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Francis C. Fekel
Tennessee State University

Gregory W. Henry
Tennessee State University

Jocelyn Tomkin
University of Texas at Austin

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New Precision Orbits of Bright Double-lined Spectroscopic Binaries. X. HD 96511, HR 7578, and KZ Andromedae

Francis C. Fekel[1,3], Gregory W. Henry[1], and Jocelyn Tomkin[2]
[1] Center of Excellence in Information Systems, Tennessee State University, Nashville, TN 37209, USA; fekel@evans.tsuniv.edu, gregory.w.henry@gmail.com
[2] Astronomy Department and McDonald Observatory, University of Texas, Austin, TX 78712, USA
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Abstract

From an extensive number of newly acquired radial velocities we determine the orbital elements for three late-type dwarf systems, HD 96511, HR 7578, and KZ And. The orbital periods are 18.89737 ± 0.00002, 46.81610 ± 0.00006, and 3.0329113 ± 0.0000005 days, respectively, and all three systems are eccentric, although KZ And is just barely so. We have detected lines of the secondary of HD 96511 for the first time. The orbital dimensions ($a_1 \sin i$ and $a_2 \sin i$) and minimum masses ($m_1 \sin^3 i$ and $m_2 \sin^3 i$) of the binary components all have accuracies of 0.2% or better. Extensive photometry of the chromospherically active binary HR 7578 confirms a rather long rotation period of 16.446 ± 0.002 days and that the K3 V components do not eclipse. We have estimated the basic properties of the stars in the three systems and compared those results with evolutionary tracks. The results for KZ And that we computed with the revised *Hipparcos* parallax of van Leeuwen produce inconsistencies. That parallax appears to be too large, and so, instead, we used the original *Hipparcos* parallax of the common proper motion primary, which improves the results, although some problems remain.

Key words: binaries: spectroscopic – stars: fundamental parameters – stars: individual (HD 96511, HR 7578, KZ And)

Supporting material: machine-readable tables

1. Introduction

Over the past several decades the overlap of spectroscopic and visual binaries that are observable with both spectroscopy and ground-based optical and near-infrared interferometry has grown significantly (Quirrenbach 2001). Thus, the possibilities for the direct determination of stellar masses and precise stellar parallaxes from their three-dimensional orbits have been greatly enhanced. Torres et al. (2010) provided a compilation of binaries with precise masses and listed 23 interferometric binaries with masses determined to an accuracy of $\leqslant 3\%$. Additional basic parameters such as absolute magnitudes, luminosities, rotational velocities, and abundances can also be determined from the interferometric and spectroscopic data, enabling valuable comparisons with stellar evolutionary theory (e.g., Hummel et al. 2001; Boden et al. 2006; Fekel et al. 2009a).

In 2002, we began an observing program to redetermine the orbits of about 50 bright field binaries. That program had several purposes. We chose binaries from the Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems (Batten et al. 1989) that could be resolved with current interferometers but had spectroscopic orbits that needed improved precision so that the uncertainties of the spectroscopic minimum masses are not the limiting factor in the mass determinations. Obtaining radial velocities of previously analyzed spectroscopic binaries at a substantially different epoch can also result in the discovery of a third component, increasing the known multiplicity of systems (e.g., Duquennoy & Mayor 1991). Such information is needed for the statistics of multiple systems and an understanding of their origin (Tokovinin 2008). A third objective of this binary star program is the spectroscopic detection of previously unseen secondary components, turning single-lined binaries into much more useful double-lined binaries. The binary mass ratio distribution, for example, is an important diagnostic for assessing models of binary formation (e.g., Halbwachs et al. 2003). Such newly detected double-lined binaries with their large light ratios are primary candidates for mass determinations once *Gaia*'s astrometric measures are available (e.g., Kiefer et al. 2016).

We have previously published the results for 26 binaries, the most recent being Fekel et al. (2015). In the current work, we have detected the secondary component of HD 96511 for the first time and determined new orbits for that system as well as improved orbits for HR 7578 and KZ And. Some basic information about these double-lined binaries is given in Table 1.

2. Brief History

2.1. HD 96511 = HIP 54632

At Mount Wilson Observatory, Sanford (1924) acquired spectrograms of HD 96511 ($\alpha = 11^h10^m55\overset{s}{.}14$, $\delta = 81°43'54\overset{''}{.}0$ (2000)) and after three observations identified the star as a spectroscopic binary. From velocity measurements of 25 spectrograms he computed a single-lined orbit that has a period of 18.892 days and a moderate eccentricity of 0.28. Although he determined a large mass function of 0.111 $M_\odot$, he detected "no certain evidence" of any lines of the secondary. He also stated that the spectrum of the primary was that of a G0 dwarf.

For over a half century little additional attention was paid to HD 96511, perhaps because of its very high northern declination of nearly 82°. However, eventually Young & Koniges (1977) included it in a spectroscopic survey of Ca II H and K emission in late-type binaries. Although no Ca emission was detected for

[3] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

Table 1
Basic Properties of the Program Stars

Name	HR	HD	Spectral Type	V (mag)	$B-V$[a] (mag)	Parallax[a] (mas)	Period[a] (days)
…	…	96511	G0	7.15	0.700	21.88	18.89737
				…	±0.007	±0.40	±0.00002
V4200 Sgr	7578	188088	K3 V	6.18	1.02	71.18	46.81610
				…	…	±0.42	±0.00006
KZ And	…	218738	K2 V	7.91	0.900	34.06	3.0329113
				…	…	±2.31	±0.0000005

Note.
[a] When available, the uncertainties are provided below the listed values.

HD 96511, they cautioned that their detectability threshold is relatively high compared to the work of Wilson (1976).

Hooten & Hall (1990) included HD 96511 in a photometric search for variability of 50 late-type stars. Despite the very limited number of observations that were acquired of it, they concluded, apparently from the rms of the meager data, that HD 96511 might have light variations.

Eggen (1992) discussed metal-rich stars that he identified as members of the HR 1614 moving group, the supposed remnant of a disrupted supercluster of stars. The inclusion by Eggen (1992) of HD 96511 as a member of the HR 1614 group increased interest in its properties. Hufnagel & Smith (1994) obtained *IUE* satellite long-wavelength, low-resolution spectra of stars considered to be group members. From a determination of a Mg II low-resolution spectral index they concluded that HD 96511 was not particularly chromospherically active and like the other dwarfs in the sample had an age of at least 3 Gyr. Feltzing & Holmberg (2000) confirmed the reality of the HR 1614 moving group, determined its age at $\sim$2 Gyr, and found an iron abundance, $[Fe/H] \simeq 0.19 \pm 0.06$, for the group. They concluded that the space motions of HD 96511 are consistent with membership in the moving group although its metallicity value, $[M/H] = 0.09$, from a photometric calibration is a bit lower than the group value.

Pourbaix & Boffin (2003) reexamined the *Hipparcos* Intermediate Astrometric Data for a number of binary stars with known orbits. With the help of the original spectroscopic orbit of Sanford (1924) they computed an astrometric orbit for HD 96511 and also mentioned that the system might well be detectable as a double-lined binary.

2.2. HR 7578 = HD 188088 = V4200 Sgr = HIP 97944 = ADS 13072 A

In a discussion about the multiplicity of stars, Evans (1968) suggested that HR 7578 ($\alpha = 19^h54^m17\overset{s}{.}75$, $\delta = -23°56' 27\overset{''}{.}9$ (2000)) is not a single star. Taylor (1970) obtained metal abundances of late-type stars in the solar neighborhood. In a note to his Table 10, Taylor reported that a spectrum of HR 7578 obtained by L. Kuhi in 1968 showed two sets of lines. Taylor (1970) concluded from his study that HR 7578 (as well as HR 1614, which was mentioned in the discussion of HD 96511) is one of a small number of super-metal-rich stars in the solar neighborhood. Gray et al. (2006) determined an overall metal abundance, [M/H], of 0.29 indicating that the star is indeed metal-rich.

Adams et al. (1929) classified HR 7578 as dK5 on the Mount Wilson system. More recent spectral types on the MK system include K2 V (Upgren et al. 1972), K3 IV (Abt 1985), K3/4 V (Houk & Smith-Moore 1988), K2 IV (Gray et al. 2006), and K3 Va CN1 (Keenan & McNeil 1989).

Radial velocities of HR 7578 from a photoelectric radial-velocity spectrometer and from coudé Reticon spectra enabled Fekel & Beavers (1983) to determine an orbital period of 46.817 days. Fekel & Beavers (1983) concluded that the components of HR 7578 are very similar in brightness and mass. They noted that the large minimum masses of the K-dwarf components suggest that despite the relatively long orbital period, eclipses might occur. Pazzi (2008) obtained photometric observations to search for such eclipses but found no evidence for them.

The components of HR 7578 are chromospherically active. Fekel & Beavers (1983) found modest Ca II H and K emission. Robinson et al. (1990) presented a spectrum of the Ca H and K region that showed the emission reversals of both components. Frasca & Catalano (1994) surveyed the Hα line of late-type active binaries and found that the Hα absorption cores of HR 7578 were partially filled by emission.

As they did for HD 96511, Hooten & Hall (1990) obtained photoelectric photometry of HR 7578. They separately analyzed several seasons of photometry and from the best one determined a period of 16.5 days. Thus, this system is a BY Dra variable. Based on those results, Kazarovets et al. (1993) assigned HR 7578 the variable star name V4200 Sgr. The photometry of Pazzi (2008) produced a period of 16.355 days and suggested a long-term variation in mean brightness of perhaps 30 years.

HR 7578 has a visual companion that is currently separated by about 40$''$ and is 4.4 mag fainter (Sinachopolous 1989). Aitken & Doolittle (1932) noted that the very significant relative motion of the system is accounted for by the large proper motion of the primary. Thus, HR 7578 and this visual companion are an optical double. However, Allen et al. (2012) included HR 7578 in a search for low-mass companions to spectroscopic binaries. They discovered an M5 dwarf common proper motion companion with $V \sim 14$ mag making the system at least triple. Chini et al. (2014) used both *WISE* satellite and new IRIS ground-based data to confirm that the faint companion has a common proper motion.

2.3. KZ And = HD 218738 = HIP 114379 = ADS 16557 B

KZ And ($\alpha = 23^h09^m57\overset{s}{.}37$, $\delta = 47°57'30\overset{''}{.}1$ (2000)) is the fainter component of a common proper motion binary that is separated by 15$\overset{''}{.}$6. Heintz (1990) showed that over a 50 year period there was very little relative motion of the pair in their wide orbit. The primary, HD 218739, is a single star (König et al. 2006; Strassmeier et al. 2012) of spectral type G1 V (Gray et al. 2003).

Krzeminski (1969) reported that J. Greenstein and R. Kraft discovered that KZ And is a spectroscopic binary, but no orbit was determined. Bopp & Fekel (1975) used radial velocities measured from photographic plates acquired at four observatories to determine an orbit with a 3.03287 day period. They found that the absorption features of the two components were nearly identical as were the minimum masses.

Bopp & Fekel (1975) classified the combined spectrum of the spectroscopic binary as dK2 and noted Ca II H and K emission in both components. They also mentioned that Hα was in absorption. Both Keenan & McNeil (1989) and Gray et al. (2003) made similar classifications of K2−Ve and K2 V k, respectively, for the composite spectrum. From high resolution, high signal-to-noise (S/N) spectrograms Fernandez-Figueeroa et al. (1994) identified nearly equal Ca II K emission from both components and very weak Hϵ emission. Vogt et al. (1983) detected the relatively rapid rotation, 12 km s^{-1}, of both components of KZ And and assumed that the stars are rotating synchronously.

Krzeminski (1969) detected light variations in KZ And and identified its variability as being of the BY Draconis type. Despite its early-K-dwarf spectral type, Bopp & Espenak (1977) included it in a photometric survey of M dwarfs with and without Balmer emission lines. They carefully excluded the common proper motion primary from their photometric observations and in agreement with Krzeminski (1969) found light variations in KZ And although with a larger *V* mag range of ~0.08. Shortly thereafter, Kholopov et al. (1978) assigned HD 218738 the variable star designation KZ And.

3. Observations and Reductions

3.1. Spectroscopic

Our new spectroscopic observations of HD 96511, HR 7578, and KZ And were obtained at three observatories. The majority were acquired from 2003 through 2017 with the Tennessee State University 2 m automatic spectroscopic telescope (AST) and a fiber-fed echelle spectrograph. That telescope is part of Fairborn Observatory near Washington Camp in the Patagonia Mountains of southeastern Arizona (Eaton & Williamson 2004, 2007). Through 2011 June we used a 2048 × 4096 SITe ST-002A CCD with 15 μm pixels as the detector. The reduction of the raw spectra and their wavelength calibration have been discussed by Eaton & Williamson (2007). Those AST echelle spectrograms have 21 orders. They primarily cover the yellow and red regions of the spectrum from 4920 to 7100 Å and have an average resolution of 0.17 Å. The typical S/N of these observations is ~80 at 6000 Å.

During the summer shutdown of 2011 the SITe CCD detector and dewar were removed and replaced with a Fairchild 486 CCD having a 4096 × 4096 array of 15 μm pixels and a new dewar. Fekel et al. (2013) have provided additional information about these changes. The echelle spectrograms from this new CCD have 48 orders that, compared to the SITe CCD, cover a broader wavelength region, 3800–8260 Å. At various times we used fibers of different diameters, so the resolution of the Fairchild spectra is either 0.24 or 0.4 Å. The S/N of the spectra was improved and ranged from 80 to 150 at 6000 Å.

From 2005 through 2011 we acquired additional spectrograms at the Kitt Peak National Observatory (KPNO) with the coudé feed telescope and coudé spectrograph. Most of the observations were obtained with a Texas Instruments (TI) CCD detector. Those spectra are centered at 6430 Å, cover a wavelength range of 84 Å, and have a resolution of 0.21 Å. In 2008 September, the TI detector was unavailable, and so we observed with a Tektronics CCD, designated T1KA. For those observations the spectrum was centered at 6400 Å. While the wavelength coverage with that CCD was increased to 172 Å, the resolution decreased to 0.34 Å. In 2010 September, the small TI CCD was retired from service. After that date our observations were acquired with a CCD made by Semiconductor Technology Associates, which was assigned the designation STA2. That CCD has a 2600 × 4000 array of 12 μm pixels. For STA2 the spectrum was once again centered at 6430 Å. The increased size of this detector resulted in a wavelength range of 336 Å. While these spectra generally have the same resolution as the TI CCD spectra, there is a worsening of the resolution at both ends.

Finally, at McDonald Observatory in 2005 and 2006 we collected four spectra with the 2.1 m telescope, the Sandiford Cassegrain echelle spectrograph (McCarthy et al. 1993), and a Reticon CCD. The wavelength range of those spectrograms is moderate, 5700–7000 Å, and the resolution of 0.13 Å is the best of our new data sets. Additional information about our McDonald and KPNO observations is given in Tomkin & Fekel (2006).

Fekel et al. (2009b) provided an extensive general description of velocity measurement of the Fairborn AST spectra. All three of our binaries are late-type stars. For HD 96511 we used our line list for solar-type stars, which includes mostly neutral Fe lines. The later spectral types of HR 7578 and KZ And result in increased line strengths and blending of many neutral lines. So for those two stars we used a subset of the solar-type star line list that consisted of just the 63 least blended lines. Like Lacy & Fekel (2011) and Fekel & Griffin (2011), we fitted the individual lines of our systems with a rotational broadening function.

The Fairborn velocities are on an absolute scale. A comparison of our unpublished measurements of several IAU standard, solar-type stars with those determined by Scarfe (2010) indicates that the Fairborn Observatory velocities from the SITe CCD have a small zero-point offset of −0.3 km s^{-1}. Velocities from the Fairchild CCD spectra have a slightly larger zero-point offset of −0.6 km s^{-1} relative to those of Scarfe (2010). Thus, we corrected our measured velocities by either 0.3 or 0.6 km s^{-1}, depending on which detector was used.

The McDonald velocities, like those from Fairborn, are on an absolute scale. The KPNO velocities on the other hand are relative velocities, determined by cross-correlation relative to stars with constant radial velocities. For the KPNO spectra of HD 96511 we used the IAU standard β Vir with its velocity adopted from Scarfe (2010). Our cross-correlation standard for HR 7578 was either β Aql or HR 7560. Like β Vir, the radial velocity that we used for HR 7560 is from Scarfe (2010). From our unpublished observations we adopt a velocity of −40.3 km s^{-1} for β Aql. More details about the procedures that we have used to measure the McDonald and KPNO radial velocities are given in Tomkin & Fekel (2006).

3.2. Photometric

We acquired nightly photometric observations of HR 7578 between 1988 April and 1997 July with our T3 0.4 m

Automatic Photoelectric Telescope (APT) at Fairborn Observatory. The T3 APT was programmed to make differential B and V brightness measurements of HR 7578 with respect to comparison and check stars in the following sequence, termed a group observation: K,S,C,V,C,V,C,V,C,S,K. Star C is the comparison star HD 188276 ($V = 7.94$, $B - V = 1.23$, K2/K3III), star K is the check star HD 188376 ($V = 4.70$, $B - V = 0.75$, G5IV), star V is the program (variable) star HR 7578 ($V = 6.18$, $B - V = 1.02$, K3V), and S is a sky position. Three $V - C$ and two $K - C$ differential magnitudes are created from each group sequence, then averaged together to create group mean differential magnitudes, corrected for differential extinction, and transformed to the Johnson photometric system. Observations with group mean standard deviations greater than 0.01 mag are discarded as taken in non-photometric conditions. Further information on the operation of our APTs and the reduction and calibration of the data can be found in Henry (1995a, 1999), Henry et al. (1995b), Eaton et al. (2003), and Fekel & Henry (2005).

4. Determination of Spectroscopic Orbits and Results

To determine the orbital elements, we first obtained preliminary elements for each component with the program BISP (Wolfe et al. 1967), which uses the Wilsing–Russell Fourier analysis method (Wilsing 1893; Russell 1902). We refined those elements with the differential corrections program SB1 (Barker et al. 1967). When the number and phase distribution of radial velocities from the different observatories were sufficient, we determined separate orbital solutions. We assigned unit weights to the velocities of the orbital solution with the smallest variance. We then set the weights of the velocities in the other data set solutions to be the inverse of their variance ratios with respect to the best orbital solution. For a simultaneous solution of the two components, we appropriately weighted the velocities and used SB2, which is a slightly modified version of SB1.

The symbols that we adopt for the orbital elements, P, T, e, ω, K, and γ, have their usual meanings of orbital period, time of periastron passage, orbital eccentricity, longitude of periastron, velocity half-amplitude, and systemic radial velocity. To compute the related parameters, $a \sin i$ and $m \sin^3 i$, which are the projected orbital separation and the minimum mass, respectively, we adopt the physical constants that are recommended by Torres et al. (2010).

4.1. HD 96511

We first observed HD 96511 at Fairborn Observatory where between 2005 and 2015 we acquired 131 useful spectrograms. From 2007 to 2011 we collected 19 additional spectrograms at KPNO plus two in 2006 at McDonald Observatory. The spectrum of HD 96511 in the 6420 Å region is shown in Figure 1 where the weaker secondary lines can be seen. All of our new velocities are listed in Table 2.

We obtained four separate orbital solutions, two for each component. We analyzed our extensive Fairborn velocities and then because of the very small number of McDonald velocities, we determined a combined solution of the McDonald and KPNO velocities. Those solutions of the Fairborn velocities and the combined McDonald and KPNO velocities resulted in weights of 1.0, 0.6, 0.15, and 0.15 for the primary and secondary, respectively. The center-of-mass velocities of the four solutions agreed to within 0.4 km s^{-1}, and so the appropriately weighted velocities of the data sets were combined into a single solution.

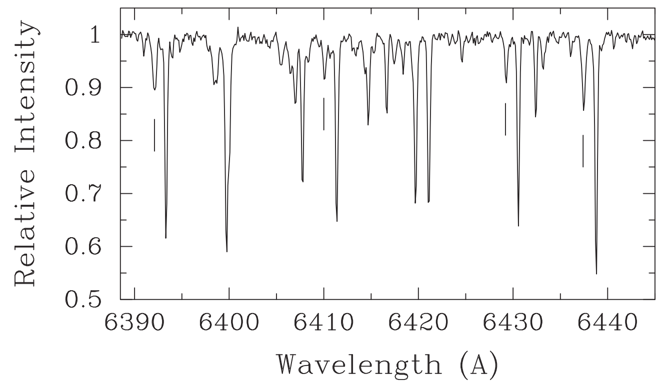

Figure 1. KPNO spectrum of the 6420 Å region of HD 96511. Vertical lines indicate four spectral features of the significantly weaker blueshifted secondary component.

The only other extensive set of radial velocities of HD 96511 produced the single-lined orbit of Sanford (1924). Those velocities were determined from Mount Wilson Observatory photographic plates. Our orbital solution with those velocities resulted in a standard error of 3.1 km s^{-1} for an observation of unit weight. Thus, those velocities have such low weights in comparison with those from Fairborn Observatory that the old Mount Wilson velocities do not improve the period or other orbital elements when they are combined in a solution with the velocities from Fairborn, KPNO, and McDonald. Thus, the new orbital elements and related parameters from our double-lined solution are given in Table 3. The velocities and the computed velocity curves are compared in Figure 2. Zero phase in that plot is a time of periastron passage.

In Table 3, the orbital elements of Sanford (1924) are compared with our new results. The period, eccentricity, and longitude of periastron of the two solutions are in reasonable agreement, although our values of those elements are about 50 times more precise. However, the center-of-mass velocity of the Mount Wilson solution is 5 km s^{-1} more positive than our new value, and the Mount Wilson semiamplitude of the primary component is nearly 4 km s^{-1} smaller than our new result. While the large center-of-mass velocity difference might suggest that the binary system orbits a third component, no evidence of a systematic velocity change is evident in our recent velocities that cover a 10 year interval. Another possibility is that the velocity difference is the result of velocity zero-point differences between observatories plus perhaps partial blending of the lines of the primary with those of the weaker secondary during part of its orbit. The possible blending would also help to explain the smaller primary semiamplitude in the Mount Wilson results.

4.2. HR 7578

For HR 7578 the vast majority of our new observations, 167 double-lined spectra, were acquired at Fairborn Observatory between 2005 and 2017. Nineteen additional observations were obtained at the KPNO from 2005 through 2008. Finally, at McDonald Observatory we collected two more spectrograms in 2005. Those observations are listed in Table 4.

Table 2
Radial Velocities of HD 96511

Hel. Julian Date (HJD–2400000)	Phase	V_1 (km s^{-1})	$(O-C)_1$ (km s^{-1})	Wt$_1$	V_2 (km s^{-1})	$(O-C)_2$ (km s^{-1})	Wt$_2$	Source[a]
53433.872	0.339	−59.7	−0.1	1.0	−41.4	0.1	0.15	Fair
53434.872	0.392	−67.9	−0.1	1.0	−30.8	−0.0	0.15	Fair
53450.914	0.241	−39.9	−0.3	1.0	−67.0	0.7	0.15	Fair
53464.787	0.975	−11.0	−0.2	1.0	−104.9	0.6	0.15	Fair
53476.930	0.617	−85.1	−0.0	1.0	−8.6	−0.4	0.15	Fair
53482.820	0.929	−29.2	−0.1	1.0	−81.5	−0.0	0.15	Fair
53496.694	0.663	−84.8	0.0	1.0	−8.7	−0.2	0.15	Fair
53509.828	0.358	−62.8	0.0	1.0	−37.4	−0.1	0.15	Fair
53526.813	0.257	−43.6	−0.2	1.0	−62.1	0.7	0.15	Fair
53539.864	0.948	−21.4	−0.1	1.0	−90.9	0.8	0.15	Fair
53552.776	0.631	−85.2	−0.0	1.0	−7.2	0.8	0.15	Fair
53747.001	0.909	−37.6	−0.1	1.0	−69.7	0.7	0.15	Fair
53775.943	0.440	−73.7	0.2	0.6	−22.5	0.3	0.15	McD
53776.960	0.494	−79.1	0.0	0.6	−16.2	−0.2	0.15	McD
53789.028	0.133	−11.8	−0.2	1.0	−103.9	0.5	0.15	Fair

Note.
[a] Fair = Fairborn Observatory, McD = McDonald Observatory, KPNO = Kitt Peak National Observatory.

(This table is available in its entirety in machine-readable form.)

Table 3
Orbital Elements and Related Parameters of HD 96511

Parameter	Sanford (1924)	This Study
P (days)	18.8922 ± 0.0090	18.897367 ± 0.000023
T (HJD)	2423154.071 ± 0.264	2455222.7212 ± 0.0045
e	0.282 ± 0.025	0.27209 ± 0.00046
ω_1 (deg)	332.97 ± 6.27	330.789 ± 0.098
K_1 (km s^{-1})	40.01 ± 0.98	43.793 ± 0.021
K_2 (km s^{-1})	⋯	57.346 ± 0.051
γ (km s^{-1})	−46.75	−51.774 ± 0.015
$m_1 \sin^3 i$ ($M_\odot$)	⋯	1.0234 ± 0.0019
$m_2 \sin^3 i$ ($M_\odot$)	⋯	0.7816 ± 0.0010
$a_1 \sin i$ (10^6 km)	9.975	10.951 ± 0.005
$a_2 \sin i$ (10^6 km)	⋯	14.340 ± 0.013
Standard error of an unit weight observation (km s^{-1})	3.4	0.2

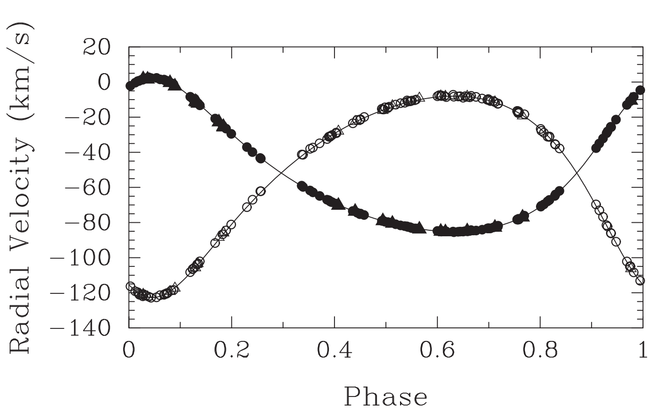

Figure 2. Radial velocities of HD 96511 compared with the computed velocity curves. Filled and open symbols represent the primary and secondary, respectively. Circles = Fairborn Observatory. Triangles = McDonald Observatory and KPNO. Zero phase is a time of periastron passage.

Initially, we determined four separate orbital solutions, two for each component. We first analyzed our extensive Fairborn velocities, and then, because of the very small number of McDonald velocities, we determined a combined solution of the McDonald and KPNO velocities. The results for the Fairborn velocities produced weights of 0.9 and 1.0 for the primary and secondary, respectively. Similarly, from the combined McDonald and KPNO velocity solutions we determined weights of 0.3 and 0.4 for the primary and secondary, respectively. The center-of-mass velocities of the four analyses agreed to within 0.3 km s^{-1}, and so the appropriately weighted velocities of the data sets were combined into a single solution. We then examined the velocities of Fekel & Beavers (1983) to see if their inclusion improved the orbital elements. Relative to our Fairborn secondary velocities, their McDonald Reticon velocities have the highest weights, just 0.05, while nearly all of the Fick Observatory velocities have significantly lower weights. The solution that includes the appropriately weighted velocities of Fekel & Beavers (1983) along with our new data is consistent with our new orbital elements, but those very low weight velocities did not significantly improve the results, and so our final orbital elements (Table 5) come from the analysis of just our new velocities. Comparing the new elements with the results of Fekel & Beavers (1983), our elements are similar but their uncertainties in most cases have been decreased by a factor of 10 or more.

Figure 3 compares our radial velocities with the computed velocity curves for the components. Zero phase is a time of periastron passage.

4.3. KZ And

Between 2004 and 2017 we acquired 105 usable spectrograms of KZ And at Fairborn Observatory (Table 6). No additional radial velocities of it were obtained at either KPNO or McDonald Observatory. However, in addition to our Fairborn observations of KZ And we also collected seven AST spectra of HD 218739, the primary of the common proper motion binary.

KZ And is the faintest of our three systems and its components are rotating significantly faster than those of the other two. As a result, because of the improved S/N of the spectra that we acquired after the telescope upgrades, we

Table 4
Radial Velocities of HR 7578

Hel. Julian Date (HJD–2400000)	Phase	V_1 (km s^{-1})	$(O-C)_1$ (km s^{-1})	Wt$_1$	V_2 (km s^{-1})	$(O-C)_2$ (km s^{-1})	Wt$_2$	Source[a]
52965.582	0.124	25.7	−0.4	0.9	−37.0	0.1	1.0	Fair
53166.949	0.425	6.7	−0.2	0.9	−17.8	−0.2	1.0	Fair
53275.635	0.746	−18.5	0.1	0.9	8.2	−0.1	1.0	Fair
53285.607	0.959	−66.1	0.3	0.9	57.1	0.2	1.0	Fair
53290.604	0.066	24.6	−0.3	0.9	−36.1	−0.2	1.0	Fair
53296.632	0.195	21.7	−0.1	0.9	−32.8	0.0	1.0	Fair
53302.653	0.324	13.2	−0.2	0.9	−24.5	−0.3	1.0	Fair
53303.621	0.344	11.9	−0.2	0.9	−22.7	0.2	1.0	Fair
53320.630	0.708	−14.8	−0.3	0.9	4.4	0.3	1.0	Fair
53467.937	0.854	−35.0	−0.3	0.9	24.5	−0.2	1.0	Fair
53481.903	0.152	24.3	−0.2	0.9	−36.0	−0.4	1.0	Fair
53486.961	0.260	17.7	0.2	0.3	−28.2	0.2	0.4	McD
53494.892	0.430	6.3	−0.3	0.9	−17.0	0.3	1.0	Fair
53507.861	0.707	−14.0	0.4	0.9	4.2	0.2	1.0	Fair
53525.946	0.093	26.5	−0.2	0.9	−38.1	−0.3	1.0	Fair
53531.913	0.221	20.0	−0.1	0.3	−31.5	−0.4	0.4	KPNO
53535.910	0.306	13.6	−0.9	0.3	−25.0	0.4	0.4	KPNO

Note.
[a] Fair = Fairborn Observatory, McD = McDonald Observatory, KPNO = Kitt Peak National Observatory.

(This table is available in its entirety in machine-readable form.)

Table 5
Orbital Elements and Related Parameters of HR 7578

Parameter	Fekel & Beavers (1983)	This Study
P (days)	46.817 ± 0.004	46.816103 ± 0.000057
T (HJD)	2444158.37 ± 0.04	2455441.0477 ± 0.0030
e	0.692 ± 0.005	0.68640 ± 0.00028
ω (deg)	241.2 ± 0.6	241.168 ± 0.046
K_1 (km s^{-1})	48.8 ± 0.5	47.840 ± 0.033
K_2 (km s^{-1})	48.7 ± 0.7	48.686 ± 0.031
γ (km s^{-1})	−5.1 ± 0.2	−5.266 ± 0.014
$m_1 \sin^3 i$ ($M_\odot$)	0.85 ± 0.03	0.8463 ± 0.0014
$m_2 \sin^3 i$ ($M_\odot$)	0.85 ± 0.03	0.8316 ± 0.0014
$a_1 \sin i$ (10^6 km)	22.7 ± 0.3	22.397 ± 0.017
$a_2 \sin i$ (10^6 km)	22.6 ± 0.3	22.793 ± 0.017
Standard error of an unit weight observation (km s^{-1})	2.2	0.3

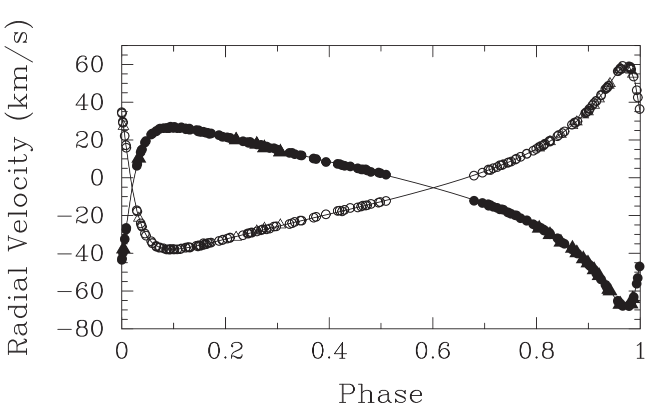

Figure 3. Radial velocities of HR 7578 compared with the computed velocity curves. Filled and open symbols represent the primary and secondary, respectively. Circles = Fairborn Observatory. Triangles = McDonald Observatory and KPNO. Zero phase is a time of periastron passage.

divided our velocities into two parts, one before and the other after the upgrades began. We then obtained four orbital solutions, two for the primary and two for the secondary. The resulting weights for the primary are 0.8 and 1.0 for the velocities before and after the telescope upgrades, respectively. For the secondary velocities the respective weights are 0.6 and 0.7. The orbital eccentricity for the four solutions ranges from 0.010 to 0.013, and the precepts of Lucy & Sweeney (1971) indicate that this small eccentricity is real. This conclusion is supported by the longitude of periastron of the secondary, which differs by approximately 180° from that of the primary. The center-of-mass velocity of the four analyses has a range of just 0.3 km s^{-1}, and so we determined a final solution using all of our appropriately weighted velocities.

The only other large velocity data set is that of Bopp & Fekel (1975). Although their observations were acquired from four observatories, most of the velocities were from coudé spectra obtained with the 5 m telescope at Mount Palomar. An orbital solution of all the velocities used by Bopp & Fekel (1975) resulted in velocity weights of 0.005 compared to our primary velocities after the telescope upgrades. With such low weights the inclusion of the Bopp & Fekel (1975) velocities in our combined solution did not significantly improve the period or other elements. Thus, in Table 7, we list our final Fairborn Observatory orbital solution along with that of Bopp & Fekel (1975). Figure 4 compares our radial velocities of KZ And with the computed velocity curves. Zero phase is a time of periastron passage.

In comparing our elements with the results of Bopp & Fekel (1975) we find reasonable agreement. Our solution confirms that despite its short 3.03 day period, the orbit of KZ And is eccentric, although our much more precise result produces an eccentricity that is a factor of three smaller than the value of Bopp & Fekel (1975). The center-of-mass velocity of the two solutions differs by less than 1 km s^{-1}. We attribute this to a difference in the zero points of the velocities from Fairborn and Mount Palomar rather than

Table 6
Radial Velocities of KZ And

Hel. Julian Date[a] (HJD–2400000)	Phase	V_1 (km s^{-1})	$(O-C)_1$ (km s^{-1})	Wt_1	V_2 (km s^{-1})	$(O-C)_2$ (km s^{-1})	Wt_2
53291.907	0.804	24.3	−0.1	0.8	−37.3	−0.4	0.6
53311.855	0.381	−62.4	−0.5	0.8	51.5	−0.3	0.6
53326.822	0.316	−41.9	−0.2	0.8	30.7	−0.4	0.6
53341.810	0.257	−18.5	−0.1	0.8	6.2	−0.9	0.6
53354.782	0.534	−70.1	0.4	0.8	60.8	0.1	0.6
53360.705	0.487	−74.2	0.1	0.8	64.2	−0.4	0.6
53451.997	0.588	−59.8	−0.2	0.8	48.9	−0.6	0.6
53464.985	0.870	47.2	−0.4	0.8	−61.1	−0.3	0.6
53477.943	0.143	30.2	0.0	0.8	−42.1	0.7	0.6
53480.950	0.134	33.8	0.4	0.8	−45.9	0.2	0.6
53490.921	0.422	−69.6	0.4	0.8	60.1	−0.1	0.6
53502.873	0.362	−56.9	0.1	0.8	46.6	−0.2	0.6
53524.816	0.597	−57.3	−0.3	0.8	46.0	−0.8	0.6
53555.858	0.832	35.1	−0.3	0.8	−48.9	−0.7	0.6
53602.980	0.369	−59.6	−0.6	0.8	48.1	−0.7	0.6
53614.987	0.328	−45.7	0.5	0.8	35.1	−0.6	0.6
53627.874	0.577	−62.5	−0.2	0.8	51.6	−0.6	0.6

Note.
[a] All observations from Fairborn Observatory.

(This table is available in its entirety in machine-readable form.)

Table 7
Orbital Elements and Related Parameters of KZ And

Parameter	Bopp & Fekel (1975)	This Study
P (days)	3.032867 ± 0.000028	3.03291126 ± 0.00000046
T (HJD)	2442370.722 ± 0.177	2455133.480 ± 0.020
e	0.034 ± 0.015	0.01174 ± 0.00056
ω (deg)	339.0 ± 22.0	7.11 ± 2.35
K_1 (km s^{-1})	67.6 ± 1.1	69.362 ± 0.046
K_2 (km s^{-1})	71.2 ± 1.9	71.300 ± 0.054
γ (km s^{-1})	−6.85 ± 0.59	−5.818 ± 0.026
$m_1 \sin^3 i$ ($M_\odot$)	0.431 ± 0.018	0.4432 ± 0.0007
$m_2 \sin^3 i$ ($M_\odot$)	0.410 ± 0.014	0.4312 ± 0.0006
$a_1 \sin i$ (10^6 km)	2.82 ± 0.05	2.8926 ± 0.0019
$a_2 \sin i$ (10^6 km)	2.97 ± 0.08	2.9734 ± 0.0022
Standard error of an unit weight observation (km s^{-1})	⋯	0.3

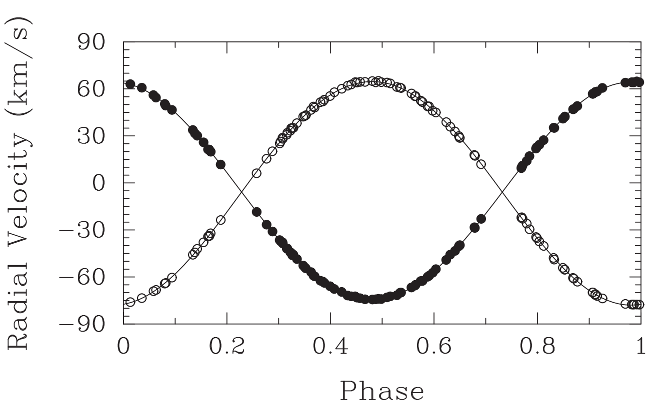

Figure 4. Radial velocities of KZ And compared with the computed velocity curves. Filled and open symbols represent the primary and secondary, respectively. All observations are from Fairborn Observatory. Zero phase is a time of periastron passage.

Table 8
Photometric Observations of HR 7578

Hel. Julian Date (HJD–2400000) (1)	$(V-C)_B$ (mag) (2)	$(V-C)_V$ (mag) (3)	$(K-C)_B$ (mag) (4)	$(K-C)_V$ (mag) (5)
47276.9765	−2.011	−1.755	−3.775	−3.267
47281.9632	−2.010	−1.748	−3.787	−3.267
47283.9629	−2.005	−1.758	−3.805	−3.293
47284.9497	−2.012	−1.752	−3.793	−3.275
47284.9542	−2.011	−1.750	−3.791	−3.273
47286.9492	−1.991	−1.742	99.999	99.999

(This table is available in its entirety in machine-readable form.)

orbital motion of the common proper motion pair. Our average velocity for the common proper motion primary, HD 218739, is -5.91 ± 0.05 km s^{-1} from seven observations. That average differs by only 0.2 km s^{-1} from the center-of-mass velocity of KZ And.

5. Photometric Variability of HR 7578

The individual group mean B and V differential magnitudes are listed in Table 8. In this paper, we present our analysis of the B observations but note that the V observations give essentially identical results. The B band $V-C$ (variable minus comparison) and $K-C$ (check minus comparison) observations are plotted in the top and bottom panels of Figure 5, respectively. HR 7578 comes to opposition in late July, so most of the 10 observing seasons have a gap in the middle because of our summer shutdown, when observing must be discontinued for 8–10 weeks due to the summer rainy season. The horizontal dotted line in each panel represents the grand mean of all the observations plotted in that panel. The standard deviation of the individual observations from their grand mean is given in the lower left corner of each panel. While there may be slight variability in the comparison

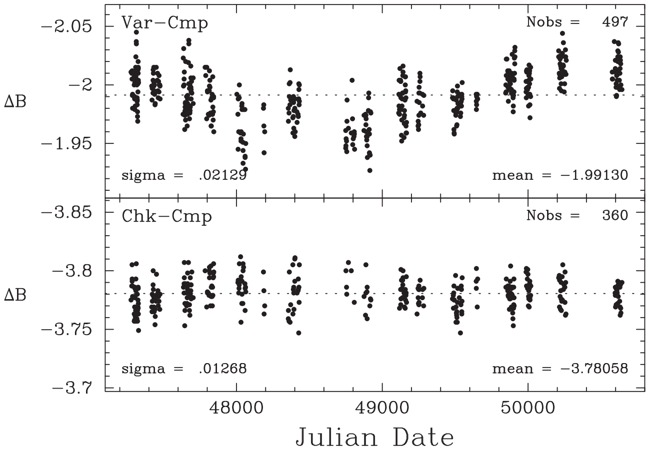

Figure 5. Top: nightly $V-C$ differential magnitudes in B of HR 7578 acquired with the T3 APT from 1988 to 1997. The seasonal means vary over a range of ∼0.05 mag. Bottom: nightly $K-C$ differential magnitudes in B vary over a range of only 0.01 mag or so.

and/or the check star, it is clear from a comparison of the two plots that HR 7578 is the dominant source of variability in this group of three stars.

In the top panel of Figure 6, we replot the B data after it has been normalized so that each observing season has the same mean, which is represented by the horizontal dotted line. With the long-term variability removed, the standard deviation decreases from 0.0213 mag for the original data in Figure 5 to 0.0145 mag for the normalized data. The middle and bottom panels of Figure 6 show the frequency spectrum of the normalized data and the phase curve computed with the best frequency, respectively. Our frequency analysis is based on least-squares sine fits with trial frequencies between 0.01 and 1.00 c d^{-1}, corresponding to periods between 1 and 100 days. The goodness of fit at each frequency is measured as the reduction factor in the variance of the data. The result demonstrates low-level brightness variability in HR 7578 with a period of 16.4457 ± 0.0019 days, in good agreement with earlier values from Hooten & Hall (1990) and Pazzi (2008). Period analysis of several individual observing seasons produced periods between 16.124 and 17.112 days, but with much larger uncertainties.

Both the night-to-night and year-to-year brightness variability in HR 7578, along with the presence of Ca II H and K emission shown by Robinson et al. (1990), argue for chromospheric activity and its accompanying spots as the source of the photometric variability. Thus, we can take the 16.446 day period as a stellar rotation period and the long-term variability as an indication of a possible magnetic cycle as posited by Pazzi (2008).

As a result of the large minimum masses of 0.85 $M_\odot$ that Fekel & Beavers (1983) found for the K-dwarf components of HR 7578, they suggested that eclipses might occur. Because of the orientation of the eccentric orbit, the phase of possible secondary eclipse is closer to periastron than that of the possible primary eclipse, and so the former is more likely to be detected. Pazzi (2008) obtained photometric observations to search for such eclipses but found no evidence for them.

With our orbital elements we determined a new ephemeris for the possible secondary eclipse, T_c(sec):

$$\text{Minimum Light (HJD)} = 2455441.573 \pm 0.003 + 46.81610 \pm 0.00006\, E \text{ days},$$

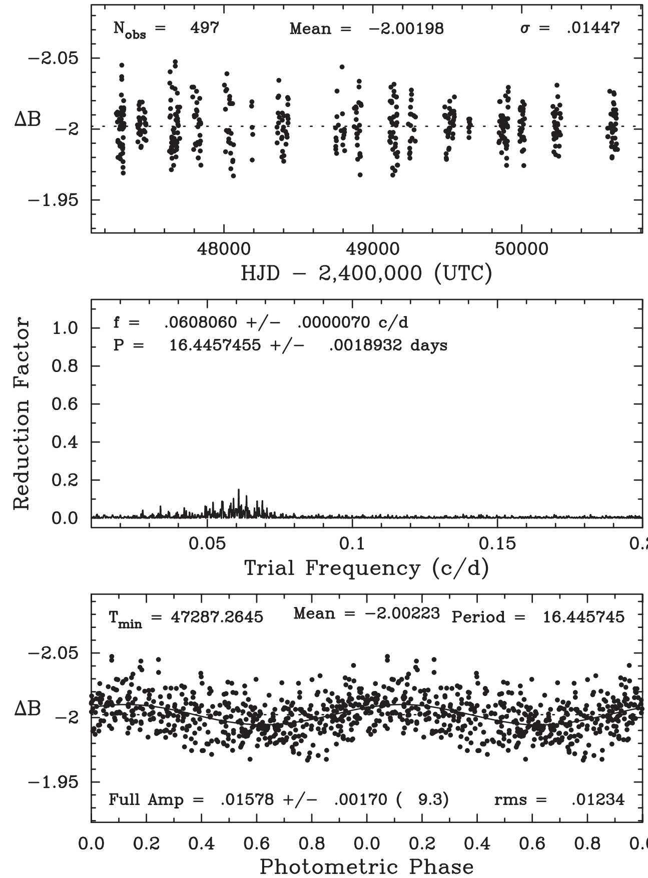

Figure 6. Top: JD plot of the Johnson B observations of HR 7578 from 1988 to 1997, normalized so that all observing seasons have the same mean, marked by the dotted line. Middle: frequency spectrum of the normalized observations identifying a photometric period of 16.4457 ± 0.0019 days. Bottom: the normalized data phased to the best period of 16.4457 days, showing a peak-to-peak amplitude of 0.016 ± 0.002 mag.

where E is an integer number of cycles. This secondary eclipse conjunction corresponds to a phase of 0.0112 from periastron, while primary eclipse conjunction occurs at phase 0.7672. Figure 7 plots our normalized ΔB data phased with the orbital period and plotted so that zero phase is a time of periastron. We indicate the two conjunctions relative to periastron to show how close secondary conjunction is to periastron passage. Confirming the result of Pazzi (2008), we find that there is no evidence of either secondary or the less likely primary eclipse.

6. Basic Properties

6.1. HD 96511

We compared our KPNO spectra of HD 96511 to the spectra of various stars with well-determined G and K spectral types and known iron abundances that are mostly from the lists of Keenan & McNeil (1989) and Fekel (1997). We acquired those reference stars at KPNO with the same telescope, spectrograph, and detector as HD 96511. From that comparison we found that stars with solar iron abundances have lines that are too weak compared to HD 96511. This supports the conclusion of Feltzing & Holmberg (2000), who determined a metal abundance estimate of [M/H] = 0.09 from a photometric calibration, that HD 96511 is metal-rich. We classify the primary as G2 V and the secondary as K0 V.

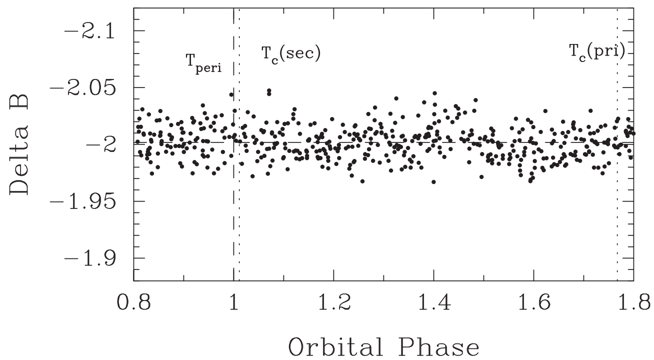

Figure 7. Normalized Johnson *B* observations of HR 7578 phased with the binary orbital period of 46.81610 days. The data have been plotted from phase 0.8 to 1.8 to more easily show the phases of periastron and secondary conjunction. The epoch for phase 1.0 is the time of periastron, HJD 2455441.048, marked with the vertical dashed line. Phases of primary and secondary conjunction are indicated by the dotted vertical lines. There is no evidence for either primary or secondary eclipse.

To obtain the magnitude difference between the two components, we first compared the equivalent widths of neutral iron and calcium lines for the two stars in our best KPNO spectra to estimate the intensity ratio of the binary components (Petrie 1939). The secondary to primary equivalent width ratio is 0.310 ± 0.006 and results in a magnitude difference of 1.3 ± 0.1. Because the secondary is the cooler component, and so has stronger neutral lines, that magnitude difference is a minimum value. In addition, our result is for a wavelength of 6430 Å, which is about 0.6 of the way between the central wavelengths of the Johnson *V* and *R* bandpasses. Revising the magnitude difference to take into account these two factors, we estimate a *V* magnitude difference of 1.8 ± 0.4. With a *V* magnitude of 7.20 from Oja (1984) for the combined system, the *V* magnitudes of the individual components are 7.39 ± 0.10 and 9.19 ± 0.40 for the primary and secondary, respectively. The estimated error for the secondary is much larger because the uncertainty of the magnitude difference has a much greater effect on the secondary than the primary.

To determine additional properties of HD 96511, we used the Stefan–Boltzmann law. From the analysis of van Leeuwen (2007) the *Hipparcos* parallax is 21.88 ± 0.40 mas and corresponds to a distance of 45.7 ± 0.8 pc. At such a distance we assume that the interstellar extinction is negligible. The apparent magnitudes and distance produce absolute magnitudes of $M_V = 4.09 \pm 0.10$ mag and $M_V = 5.89 \pm 0.40$ mag for the primary and secondary, respectively. From Johnson (1966) for the G2 V star we adopt a $B - V$ color of 0.63, and for the K0 V component we use a value of 0.82. For the two components the effective temperatures and bolometric corrections come from Table 3 of Flower (1996). From spectral type and temperature calibration uncertainties, we estimate effective temperature uncertainties of 200 K for both components. Then our luminosities of the primary and secondary are $L_1 = 1.9 \pm 0.2\,L_\odot$ and $L_2 = 0.42 \pm 0.16\,L_\odot$, respectively, while the radii are $R_1 = 1.4 \pm 0.1\,R_\odot$ and $R_2 = 0.79 \pm 0.16\,R_\odot$, respectively.

Our detection of the secondary spectrum of HD 96511 means that the lines of the primary will be diluted by the continuum of the secondary. Thus, the metal abundance estimate, [M/H] = 0.09, of Feltzing & Holmberg (2000) is actually a lower limit. Thus, we compare our estimated effective temperatures and luminosities for the components of HD 96511 with the metal-rich, $Z = 0.03$, evolutionary tracks of Girardi et al. (2000) in Figure 8. Such a Z value corresponds to an iron abundance [Fe/H] = 0.2 (Kim et al. 2002), which is the value found for the HR 1614 moving group (Feltzing & Holmberg 2000). The primary has a minimum mass of $1.02\,M_\odot$ so its position next to the $1.1\,M_\odot$ track is reasonable. Such a mass for the primary would result in an orbital inclination of 77° and produce a mass of $0.85\,M_\odot$ for the secondary. While the position of the secondary with respect to the evolutionary tracks indicates a mass greater than $0.9\,M_\odot$, the large error bars for the secondary encompass the $0.85\,M_\odot$ value. The astrometric orbit of Pourbaix & Boffin (2003) produces an orbital inclination of $122° \pm 18°$. That rather uncertain value is equivalent to 58° and results in a primary mass of $1.68\,M_\odot$, a value seriously at odds with our evolutionary track comparison.

6.2. HR 7578

The spectral classifications of HR 7578 are in reasonable agreement, and we adopt K3 V from Keenan & McNeil (1989) for both of the nearly identical components. While some classifiers have called the system a subgiant, its parallax clearly indicates that it is a dwarf, and the subgiant classification is likely the result of its metal-rich nature. The stars are chromospherically active, and light variability due to starspots rotating in and out of view is seen (Hooten & Hall 1990; Pazzi 2008).

As noted by Fekel & Beavers (1983), the two components of HR 7578 have similar but slightly different line strengths. Measurement of the secondary to primary component equivalent width ratio from our Fairborn spectra results in a value of 0.89 ± 0.03 for a central wavelength of 6000 Å. This converts to a *V* magnitude difference of 0.13 ± 0.03. From Johnson et al. (1966) we have adopted $V = 6.18$ mag and $B - V = 1.02$ mag. The *V* magnitude difference then produces individual values of 7.00 ± 0.05 mag and 7.13 ± 0.05 mag for the primary and secondary, respectively. We have slightly increased the uncertainty because the stars have starspots, and thus their unspotted surfaces could be brighter than the adopted *V* magnitude.

The revised *Hipparcos* parallax of 71.18 ± 0.42 mas (van Leeuwen 2007) corresponds to a distance of 14.0 ± 0.1 pc. Because HR 7578 is such a very nearby object, we assumed that there is no significant interstellar extinction. As a result, the individual *V* magnitudes and distance produce absolute magnitudes of $M_V = 6.26 \pm 0.05$ mag and $M_V = 6.39 \pm 0.05$ mag for the primary and secondary, respectively. We then used the Stefan–Boltzmann law to estimate additional properties of the stars. As usual, for the two components the effective temperatures and bolometric corrections come from Table 3 of Flower (1996). From spectral type and temperature calibration uncertainties, we estimated effective temperature uncertainties of 100 K for the nearly identical components. The resulting luminosities of the primary and secondary are $L_1 = 0.35 \pm 0.02\ L_\odot$ and $L_2 = 0.31 \pm 0.02\ L_\odot$, respectively, while the radii are $R_1 = 0.86 \pm 0.04\,R_\odot$ and $R_2 = 0.81 \pm 0.04\,R_\odot$, respectively.

Gray et al. (2006) determined an overall metal abundance [M/H] of 0.29, indicating that the system is indeed metal-rich. Thus, our estimated effective temperatures and luminosities for the components of HR 7578, like those of HD 96511, are compared with the metal-rich, $Z = 0.03$, evolutionary tracks of Girardi et al. (2000) in Figure 8. As noted for HD 96511, such a Z value corresponds to an iron abundance [Fe/H] = 0.2. The positions of the two components indicate masses below

$0.8\,M_{\odot}$. However, such values are clearly at odds with the large minimum masses of about 0.84. Increasing the metallicity of the evolutionary tracks, as indicated by the metal abundance of Gray et al. (2006), would shift the tracks to cooler temperatures and lower luminosities (e.g., Girardi et al. 2000) and would improve the agreement with the observational results.

6.3. KZ And

As noted previously, KZ And is the secondary of a common proper motion pair. Bopp & Fekel (1975) classified the variable system as dK2 and noted that the absorption lines as well as the Ca H and K emission features were "virtually identical." Keenan & McNeil (1989) and Gray et al. (2003) made similar classifications of K2−V and K2 V, respectively, for the combined spectral type of KZ And, and both noted the Ca K line emission. Our spectra show that while the Hα features of the two components do not rise above the continuum level, the emission from both almost completely fills the absorption features. Thus, the system is clearly a chromospherically active one with spots on the surface of both stars.

Our Fairborn spectra show that the absorption features of the two components have somewhat different strengths. Measurement of the secondary to primary component equivalent width ratio produces a value of 0.73 ± 0.04 for a central wavelength of 6000 Å. This converts to a V magnitude difference of 0.34 ± 0.06, which corresponds to about one spectral subclass, indicating that the components are quite similar. From Eggen's *UBV* data given in SIMBAD we adopt a V magnitude of 7.91 as well as $B - V = 0.900$. Then the V magnitudes of the primary and secondary are 8.51 ± 0.10 mag and 8.85 ± 0.10 mag. Because the components are spotted, the estimated uncertainty for both of them has been increased as their unspotted surfaces would be brighter.

The revised *Hipparcos* parallax of van Leeuwen (2007) is 42.23 ± 3.73 mas, which corresponds to a distance of 23.7 ± 2.1 pc. Thus, the system is quite close to the Sun, and so we assume that the interstellar extinction is negligible. Then the apparent magnitudes and distance produce absolute magnitudes of $M_V = 6.64 \pm 0.22$ mag and $M_V = 6.98 \pm 0.22$ mag for the primary and secondary, respectively. We next used the Stefan–Boltzmann law to estimate additional properties of the stars. For the two components the effective temperatures and bolometric corrections come from Table 3 of Flower (1996). From spectral type and temperature calibration uncertainties, we estimated effective temperature uncertainties of 100 K for both components. Then our luminosities of the primary and secondary are $L_1 = 0.22 \pm 0.04\,L_{\odot}$ and $L_2 = 0.16 \pm 0.03\,L_{\odot}$, respectively, while the radii are $R_1 = 0.62 \pm 0.07\,R_{\odot}$ and $R_2 = 0.53 \pm 0.06\,R_{\odot}$, respectively.

Unfortunately, there are problems with these values for the luminosities and radii. The radii of 0.62 and $0.53\,R_{\odot}$ are significantly smaller than the *minimum* radii of $\sim 0.74\,R_{\odot}$ that are computed assuming synchronous rotation. In addition, as shown in Figure 9, the luminosities of the two components, determined from the Stefan–Boltzmann law, fall well below the solar-abundance evolutionary tracks of Girardi et al. (2000), and so, if taken at face value, would suggest that the components must be very metal-rich.

Instead, Gray et al. (2003) find a metal abundance, [M/H], of −0.53 for the K-dwarf binary, making it rather metal-poor. However, that metal-poor value is at odds with their metallicity result of +0.06 for HD 218739, the G dwarf primary of the common proper motion pair. One possibility for the huge difference is that the spectrum of KZ And may have been polluted by some of the light from its common proper motion primary. The metallicity values of Gray et al. (2003) come from a comparison of photometric fluxes with model fluxes from spectrum synthesis. The near solar metallicity for HD 218739 is supported by the iron abundance, [Fe/H], of 0.08 ± 0.07 determined from the spectrum synthesis analysis of König et al. (2006).

To further explore the luminosities and radii of KZ And, we examined the results for HD 218739, the G1-2 V primary of the common proper motion pair. We adopted $V = 7.14$ mag and $B - V = 0.647$ from Hog et al. (2000) and used its parallax of 40.03 ± 2.17 mas from van Leeuwen (2007). With the effective temperature and bolometric correction once again from Table 3 of Flower (1996), we computed its luminosity and radius with the Stefan–Boltzmann law. The results for HD 218739 are $L = 0.74 \pm 0.09\,L_{\odot}$ and $R = 0.87 \pm 0.06\,R_{\odot}$. Such luminosities and radii are smaller than expected for its G1-2 V spectral type, a situation similar to that for the components of KZ And.

We next used the original *Hipparcos* parallax value of 34.06 ± 2.31 mas (Perryman & ESA 1997) to compute the luminosity and radius of HD 218739. With that parallax the luminosity and radius of the G1-2 V star are $L = 1.012 \pm 0.15\,L_{\odot}$ and $R = 1.03 \pm 0.08\,R_{\odot}$. Such values are in line with its spectral type, and so we have adopted that parallax for KZ And as well.

Recomputing the results for KZ And with the original *Hipparcos* parallax for HD 218739 results in $L = 0.34 \pm 0.06\,L_{\odot}$ and $R = 0.77 \pm 0.07\,R_{\odot}$. For the secondary the values are $L = 0.25 \pm 0.04\,L_{\odot}$ and $R = 0.66 \pm 0.06\,R_{\odot}$. As shown in Figure 9, the luminosity and radius for both components have significantly increased, reducing the discrepancy of their positions with the solar-abundance evolutionary tracks. However, although the radii have significantly increased with the primary's value now greater than the minimum value of $0.74\,R_{\odot}$ that is computed in the next section, the secondary is still below its minimum value. Reducing the effective temperature of the secondary by 200 K increases its radius to $0.75 \pm 0.07\,R_{\odot}$, putting it just above the minimum radius value.

However, in the radius comparisons there is another factor to consider. Results for short-period G, K, and M dwarf eclipsing binaries (e.g., López-Morales & Ribas 2005; Torres et al. 2006) show that the radii of such stars are greater than those predicted from standard stellar models. Torres et al. (2006) and López-Morales (2007) as well as others have concluded that this is caused by enhanced surface activity in rapidly rotating stars. Their magnetic activity and starspots cause reduced convective efficiency. Theoretical work by Mullan & MacDonald (2001) and the results of Torres et al. (2006) on the observational side indicate that the fit between observations and theory is improved by reducing the mixing-length parameter to simulate decreased convective efficiency.

In their compilation of accurate eclipsing binary masses and radii, Torres et al. (2010) list three stars with spectral types between K2 V and K3 V that are components of short-period binaries (periods between 0.6 and 4.3 days). The average radius for those three components is $0.83\,R_{\odot}$. With Ca K and Hα emission plus photometric light variations from spots, the components of KZ And are clearly chromospherically active,

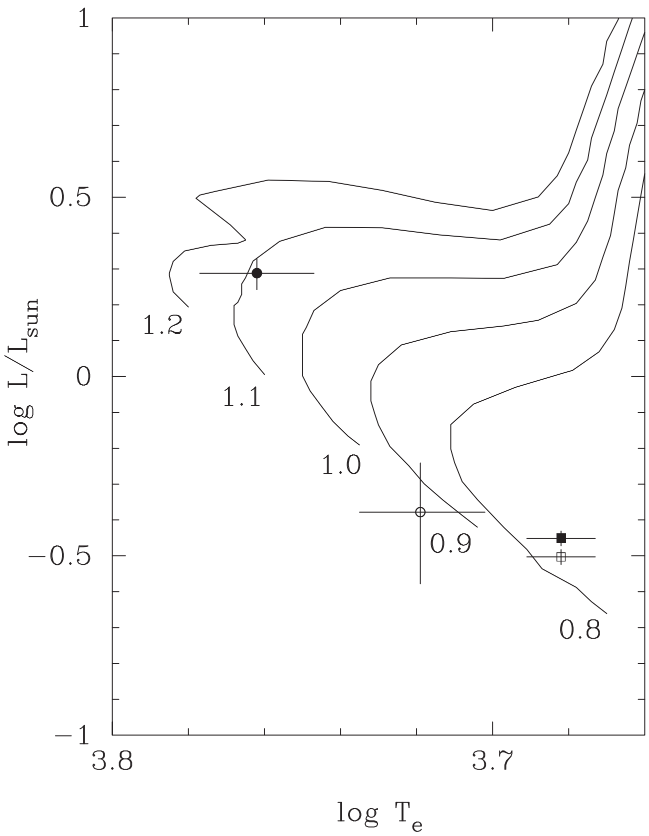

Figure 8. Positions of the components of HD 96511 (circles) and HR 7578 (squares) compared with the 0.8–1.2 $M_\odot$ $Z = 0.03$ metal-rich evolutionary tracks of Girardi et al. (2000). Such a Z value corresponds to an iron abundance [Fe/H] = 0.2. The more massive star in each system corresponds to the filled symbol. Our estimated uncertainties are shown.

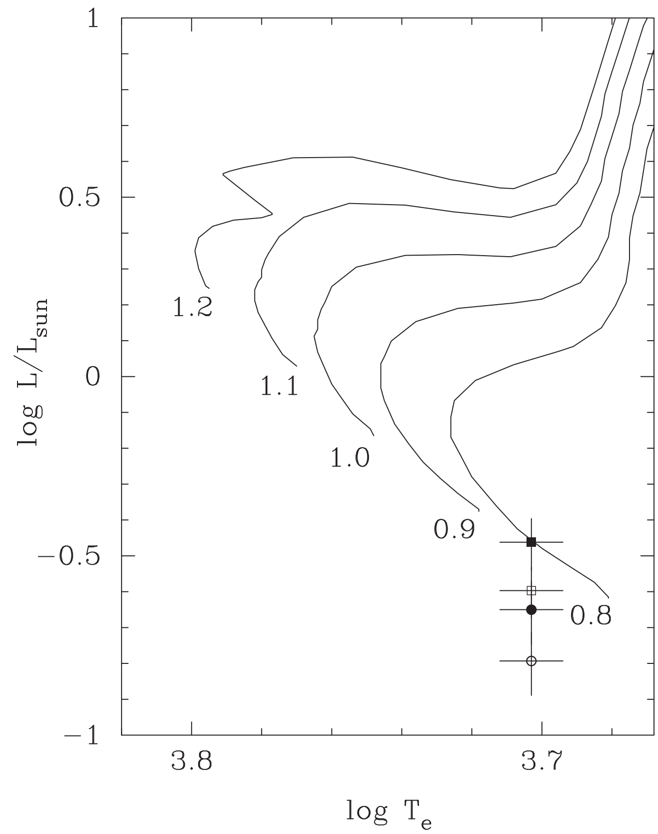

Figure 9. Positions of the components of KZ And for two different parallaxes compared with the 0.8–1.2 $M_\odot$ solar-abundance evolutionary tracks of Girardi et al. (2000). The positions of the circles were computed with the van Leeuwen (2007) parallax of 42.23 mas. Those positions are well below the solar-abundance tracks. The squares result when the original *Hipparcos* parallax of 34.06 mas (Perryman & ESA 1997) for the common proper motion primary, HD 218739, is adopted. In each case, the more massive star corresponds to the filled symbol. Our estimated uncertainties are shown. The fit is improved with the original *Hipparcos* parallax.

and both would be expected to have enhanced radii similar to the values of the eclipsing binary components.

7. Synchronization

7.1. HD 96511

Hut (1981) has shown that in an eccentric orbit the rotational angular velocity of a star will tend to synchronize with that of the orbital motion at periastron, a condition called pseudosynchronous rotation. To determine whether the components of HD 96511 are rotating pseudosynchronously, we computed equatorial velocities from our projected rotational velocities, determined with the procedure of Fekel (1997), and compared them with the predicted pseudosynchronous velocities. To convert the $v \sin i$ values into equatorial rotational velocities, we assume, as is generally done, that the axes of the orbital and rotational planes are parallel. If that is the case, then the two inclinations are equal, and we can adopt the orbital inclination as the rotational inclination.

For the primary of HD 96511 our $v \sin i$ value is 3.2 ± 1.0 km s^{-1}, while that for the secondary is 4.3 ± 2.0 km s^{-1}. The increased rotational velocity for lines of the secondary likely results from their weakness in the spectrum and blending with random weak lines of the primary. Thus, that value may be an upper limit and our increased estimated uncertainty partly accounts for that possibility. From our comparison with the solar-abundance evolutionary tracks (Figure 8) we adopt a mass of 1.1 $M_\odot$ for the primary. That mass combined with its $m \sin^3 i$ value (Table 3) produces an orbital inclination of $77\overset{\circ}{.}4 \pm 0\overset{\circ}{.}2$. Adopting that inclination results in rotational velocities of 3.3 ± 1.0 and 4.4 ± 2.0 km s^{-1} for the primary and secondary. With a pseudosynchronous period of 11.7 days and our computed radii from the Stefan–Boltzmann law, the pseudosynchronous rotational velocities are 6.1 ± 0.4 and 3.5 ± 0.9 km s^{-1} for the primary and secondary. Thus, the primary appears to be rotating more slowly than its pseudosynchronous velocity, while the secondary may be rotating pseudosynchronously.

7.2. HR 7578

The components of HR 7578 are essentially identical in mass, brightness, and chromospheric activity. Thus, similar photometric variations likely arise in both components, and they probably have identical rotational periods. Indeed, the frequency spectrum of our photometric data shows no sign of a secondary period. Thus, we adopt our spot period value of 16.446 days as the rotation period of both stars. The orbital period at periastron is 8.24 days or one-half the photometric value, which indicates that the stars are rotating more slowly than their pseudosynchronous values. For a rotation period 16.446 days and a range of radii from 0.75 to 0.9 $R_\odot$, the rotational velocity ranges from 2.3 to 2.8 km s^{-1}, respectively.

For comparison, the $v \sin i$ values of the stars from our KPNO spectra are 4.1 and 4.5 km s^{-1} with estimated uncertainties of 1 km s^{-1} each. Although we find no evidence of eclipses, the large minimum masses of the stars indicate that the orbital inclination is close to 90°. We assume again that the rotational inclination has the same value as the orbital inclination, and therefore the above values are the equatorial rotational velocities of the two stars. However, our measured rotational velocities, even taking into account the uncertainties, are larger than the range of values predicted from the photometric rotation period. This argues that our measured values are upper limits that may well result from line blending because the K-dwarf, double-lined spectra are very crowded with lines even at red wavelengths.

7.3. KZ And

Like HR 7578, KZ And is a chromospherically active binary (Bopp & Fekel 1975). Unfortunately, because KZ And is the significantly fainter secondary of a 15″ common proper motion pair, photometric observations to determine a rotation period are very difficult. Nevertheless, Bopp & Espenak (1977) observed it briefly over a period of 10 days. Their modest number of observations are consistent with a rotation period of 3.03 days and thus synchronization, which would be expected for a system with such a very short orbital period and a nearly circular orbit.

The $v \sin i$ values of Vogt et al. (1983) for the two components are 12.3 and 11.6 km s^{-1} for the primary and secondary, respectively. The values for the same two stars from our Fairborn observations are 12.7 ± 1.0 and 12.9 ± 1.0 km s^{-1}. Thus, the average values are 12.5 for the primary and 12.2 km s^{-1} for the secondary. Assuming synchronous rotation produces minimum radii of 0.75 ± 0.06 $R_\odot$ and 0.73 ± 0.06 $R_\odot$ for the same two components. If the radii are 0.83 $R_\odot$, adopted from the Torres et al. (2010) compilation mentioned in the discussion of KZ And's basic properties, then the rotational inclination is ~63°.

8. Results and Conclusions

We have detected lines of the secondary in the spectra of HD 96511 and determined improved orbital elements for it as well as two other known double-lined spectroscopic binaries. The orbital periods of the systems range from 3.03 to 46.816 days, and all three have eccentric orbits, although that of KZ And, which has the 3.03 day period, is nearly circular. The minimum masses of the six short-period binary components have been determined to an accuracy of 0.2% or better.

Our extensive photometry of the chromospherically active binary HR 7578 confirms a rather long rotation period of 16.4 days. In addition, despite the large minimum masses of 0.85 and 0.83 $M_\odot$ for the K3 V components of HR 7578, our photometry shows no evidence of eclipses.

Determining the basic properties of KZ And with the revised *Hipparcos* parallax of van Leeuwen (2007) produces problematic results. That parallax appears to be too large, and so instead we have adopted the original *Hipparcos* parallax of the common proper motion primary, which improves the results. However, even with that parallax there remain consistency problems in the values of some of the basic properties. Results from the *Gaia* mission should resolve the parallax problems and produce improved derived basic properties for KZ And.

The secondary of HD 96511 may be rotating pseudosynchronously while its primary is rotating more slowly than its pseudosynchronous value. The components of HR 7578 are rotating more slowly than their pseudosynchronous values. With its short 3 day period the components of KZ And are rotating synchronously.

With the *Hipparcos* parallax for its common proper motion component, HD 218739, and estimated masses, we computed a maximum angular separation of 1.6 mas for KZ And in good agreement with the value of 1.7 mas determined by Halbwachs (1981). In the case of the much more eccentric systems HD 96511 and HR 7578, we determined the maximum angular nodal separation of their components (Halbwachs 1981). Those values for HD 96511 and HR 7578 are 4.6 and 17.0 mas, respectively. Such systems can be resolved with modern optical and infrared interferometers. Orbits from such observations would enable the inclinations of those systems to be determined providing precise masses that would allow for improved comparisons with evolutionary tracks. In addition, because of the significant magnitude difference of the components of HD 96511, an improved inclination value should result from a *Gaia* astrometric orbit.

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ORCID iDs

Francis C. Fekel https://orcid.org/0000-0002-9413-3896
Gregory W. Henry https://orcid.org/0000-0003-4155-8513

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