1-22-2016

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Recommended Citation
Francis C. Fekel et al 2016 AJ 151 26

The Astronomical Journal, 151:26 (9pp), 2016 February
doi:10.3847/0004-6256/151/2/26

THE SPECTROSCOPIC ORBITS OF FIVE γ DORADUS STARS

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Received 2015 September 3; accepted 2015 December 3; published 2016 January 22

ABSTRACT

We have determined the spectroscopic orbits of five γ Dor variables, HD 776, HD 6568, HD 17310, HD 19684, and HD 62196. Their orbital periods range from 27.8 to 1163 days and their eccentricities from 0.01 to 0.65. Of the five systems, only HD 19684 shows lines of its binary companion, but those lines are always so weak and blended with the lines of the primary that we were unable to measure them satisfactorily. The velocity residuals of the orbital fits were searched for periodicities associated with pulsation. No clear, convincing case for velocity periodicities in the residuals was found in four of the five stars. However, for HD 17310 we identified a period of 2.13434 days, a value in agreement with the largest amplitude period previously found photometrically for that star. The velocity residuals of HD 62196 have a long-term trend suggesting that it is a triple system.

Key words: binaries: spectroscopic – stars: oscillations

Supporting material: machine-readable tables

1. INTRODUCTION

Cousins & Warren (1963) discovered the light variability of γ Doradus. Later, Cousins (1992) made a series of more extensive photometric observations of this early-F dwarf and determined low-amplitude variations that have periods of 0.733 and 0.757 days. Over the years, similar variables such as 9 Aur (Krisciunas et al. 1993), HD 224638, and HD 224945 (Mantegazza et al. 1994) were discovered, and eventually γ Dor became the prototype of a new variable star class that was initially defined from the properties of 13 confirmed members by Kaye et al. (1999). These objects have non-radial pulsations with periods that range from about 0.2–3 days. They straddle the cool boundary of the δ Scuti instability strip and have late-A or early-F dwarf or subgiant spectral types.

The γ Dor stars pulsate in high order, low degree, gravity modes (*g*-modes), and therefore probe the stellar interior of these stars. As a result, they are of great interest to asteroseismology. Guzik et al. (2000), followed by Dupret et al. (2004), obtained theoretical models that showed that the *g*-modes can be explained by a convective flux-blocking mechanism at the bottom of the convective envelope.

To substantially expand the number of confirmed members of this variable star class, over 15 years ago an extensive photometric search for additional γ Dor variables was begun (Henry et al. 2001; Henry & Fekel 2002). As part of the program carried out by Henry and collaborators, they obtained complementary spectroscopic observations to characterize the basic properties of the stars and to help to confirm that the photometric variability is not the result of ellipsoidal variations. From the observed radial velocity variability a number of spectroscopic binaries were identified. Here, we present the orbits for five of the systems, HD 776, HD 6568, HD 17310, HD 19684, and HD 62196. The basic properties of these binaries are provided in Table 1. Photometric and spectroscopic analyses of γ Dor stars sometimes find different pulsational periods. Such complementary results are important because the amount of information acquired from analyses of non-radial pulsation is related to the number of modes that can be successfully identified (Aerts & Eyer 2000). Thus, after determining the spectroscopic orbits we searched the orbital velocity residuals for pulsation periods. We also examined the *Hipparcos* astrometric observations to see whether the fit to that data could be improved by an orbital model. The results of the various analyses and a brief discussion of the stars are given.

2. OBSERVATIONS AND VELOCITY MEASUREMENTS

From 2001 through 2011 we obtained observations at the Kitt Peak National Observatory (KPNO) with the coudé feed telescope and coudé spectrograph. The vast majority were acquired with a TI CCD detector, and those spectrograms are centered at 6430 Å, cover a wavelength range of 84 Å, and have a resolution of 0.21 Å. In 2004 September and October three spectra (one for HD 17310 and two for HD 19684) were obtained in the blue, centered at 4500 Å. They cover the same wavelength range and have the same resolution as the red wavelength spectra. The TI CCD was unavailable in 2008 September, so a Tektronics CCD, designated T1KA, was used instead. With that CCD the spectrum was centered at 6400 Å. Although the wavelength range covered by the chip increased to 172 Å, the resolution decreased to 0.35 Å. Beginning in 2010 September we acquired spectra with a CCD, consisting of a 2600 × 4000 array of 12 μm pixels, that was made by Semiconductor Technology Associates and designated STA2. With STA2 the spectrum was once again centered at 6430 Å, and the much larger size of the detector produced a wavelength range of 336 Å. The spectrograph slit was set so that the STA2 spectra have the same resolution as those acquired with the TI CCD although there is some worsening of the resolution at both ends of the STA2 spectra. Our KPNO spectra have signal-to-noise ratios (S/N) of 50–100.

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Table 1
Basic Properties

HD	HIP	Spectral Type	V^a (mag)	$B-V^a$ (mag)	Parallax[b] (mas)	$v \sin i$ (km s^{-1})
776	986	A9m dwarf	7.43	0.335	10.53 ± 0.55	64
6568	5209	F1 dwarf	6.93	0.301	14.77 ± 0.81	55
17310	12953	F2 dwarf	7.76	0.378	9.15 ± 0.92	10
19684	14871	F1 subgiant	6.96	0.301	9.00 ± 0.57	59
62196	37802	F2 dwarf	7.67	0.313	13.65 ± 1.63	6

Notes.
[a] Perryman & ESA (1997).
[b] van Leeuwen (2007).

Starting in 2006, we collected additional spectrograms with the Tennessee State University (TSU) 2 m automatic spectroscopic telescope (AST) and a fiber-fed echelle spectrograph, situated at Fairborn Observatory near Washington Camp in the Patagonia Mountains of southeastern Arizona (Eaton & Williamson 2004, 2007). Through 2011 June the detector was a 2048×4096 SITe ST-002A CCD with 15 μm pixels. Eaton & Williamson (2007) have discussed reduction of the raw spectra and their wavelength calibration. These AST echelle spectrograms have 21 orders that cover the wavelength range 4920–7100 Å, and most have an average resolution of 0.17 Å, although a few have a slightly lower resolution of 0.24 Å. The S/N ranged from 30 to 50 at 6000 Å.

In the summer of 2011 the SITe CCD detector and its dewar were replaced by a Fairchild 486 CCD with 4K × 4K 15 μm pixels and a new dewar. This larger CCD results in echelle spectrograms that have 48 orders that span the wavelength range 3800–8260 Å. Fekel et al. (2013) have given a more extensive discussion of the changes. Because different diameter fibers were used at various times, the resolution for these spectra was either 0.24 or 0.4 Å, which resulted in S/N that ranged from 60 to 100 at 6000 Å.

The KPNO coudé feed velocities are relative velocities that were determined by cross-correlation with respect to IAU radial velocity standard stars of similar spectral type: 10 Tau, β Vir, HR 7560, and ι Psc. In all the red wavelength spectra, velocities were determined for lines in the wavelength region 6390–6445 Å. For the three blue wavelength spectra lines in the 4470–4535 Å region were measured. The average velocity for each spectrum was placed on an absolute scale by adopting the velocities of Scarfe et al. (1990) for the standard stars.

For our Fairborn Observatory AST spectra, we determined radial velocities of 168 mostly neutral Fe lines from a solar-type star line list that covers the region 4920–7120 Å. Because of the extensive line broadening of most of the binaries, a rotational broadening function was used to fit the line profiles and measure their radial velocities (Fekel & Griffin 2011; Lacy & Fekel 2011). The velocites from Fairborn Observatory are absolute velocities. Fekel et al. (2009) have provided additional information about the velocity reductions.

Our unpublished velocities of several IAU solar-type standard stars indicate that the Fairborn Observatory velocities taken with the SITe CCD have a small zero-point offset of -0.3 km s^{-1} relative to the velocities of Scarfe et al. (1990). Starting in the fall of 2011, velocities from spectra obtained with the new CCD system have a zero-point offset of -0.6 km s^{-1} relative to those of Scarfe et al. (1990). Thus, we added either 0.3 or 0.6 km s^{-1}, depending on which detector was used, to each measured velocity so that the zero point of the Fairborn velocities is the same as that of the KPNO velocities.

3. ORBITAL ANALYSES

3.1. Spectroscopic Orbits

The coudé feed spectra have been acquired with several different detectors. Nevertheless, the spectra have similar resolutions, and although the extent of the red wavelength region coverage varried from detector to detector, the same wavelength region was used for velocity measurement. Thus, the velocity precision should be similar for the spectra taken with those detectors. Our AST spectra have resolutions similar to those of the coudé feed spectra, but many more lines were measured in the AST spectra than in the coudé spectra. Thus, the AST velocities might be expected to be somewhat more precise than those from the coudé. However, any possible improvement in velocity precision is masked by the significant velocity variations that result from the γ Dor pulsations. So, in our orbital solutions, all of the radial velocities have been given unit weights.

For each of the five stars we first found a preliminary orbital period with the program PDFND, which uses the least string method, implemented by T. J. Deeming (Bopp et al. 1970), to identify the period. We then computed a preliminary orbit for each star with the program BISP (Wolfe et al. 1967), which uses the Wilsing–Russell Fourier analysis method (Wilsing 1893; Russell 1902). We refined those orbits with SB1 (Barker et al. 1967), a program that computes differential corrections.

For each of the five binaries the final values of the orbital elements, the orbital period, P, time of periastron passage, T, eccentricity, e, longitude of periastron, ω, velocity semiamplitude, K, and center-of-mass velocity, γ, plus their uncertainties are listed in Table 2. In addition, the radial velocity rms residual (RV rms) to the computed orbit is given, which provides an indication of how strongly the velocities are affected by pulsation. Also listed are two quantities that are computed from the orbital elements, the minimum semimajor axis of the primary and the mass function (e.g., Batten et al. 1989).

3.2. Astrometric Orbits

For the five systems considered in this paper, the *Hipparcos* astrometric observations (Perryman & ESA 1997) remain well represented by a single star model for HD 776, HD 17310, and HD 19684. However, the fit of the *Hipparcos* astrometric data

Table 2
Orbital Elements and Related Parameters

HD	P (days)	T (HJD)	e	ω (deg)	K (km s^{-1})	γ (km s^{-1})	RV rms (km s^{-1})	$a \sin i$ (10^6 km)	$f(m)$ ($M_\odot$)
776	45.533	2455798.52	0.646	323.6	10.26	−28.36	0.8	4.90	0.00226
	±0.029	±0.91	±0.017	±2.5	±0.30	±0.13	...	±0.17	±0.00024
6568	126.664	2455008.99	0.092	332.8	11.13	−3.83	1.1	19.30	0.01786
	±0.040	±3.06	±0.016	±8.7	±0.18	±0.12	...	±0.31	±0.00086
17310	27.8683	2454768.25	0.113	133.9	22.53	22.05	2.2	8.579	0.032
	±0.0013	±0.41	±0.010	±5.2	±0.23	±0.16	...	±0.089	±0.010
19684	697.51	2454546.0	0.089	280.3	15.89	12.81	1.3	151.77	0.286
	±0.90	±13.4	±0.014	±7.1	±0.20	±0.14	...	±1.89	±0.011
62196	1163.4	2455219.9	0.0124	21.7	7.125	−7.386	0.3	113.98	0.04359
	±1.6	±72.2	±0.0055	±22.3	±0.034	±0.024	...	±0.58	±0.00064

with an orbital model for HD 6568 and 62196 (respectively, HIP 5209 and 37802) departs from the original single star model. The results for those two systems are discussed in the sections on the individual stars.

4. PULSATION PERIOD ANALYSIS

While pulsation periods of γ Dor variables have primarily been determined from photometric observations, spectroscopic determinations are also valuable because the line profiles are sensitive to higher degree modes. Spectroscopic analyses often find the same periods seen in the photometry (De Cat et al. 2006; Griffin & Boffin 2006), but in at least some variables different periods are detected in the photometry and spectroscopy (e.g., Uytterhoeven et al. 2008; Maisonneuve et al. 2011). Thus, the combination of photometry and spectroscopy can lead to a more complete identification of the pulsation periods of a star and improved mode identification on which asteroseismology relies.

Pulsation periods have previously been determined from photoelectric photometry for HD 6568 (Henry et al. 2011), HD 17310 (Henry et al. 2005), HD 19684 (Henry & Fekel 2002), and HD 62196 (Henry et al. 2011). The ongoing analysis of our unpublished photometry of HD 776, done in a manner similar to that outlined in the above papers, produces pulsation periods of 0.19968 and 0.19389 days.

After determining the orbital elements we searched the radial velocity residuals for pulsation periods. Our period-search technique is briefly described in Henry et al. (2011) and is particularly effective in uncovering multiple periods. In all cases, trial frequencies extended from 0.01 to 30 cycles per day, which correspond to periods ranging from 0.033 to 100 days.

We note that the distribution of our radial velocities is not optimized to search for pulsation periods that in the case of four of the five pulsators are quite short, between 0.2 and 1.0 day. The total number of velocities for our stars ranges from 42 to 205, but those velocities are spread over eight to 13 years, and the highest cadence of the observations, except for HD 17310, is one per night. For HD 17310 there is a three week stretch during which, when it was possible, we acquired two observations per night. Finally, in addition to the line profile asymmetries produced by pulsation, the $v \sin i$ values of three of the five stars, HD 776, HD 6568, and HD 19684, range from 55 to 64 km s^{-1} (Table 1), making the velocity measurements less precise than, for example, those of narrow-lined solar-type stars.

From our analysis we find that there are no clear, convincing periodicities in the residual radial velocities of HD 776, HD 6568, HD 19684, and HD 62196. On the other hand, the velocity residuals of HD 17310, which has the largest velocity rms of our five binaries, does show a periodicity. This result is discussed in the section for that star.

5. INDIVIDUAL STARS

5.1. HD 776 = HIP 986

5.1.1. Brief History

From our spectroscopy, HD 776 [$\alpha = 00^h12^m13\overset{s}{.}94$ $\delta = 39°54'05\overset{''}{.}7$ (2000)] is an A9m dwarf with a $v \sin i$ value of 64 ± 3 km s^{-1}. As stated previously, our unpublished photometry indicates that HD 776 pulsates with two periods near 0.2 days. Kaye et al. (1999) examined the properties of 13 confirmed γ Dor pulsators and defined their general characteristics. From that limited sample of stars they concluded that this new variable star class has pulsation periods ranging from 0.4 to 3 days, making the shortest, initially proposed periods for γ Dor pulsators at least 0.1 days longer than the longest period δ Scuti variables (Handler & Shobbrook 2002). Examining a more extensive sample of γ Dor stars, Handler & Shobbrook (2002) extended the period range at the short end. They noted a near overlap at 0.3 days in the pulsation periods of δ Sct and γ Dor stars. While there may be some overlap of the period ranges of the two types of variable stars, Handler & Shobbrook (2002) pointed out that δ Sct and γ Dor variables are clearly separated by their different values of the pulsation constant Q.

Our photometric periods of 0.19968 and 0.19389 days for HD 776 are shorter than those of other known γ Dor stars and instead are at the long end of the δ Scuti range (e.g., Handler & Shobbrook 2002). However, the value of log Q for HD 776 lies in the gap between the two types of variables (Handler & Shobbrook 2002) and is significantly closer to the log Q values of the γ Dor stars. Thus, we believe that this pulsator is more likely to be a γ Dor variable.

Duflot et al. (1990) included HD 776 in an extensive objective prism radial velocity survey of bright stars in several stellar fields. Their average radial velocity from seven observations is -19.7 ± 2.9 km s^{-1}, a value that differed by more than 10 km s^{-1} from our initial average of -31.5 ± 0.3 km s^{-1}, which was determined from our three KPNO observations. This difference suggested that the star might be a spectroscopic binary, and so we acquired additional observations at Fairborn Observatory.

Table 3
Radial Velocities of HD 776

Hel. Julian Date −2400000	Phase	Rad. Vel. (km s^{-1})	$(O - C)$ (km s^{-1})	Source[a]
54367.7918	0.578	−31.3	0.7	KPNO
54729.8641	0.530	−32.1	−0.5	KPNO
54730.8717	0.552	−31.1	0.7	KPNO
56673.6150	0.219	−25.9	0.5	Fair
56674.6408	0.241	−28.5	−1.4	Fair
56675.6720	0.264	−27.4	0.2	Fair
56676.6711	0.286	−28.0	0.1	Fair
56677.6268	0.307	−28.8	−0.3	Fair
56678.6824	0.330	−27.5	1.4	Fair
56706.6360	0.944	−28.5	0.2	Fair
56775.9871	0.467	−32.4	−1.5	Fair
56789.9587	0.774	−33.0	0.3	Fair
56810.8842	0.234	−27.8	−1.0	Fair
56825.9548	0.564	−30.7	1.2	Fair
56828.8457	0.628	−32.5	−0.0	Fair
56830.8406	0.672	−33.7	−0.9	Fair
56831.8355	0.694	−32.5	0.4	Fair
56832.8317	0.716	−34.1	−1.1	Fair

Note.
[a] KPNO—Kitt Peak National Observatory, Fair—Fairborn Observatory.

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

5.1.2. Orbital Analysis

Our three KPNO observations, acquired in 2007 and 2008, have been supplemented with 39 observations from Fairborn that were obtained in 2014 and 2015. Analysis of the 42 radial velocities (Table 3) produced an orbital period of 45.53 ± 0.03 days and a relatively high eccentricity of 0.65 ± 0.02. When the individual objective prism radial velocities were included in the solution, three of the velocities had residuals between 9 and 20 km s^{-1}, and so the objective prism velocities were not used in our final solution, which is given in Table 2. A comparison of our radial velocities and the computed orbit is shown in Figure 1.

5.1.3. Discussion

The value of the mass function for HD 776 is 0.0023 $M_\odot$ (Table 2), which is at least an order of magnitude smaller than for our other four binaries. The equation for the mass function relates the primary star's mass to that of the secondary for orbital inclinations from 0° to 90°. If from its spectral type we adopt a mass of 1.6 $M_\odot$ (e.g., Gray 1992) for the primary, then the mass of the secondary corresponds to that of an M dwarf for inclinations greater than 25°. If binaries have a random orientation of orbital inclinations, then there is less than a 10% chance that the secondary is a K dwarf or more massive star.

5.2. HD 6568 = HIP 5209

5.2.1. Brief History

Henry et al. (2011) included HD 6568 [$\alpha = 01^h06^m37\overset{s}{.}62$ $\delta = 08°21'36\overset{''}{.}1$ (2000)] in their volume-limited photometric survey of γ Dor candidates. They identified it as a γ Dor variable with two pulsation periods near 0.75 days. They classified it as an F1 dwarf, determined a $v \sin i$ value of 55 ± 3 km s^{-1}, found it to be a spectroscopic binary, and

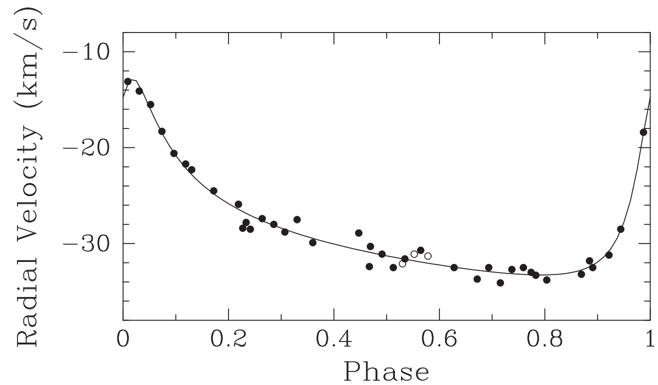

Figure 1. Radial velocities of HD 776 compared with the computed velocity curve. Filled circles = Fairborn Observatory, open circles = KPNO. Zero phase is a time of periastron passage.

Table 4
Radial Velocities of HD 6286

Hel. Julian Date −2400000	Phase	Rad. Vel. (km s^{-1})	$(O - C)$ (km s^{-1})	Source[a]
52940.8196	0.672	−13.8	−0.9	KPNO
52942.7769	0.687	−13.8	−1.3	KPNO
53273.9016	0.302	−4.1	−1.0	KPNO
53534.9783	0.363	−6.4	0.5	KPNO
53634.8373	0.151	8.4	2.4	KPNO
53635.9070	0.160	4.2	−1.4	KPNO
53637.8705	0.175	6.3	1.4	KPNO
54001.8655	0.049	9.5	1.4	KPNO
54364.8099	0.914	0.7	−1.3	KPNO
54367.8105	0.938	3.7	0.1	KPNO
54407.7387	0.253	−2.6	−2.7	KPNO
54408.7553	0.261	−0.8	−0.3	KPNO
54730.9204	0.805	−4.9	1.4	KPNO
55006.9643	0.984	6.5	0.2	KPNO
55094.8376	0.678	−14.9	−2.1	KPNO
55095.7963	0.685	−13.0	−0.5	KPNO
55338.9660	0.605	−13.3	0.7	Fair
55349.9661	0.692	−9.5	2.8	Fair

Note.
[a] KPNO—Kitt Peak National Observatory, Fair—Fairborn Observatory.

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

estimated a preliminary period of 126.5 days. Recently, in a spectroscopic survey of F dwarfs that might be suitable for planetary searches, Pribulla et al. (2014) also identified HD 6568 as a spectroscopic binary.

5.2.2. Orbital Analysis

HD 6568 was first observed at KPNO where we acquired 20 observations between 2003 and 2011. An additional 86 observations were obtained at Fairborn Observatory from 2010 through 2014. Analysis of those 106 velocities (Table 4) resulted in an orbital period of 126.66 ± 0.04 days and an eccentricity of 0.09 ± 0.02. The orbital elements and related quantities are listed in Table 2. Figure 2 shows the radial velocities and our computed orbit.

5.2.3. Astrometric Orbit

We adopted our values of the spectroscopic orbital elements for P, T, e, and ω of HD 6568 and computed an orbital model

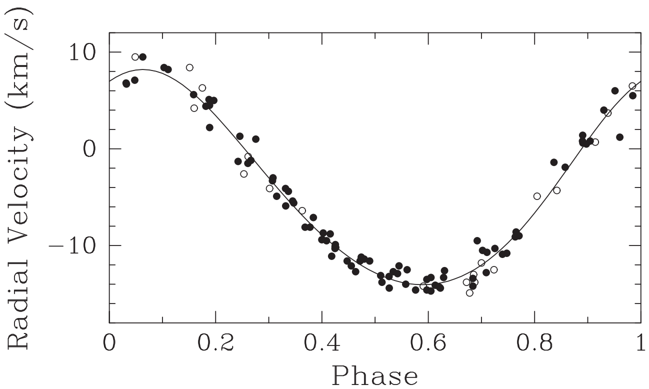

Figure 2. Radial velocities of HD 6568 compared with the computed velocity curve. Filled circles = Fairborn Observatory, open circles = KPNO. Zero phase is a time of periastron passage.

for the *Hipparcos* astrometric observations. That solution yields an orbital inclination, i, of 140° ± 11° and a longitude of the node, Ω, (epoch 1991.25) of 236° ± 15°. The semimajor axis of the absolute orbit of the photocenter is 3 ± 2 mas. Because of the short period of the system, neither the parallax nor the components of the proper motion are affected. This solution fulfills the criteria of Pourbaix & Boffin (2003).

5.2.4. Discussion

If the F1 dwarf primary has a mass of 1.5 $M_\odot$ (e.g., Gray 1992), and we adopt the orbital inclination of 140°, then the mass function value for HD 6568 (Table 2) results in a mass of 0.6 $M_\odot$ for the secondary, which corresponds to a late-K dwarf (Gray 1992, p. 431).

5.3. HD 17310 = KU Eri = HIP 12953

5.3.1. Brief History

Grenier et al. (1999) observed HD 17310 [$\alpha = 02^h46^m33^s.96$ $\delta = -06°42'06''.8$ (2000)] and from three observations determined an average radial velocity of 21.4 ± 3.6 km s^{-1}. Henry et al. (2005) identified the F2 dwarf as a γ Dor variable, found a low $v \sin i$ value of 10 ± 1 km s^{-1}, and determined three pulsation periods between 1.8 and 2.5 days. The first four radial velocities of Henry et al. (2005) differed by more than 20 km s^{-1} from the Grenier et al. (1999) average, suggesting that it is a binary. The seven additional velocities that Henry et al. (2005) obtained, combined with the first four, result in a velocity range of 44 km s^{-1}. While a period search of those velocities produced a best period of 0.965 days, they preferred a much longer one of 27.79 days. Griffin & Boffin (2006) obtained 11 additional velocities of the star, combined them with those of Henry et al. (2005), and determined an orbit with a period of 27.82 days.

5.3.2. Orbital Analysis

From 2002 through 2010 we obtained 39 spectra of HD 17310 at KPNO. Starting in 2006 at Fairborn Observatory we began observing it more intensively and continued through 2014, accumulating an additional 166 useful spectra. Analysis of the combined velocities (Table 5) resulted in an orbital period of 27.868 ± 0.001 days and an eccentricity of 0.11 ± 0.01. The full set of orbital elements is listed in Table 2, and Figure 3 presents a plot of our radial velocities and the computed orbit. The orbital period of Griffin & Boffin (2006), 27.82 ± 0.02 days, differs from ours by 2.5σ, and their other orbital elements are also somewhat different from ours. This should not be too surprising because the orbit of Griffin & Boffin (2006) resulted from the combination of two data sets that included just 11 radial velocities each. The significant pulsational variability of the star and small number of velocities made it difficult to assess the reality of the zero point difference of 1.6 ± 1.2 km s^{-1} between the two modest data sets. In the end Griffin & Boffin (2006) chose to make no velocity shift to either set of data. Their orbital solution of the combined velocities resulted in a large rms velocity residual of 2.1 km s^{-1}.

Our rms velocity residual of 2.2 km s^{-1} for HD 17310 is similar to that of Griffin & Boffin (2006). Its value is much larger than that for the velocities of the other four systems in this paper. Our substantially larger number of observations results in a more uniform distribution of the pulsational changes with respect to orbital phase. Thus, that distribution

Table 5
Radial Velocities of HD 17310

Hel. Julian Date −2400000	Phase	Rad. Vel. (km s^{-1})	$(O - C)$ (km s^{-1})	Source[a]
52542.9111	0.148	−3.7	−2.6	KPNO
52902.9079	0.066	−1.9	−0.6	KPNO
52903.9247	0.102	1.1	3.3	KPNO
52904.9023	0.137	−3.7	−2.1	KPNO
52940.8793	0.428	28.6	−0.5	KPNO
52941.8688	0.464	28.6	−4.1	KPNO
53273.9266	0.379	29.7	6.1	KPNO
53274.8852	0.414	23.7	−3.8	KPNO
53275.8706	0.449	35.7	4.4	KPNO
53276.8441	0.484	31.1	−3.4	KPNO
53277.8703	0.521	40.4	2.9	KPNO
53279.9631	0.596	42.7	1.0	KPNO
53634.9042	0.332	20.2	2.3	KPNO
53635.9314	0.369	22.8	0.4	KPNO
53636.8410	0.402	28.9	2.7	KPNO
53636.9940	0.407	28.1	1.3	KPNO
53637.8856	0.439	30.4	0.1	KPNO
53638.9345	0.477	37.7	3.8	KPNO

Note.
[a] KPNO—Kitt Peak National Observatory, Fair—Fairborn Observatory.
(This table is available in its entirety in machine-readable form.)

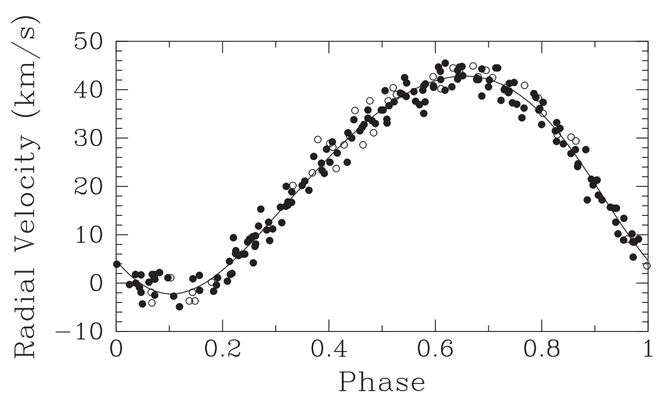

Figure 3. Radial velocities of HD 17310 compared with the computed velocity curve. Filled circles = Fairborn Observatory, open circles = KPNO. Zero phase is a time of periastron passage.

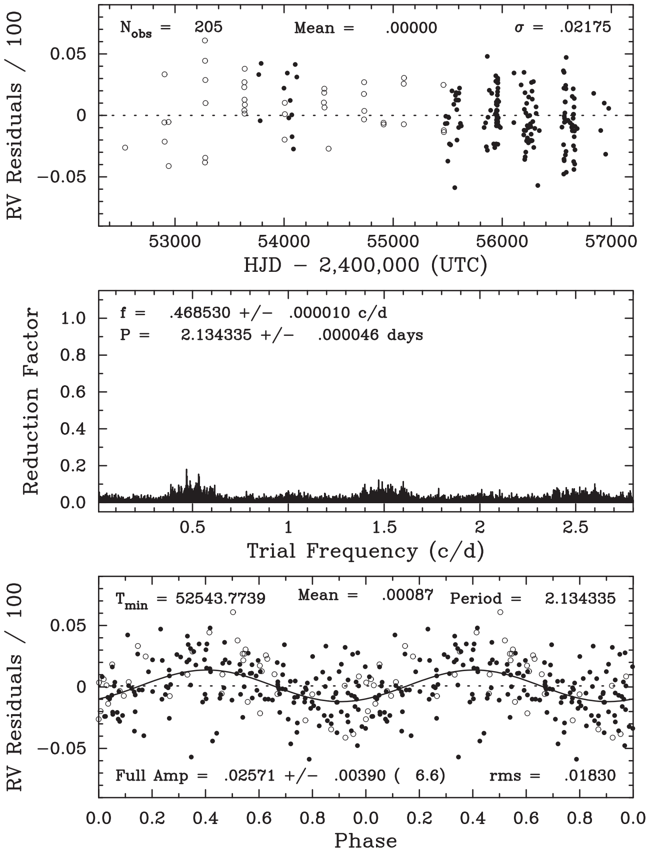

Figure 4. Radial velocity residuals of HD 17310 from the computed velocity curve in Figure 3. (Top): Radial velocity residuals divided by 100 from the 27.868 day orbital period. Open circles = KPNO, filled circles = Fairborn Observatory. The 205 velocities span the years 2002–2014. (Middle): A frequency spectrum of the radial velocity residuals based on least-squares fitting of sine curves. The frequency giving the largest reduction in variance of the data is 0.46853 cycles per day, corresponding to a period of 2.13434 ± 0.00005 days. (Bottom): The radial velocity residuals phased to the best period of 2.13434 days. The peak-to-peak amplitude of the sine curve is 2.6 km s^{-1} and has an approximate S/N of 6.6.

and a possible velocity zero point difference are the most likely contributors to the differences in the two sets of orbital elements.

5.3.3. Discussion

Our analysis of the radial velocity residuals of HD 17310 identifies a period of 2.134335 ± 0.000046 days (Figure 4), similar to that found by Griffin & Boffin (2006) from a much smaller velocity set. Additional analysis of the residuals, fixing the 2.134335 day period, failed to reveal any significant additional periods. Our value is in excellent agreement with the largest amplitude period of 2.1358 ± 0.0018 days that is one of three independent periods found in the Johnson *B* photometry of Henry et al. (2005). Our radial velocity full amplitude of 2.6 km s^{-1} is at the high end of the values found in other γ Dor variables (e.g., Fekel & Henry 2003; Mathias et al. 2004; Griffin & Boffin 2006).

5.4. HD 19684 = V889 Per = HIP 14871

5.4.1. Brief History

HD 19684 [$\alpha = 03^h11^m58\overset{s}{.}87$ $\delta = 46°07'43\overset{''}{.}0$ (2000)] was one of nearly 450 stars for which Fehrenbach et al. (1987) obtained objective prism plates and measured radial velocities. Their objective was to characterize the basic stellar data for the input catalog of the *Hipparcos* satellite. Their six measurements of HD 19684 had a mean velocity of -5 ± 4 km s^{-1}. Henry & Fekel (2002) found the star to be a γ Dor variable with five periods between 0.3 and 0.4 days. They obtained three spectra from which they determined it to be a F1 subgiant with a projected rotational velocity of 59 ± 3 km s^{-1}. Their radial velocities showed that the star had a radial velocity range of nearly 20 km s^{-1}, indicating that it is likely to be a spectroscopic binary. Kaye & Fekel (2003) used the velocities of Fehrenbach et al. (1987) and Henry & Fekel (2002) to obtain a preliminary orbit with a period of 31.95 days.

Table 6
Radial Velocities of HD 19684

Hel. Julian Date −2400000	Phase	Rad. Vel. (km s^{-1})	$(O-C)$ (km s^{-1})	Source[a]
52013.6050	0.369	19.8	−1.2	KPNO
52326.6198	0.818	0.0	1.3	KPNO
52328.6098	0.821	0.1	1.3	KPNO
52902.9509	0.644	1.3	1.2	KPNO
52904.9208	0.647	0.1	0.2	KPNO
52940.9046	0.699	−1.9	0.2	KPNO
53273.9442	0.176	26.7	−2.1	KPNO
53274.9141	0.178	27.4	−1.5	KPNO
53276.8982	0.180	30.7	1.8	KPNO
53277.9304	0.182	26.6	−2.3	KPNO
53279.0174	0.183	28.6	−0.3	KPNO
53280.0115	0.185	28.8	−0.1	KPNO
53634.9428	0.694	0.9	2.8	KPNO
53636.9317	0.697	−1.4	0.6	KPNO
53639.9813	0.701	−2.0	0.2	KPNO
53767.7564	0.884	2.1	−1.0	Fair
53781.7788	0.904	5.4	0.4	Fair
53803.7054	0.936	8.1	−0.2	Fair

Note.
[a] KPNO—Kitt Peak National Observatory, Fair—Fairborn Observatory.
(This table is available in its entirety in machine-readable form.)

5.4.2. Orbital Analysis

Between 2001 and 2009 we acquired 31 observations from KPNO. In 2006 we also began observing HD 19684 at Fairborn Observatory and obtained an additional 70 spectra. A period search of the 101 radial velocities, listed in Table 6, found no evidence for the previously suggested period of 31.95 days but instead resulted in a period of 697 days.

A number of spectra taken at KPNO show evidence of a secondary component that is broader and much weaker than that of the primary (Figure 5). Similar secondary features were detected in the best of our Fairborn spectra. Unfortunately, the secondary lines never completely separate from the primary lines, and so, the two sets of features remain significantly blended. This substantial blending and the extreme weakness of the secondary lines make the full extent of those lines unknown. As a result, we were unable to measure satisfactorily the velocity of the secondary. Thus, with our 101 velocities of the primary we determined a single-lined spectroscopic orbit that has an orbital period of 697.5 ± 0.9 days and an eccentricity of 0.09 ± 0.01 (Table 2). Figure 6 shows a comparison of the radial velocities with the computed orbit.

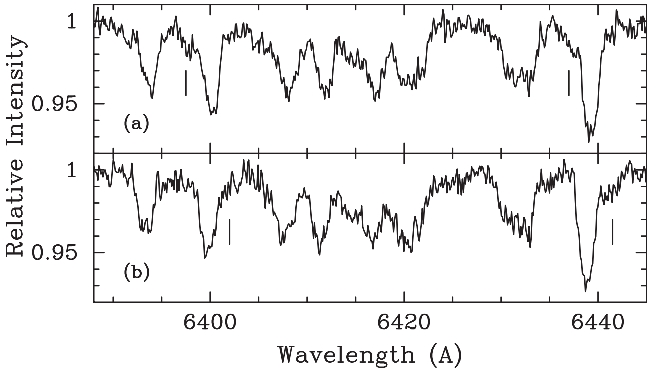

Figure 5. Red wavelength spectra of HD 19684. Panel (a): tick marks indicate the most obvious weak, blended, blueshifted secondary features, which are significantly broader than those of the primary. Panel (b): tick marks indicate the most obvious redshifted secondary features.

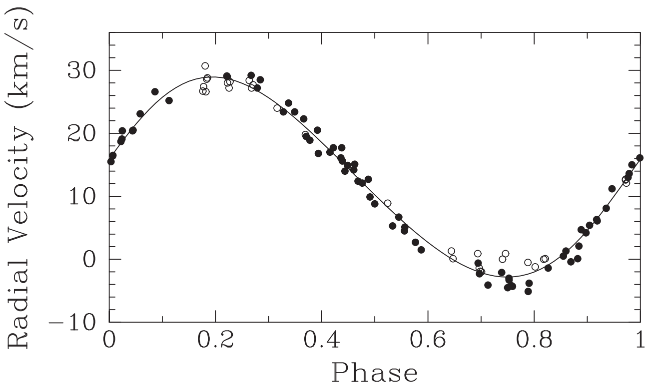

Figure 6. Radial velocities of HD 19684 compared with the computed velocity curve. Filled circles = Fairborn Observatory, open circles = KPNO. Zero phase is a time of periastron passage.

5.4.3. Discussion

The detection of lines of the secondary in the spectra of HD 19684 indicates that, unlike the other four binaries, the secondary component of HD 19684 is relatively massive. This conclusion is supported by the large value of the mass function of the orbit, 0.29 $M_{\odot}$. Adopting a mass of 1.6 $M_{\odot}$ for the F1 subgiant primary results in a minimum mass (corresponding to an inclination of 90°) of 1.37 $M_{\odot}$ for the secondary.

5.5. HD 62196 = HIP 37802

5.5.1. Brief History

Henry et al. (2011) also observed HD 62196 [$\alpha = 07^{h}45^{m}04^{s}.14$ $\delta = 48°23'40''.4$ (2000)] in their volume-limited survey of γ Dor candidates and like HD 6568, they identified it as a γ Dor variable. They classified the star as an F2 dwarf, found a low $v \sin i$ value of just 6 ± 1 km s^{-1}, and detected two photometric periods near 1 day. The mean velocity from eight observations by Nordström et al. (2004) shows a large standard deviation indicating that the star is a spectroscopic binary. From their velocity results, Henry et al. (2011) suggested an orbital period of about 3.3 years.

5.5.2. Orbital Analysis

From 2006 through 2012 we acquired 17 spectra of HD 62196 at KPNO. These observations were supplemented with 109 spectra obtained at Fairborn Observatory from 2009 through 2015. Analysis of all 126 radial velocities from those spectra (Table 7) resulted in an orbital period of 1163.4 ± 1.6 days. The eccentricity of that orbit, 0.012 ± 0.006 is close to zero, and the precepts of Lucy & Sweeney (1971) indicate that such a low eccentricity is not significant, and so a circular orbit should be adopted. However, we have chosen to retain the eccentricity because of the relatively long orbital period. The orbital elements of the eccentric orbit are listed in Table 2. The radial velocities compared to the computed curve are shown in Figure 7.

Table 7
Radial Velocities of HD 62196

Hel. Julian Date −2400000	Phase	Rad. Vel. (km s^{-1})	$(O - C)$ (km s^{-1})	Source[a]
54005.0066	0.956	−0.2	0.0	KPNO
54006.0114	0.957	−0.3	−0.1	KPNO
54368.0237	0.268	−10.8	0.0	KPNO
54370.0165	0.270	−11.0	−0.1	KPNO
54408.0044	0.302	−12.0	0.1	KPNO
54408.9676	0.303	−12.4	−0.3	KPNO
54526.7139	0.404	−14.1	0.2	KPNO
54584.6475	0.454	−14.2	0.2	KPNO
54731.0237	0.580	−12.0	−0.1	KPNO
54865.8146	0.696	−7.9	−0.7	Fair
54909.8276	0.734	−5.6	−0.1	Fair
54911.7393	0.735	−5.7	−0.2	KPNO
54921.8400	0.744	−5.1	0.0	Fair
54942.7004	0.762	−4.2	0.1	Fair
54945.7478	0.764	−4.7	−0.5	Fair
54950.6796	0.769	−4.1	0.0	KPNO
54958.6518	0.775	−4.1	−0.3	Fair
54985.7152	0.799	−3.3	−0.4	Fair

Note.
[a] KPNO—Kitt Peak National Observatory, Fair—Fairborn Observatory.

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

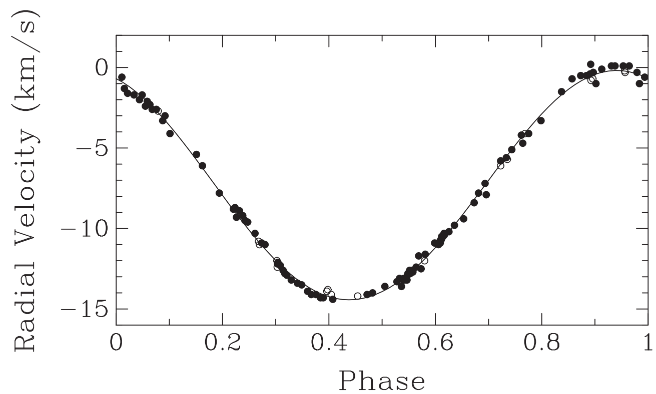

Figure 7. Radial velocities of HD 62196 compared with the computed velocity curve. Filled circles = Fairborn Observatory, open circles = KPNO. Zero phase is a time of periastron passage.

5.5.3. Astrometric Orbit

Unlike HD 6568, for which we were able to compute a satisfactory orbital model, the situation for HD 62196, which has the longest orbital period of our five binaries, is not clear. The original *Hipparcos* and Tycho-2 proper motions are discrepant at the 3 + σ level, which is often the indication of a long-period binary (e.g., HD 166181 = HIP 88848, Fekel et al. 2005). However, the number of *Hipparcos* observations is rather limited, which makes any orbital model questionable. Assuming spectroscopic values for the four orbital elements P, T, e, and ω, as was done for HD 6568, results in a fit of the astrometric data of HD 62196 that is significantly better than the single star model and the agreement with the Tycho-2 proper motion component $\mu_{\alpha*}$ is much better. However, with that orbital model, the proper motion component μ_δ is in poorer agreement. In addition, some statistical indicators from the orbital fit do not make the cut for acceptance (Pourbaix & Boffin 2003), so we await the new results from *Gaia* for this system. Even if HD 62196 turns out to be a triple star, as suggested below, the extremely long period of the possible third component makes it unlikely to have caused the poor fit of the *Hipparcos* data.

5.5.4. Discussion

Observationally, Duquennoy & Mayor (1991) examined the multiplicity of solar-type stars in the solar neighborhood. They determined that while systems with periods ⩽10 days had circular orbits, longer period orbits are generally eccentric. For A stars, Matthews & Mathieu (1992) found that many circular and nearly circular orbits occurred in the period range of 3–10 days, but again, longer period orbits are generally eccentric. Thus, with periods ranging from 28 to 1163 days for our five binaries, it is not surprising that four of them have significant eccentricities. What is surprising is that HD 62196, the binary with the longest period, which is 1163 days, has a nearly circular orbit.

In addition to its very low eccentricity of 0.012 ± 0.006 it also has a mass function that is very small, 0.0436 $M_\odot$. Such characteristics are reminiscent of barium stars (McClure & Woodsworth 1990; Jorissen et al. 1998), chemically peculiar red giants with overabundances of s-process elements that have white dwarf companions. North et al. (1994) have identified a number of F-type dwarf counterparts to the barium giants. Thus, it is possible that HD 62196 is one of these counterparts and has a white dwarf secondary.

HD 62196 has been identified as a metal weak F star from photometry (Olsen 1980; Hauck et al. 1991) and spectroscopy (Jaschek et al. 1989). Giridhar et al. (2013) used an artificial neural network on moderate resolution spectra of a sample of metal-poor stars and determined their basic parameters including iron abundance. For HD 62196 they found [Fe/H] = −0.78. While photometric and spectroscopic analyses indicate that this star is metal-poor, there is no evidence to date of abundance peculiarities similar to those of barium stars or their F-type dwarf counterparts.

HD 62196 has the smallest velocity rms of our five binaries (Table 2). Figure 8 plots the KPNO and Fairborn velocity residuals versus Julian date. Those from Fairborn show a positive trend of about 0.5 km s^{-1} over a 2300 day interval, suggesting that there is a third component in this system.

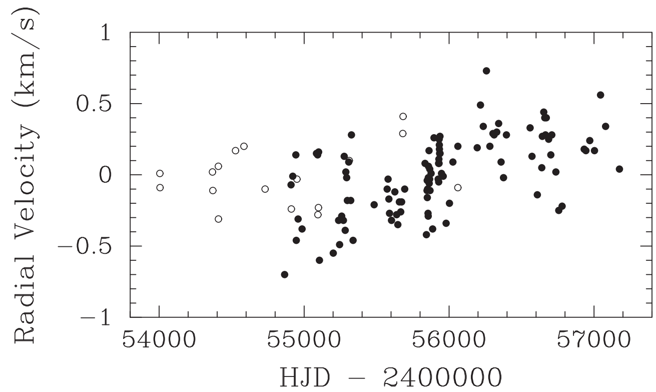

Figure 8. Orbital velocity residuals of HD 62196. Filled circles = Fairborn Observatory, open circles = KPNO. The Fairborn residuals indicate a systematic increase of ~0.5 km s^{-1} over about 2300 days.

6. SUMMARY

We have determined the period and other spectroscopic orbital elements of five γ Dor variables, HD 776, HD 6568, HD 17310, HD 19684, and HD 62196. Their orbital periods range from 27.8 to 1163 days and their eccentricities, from 0.01 to 0.65. Of the five systems, only HD 19684 shows lines of its binary companion, but those lines are always blended with the lines of the primary and do not allow for satisfactory measurement. The velocity residuals of HD 62196 have a long-term trend suggesting that it is a triple system.

The dominant pulsation modes of γ Dor variables are often detected in both the photometric and spectroscopic observations. However, because the line profiles of such pulsators are sensitive to higher degree modes than those found in photometric data, we searched the velocity residuals of the orbital fits for periodicities associated with pulsation. No clear, convincing case for velocity periodicities was found in four of the five stars. However, for HD 17310 we identified a period of 2.13434 days, a value in agreement with the largest amplitude period previously found photometrically for that star.

We thank the referee for helpful suggestions that improved the presentation and clarity of our paper. Astronomy at Tennessee State University is supported by the state of Tennessee through its Centers of Excellence program. This research made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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