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THE SPECTROSCOPIC AND ASTROMETRIC ORBITS OF HR 672

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ABSTRACT

From a very extensive set of radial velocities obtained at Fairborn Observatory we have computed a new spectroscopic orbit for HR 672. This binary has an orbital period of 93.290 days and an eccentricity of 0.5249. The greatly improved orbital elements have been incorporated into a new astrometric orbit, which has an inclination of 110°, from *Hipparcos* data. The primary is a slowly rotating early G star that is situated nearly 1 mag above the main sequence and is likely pseudosynchronously rotating. It has an iron abundance that is greater than that of the Sun. Lines of the secondary were not detected at red wavelengths, consistent with an adopted M0 dwarf spectral type. The age of the system is estimated to be about 5 billion years. The binary is a good candidate for interferometric resolution at infrared wavelengths.

Key words: binaries: spectroscopic — stars: fundamental parameters — stars: individual (HR 672)

Online material: machine-readable table

1. INTRODUCTION

HR 672 (HD 14214, HIP 10723; $\alpha = 02^h18^m01.4^s$, $\delta = 01°45'28.1''$ [J2000.0], $V = 5.60$ mag) is a slowly rotating, early G star in the constellation of Cetus. Roman (1955) gave its spectral type as F9 V, while classifications of G0.5 IV (Barry 1971) and G0 V (Harlan 1974; Cowley 1976) followed. Most recently, Gray et al. (2003) determined a spectral type of G0 IV. Saar & Osten (1997) measured a value of 3 km s^{-1} for its projected rotational velocity.

In 1922 Harper (1930) discovered that HR 672 is a spectroscopic binary, and after obtaining a total of 42 observations he determined an orbit with a period of 93.5 days. As a result of his analysis, Harper (1930) found a trend in the velocity residuals and considered the possibility of a third body with a period of about 1 or 2 yr. However, he ultimately concluded that the apparently systematic residuals were probably accidental. In several surveys of late-type stars, Abt and his colleagues (Abt & Levy 1969; Abt & Willmarth 1987, 2006) obtained additional velocities of HR 672. Abt & Willmarth (2006) combined these sets of more recent velocities and refined the orbital period to 93.304 days. Using the orbital elements of Harper (1930) the *Hipparcos* team (Perryman et al. 1997) computed an astrometric orbit for HR 672.

Our interest in HR 672 arose from its inclusion by Fekel & Tomkin (2004) in a list of known single-lined binaries with relatively large mass functions that could be resolved by optical interferometers. It was hoped that observations at red wavelengths would detect lines of the secondary in many of those single-lined systems, enabling precise masses of both components to be determined once an orbital inclination is known. Although secondary lines have now been detected for 10 single-lined binaries in that survey (Fekel & Tomkin 2007), HR 672 is not one of those systems. Another characteristic of HR 672 that piqued our interest is that it has an eccentric orbit oriented such that its velocity falls from maximum to minimum velocity over a period of 18 days. After our observations were begun Abt & Willmarth (2006) published a greatly improved single-lined orbit for HR 672, but the phase of rapid velocity change remains poorly covered. Although we have been unable to detect lines of the secondary, the combination of the improved spectroscopic and astrometric orbits and an estimate of the mass of the primary has enabled us to determine basic properties of the system.

2. SPECTROSCOPIC OBSERVATIONS AND REDUCTIONS

From 2004 January to 2007 January we acquired 281 observations with the Tennessee State University 2 m Automatic Spectroscopic Telescope (AST), a fiber-fed echelle spectrograph, and a 2048 × 4096 SITe ST-002A CCD. The echelle spectrograms have 21 orders, covering the wavelength range 4920–7100 Å with an average resolution of 0.17 Å. The typical signal-to-noise ratio of these observations is ~30. Eaton & Williamson (2004) have given a more extensive description of the telescope, situated at Fairborn Observatory near Washington Camp in the Patagonia Mountains of southeastern Arizona, and its operation.

From 2006 June to 2006 September we obtained three red wavelength observations of HR 672 with the Kitt Peak National Observatory (KPNO) coudé-feed telescope, coudé spectrograph, and a TI CCD detector. The spectrograms are centered at 6430 Å, cover a wavelength range of about 80 Å, have a resolution of 0.21 Å, and have signal-to-noise ratio of ~250.

For the Fairborn Observatory AST spectra, a Gaussian function was fitted to each of approximately 100 relatively strong, mostly Fe I lines, which were not strong blends. Lines at the ends of each echelle order were excluded because of their lower signal-to-noise ratios. The difference between the observed wavelength

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TABLE 1
Radial Velocities and Orbital Residuals

HJD − 2,400,000	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})
53,022.747	0.617	32.9	0.0
53,051.671	0.927	40.6	0.0
53,275.895	0.331	20.0	0.0
53,283.933	0.417	24.3	0.0
53,288.947	0.471	26.7	0.0
53,293.954	0.524	29.0	0.0
53,298.851	0.577	31.2	0.0
53,308.833	0.684	35.7	0.0
53,315.796	0.758	38.7	−0.1
53,321.789	0.823	41.3	0.0

Note.— Table 1 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

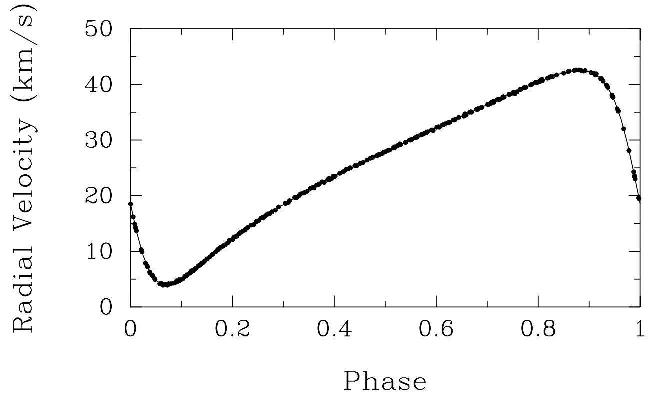

Fig. 1.—Our Fairborn Observatory radial velocities (*circles*) compared with the computed radial velocity curve of HR 672. Zero phase is a time of periastron passage.

and that given in the solar line list of Moore et al. (1966) was used to compute the radial velocity, and a heliocentric correction was applied. The final mean velocity for each observation is given in Table 1. Our unpublished velocities of several IAU standard stars with similar spectral types to HR 672 indicate that the Fairborn Observatory velocities have a small zero-point offset of -0.3 km s^{-1} relative to the velocities of Scarfe et al. (1990).

3. SPECTROSCOPIC ORBIT

With the period of Abt & Willmarth (2006) adopted and 0.3 km s^{-1} added to each Fairborn Observatory velocity, initial orbital elements were computed with a program that implements a slightly modified version of the Wilsing-Russell method (Wolfe et al. 1967). The orbit was then refined with a program that uses differential corrections (Barker et al. 1967).

Additional velocities of HR 672 are available from several other sources. Combining the published radial velocities of Abt & Willmarth (1987, 2006) with our velocities decreases the period by 0.0005 days. A solution with our velocities and the much less precise velocities of Harper (1930), which were obtained over 74 yr ago and thus are separated from the current velocities by 290 cycles or more, results in a period decrease of 0.002 days, a difference of 1.5 σ. However, given the uncertainties in the velocity zero points of those sets of observations, neither the velocities of Abt & Willmarth (1987, 2006) nor those of Harper (1930) were used for the final solution.

The orbital elements and related parameters, determined solely from the Fairborn Observatory velocities, are listed in Table 2. The phases of our observations and the velocity residuals to the computed curve are included in Table 1. There is no evidence in the residuals of the possible 1 or 2 yr period conjectured but rejected by Harper (1930), validating his conclusion that his apparent systematic residuals were accidental rather than evidence of a third body. Our observed velocities and the computed radial velocity curve are compared in Figure 1, where zero phase is a time of periastron passage. The rapid decline of the radial velocities from phase 0.882 to 0.070 is well covered.

4. ASTROMETRIC ORBIT

For HR 672 (= HIP 10723) the *Hipparcos* observations show an astrometric wobble with an amplitude that exceeds the typical observational precision. The *Hipparcos* team (Perryman et al. 1997) therefore fitted the data with an orbital model. In addition to the five basic astrometric parameters (position, parallax, and proper motion), four orbital elements were determined. The remaining three, namely the orbital period, the argument of the periastron, and the eccentricity, were adopted from Harper (1930). That initial orbital solution was included in part O of the *Hipparcos* Double and Multiple Systems Annex (Perryman et al. 1997).

Our significantly improved spectroscopic orbit makes it worthwhile to recompute the astrometric orbit. Here we impose our spectroscopic values for the elements P, e, ω, and T (Table 2) on the *Hipparcos* data to obtain a new astrometric solution. In Table 3 our results are compared with those of the earlier *Hipparcos* solution. The two solutions are very consistent. The adoption of the parameters from the new spectroscopic orbit has no significant effect on the parallax and proper motion of the system. The major improvements occur in the uncertainties of a_0 (the semimajor axis of the photocentric orbit) and the inclination, which are reduced

TABLE 2
Orbital Elements and Related Parameters

Parameter	Value
P (days)	93.290 ± 0.001
T (HJD)	$2,453,338.33 \pm 0.01$
γ (km s^{-1})	25.724 ± 0.005
K (km s^{-1})	19.275 ± 0.008
e	0.5249 ± 0.0003
ω (deg)	104.04 ± 0.05
$a \sin i$ (10^6 km)	21.05 ± 0.01
$f(m)$ ($M_\odot$)	0.04279 ± 0.00006
Standard error of an observation of unit weight (km s^{-1})	0.1

TABLE 3
Astrometric Solutions of *Hipparcos* Observations

Parameter	Perryman et al. (1997)		This Paper	
	Value	Uncertainty	Value	Uncertainty
Parallax (mas)	40.04	0.92	40.02	0.90
μ_α (mas yr^{-1})	365.99	1.08	366.12	1.07
μ_δ (mas yr^{-1})	371.16	0.66	371.17	0.65
a_0 (mas)	5.55	0.80	6.07	0.38
i (deg)	118.28	15.22	110.0	8.4
Ω (deg)	176.19	17.29	172.0	14

by a factor of 2. In particular, the inclination has been revised from $118^\circ \pm 15^\circ$ to $110^\circ \pm 8^\circ$.

5. SPECTRAL TYPE, ABUNDANCE, AND $v \sin i$

Our Fairborn Observatory spectra, although very numerous and covering a wavelength range of over 2000 Å, have relatively low signal-to-noise ratios. Thus, it is not surprising that those spectra show no evidence of the secondary, even when the spectra at phases near maximum velocity were coadded to significantly improve the signal-to-noise ratio. The red-wavelength KPNO spectra, with their much higher signal-to-noise ratios, were obtained specifically to search for the secondary, but residuals to the spectrum fits, discussed below, showed no lines from the secondary. In addition, we cross-correlated the KPNO spectra with a reference star having a spectral type similar to that expected for the secondary, but these correlations revealed no evidence of the secondary.

Given the previous classifications of HR 672, its spectrum was compared with those of late-F and early-G dwarfs and subgiants from the lists of Keenan & McNeil (1989), Fekel (1997), and Gray et al. (2003). Spectra of the reference stars were obtained at KPNO with the same telescope, spectrograph, and detector as were used for our spectra of HR 672. Comparisons with early-G stars having near solar abundances (Taylor 2003), such as λ Ser and β Com, and HR 483, produced less than the required line depths to fit the spectrum of HR 672. Better agreement was found with the spectrum of HR 4529 after rotationally broadening the lines of HR 672 to match the broadening of HR 4529. This reference star has a spectral type of G0 IV (Strassmeier & Fekel 1990) and $[\mathrm{Fe/H}] = 0.16$ (Edvardsson et al. 1993; Allende Prieto et al. 1999). As discussed in § 6, the *Hipparcos* parallax results in an absolute magnitude that is $\sim$0.8 mag above the average main sequence (Gray 1992), suggesting an intermediate IV-V luminosity class. Thus, our results are in good agreement with previous spectral classifications.

HR 672 has been the subject of several abundance analyses, resulting in values of [Fe/H] ranging from -0.07 (McWilliam 1990) to 0.17 (Takeda et al. 2005), with a mean [Fe/H] abundance of 0.05 from four determinations. Our comparison with reference stars having various iron abundances supports the conclusion that HR 672 is slightly metal-rich when compared to the Sun.

We have determined the projected rotational velocity of HR 672 from our three red-wavelength KPNO spectra with the procedure of Fekel (1997). For each star the full widths at half-maximum of several metal lines in the 6430 Å region were 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. We adopted the macroturbulence of 4 km s^{-1} that was determined for HR 672 by Saar & Osten (1997). Our resulting average $v \sin i$ is 2.1 km s^{-1} with an estimated uncertainty of 1 km s^{-1}. This value is in accord with the value of 2.8 ± 1.8 km s^{-1} measured by Saar & Osten (1997).

6. DISCUSSION

In agreement with Abt & Willmarth (2006) we detect only lines of the primary, component A. At our observed wavelength of 6430 Å the secondary, component B, is at least 2.5 mag fainter (e.g., Stockton & Fekel 1992). From the *Hipparcos* catalog (Perryman et al. 1997) the V magnitude and $B - V$ color of HR 672 are 5.60 and 0.588, respectively. Its *Hipparcos* parallax of $0.04004'' \pm 0.00092''$ (Perryman et al. 1997) corresponds to a distance of 25.0 ± 0.6 pc. Because HR 672 is such a nearby star, we have assumed that it is unaffected by interstellar reddening. As a result, the parallax plus the V magnitude produces an absolute magnitude $M_V = 3.61 \pm 0.05$ mag for the primary. We then used its $B - V$ color of 0.588 from the *Hipparcos* catalog (Perryman et al. 1997) in conjunction with Table 3 of Flower (1996) to obtain a bolometric correction of -0.054 mag and effective temperature of 5934 K. The resulting luminosity and radius of the primary are $L_A = 3.0 \pm 0.1\ L_\odot$ and $R_A = 1.64 \pm 0.07\ R_\odot$, respectively. The uncertainties in the computed quantities are dominated by the parallax and the effective temperature, the latter having an estimated uncertainty of $\pm$100 K. The above properties are summarized in Table 4.

TABLE 4
FUNDAMENTAL PROPERTIES

Parameter	Value	Reference
V (mag)	5.60	1
$B - V$ (mag)	0.588	1
Parallax (mas)	40.04 ± 0.92	1
Spectral type of A	G0 IV	2
Spectral type of B	$\sim$M0 V	3
$v_A \sin i$ (km s^{-1})	2.1 ± 1	3
M_V (A) (mag)	3.61 ± 0.05	3
L_A ($L_\odot$)	3.0 ± 0.1	3
R_A ($R_\odot$)	1.64 ± 0.07	3
M_A ($M_\odot$)	1.15	3

REFERENCES.—(1) Perryman et al. 1997; (2) Gray et al. 2003; (3) this work.

For the primary of HR 672 Allende Prieto et al. (1999) estimated a mass of 1.01 $M_\odot$, while Takeda et al. (2005) obtained a value of 1.27 $M_\odot$. Our comparison with the solar-abundance evolutionary tracks of Girardi et al. (2000) places the primary between the 1.1 and 1.2 $M_\odot$ tracks near the end of its main-sequence lifetime. We adopt a mass of 1.15 $M_\odot$ and an age of about 5 billion years. The mass function value of 0.043 $M_\odot$, a mass of 1.15 $M_\odot$ for the primary, and an orbital inclination of 110° from the astrometric orbit combine to produce a mass of 0.53 $M_\odot$ for the secondary, resulting in a spectral type of about M0 V (Gray 1992). Tables of canonical properties (Gray 1992) indicate that such a star is about 5 mag fainter than the primary, a result consistent with our lack of detection of its lines in the 6430 Å region.

The orbit of HR 672 is not circular but instead has a substantial eccentricity of 0.525. Thus, the rotational angular velocity of the G subgiant will tend to synchronize with that of the orbital motion at periastron, a condition called pseudosynchronous rotation (Hut 1981). With equation (42) of Hut (1981) we calculated a pseudosynchronous period of 30.5 days.

To determine whether the primary might be pseudosynchronously rotating, we combined the calculated pseudosynchronous period and our derived radius of 1.64 $R_\odot$ from Table 4 and computed a pseudosynchronous rotational velocity of 2.7 km s^{-1}. The measured $v \sin i$ values from this paper and Saar & Osten (1997) are 2.1 and 2.8 km s^{-1}, respectively. If, as is generally assumed, the orbital and rotational axes are parallel, then the rotational inclination is also 110°. Such a relatively high inclination converts the $v \sin i$ values to very similar equatorial rotational velocities, which are in reasonable agreement with the predicted pseudosynchronous velocity. Thus, we conclude that the primary of HR 672 is probably rotating pseudosynchronously.

From calibrations of the decrease of Ca II emission flux with increased age, Barry et al. (1981) and Duncan (1981) determined an age of about 5 billion years for HR 672, a value that is in agreement with our result from evolutionary tracks. Although the primary of HR 672 is more massive than the Sun and hence more evolved, its rotational velocity, like its age, is similar to the Sun's. However, Duncan (1981) determined $\log n(\mathrm{Li}) = 2.57$ for the primary. This relatively large value is similar to the upper envelope of lithium abundances determined for stars of similar temperature in the open cluster M67 (Balachandran 1995; Jones et al. 1999; Sestito & Randich 2005), which has an age of 4–5 billion years, but it is much greater than the Sun's logarithmic lithium abundance of 1.05 (King et al. 1997). From an examination of several young clusters Jones et al. (1997) proposed that solar-type stars with high rotation rates deplete their lithium faster on the main sequence than more slowly rotating stars. If true, then the primary of HR 672 was initially a slow rotator.

While the magnitude difference at visual wavelengths is estimated to be 5 mag, in the K band of the Johnson system the magnitude difference between the primary and secondary would decrease to $\sim$2.6 mag (Johnson 1966). This leads to an apparent K magnitude of $\sim$4.2 for the system, so the binary should be resolvable with the Center for High Angular Resolution Astronomy interferometric array (ten Brummelaar et al. 2003; McAlister et al. 2003). Mazeh et al. (2002) successfully used infrared spectroscopic observations at 1.555 μm to measure the radial velocities of faint secondaries in known low-mass main-sequence single-lined binaries. Such observations might be able to detect the secondary of HR 672.

The 2 m AST at Fairborn Observatory, built almost single-handedly by J. Eaton, has begun its valuable contribution to science. We acknowledge the dream, dedication, and hard work of J. Eaton and the support provided by M. Busby and L. Boyd, who together made our observations with the 2 m AST possible. This research at Tennessee State University has been supported in part by NASA grant NCC5-511 and NSF grant HRD-9706268.

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