P (days)	9.945080	9.9450740 ± 0.0000007	9.945080 ± 0.000059
T (HJD)[a]	2,438,048.97 ± 0.02	2,444,988.49594 ± 0.00030	2,453,334.634 ± 0.017
e	0.081 ± 0.006	0.0782 ± 0.0009	0.0793 ± 0.0009
ω (deg)	176.1 ± 5.6	185 ± 5	179.4 ± 0.6
K_1 (km s^{-1})	65.87 ± 0.46	...	65.65 ± 0.06
K_2 (km s^{-1})	83.1 ± 1.3	...	83.92 ± 0.17
γ (km s^{-1})	−11.61 ± 0.30	...	−12.03 ± 0.04
$m_1 \sin^3 i$ ($M_\odot$)	1.88 ± 0.07	...	1.921 ± 0.008
$m_2 \sin^3 i$ ($M_\odot$)	1.49 ± 0.05	...	1.503 ± 0.004
$a_1 \sin i$ (10^6 km)	...	...	8.950 ± 0.008
$a_2 \sin i$ (10^6 km)	...	...	11.441 ± 0.024
rms residual (km s^{-1}) (unit weight)	...	...	0.11

[a] The orbital element T usually denotes a time of periastron in an eccentric orbit. However, Kondo's T, for which he uses the symbol T_0, identifies a time of the descending node of the primary. Khaliullin et al.'s value is a time of primary minimum, since they analyzed the star as an eclipsing binary; our value is a time of periastron passage.

photometric estimate of the system's distance, 73.5 ± 2.8 pc, and its age, 1.08 ± 0.15 billion years. We now look at the question of the third body in the system.

As already mentioned, Khaliullin & Khaliullina (2002) proposed the presence of a third star in an extremely eccentric orbit ($e = 0.96$) with a period of 39.7 yr as an explanation of variations in the times of minima of the primary and secondary eclipses. The proposed star is of low mass, estimated to be 0.10 $M_\odot$ if its orbit is coplanar with that of the eclipsing pair. Thus, it would make a negligible contribution to the spectrum, but its presence would cause a regular variation of the systemic velocity of the eclipsing pair as the center of mass of the eclipsing pair orbits the center of mass of the entire system. In view of the long interval between the observations of Kondo (1976) and ours, it is natural to compare Kondo's systemic velocity with ours to see if there is a variation.

The difference between our and Kondo's γ-velocities is insignificant. From Table 5 we see that it is −0.42 ± 0.30, with the estimated uncertainty being set by the uncertainty in Kondo's result. The observations thus set an upper limit of ~0.3 km s^{-1} on any difference between the two γ-velocities. What is the predicted difference that would be caused by the proposed third star? To answer this question we note that we do *not* need to know the (unknown) systemic velocity of the entire system; calculation of the *orbital motion* alone, of the center of mass of the eclipsing pair, is sufficient to provide the predicted γ-velocity difference that we want. Khaliullin & Khaliullina (2002) have provided estimates of all the orbital elements needed to calculate the predicted variation of the γ-velocity of the eclipsing pair, with the exception of K_{12}, and, from the information they give, one can infer $K_{12} = 1.31$ km s^{-1}. We can thus calculate the predicted variation of the γ-velocity of the eclipsing pair due to its motion in the proposed 39.7 yr orbit, and this is shown in Figure 2. It is apparent from that figure that the predicted difference of γ-velocities is tiny, only −0.002 km s^{-1}. The smallness of the difference results from the extreme eccentricity of the proposed orbit, so the velocity variation outside of periastron

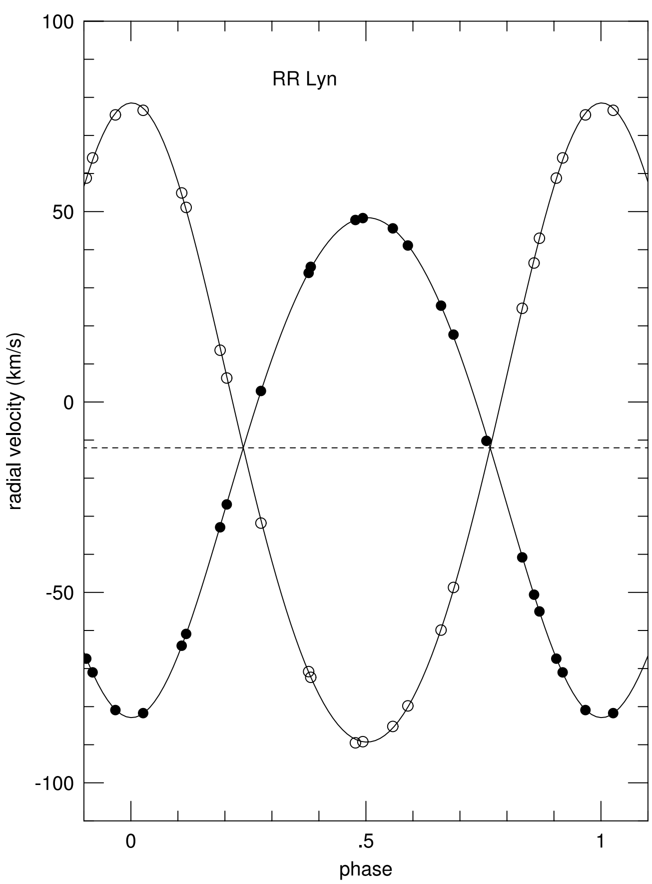

Fig. 1.—Observed and calculated radial velocity curves for RR Lyn. Zero phase is a time of periastron passage. Filled and open circles are our primary and secondary velocities, respectively.

TABLE 6

Photometric Elements and Physical Characteristics of RR Lyn

Parameter	Value
i (deg)	87.45 ± 0.11
r_1	0.0878 ± 0.0005
r_2	0.0541 ± 0.0011
$a(=a_1 + a_2)$ ($R_\odot$)	29.32 ± 0.04
m_1 ($M_\odot$)	1.927 ± 0.008
m_2 ($M_\odot$)	1.507 ± 0.004
R_1 ($R_\odot$)	2.57 ± 0.02
R_2 ($R_\odot$)	1.59 ± 0.03

Note.—Inclination and fractional radii (r_1 and r_2) are from Khaliullin et al. (2001).

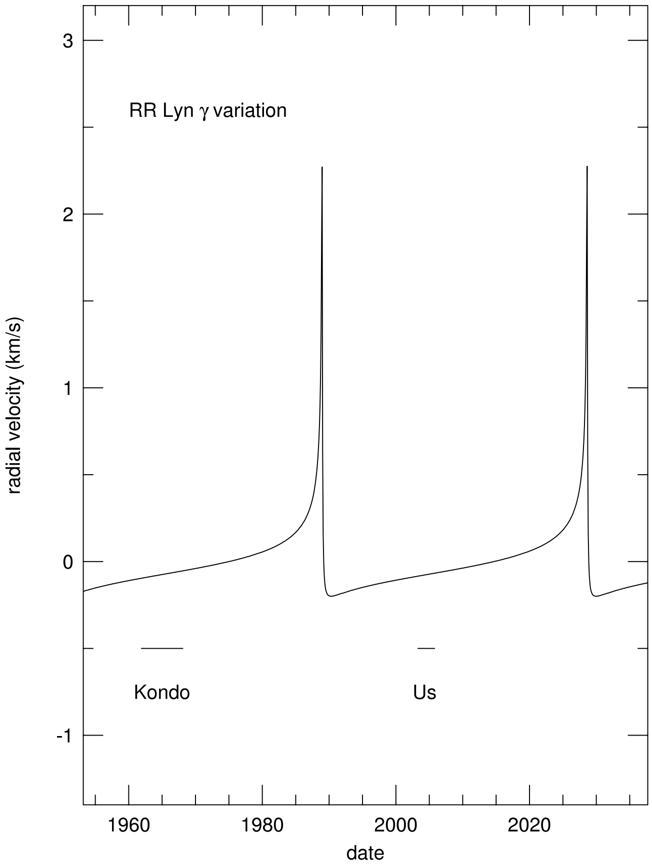

FIG. 2.—Predicted variation in the γ-velocity of the eclipsing pair in RR Lyn due to the third body proposed by Khaliullin & Khaliullina (2002). The horizontal bars mark the dates spanned by Kondo's (1976) and our observations. The tiny predicted difference, -0.002 km s^{-1}, between our and Kondo's γ-velocities is well below the threshold of measurement uncertainty.

passage is slight, and because, by chance, Kondo's observations and ours are separated by almost exactly one orbit and thus are at the same phase.

Our null result, therefore, is consistent with the predicted minute change in the γ-velocity of the eclipsing pair of stars caused by the presence of the proposed low-mass third star. Of course, the result is also consistent with the absence of such a body, and so we are unable to either confirm or deny its existence. As can be seen in Figure 2, the extreme eccentricity of the 39.7 yr orbit means that usually the γ-velocity of the eclipsing pair changes very gradually. So, during most of the orbit, radial velocities are almost impervious to the presence or absence of the third body. Near periastron it is a different story, however, as the third star swoops toward the eclipsing pair, and their γ-velocity suffers an abrupt change with a total amplitude of 2.5 km s^{-1}. At the next periastron passage in 2028 one or two precise radial velocities will readily confirm or refute the existence of the third star.

6.2. *12 Boo*

In their recent investigation of the 12 Boo system Boden et al. (2005) combined their interferometric observations of the visual orbit and complementary new radial velocities to make an accurate determination of the system's three-dimensional orbit and the masses and radii of its components. They then used these basic parameters to discuss the system's evolutionary status. Although our own work duplicates theirs to some extent, our radial velocities are more precise, so our results provide a useful check on the spectroscopic component of their investigation.

Table 7 lists the spectroscopic orbital elements from the combined interferometric and radial velocity solution of Boden et al. (2005) with our new radial velocity solution. The two sets of orbital elements are in excellent agreement, and the uncertainties of our elements are usually smaller than those of Boden et al. (2005). With the exception of the period, for which our observational time span is quite short, all our elements are improved determinations, and for four of them (e, K_1, K_2, and γ) the improvement is a factor of 2. There is also good agreement between the two γ-velocities, where we find $\gamma = 9.588 \pm 0.024$ km s^{-1}, while they find $\gamma = 9.551 \pm 0.051$ km s^{-1}, which argues that our and their radial velocities have the same zero point. To make the most of the radial velocities, we also obtained a combined solution of our radial velocities and theirs, making no adjustment to either set of velocities. (The weights for our velocities in this solution are given in Table 3, while the weights for theirs were 0.1 and 0.05 for the primary and secondary, respectively.)

The elements from this combined spectroscopic solution are also listed in Table 7. They represent an all-around improvement, with the period determination, in particular, being sharpened

TABLE 7
ORBITAL ELEMENTS OF 12 BOO

Parameter	BTH[a]	McD+KPNO Solution	McD+KPNO+CfA Solution
P (days)	9.6045492 ± 0.0000076	9.604596 ± 0.000021	9.6045529 ± 0.0000048
T (HJD)[b]	2,451,238.2729 ± 0.0051	2,452,400.4266 ± 0.0043	2,452,400.4292 ± 0.0035
e	0.19233 ± 0.00086	0.19243 ± 0.00047	0.19268 ± 0.00042
ω (deg)	286.67 ± 0.19	286.88 ± 0.16	286.87 ± 0.14
K_1 (km s^{-1})	67.302 ± 0.087	67.283 ± 0.042	67.286 ± 0.037
K_2 (km s^{-1})	69.36 ± 0.10	69.29 ± 0.06	69.30 ± 0.05
γ (km s^{-1})	9.551 ± 0.051	9.588 ± 0.024	9.578 ± 0.022
$m_1 \sin^3 i$ ($M_\odot$)	...	1.218 ± 0.002	1.218 ± 0.002
$m_2 \sin^3 i$ ($M_\odot$)	...	1.183 ± 0.002	1.183 ± 0.001
$a_1 \sin i$ (10^6 km)	...	8.720 ± 0.006	8.720 ± 0.005
$a_2 \sin i$ (10^6 km)	...	8.981 ± 0.008	8.981 ± 0.007
rms residual (km s^{-1})[c]	0.49	0.18	0.18
rms residual (km s^{-1})[d]	...	0.10	0.11

[a] BTH (Boden et al. 2005) elements are from their "full-fit" solution in their Table 4.
[b] The BTH value of T is incremented by 0.5 to convert from the MJD they used to the HJD used here.
[c] The rms residuals for solutions of McD+KPNO and McD+KPNO+CfA velocities are for McDonald and KPNO primary and secondary velocities.
[d] The rms residuals for McDonald primary velocities, i.e., the velocities of unit weight.

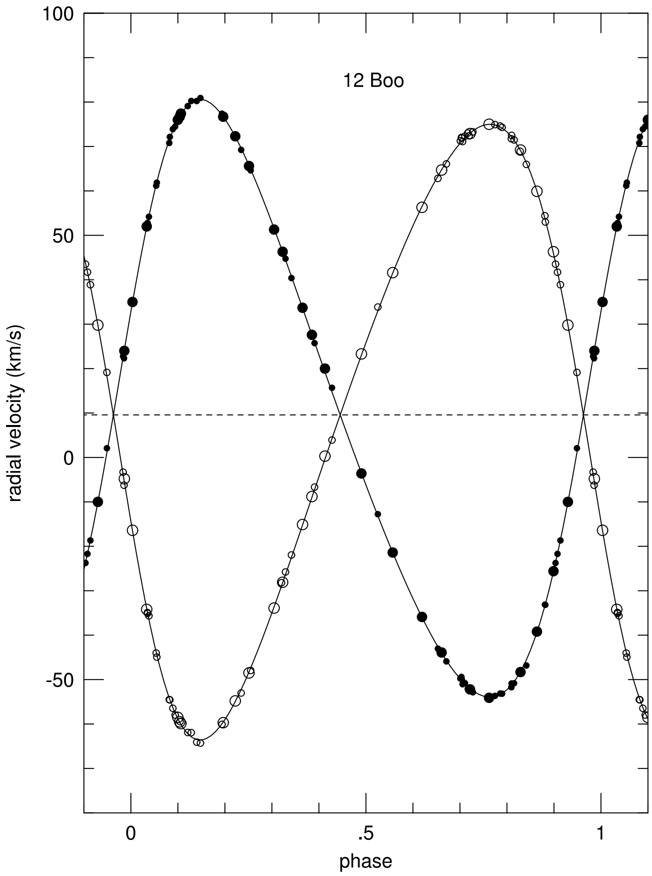

FIG. 3.—Observed and calculated radial velocity curves for 12 Boo. Filled and open circles are the primary and secondary velocities, respectively; large and small circles are the new (McDonald and KPNO) and CfA velocities, respectively.

thanks to the longer time span, 1987–2005, of the combined observations. Figure 3 shows our radial velocities and those of Boden et al. (2005) along with the calculated radial velocity curves for the combined solution of the two sets.

With the help of the inclination, $i = 107\overset{\circ}{.}990 \pm 0\overset{\circ}{.}077$, from the orbit of Boden et al. (2005) we determine new values of the stellar masses and the semimajor axis of the relative orbit. We find $m_1 = 1.416 \pm 0.003$ $M_{\odot}$, $m_2 = 1.375 \pm 0.002$ $M_{\odot}$, and $a = 18.611 \pm 0.012$ Gm. These results certainly confirm those of Boden et al. (2005), which are $m_1 = 1.4160 \pm 0.0049$ and $m_2 = 1.3740 \pm 0.0045$ $M_{\odot}$ but are more precise.

Finally, we look at the orbital parallax, $\pi_{\rm orb}$, and distance of the system. The orbital parallax is simply a(arcsec)/a(AU), where a denotes the angular and linear sizes, respectively, of the true orbit. The angular size of the orbit, $a = 3.451 \pm 0.018$ mas, of course, comes from the visual-orbit determination (Boden et al. 2005). We note, however, that the uncertainty in the angular size of the orbit, which is 0.5% and is much bigger than the uncertainties in the determinations of the linear size of the orbit (0.1% for theirs and 0.06% for ours), dominates the uncertainty in the orbital parallax. Thus, although we have improved the determination of the linear size of the orbit, there are no corresponding improvements in the orbital parallax or distance of 12 Boo, so we content ourselves with restating the results of Boden et al. (2005): $\pi_{\rm orb} = 27.72 \pm 0.15$ mas and a distance to the system of 36.08 ± 0.19 pc.

6.3. *HR 6169*

Table 8 lists the orbital elements of HR 6169, derived from the solution of our radial velocities, as well as the elements obtained by Young (1920). In Figure 4 our radial velocities and those of Young (1920) are compared with the radial velocity curves calculated from our elements alone. For HR 6169, in the yellow and red regions of the spectrum where we measured our radial velocities, the only useful lines representing the primary are the two Si II lines at 6347 and 6371 Å and a smattering of very weak Fe II lines, while the secondary is represented by lines of neutral and ionized species that are both more numerous and sharper. For this reason the secondary velocities are more precise than those of the primary. It follows that the secondary velocities have much higher weight than those of the primary (see Table 3), the secondary radial velocity curve is better defined than that of the primary, and K_2 is better determined than K_1.

Comparison of our results with Young's reveals some very significant discrepancies, especially for the γ-velocity. At first sight the large difference of -8.45 km s^{-1} between our γ-velocity (-18.33 ± 0.09 km s^{-1}) and Young's (-9.88 ± 0.85 km s^{-1}) suggests the presence of an unseen third star, which must have changed the γ-velocity of the spectroscopic binary pair in the 84 yr between the two measurements. A glance at Figure 4, however, shows that there is no need to invoke a third star. Instead, a simpler explanation of the difference can be found because of a systematic error in Young's γ-velocity caused by blending of the primary and secondary lines in his spectra. Young (1920) remarked that in his spectra with smaller primary-secondary velocity separations the primary lines and their secondary counterparts were blended, so that he was only able to measure a single blend velocity, which he adopted as the primary velocity. Inspection of

TABLE 8
ORBITAL ELEMENTS OF HR 6169

Parameter	Young (1920)	This Study
P (days)	10.56 ± 0.005	10.559435 ± 0.000055
T (HJD)	2,422,422.236 ± 0.046	2,453,171.529 ± 0.004
e	0.430 ± 0.012	0.4140 ± 0.0012
ω (deg)	4.12 ± 2.66	10.69 ± 0.20
K_1 (km s^{-1})	62.41 ± 1.08	71.35 ± 0.38
K_2 (km s^{-1})	101.36 ± 1.64	95.46 ± 0.13
γ (km s^{-1})	−9.88 ± 0.85	−18.33 ± 0.09
$m_1 \sin^3 i$ ($M_{\odot}$)	2.19	2.197 ± 0.012
$m_2 \sin^3 i$ ($M_{\odot}$)	1.35	1.642 ± 0.015
$a_1 \sin i$ (10^6 km)	8.18	9.431 ± 0.051
$a_2 \sin i$ (10^6 km)	13.28	12.618 ± 0.019
rms residual (km s^{-1}) (unit weight)	4.3	0.26

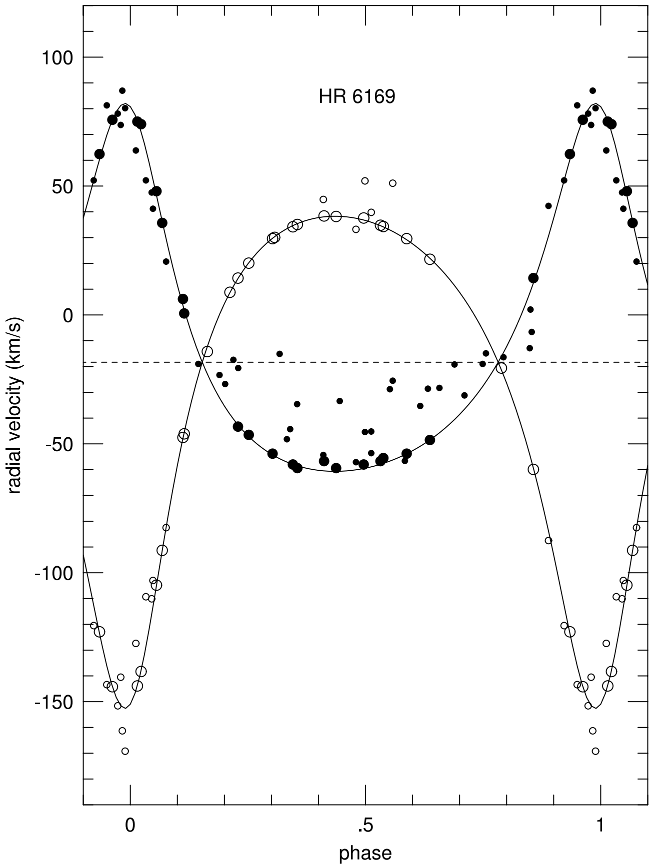

Fig. 4.—Radial velocities and calculated radial velocity curves for HR 6169. Filled and open circles are the primary and secondary velocities, respectively; large and small circles are our and Young's (1920) velocities, respectively. The latter set of velocities is shown for comparison only and was not used in our orbital analysis. In this system the secondary, which has sharper and—in the red—more numerous lines than the primary, has the more precise velocities.

Figure 4 shows that these blended primary velocities cluster around the smaller velocity extremum associated with the nodal passage near apastron. They mostly fall below the γ-velocity and, being dragged upward and toward it, are too positive; not being balanced by the few velocities that are dragged downward, their presence in Young's orbit solution made his γ-velocity too positive. Similar considerations account for his semiamplitude of the primary being too small, 62.41 ± 1.08 km s^{-1} compared with our value of 71.35 ± 0.38 km s^{-1}.

Unlike our other two systems, RR Lyn, which is an eclipsing system, and 12 Boo, for which interferometric observations have been used to determine a visual orbit, HR 6169 has no direct determination of its orbital inclination. Thus, at present we can only compute the minimum masses of its two components, which are 2.20 ± 0.01 and 1.64 ± 0.02 $M_\odot$ for the primary and secondary, respectively.

7. SPECTRAL TYPES AND MAGNITUDE DIFFERENCE

7.1. *RR Lyn*

Abt & Morrell (1995) classified the combined spectrum of RR Lyn as A3/A8/A6, based on its Ca II K, hydrogen Balmer, and metal lines, respectively, providing a general starting point for our determination. The rapid rotation of most A-type stars plus a variety of abundance peculiarities make it difficult to identify a significant number of slowly rotating reference stars for that spectral class. Despite the limited choices, identified primarily from the work of Abt & Morrell (1995), we obtained a reasonable fit to the spectrum of RR Lyn with HR 3354 (spectral classes of A3/A5/A7 = calcium/hydrogen/metals [Abt & Morrell 1995]) for the primary plus HR 1613 (spectral type A9 V [Abt & Morrell 1995] and [Fe/H] $\simeq$ 0.0 [Bikmaev et al. 2002]) for the secondary. While the iron lines of the primary are fitted relatively well by HR 3354, the calcium lines of this reference star are too weak. Our results for the stellar components, however, are similar to those of Khaliullin et al. (2001), who determined spectral types of A6 IV plus F0 V from their *WBVR* photometry and a comparison with evolutionary tracks. The continuum intensity ratio of our fit is 0.236, which corresponds to a magnitude difference of 1.6. This is in rough agreement with the results of Khaliullin et al. (2001), who used the *WVBR* photometric system (Khaliullin et al. 1985) and found a *V*-band luminosity ratio of 0.276, which corresponds to a magnitude difference of 1.40. Our magnitude difference is consistent with the luminosity classes assigned by Khaliullin et al. (2001). Thus, we adopt their estimated spectral types.

7.2. *12 Boo*

Guided by previous spectral classifications, we used HR 7560 (F8 V; Roman 1952; Gray et al. 2001) and mean [Fe/H] $= 0.06$ (Taylor 2003) as a proxy for both components but found the lines of the resulting composite spectrum fit to be too strong. However, with HR 5694 (F8 IV–V; Johnson & Morgan 1953) and mean [Fe/H] $= -0.10$ (Taylor 2003) used for both components we found an excellent fit to the spectrum of 12 Boo. The continuum intensity ratio of this fit is 0.637. Because the spectral classes of the two stars are essentially identical, this value is also the luminosity ratio at 6430 Å, a wavelength that is about 0.6 of the way between the center of the Johnson *V* and *R* bandpasses. The intensity ratio produces a magnitude difference of 0.5 with an estimated uncertainty of 0.1. Such a difference is in accord with the more precise ΔV magnitude of 0.48 determined by Boden et al. (2005). The slightly subsolar iron abundance is also in agreement with the results of Balachandran (1990) and Lèbre et al. (1999), who found [Fe/H] $= -0.03 \pm 0.09$ and -0.1 ± 0.1, respectively.

7.3. *HR 6169*

From DAO photographic plates, Petrie (1950) determined magnitude differences for 82 spectroscopic binaries, including HR 6169. He described the spectrum of this system as consisting of two narrow-line early-A stars and concluded that both components were dwarfs. His low-weight magnitude difference in the blue region of the spectrum is 0.7 ± 0.4.

Unlike our results for 12 Boo and RR Lyn, we have had difficulty finding a good combination of reference stars to represent the spectrum of HR 6169. Given the A spectral class of the components, the lines of both stars are quite weak in the 6430 Å region, with all but one of the lines being less than 5% deep in the combined spectrum. The primary component has the stronger Fe II lines and weaker Fe I lines and so is earlier in spectral class. From the metal lines our best estimates of those spectral classes are A1 for the primary and A7 for the secondary, with a continuum intensity ratio in the 6430 Å region that corresponds to a minimum magnitude difference of $\sim$1.

Alternatively, the spectral types may be estimated from the colors of the components. Guided by the above results, we found that the $B - V$ colors for stars of spectral types A1 V and A5 V, taken from Table II of Johnson (1966), plus an adopted *V* magnitude difference of 0.9 result in the observed $B - V = 0.06$ from *Hipparcos* (Perryman et al. 1997). We have adopted those spectral types and colors in our additional analyses.

8. CIRCULARIZATION AND SYNCHRONIZATION

The two main theories of orbital circularization and rotational synchronization (e.g., Zahn 1977; Tassoul & Tassoul 1992) disagree significantly on absolute timescales but do agree that synchronization should occur first. From surveys of B and A stars Abt et al. (2002) concluded that synchronization occurs faster than circularization, confirming for early-type stars the theoretical results. The three systems discussed here have orbital periods between 9.6 and 10.6 days and eccentric rather than circular orbits. Since two of the three systems contain A-type stars, the observed eccentricities of their orbits are not surprising. Matthews & Mathieu (1992) examined 62 spectroscopic binaries with A-type primaries and periods less than 100 days. They concluded that all systems with orbital periods $\lesssim$3 days have circular or nearly circular orbits. They also found that many binaries with periods in the range of 3–10 days have circular orbits, while all those with periods greater than 10 days have eccentric orbits. Thus, the eccentric orbits of RR Lyn and HR 6169 appear to be typical of A-type systems with periods near 10 days.

Hut (1981) has shown that in an eccentric orbit a star's rotational angular velocity will tend to synchronize with that of the orbital motion at periastron, a condition called pseudosynchronous rotation. With equation (42) of Hut (1981) we calculated pseudosynchronous periods for the three systems.

8.1. *RR Lyn*

For RR Lyn our $v \sin i$ values are 14.6 ± 1 and 11.3 ± 2 km s^{-1} for its primary and secondary, respectively. The uncertainties are estimated, with that for the secondary being larger because of the weakness of its lines. We assume that the orbital and rotational axes are parallel, so the rotational inclination is 87°.4. Since it is so close to 90°, we adopt our $v \sin i$ values as the equatorial rotational velocities of the components. From Table 6 the radii are 2.57 and 1.59 $R_\odot$ for the primary and secondary, respectively. Those values, combined with the pseudosynchronous period of 9.59 days, lead to rotational velocities of 13.6 and 8.4 km s^{-1}. Thus, the rotation of the primary is consistent with its pseudosynchronous value, while the secondary appears to be rotating slightly faster than pseudosynchronous.

8.2. *12 Boo*

Our projected rotational velocities for 12 Boo, 13.0 ± 1 and 10.3 ± 1 km s^{-1} for its primary and secondary, respectively, are in good agreement with those determined by De Medeiros & Udry (1999) and Boden et al. (2000). Again, we assume that the orbital and rotational axes are parallel, so the rotational inclination is 108°. Thus, the observed equatorial rotational velocities become 13.7 and 10.8 km s^{-1}. The radii of the two components (Boden et al. 2005) and the pseudosynchronous period of 7.84 days lead to predicted rotational velocities of 15.9 and 12.0 km s^{-1}. Thus, the primary is rotating slightly slower than its predicted velocity, while the secondary may well be rotating pseudosynchronously.

8.3. *HR 6169*

To determine whether the components of HR 6169 are pseudosynchronously rotating we must first estimate their radii. From the *Hipparcos* catalog (Perryman et al. 1997) the V magnitude and $B - V$ color of the HR 6169 system are 6.42 and 0.062, respectively. The *Hipparcos* parallax of 6.17 ± 0.087 mas (Perryman et al. 1997) corresponds to a distance of 162 ± 24 pc. Although at such a distance there may be a modest amount of interstellar reddening, the color of the system is consistent with the spectral type of the primary, and so we have assumed no interstellar reddening. As a result, the parallax, the V magnitude, and the adopted V magnitude difference of 0.9 (§ 7.3) were combined to obtain absolute magnitudes $M_V = 0.8 \pm 0.3$ and $M_V = 1.7 \pm 0.3$ mag for the primary and secondary, respectively. A $B - V$ color of 0.03 for the primary and a $B - V$ of 0.14 for the secondary (Johnson 1966) were adopted and then used in conjunction with Table 3 of Flower (1996) to obtain the bolometric corrections and effective temperatures of the two components. The resulting luminosities of the primary and secondary are $L_1 = 43 \pm 12$ and $L_2 = 17 \pm 5$ $L_\odot$, respectively, while the radii are $R_1 = 2.6 \pm 0.4$ and $R_2 = 2.1 \pm 0.3$ $R_\odot$, respectively. The uncertainties in the computed quantities are dominated by the parallax and magnitude difference uncertainties plus, to a lesser extent, the effective temperature uncertainty, which is estimated to be $\pm$200 K.

Because the orbit of HR 6169 has a moderately large eccentricity of 0.414, the pseudosynchronous period of 4.95 days is less than half of the orbital period. With that period and the above radii, we obtain pseudosynchronous rotational velocities of 26.6 and 21.5 km s^{-1} for the primary and secondary, respectively. We have determined $v \sin i$ values of 32 ± 5 and 18 ± 2 km s^{-1} for the primary and secondary, where the uncertainties are estimated. The minimum masses of the components are rather large, suggesting a relatively high orbital inclination. A comparison with canonical values of absolute magnitudes and masses for dwarfs of the appropriate spectral types (Gray 1992) suggests an inclination of about 70°. Adopting this value, assuming, as has been done for the other two systems, that the rotational inclination has the same value, produces equatorial velocities of 34 and 19 km s^{-1}. Thus, the primary appears to be rotating slightly faster than its pseudosynchronous velocity, while the secondary may be rotating pseudosynchronously.

9. SUMMARY

We have determined new spectroscopic orbits for the bright SB2 systems RR Lyn, 12 Boo, and HR 6169. The accuracies of the minimum masses ($m_1 \sin^3 i$ and $m_2 \sin^3 i$) range from 0.13% for the secondary of 12 Boo to 0.9% for the secondary of HR 6169, while the accuracies of the linear sizes of the relative orbit ($a \sin i$) range from 0.05% for 12 Boo to 0.25% for HR 6169. These results show that our radial velocities provide well-determined spectroscopic orbits, which do justice to interferometric measurements of 12 Boo (Boden et al. 2005) and, we expect, will also do justice to prospective interferometric measurements of RR Lyn, HR 6169, and other systems in our program.

For RR Lyn, an eclipsing binary with a well-determined orbital inclination, we have determined accurate new masses and radii for its components. The semimajor axis of the relative orbit, $a = 29.32 \pm 0.04$ $R_\odot$, plus the distance to the system, 73.5 ± 2.8 pc (Khaliullin et al. 2001), lead to a predicted angular size $a = 1.86$ mas for the true orbit and, because ω (179°.4 ± 0°.6) is 180° to within its measurement error so that the semimajor axis lies across the line of sight, this will also be the a of the apparent orbit. We find that the expected effect of the unseen third star proposed by Khaliullin & Khaliullina (2002) on our and Kondo's (1976) radial velocities is so slight as to be well below the threshold of our measurement errors.

We have determined a new spectroscopic orbit for 12 Boo, which confirms, and is more precise than, that determined by Boden et al. (2005) as part of their measurement of the three-dimensional orbit of this system. Our investigation of HR 6169 corrects systematic errors in Young's (1920) orbit and leads to significant revisions of the minimum masses and $a_{1,2} \sin i$. At the distance of HR 6169, 162 ± 23 pc (Perryman et al. 1997), the $a \sin i$ of 22.05 ± 0.05 Gm corresponds to an angular separation of 0.91 mas.

In conclusion, we find that radial velocities observed with small and medium-sized telescopes and measured by traditional methods provide a suitable spectroscopic contribution to the combination of measurements required for determination of three-dimensional orbits.

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