Astron. Astrophys. 355, 1015–1030 (2000)

ASTRONOMY
AND
ASTROPHYSICS

A study of bright southern slowly pulsating B stars

I. Determination of the orbital parameters and of the main frequency of the spectroscopic binaries*

P. De Cat, C. Aerts, J. De Ridder, K. Kolenberg***, G. Meeus, and L. Decin*****

Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200 B, 3001 Heverlee, Belgium

Received 30 September 1999 / Accepted 22 December 1999

Abstract. In 1996, we started a long-term spectroscopic and photometric study of 17 southern Slowly Pulsating B-stars. In this paper, we report our finding that at least 8 of them turn out to be spectroscopic binaries. We present the results of the determination of the orbits from the spectroscopic data.

There is a great variety in the derived orbits. HD123515 and HD140873 were known as single-lined spectroscopic binaries, but both turn out to be double-lined. All the others binaries are single-lined. For HD140873 and HD177863, we find orbits with a large eccentricity of respectively $e = 0.731 \pm 0.006$ and $e = 0.603 \pm 0.007$. HD69144, HD92287 and HD169978 are three circular binaries with a very short orbital period (a few days). Since their photometric measurements are dominated by a (close to) sinusoidal variation with twice the orbital frequency, these stars are ellipsoidal variables. Their orbital periods are of the same order of magnitude as the periods of pulsation.

After removing the orbit, we find the same first frequency in the residual radial velocities as in the gathered photometric measurements for 6 stars. For HD69144 and HD169978 we did not yet succeed in deriving an intrinsic period, although HD69144 has prominent line profile variations. HD169978 was misclassified as an SPB.

Key words: stars: early-type – stars: variables: general – stars: oscillations – stars: binaries: spectroscopic – line: profiles

1. Introduction

The satellite Hipparcos gave us an unbiased view of the occurence of stellar variability in our close environment and led to the discovery of 267 new variable B-stars. Waelkens et al. (1998) classified some 100 of them as new "Slowly Pulsating B-stars" (SPBs), a group of mid-B type variables pulsating in high-radial-order g-modes (Waelkens 1991). Since these modes penetrate deep into the stellar interior, this class of variables is very promising from an astroseismological point of view. All previously known SPBs are multiperiodic. Their pulsation periods range from 1 up to 3 days, resulting in beat periods of the order of months/years. Therefore, a long time-base is needed to disentangle the complete frequency spectrum and to perform mode identification.

In order to study their pulsational behaviour, we selected the brightest southern Hipparcos SPBs and started a long-term spectroscopic and photometric follow-up campaign in 1996. Also a few previously known SPBs are included in our target list. The selection of the targets is described in detail by Aerts et al. (1999), who list the stellar parameters in their Table 1. This sample is unbiased regarding spectral type, periodicity, binarity, and rotation velocity. Consequently, our targets are interesting objects to study possible interactions between these different properties.

In this first of a series of papers, we present (new) observational evidence that (at least) 8 of our targets are spectroscopic binaries with a pulsating component. For these multiple systems, we determine the radial velocity of the observed component(s) and derive an orbital solution. We use these orbits to shift the spectra to the velocity frame relative to the B-star itself. Afterwards, we search for evidence of at least one pulsation mode in the first normalised moment as defined by Aerts et al. (1992) and confront these results with those of a frequency analysis of the Geneva photometry and the Hipparcos photometry. Aerts et al. (1999) already searched for the main frequency in the single target SPBs but postponed to present the results for the binaries. This paper should be considered as the "twin"-paper for the binaries. Subsequent papers will be devoted firstly to a detailed frequency analysis of the spectra and the photometry and secondly to the interpretation of the observed variability in terms of non-radial pulsations for both the single and the binary SPBs in our sample.

The plan of this paper is as follows. The observations performed during the last two years, and the reduction of the data, are described in Sect. 2. Sect. 3 is devoted to the determination of the radial velocity. The searches for the orbital parameters and for the first pulsation frequency are described in Sect. 4. In Sect. 5, we give an overview of our results. Finally, a discussion of our results and some future plans are given in Sect. 6.

* Based on observations collected with the CAT Telescope of the European Southern Observatory and with the Swiss Photometric Telescope of the Geneva Observatory, both situated at La Silla in Chile

** Postdoctoral Fellow, Fund for Scientific Research, Flanders

*** Research Assistant, Fund for Scientific Research, Flanders

2. Observations and data reductions

In Table 1, we give the characteristics of the two different sets of ground-based data we have at our disposal. The satellite Hipparcos gave us between 60 and 180 data points of the Hipparcos magnitude H_p for every of our program stars, spread over 3.3 years.

The ground-based observations were gathered during some 20 observation campaigns (see Table 2). The photometric observations were conducted with the Swiss Photometric Telescope of the Geneva Observatory, situated at La Silla in Chile. The dedicated photometric monitoring was almost entirely performed in the course of 1997, but for many of the targets earlier measurements are available as well. The data reduction of these measurements is centralised in Geneva (Burki et al. 1995).

The selected stars are sufficiently bright in order to study their line profile variations (hereafter LPVs). During 11 different observation runs, we gathered high resolution spectra for these stars with the Coudé Auxiliary Telescope / Coudé Echelle Spectrometer (CAT/CES) combination, also situated at La Silla in Chile. We obtained between 40 and 120 high signal-to-noise spectra for all of our program stars in the region of the SiII-doublet λ = 4128, 4130 Å. Each spectrum was corrected for the pixel-to-pixel response through division by the mean of several flat field spectra obtained using a tungsten lamp. The wavelength calibration was done using about 100 lines of a thorium lamp. The spectra were normalized to the continuum by a cubic spline function, and the heliocentric corrections were computed. We rebinned all spectra such that $\Delta\lambda = 0.02$ Å.

Table 1. Overview of the different ground-based observation campaigns of our SPB-project.

Spectroscopy (ESO, CAT/CES)		
period	nights	observer(s)
Mar 1996	8	C. Aerts/G. Meeus
Apr 1996	7	G. Meeus
Jul 1996	7	C. Aerts
Feb 1997	5	C. Aerts
Mar 1997	5	P. De Cat
May 1997	6	C. Aerts/J. De Ridder
Jun 1997	6	J. De Ridder
Jul 1997	7	P. De Cat
Oct 1997	7	P. De Cat
Nov/Dec 1997	7	P. De Cat
Jan 1998	7	P. De Cat
Mar 1998	5	L. Decin
Geneva Photometry (Swiss Telescope)		
period	nights	observer(s)
Nov 1996	21	J. De Ridder
Jan/Feb 1997	21	G. Meeus
Feb 1997	21	P. De Cat
Apr 1997	21	K. Kolenberg
Apr/May 1997	21	G. Meeus
May/Jun 1997	21	K. Kolenberg
Nov 1997	21	P. De Cat
Dec 1997	21	G. Meeus

3. Determination of the radial velocities

There are different ways to determine the radial velocity from an observed spectrum. A first one is to make a Gaussian approximation of the line profile. For deep, sharp lines without subfeatures, such an approximation is justified, and μ, being the mean of the Gaussian, will be a good approximation of the radial velocity. Nearly all our targets show (prominent) moving bumps and troughs across their profiles. According to their position, these bumps and troughs can "pull" the Gaussian fit to the red or the blue wing of the considered absorption line, which leads to respectively an overestimation or an underestimation of the radial velocity. In these cases, it is more appropriate to use the first normalised moment M_1/M_0, as defined by Aerts et al. (1992), to approximate the radial velocity. The moments of a line profile, however, strongly depend on the choice of the intergration limits. With too narrow limits, much information about the line wings is lost, while too broad ones introduce much additional noise. In this paper, we are dealing with spectroscopic binaries. The use of "dynamic" integration limits to calculate the first moment is preferred: the integration limits are determined for each spectrum separately by visual inspection of the local continuum. In this way, differences in line-width during the pulsation cycle are also accounted for.

The first normalised moment was calculated for each of the SiII-lines separately, using λ_c = 4128.053 Å, and 4130.884 Å (Moore 1945) as central wavelenghts for respectively the first and second SiII-line. Afterwards, the average first normalised moment for the SiII-doublet was determined. Hereafter, "radial velocity" is used for "first normalised moment".

4. Determination of the orbital parameters and of the main intrinsic frequency

4.1. Used methods

Only three of our target stars were known to be single-lined spectroscopic binaries. For at least five others, the binary nature is revealed for the first time in our new spectroscopic data.

To derive the orbital parameters, we used a modern version of the VCURVE-code (Bertiau & Grobben 1969). This code is based on the Lehmann-Fihlés method for the initial input data, on the Schlesinger method for orbits of high eccentricity ($e > 0.05$) and on the Sterne method for orbits of small eccentricity ($e < 0.05$). Orbits were determined using all the individual averaged radial velocities of the SiII-doublet. VCURVE allows the assignment of weights from 0 (= bad) up to 1 (= good) to every used velocity. Since the standard deviation of the average radial velocity of the two SiII-lines is a good estimator of the error of the measured velocities, we used weights based on these standard deviations. In most of the cases, the solutions with this kind of weights or without weights lead to orbital parameters which differ less than one standard error. We chose to work with the solutions obtained with weights.

Table 2. Logbook of the observations of our targets. The SPBs that were known before the Hipparcos mission are marked with an asterisk. The stars are devided in two main groups: the single stars (Single) and the spectroscopic binaries (Binary). The group of the binaries is subdivided in Single-Lined Binaries (SB1) and Double-Lined Binaries (SB2), and subsequently in circular orbits ($e = 0$) and eccentric orbits ($e \neq 0$). For each data set (Spec = Spectra, Gen = Geneva photometry, Hipp = Hipparcos photometry), N gives the number of measurements and T(d) gives the total time-span in days. For the Geneva photometry, T*(d) gives the total time-span of the dedicated SPB-runs. S/N gives the average signal-to-noise ratio of the spectra of every target.

			Star	Spec			Gen			Hipp	
				N	T(d)	S/N	N	T(d)	T*(d)	N	T(d)
Singles			HD26326	65	606	325	135	7367	454	85	1158
			HD74195 ∗	94	718	425	737	7792	6292	115	1157
			HD85953	71	716	300	164	6883	415	156	1180
			HD131120	83	718	400	115	7296	116	60	885
			HD138764	68	719	325	93	7726	115	95	786
			HD181558 ∗	33	470	300	320	7854	5544	72	1093
			HD215573	43	554	300	63	7350	451	146	1142
Suspected			HD53921	75	715	325	145	7270	415	123	1185
Binaries			HD55522	65	715	350	122	6588	416	222	1149
Binaries	SB2	$e \neq 0$	HD123515 ∗	78	719	325	648	6921	5846	179	1166
			HD140873	45	472	300	59	7746	106	79	1088
	SB1	$e \neq 0$	HD24587	74	606	350	142	7372	454	128	1134
			HD74560 ∗	115	719	400	721	7713	5961	127	1157
			HD177863 ∗	41	470	300	301	7854	5319	85	1055
		$e = 0$	HD69144	93	718	400	148	7190	414	109	1132
			HD92287	65	716	325	232	7110	6053	136	1158
			HD169978	48	510	375	74	7110	377	77	1123

The found orbit was used to shift the spectra to the velocity frame centered at the B-star itself. The first normalised moment was recalculated, and we tried to find (new) evidence for the pulsational character of the primary components in these “residual” velocities, as well as in the Hipparcos magnitude and in the Geneva V magnitude. Hereto, we used three different frequency search algorithms: Stellingwerf’s PDM-algorithm (Stellingwerf 1978), the Scargle periodogram (Scargle 1982), and the CLEAN-algorithm (Roberts et al 1987). Since the three different methods always lead to the same main frequency, we restrict ourselves to discuss the Scargle periodogram in the text below. This method has an extra advantage, since the “false alarm probability” as defined by Scargle (1982) can be used. On every shown Scargle periodogram, a dashed line is drawn on the amplitude-level that corresponds to a false alarm probability of $p_o = 0.01$. This means that a peak with an amplitude higher than this level only has a 1% chance of being due to noise fluctuations.

4.2. Results

For every star, we show subsequently the observed radial velocities as a function of the orbital phase, some line profiles of the SiII-doublet centered at 4130 Å at different orbital phases, a phase diagram for the first intrinsic frequency (if found) in the three different data sets, together with the corresponding Scargle periodograms and window functions.

In the following, we discuss the results for each of the targets. We first concentrate on the double-lined binaries in our sample. The following subsections are devoted to the single-lined binaries, respectively with eccentric and circular orbits.

4.2.1. Double-lined binaries with eccentric orbits

Two of our targets, HD123515 and HD140873, turn out to be double-lined binaries with an eccentric orbit: our spectra clearly reveal absorption lines of both the primary and the secondary component, as can be seen on Fig. 1. For the majority of the spectra, we were able to determine the radial velocity of both components. The averaged first moment of the SiII-doublet was taken for the primary, while a Gaussian approximation was preferred for the secondary. We chose to use only the SiII-line at 4130 Å for the secondary because the SiII-line at 4128 Å of the secondary is more frequently blended with the SiII-line at 4130 Å of the primary. All the individual velocities of both components were used to determine the orbital parameters. For the primary component, we used weights according to the standard errors as described above. Since we have less confidence in the determination of the radial velocities of the secondary component, we used weights of 0.5 for these data points. For our double-lined binaries, no evidence of the binarity is found in the photometric measurements.

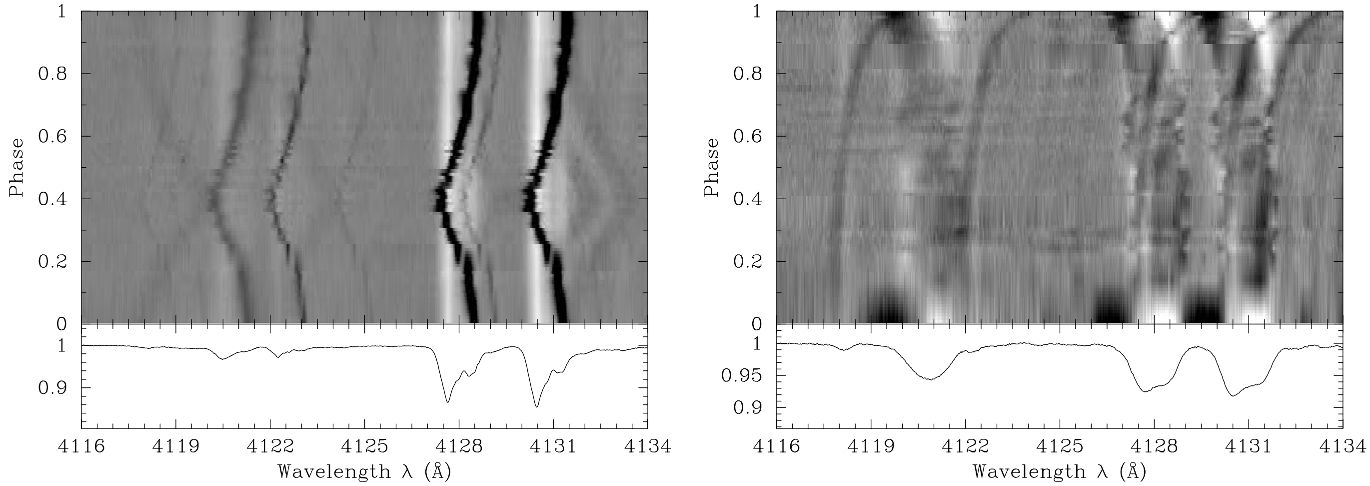

Fig. 1. A grey scale representation (top) of the residual individual spectra with respect to the overall average spectrum (bottom) for HD123515 (left panel) and HD140873 (right panel). The phase corresponds to the orbital period. Both the absorption lines of the primary and of the secondary can be seen.

Table 3. The orbital parameters for HD123515. The parameters of the primary and of the secondary have respectively subscript 1 and 2

P (d)	=	26.036	$\pm$	0.004
v_γ (km/s)	=	5.0	$\pm$	0.3
$t(\tau)$ (HJD)	=	2450034.8	$\pm$	0.1
e	=	0.264	$\pm$	0.007
ω (°)	=	340	$\pm$	2
K_1 (km/s)	=	39.4	$\pm$	0.4
$a_1 \sin i$ (A.U.)	=	0.146		
$M_1 \sin^3 i (M_\odot)$	=	1.602		
K_2 (km/s)	=	63.1	$\pm$	0.5
$a_2 \sin i$ (A.U.)	=	0.091		
$M_2 \sin^3 i (M_\odot)$	=	1.000		
rms (km/s)	=	2.600		

Table 4. The orbital parameters for HD140873. The parameters of the primary and of the secondary have respectively subscript 1 and 2

P (d)	=	38.927	$\pm$	0.004
v_γ (km/s)	=	-9.5	$\pm$	0.3
$t(\tau)$ (HJD)	=	2450132.80	$\pm$	0.06
e	=	0.731	$\pm$	0.006
ω (°)	=	201.8	$\pm$	0.8
K_1 (km/s)	=	43.1	$\pm$	0.7
$a_1 \sin i$ (A.U.)	=	0.209		
$M_1 \sin^3 i (M_\odot)$	=	1.824		
K_2 (km/s)	=	86	$\pm$	1
$a_2 \sin i$ (A.U.)	=	0.105		
$M_2 \sin^3 i (M_\odot)$	=	0.916		
rms (km/s)	=	2.009		

4.2.1.1. HD123515 - HR5296 - HIC69174

HD123515 ($m_V = 5.94$, SpT B9IV) is one of the coolest known SPBs with at least four pulsation modes (Waelkens 1991). It is known as a visual binary with a late type companion. The primary itself was known as a single-lined spectroscopic binary with an orbital period $P_{\rm orb} = 26\overset{\rm d}{.}005$ (Barker et al. 1967).

Our spectra confirm the orbital parameters known in the literature (Table 3). A phase diagram for the orbital period is given on Fig. 2a, while some line profiles of the SiII-doublet in function of the orbital phase are presented on Fig. 2b. On this figure, the broad, weak SiII-lines of the secondary component are not easily seen close to the sharp, very prominent SiII-lines of the primary.

After removing the orbit from the spectra, the three sets of data clearly point towards the same first intrinsic frequency, $\nu_1 = 0.68528$ c/d, which coincides with the first known photometric frequency as found by Waelkens (1991). Phase plots are shown in Fig. 2c, while the corresponding Scargle periodograms and window functions are given on respectively Fig. 2d and Fig 2e. The main peak is well above the $p_o = 0.01$ level for all data and 40% up to 60% of the (remaining) variance is already explained with this one frequency in the different data sets.

4.2.1.2. HD140873 - HR5863 - HIC77227

HD140873 ($m_V = 5.37$, SpT B8III) was also known as a single-lined spectroscopic binary for a long time, but it was not known yet as a photometric variable before the Hipparcos mission. Petrie & Phibbs (1949) found a very eccentric orbit with an orbital period $P_{\rm orb} = 38\overset{\rm d}{.}937$.

The line profiles of the SiII-doublet λ = 4128, 4130 Å show very large variations. They are not caused by stellar pulsation only, since the weak, sharp SiII-lines of the secondary are clearly superposed on the broad SiII-lines of the primary (Fig. 3b). Orbital elements similar to those known in the literature are found (Table 4). A phase diagram for the orbital period is given on Fig. 3a.

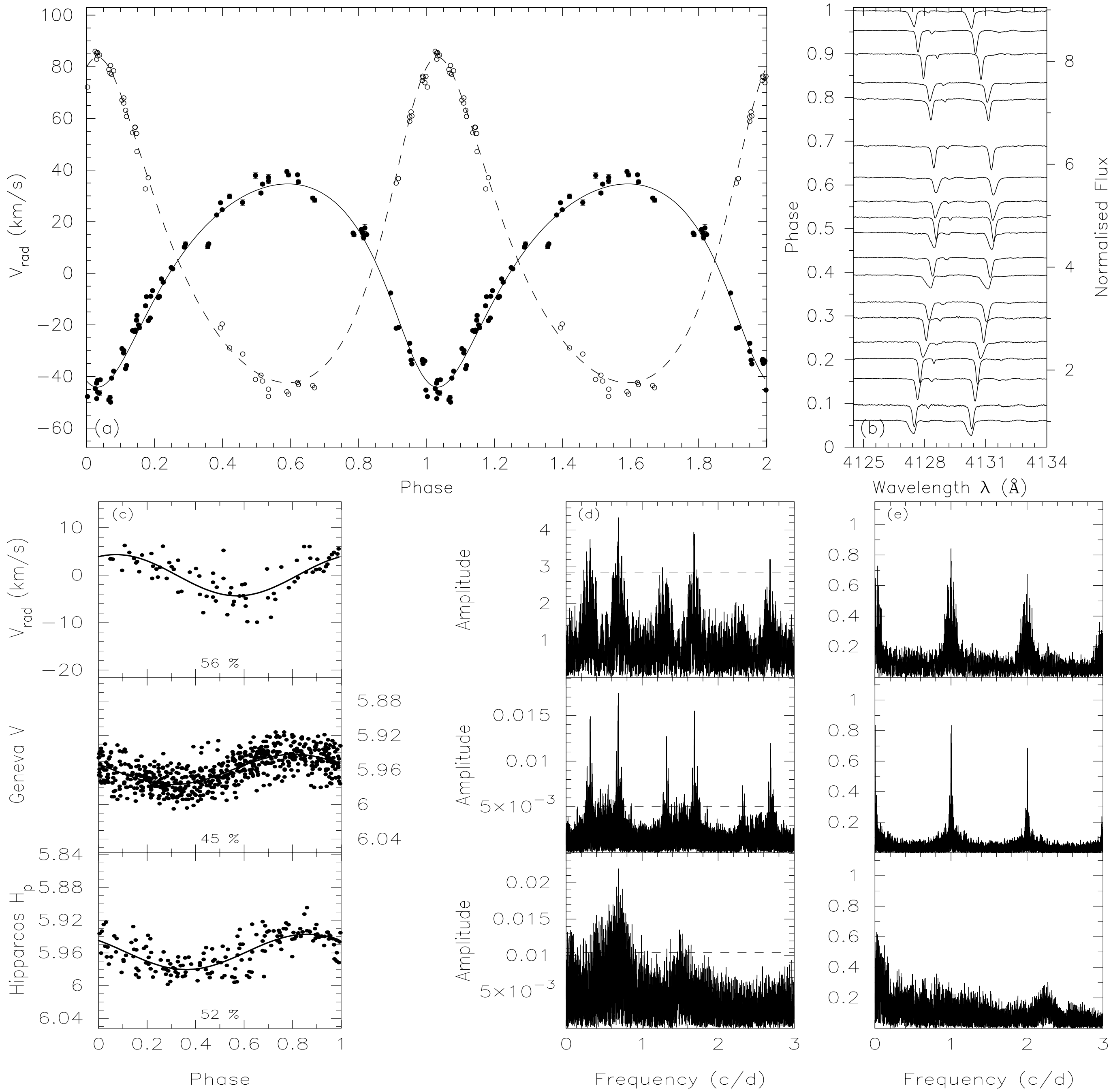

Fig. 2. a Observed radial velocities versus orbital phase of HD123515. The full dots denote primary component data while the open dots are the data of the secondary. The full line represents the theoretical velocity defined by the orbital elements given in Table 3 for the primary, the dashed line is the theoretical velocity for the secondary. Phase zero corresponds to periastron passage. **b** Some of the observed line profiles of HD123515, centered at λ = 4130 Å. The corresponding orbital phase is given on the left hand side of the figure. The successive spectra are shifted according to the phase. **c** Phase diagram for the first pulsation frequency of HD123515, given in Table 11. The dots denote respectively from top to bottom the radial velocity after removing the orbital motion, the V magnitude of the Geneva photometric system and the Hipparcos magnitude H_p. The percentages indicate the explained fraction of the variance. **d** The Scargle periodogram for the different data sets. The dashed line corresponds to a false alarm probability $p_o = 0.01$. **e** The window function for the different data sets.

Both in the residual radial velocities as in the Geneva photometry, two frequencies which are aliases from each other are found as best candidates for the first intrinsic frequency: $\nu_1 = 1.1516$ c/d and $\nu_1' = 0.1487$ c/d (Fig. 3d). They both explain about the same amount of the (remaining) variance in the different data sets and reach far above the $p_o = 0.01$ level. Thanks to the particular time-sampling of the Hipparcos measurements, we do not encounter this kind of alias problem in

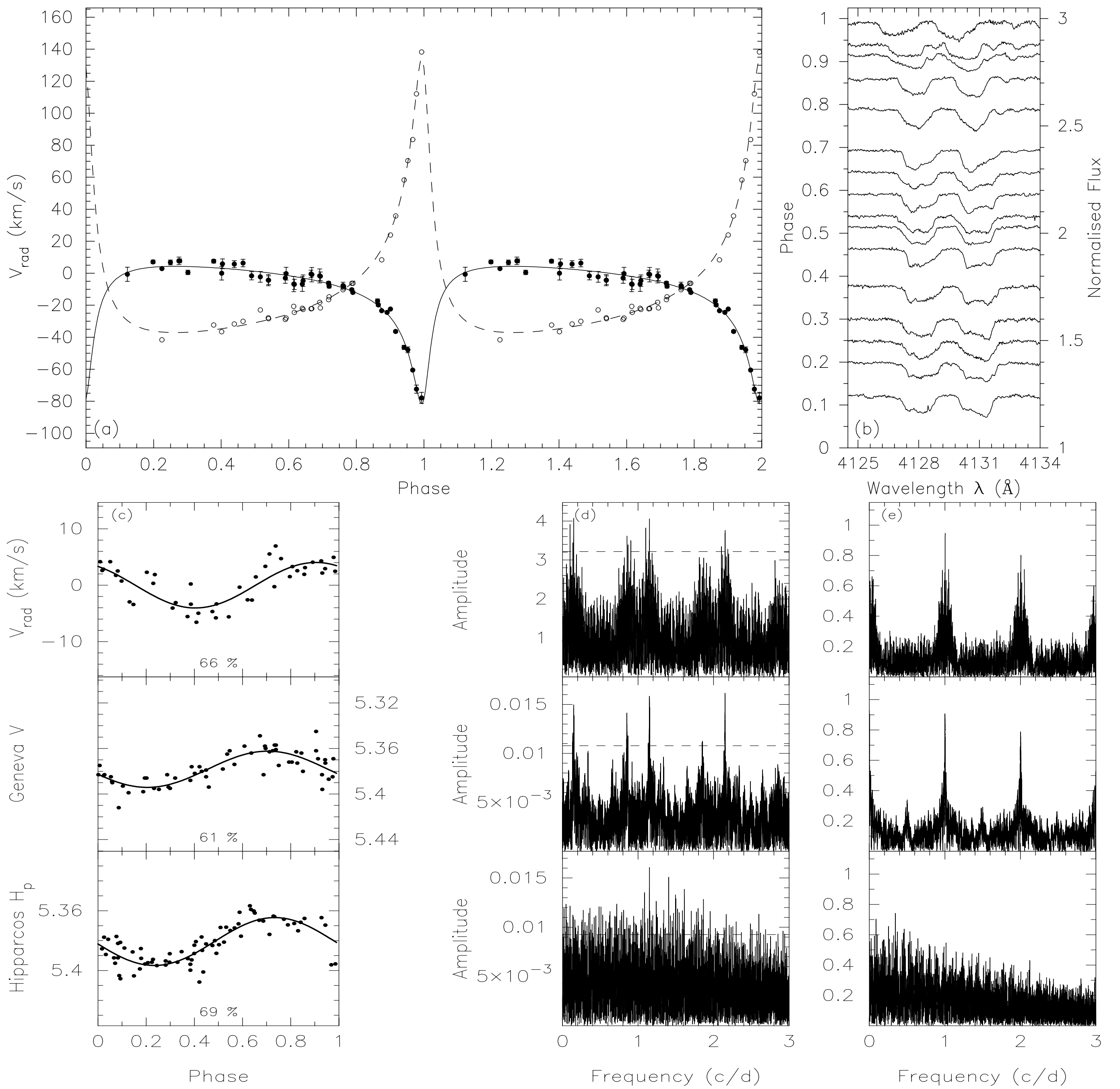

Fig. 3. Same as Fig. 2, but for HD140873.

these data. We conclude that $\nu_1 = 1.1516$ c/d is the main pulsation frequency, since no sign of $\nu_1' = 0.1487$ c/d is found in the periodogram of the Hipparcos measurements.

4.2.2. Single-lined binaries with eccentric orbits

For all other binaries in our sample, no evidence of the presence of a secondary component is found in our spectra. We find three additional single-lined spectroscopic binaries with an eccentric orbit: HD24587, HD74560, and HD177863. For these stars, the evidence of the binarity is found only in the spectroscopic measurements.

4.2.2.1. HD24587 - HR1213 - HIC18216

HD24587 ($m_V = 4.60$, SpT B5V) was not known as a binary before the start of our follow-up campaign in 1996. Aerts et al. (1999) already suggested that this star might be a spectroscopic binary since a slight radial velocity shift was observed between observations of two different runs. Now, 7 observation runs later, the binary nature of this star is easily confirmed. We

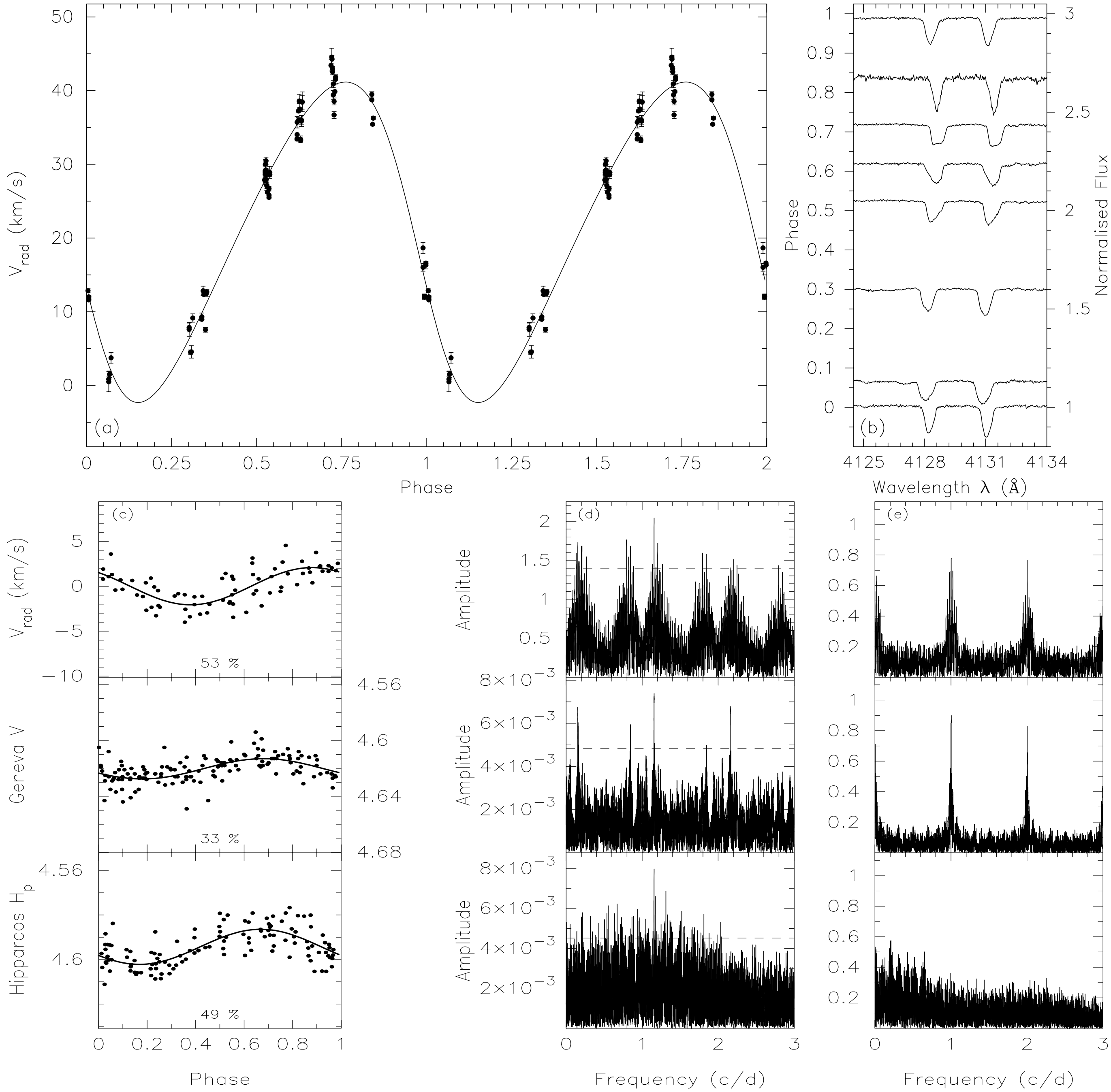

Fig. 4. Same as Fig. 2, but for HD24587.

find an eccentric orbit with a period of more than 450 days (see Table 5), which is the longest orbital period in our sample. This result nicely illustrates the importance of the long-term character of our follow-up study. On Fig. 4a, one can clearly see the superposition of the intrinsic variability and the orbital motion. HD24587 also shows clear LPVs, as can be seen on Fig. 4b.

After removing the orbit in the spectroscopic data, we find $\nu_1 = 1.1571$ c/d as the first intrinsic frequency, which coincides with the frequency already found in the Hipparcos and Geneva photometry by Aerts et al. (1999) (Fig. 4c).

4.2.2.2. HD74560 - HR3467 - HIC42726

HD74560 ($m_V = 4.86$, SpT B3IV) is one of the known SPBs for which Waelkens (1987) already reported LPVs. They are indeed clearly present in our spectroscopic data, as can be seen on Fig. 5b. The star has at least three photometric pulsation modes of which the dominant one has a frequency of 0.64472 c/d (Waelkens 1991).

Aerts et al. (1999) already found a longer than expected period of $8\overset{d}{.}8$ with a rather large amplitude of about 8 km/s in their radial velocity data. This period was not found in their exten-

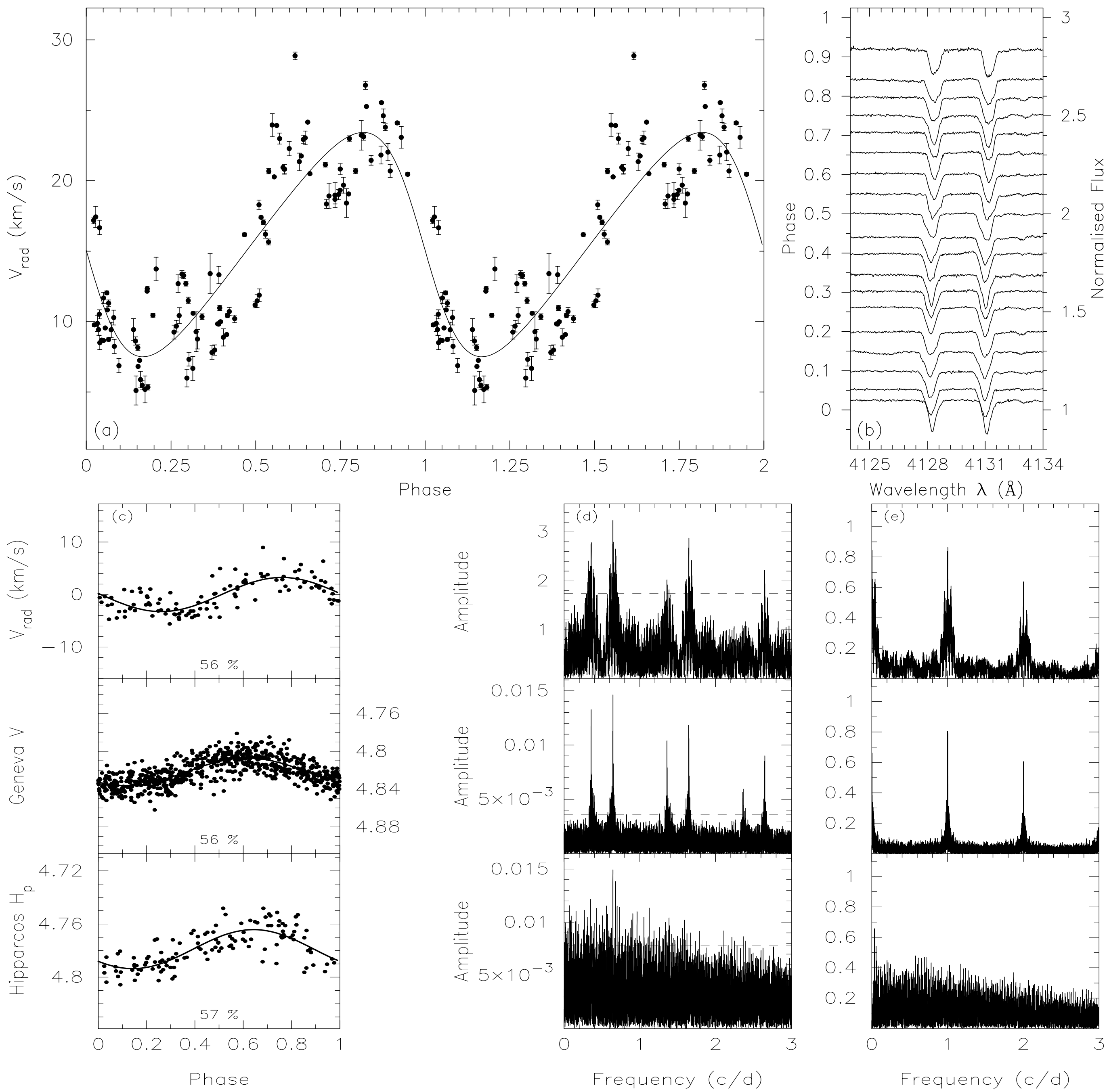

Fig. 5. Same as Fig. 2, but for HD74560.

sive set of photometric data. Therefore, these variations can not be due to a large-amplitude, low-degree pulsation. Now, we are able to assign these spectroscopic variations to a short, eccentric orbital motion, with orbital parameters as given in Table 6. Since this is the binary with the smallest orbital amplitude, the phase plot for the orbital period (Fig. 5a) seems rather noisy in comparison with the other binaries in our sample. This effect is strengthened by the multiperiodic character of this star.

In the residual radial velocities as well as in the Hipparcos photometry, we can easily confirm the first known photometric frequency $\nu_1 = 0.64472$ c/d (Fig. 5c). About 55% of the (remaining) variance is already explained by this frequency alone.

4.2.2.3. HD177863 - HR7241 - HIC93887

It were Waelkens & Rufener (1985) who first reported HD177863 ($m_V = 6.29$, SpT B8V) as a variable star. After 9 years of photometric observations in the Geneva system, two photometric pulsation frequencies were determined: $\nu_1 = 0.84068$ c/d and $\nu_2 = 0.90167$ c/d (Waelkens 1991). This star became one of the first known SPBs.

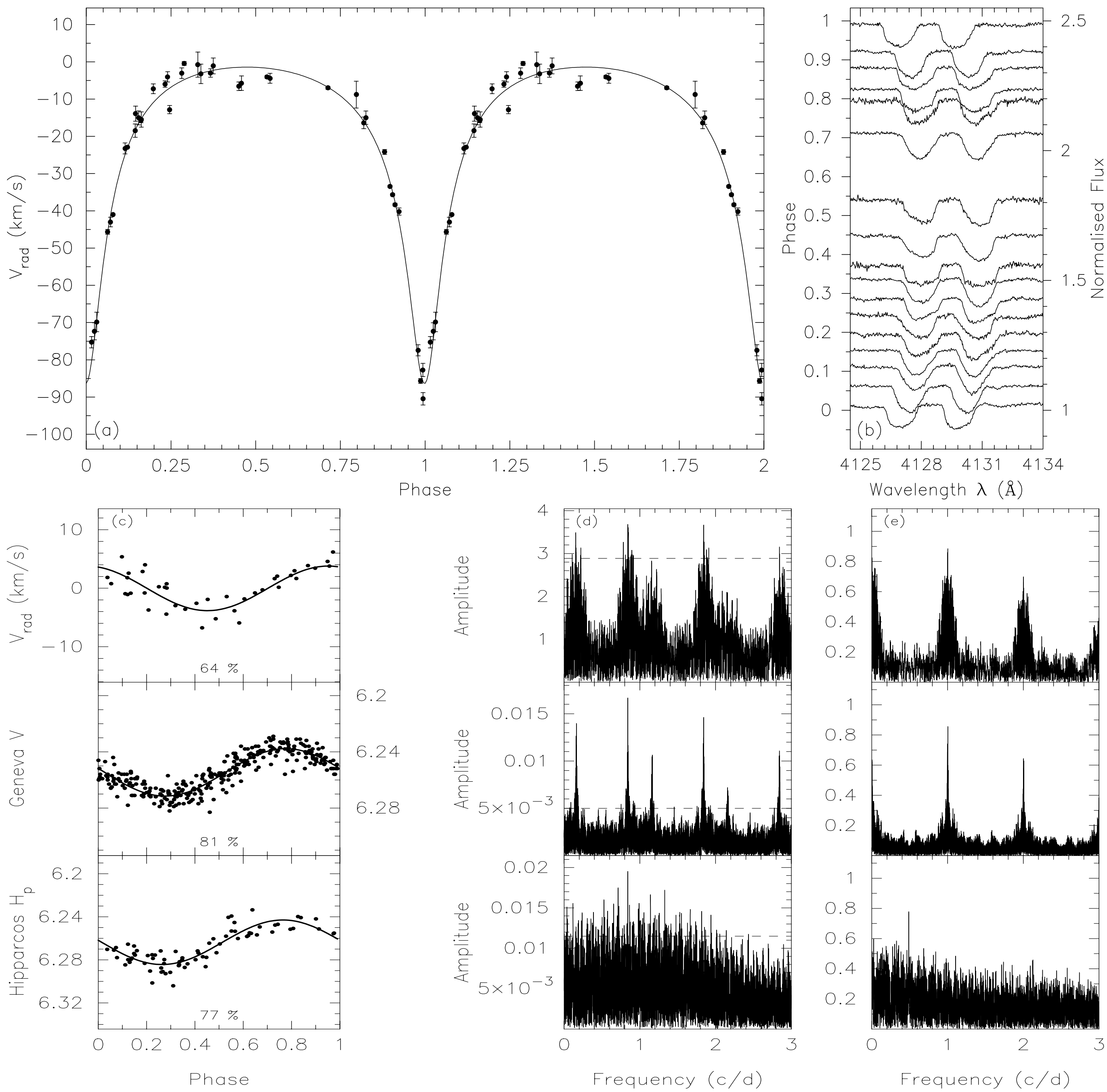

Fig. 6. Same as Fig. 2, but for HD177863.

The line profiles show a lot of asymmetries due to pulsation and the large, global Doppler shifts point out that we are dealing with a spectroscopic binary (Fig. 6b). For this object, we find a very eccentric orbit: $e = 0.603 \pm 0.007$ (Table 6).

After removing the orbit, the first photometric pulsation frequency $\nu_1 = 0.84060$ c/d also dominates the radial velocity variations (Fig. 6c). It accounts for 60% up to 80% of the (remaining) variance in the three data sets.

4.2.3. Single-lined binaries with circular orbits

Another three stars turn out to be the primary component of a close binary system with a very short, circular orbit. For these objects, evidence of the binarity is also found in the Geneva photometry and in the Hipparcos photometry, where we find a variability with twice the orbital frequency. The variations are therefore typical for ellipsoidal variable stars.

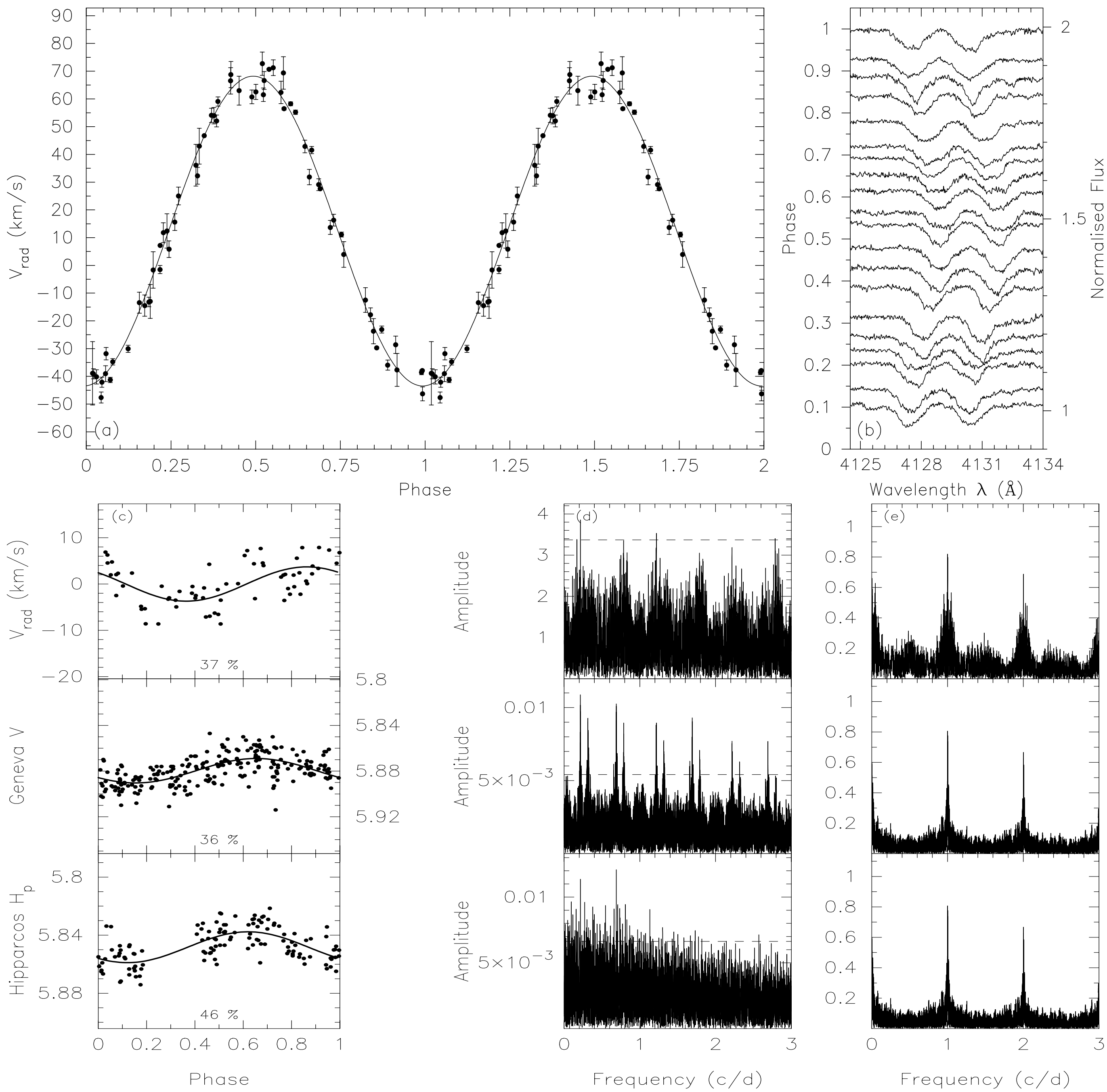

Fig. 7. Same as Fig. 2, but for HD92287.

4.2.3.1. HD92287 - HR4173 - HIC52043

HD92287 ($m_V = 5.91$, SpT B3IV) was first mentioned by Rufener & Bartholdi (1982) in the "List of variable, microvariable or suspected variable stars". Waelkens & Rufener (1985) monitored this star photometrically and found the same frequency, $\nu = 0.6812$ c/d in data of two different seasons, but with a small amplitude and much additional noise. Therefore, this star was not accepted as an SPB at that time and was omitted from their target list.

A quick look at the line profiles of the SiII-doublet shown on Fig. 7b is already sufficient to conclude that HD92287 is a spectroscopic binary. We find a standard deviation of 40 km/s for the radial velocity, which is far too large to be explained by pulsation only. Preliminary solutions for the orbital elements resulted in a slightly eccentric orbit with $e = 0.031$, but after applying the Lucy & Sweeney test (1971), we conclude that we are dealing with circular orbit with a very short period, $P_{\rm orb} = 2\overset{\rm d}{.}90457 \pm 0\overset{\rm d}{.}00007$. The final orbital elements are given in Table 8 and a phase plot of the radial velocity measurements

Table 5. The orbital parameters for HD24587.

P (d)	=	459	$\pm$	4
v_γ (km/s)	=	20.5	$\pm$	0.2
$t(\tau)$ (HJD)	=	2450954	$\pm$	7
e	=	0.18	$\pm$	0.02
ω (°)	=	106	$\pm$	5
K (km/s)	=	21.7	$\pm$	0.4
$a \sin i$ (A.U.)	=	0.902		
$f(m)$ ($M_\odot$)	=	0.465		
rms (km/s)	=	1.301		

Table 6. The orbital parameters for HD74560.

P (d)	=	8.378	$\pm$	0.001
v_γ (km/s)	=	15.6	$\pm$	0.2
$t(\tau)$ (HJD)	=	2450741.3	$\pm$	0.2
e	=	0.24	$\pm$	0.04
ω (°)	=	93	$\pm$	9
K (km/s)	=	8.0	$\pm$	0.3
$a \sin i$ (A.U.)	=	0.006		
$f(m)$ ($M_\odot$)	=	0.001		
rms (km/s)	=	1.972		

Table 7. The orbital parameters for HD177863.

P (d)	=	11.9154	$\pm$	0.0009
v_γ (km/s)	=	-18.3	$\pm$	0.4
$t(\tau)$ (HJD)	=	2450155.78	$\pm$	0.03
e	=	0.603	$\pm$	0.007
ω (°)	=	182	$\pm$	1
K (km/s)	=	42.5	$\pm$	0.6
$a \sin i$ (A.U.)	=	0.037		
$f(m)$ ($M_\odot$)	=	0.048		
rms (km/s)	=	1.745		

Table 8. The orbital parameters for HD92287.

P (d)	=	2.90457	$\pm$	0.00007
v_γ (km/s)	=	12.7	$\pm$	0.4
$t(\tau)$ (HJD)	=	2450512.095	$\pm$	0.005
e	=	0.0		
ω (°)	=	186	$\pm$	18
K (km/s)	=	55.2	$\pm$	0.5
$a \sin i$ (A.U.)	=	0.015		
$f(m)$ ($M_\odot$)	=	0.051		
rms (km/s)	=	2.585		

is given on Fig. 7a. The dominant period in the Hipparcos photometry and the Geneva photometry is half the orbital period. On Fig. 8, we show the photometric measurements folded with the orbital period as found in these measurements. The signal is close to sinusoidal. This kind of variation in our photometric data is typical for ellipsoidal variable stars. They are due to the non-spherical shape of the components in a non-eclipsing binary and to the contribution of reflection effects.

After prewhitening with the orbit, $\nu_1 = 0.2148$ c/d is found as first frequency of pulsation in the radial velocities. In the phase diagrams of Fig. 7c, the original Geneva V and Hipparcos H_p measurements are folded with this period. Also the Scargle periodogram of the original photometric data is shown there. It is easily seen that both the "orbital" signal and the "pulsational" signal are prominently present. Indeed, in the Hipparcos photometry, the "orbital" peak is slightly higher than the "pulsational" peak, while in the Geneva photometry it is vice versa. In both cases, both peaks are well above the $p_o = 0.01$ level.

We conclude that HD92287 is an ellipsoidal variable star with a pulsating component. Since the observed orbital period is of the same order of magnitude as the period of pulsation, this object is extremely interesting in order to search for possible resonances between pulsational behaviour and orbital motion.

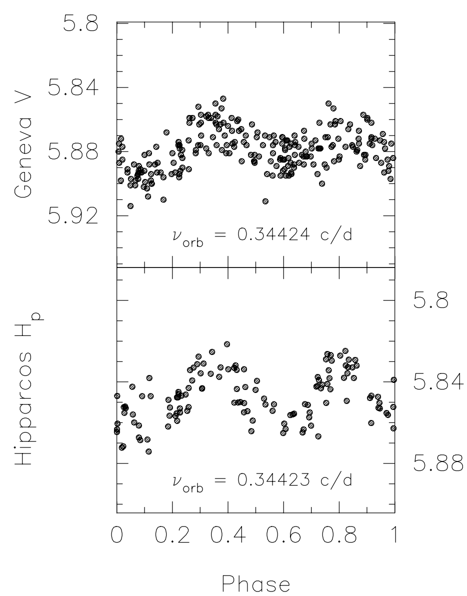

Fig. 8. A phase diagram for the orbital frequency as found in the Geneva photometry (top) and in the Hipparcos photometry (bottom) for HD92287.

4.2.3.2. HD69144 - HR3244 - HIC40285

HD69144 ($m_V = 5.10$, SpT B2.5IV) is a known visual binary with a late type companion of spectral type K5V (Lindroos 1985). The two stars have a separation of 35" and are not physically bound. Lindroos (1985) already marked HD69144 as a spectroscopic binary, but no orbital parameters are found yet.

With our spectroscopic data, we are able to determine a circular orbit with a short period of $P_{\rm orb} = 4\overset{\rm d}{.}82306 \pm 0\overset{\rm d}{.}00004$. All the orbital parameters can be found in Table 9 and a phase diagram is given on Fig. 9a. The photometric data is dominated by twice the orbital frequency, as shown on Fig. 9c. According to the SIMBAD astronomical database, this star is an eclipsing binary of the β Lyrae type, although we find equal depths for the primary and secondary minima, which is more typical for

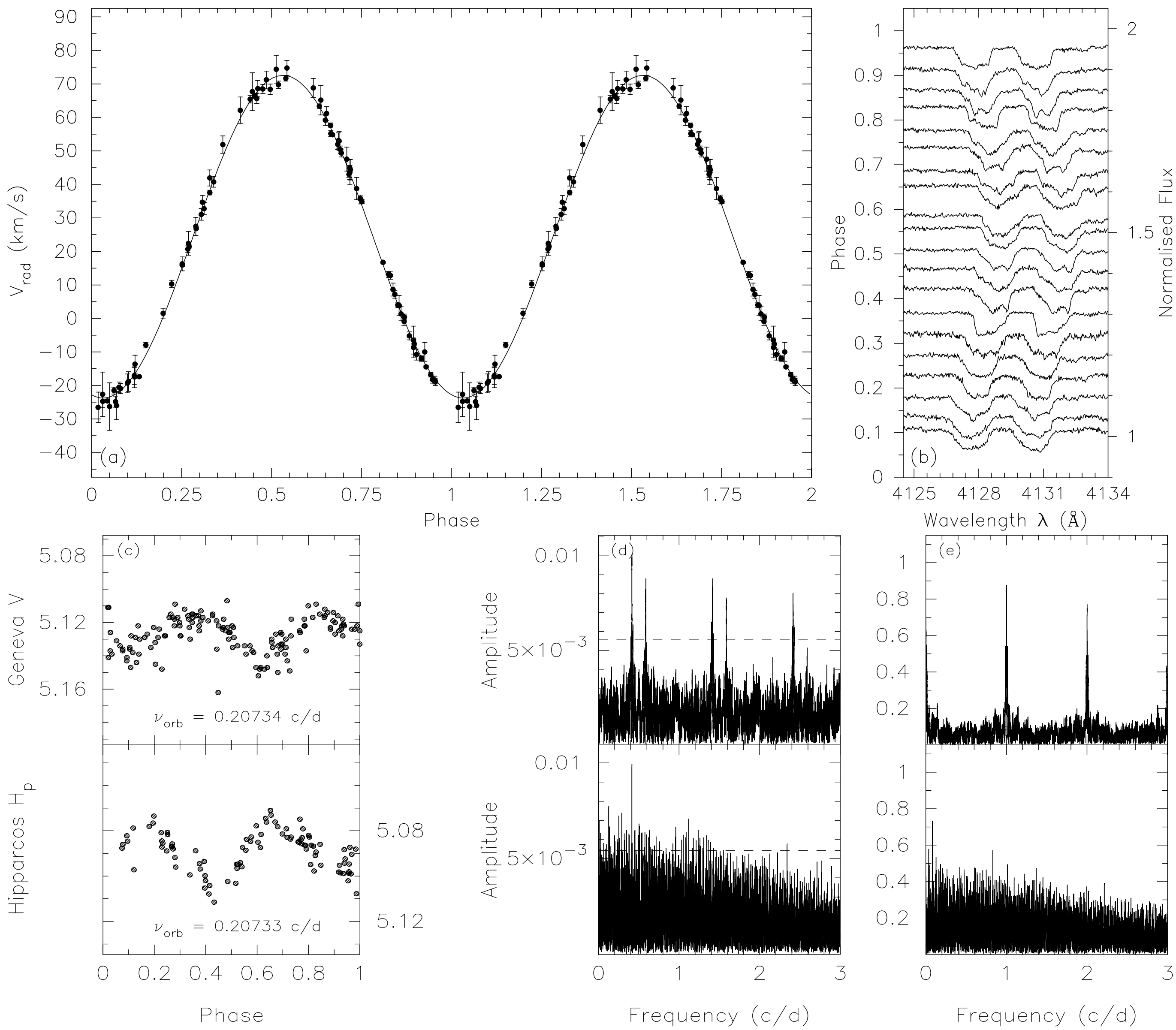

Fig. 9. a,b Same as Fig. 2, but for HD69144. **c** Same as Fig. 8, but for HD69144. **d,e** Same as Fig. 2, but for HD69144.

Table 9. The orbital parameters for HD69144.

P (d)	=	4.82306	$\pm$	0.00004
v_γ (km/s)	=	24.4	$\pm$	0.1
$t(\tau)$ (HJD)	=	2450199.996	$\pm$	0.003
e	=	0.0		
ω (°)	=	348	$\pm$	10
K (km/s)	=	48.1	$\pm$	0.2
$a \sin i$ (A.U.)	=	0.021		
$f(m)$ ($M_\odot$)	=	0.056		
rms (km/s)	=	0.938		

eclipsing binaries of the W Ursae Majoris type (e.g. Heintz 1978). We find that HD69144 is an ellipsoidal variable star.

The spectra were shifted to remove the orbital motion and the residual radial velocities were calculated. In the photometric data, the orbital frequency and its first harmonic were prewhitened as an attempt to remove the orbital variations. We were not able yet to determine a first intrinsic frequency for this star, nor in the residual radial velocities, nor in the residual photometric data. The highest peaks in the Scargle periodograms barely reach the $p_o = 0.01$ level, and the corresponding phase diagrams are not very convincing. Moreover, the Scargle periodograms of the velocities of the two separate SiII-lines look different. On the other hand, the line profiles shown on Fig. 9b are clearly asymmetric and give evidence of the presence of moving subfeatures, which points toward the presence of a high-degree pulsation mode. It may be very well possible that this star has a short-period p-mode that is very hard to find with our

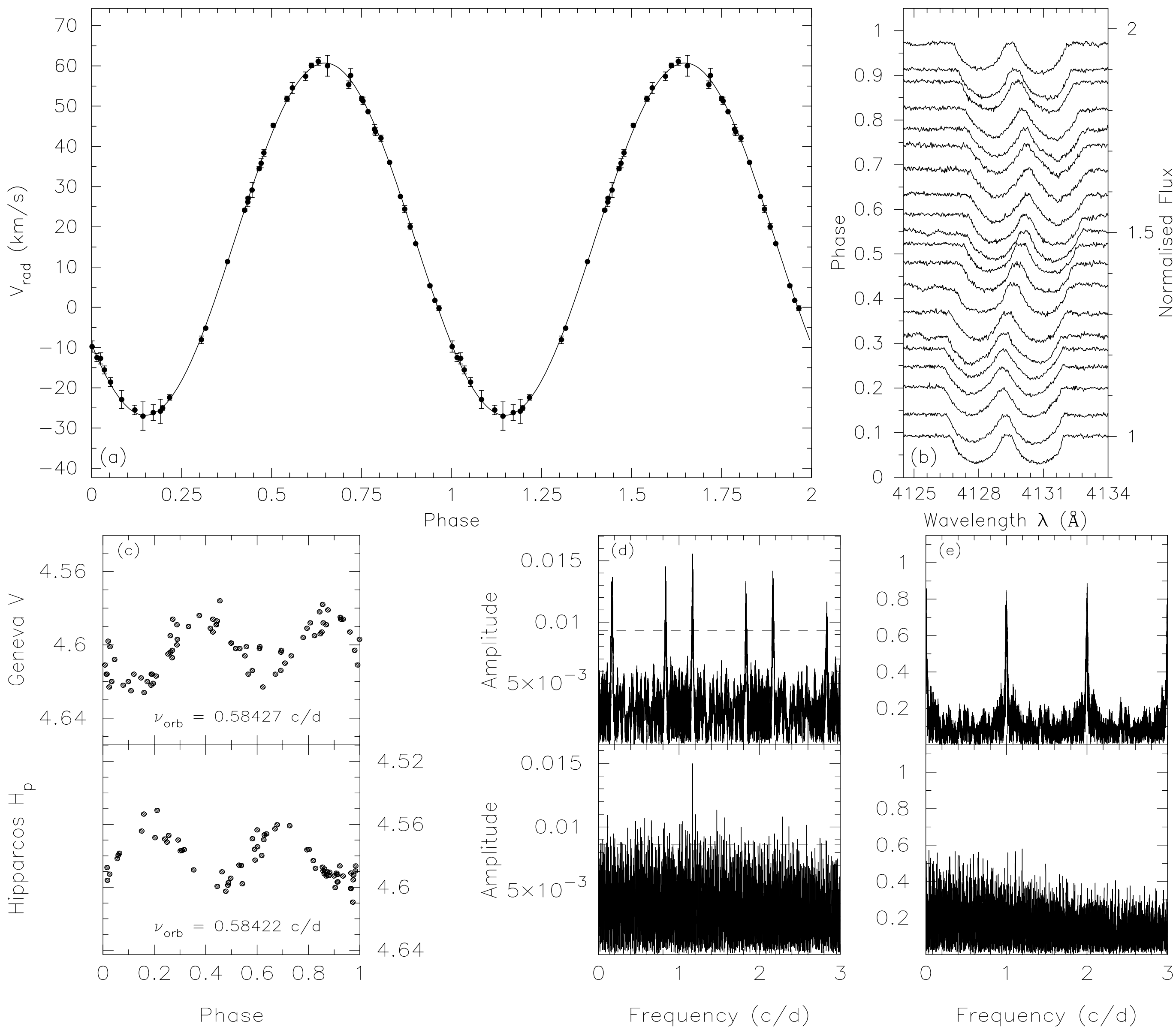

Fig. 10. a,b Same as Fig. 2, but for HD169978. **c** Same as Fig. 8, but for HD169978. **d,e** Same as Fig. 2, but for HD169978.

Table 10. The orbital parameters for HD169978.

P (d)	=	1.711529	$\pm$	0.000005
v_γ (km/s)	=	16.95	$\pm$	0.07
$t(\tau)$ (HJD)	=	2450276.5502	$\pm$	0.0007
e	=	0.0		
ω (°)	=	127	$\pm$	12
K (km/s)	=	43.8	$\pm$	0.1
$a \sin i$ (A.U.)	=	0.007		
$f(m)$ ($M_\odot$)	=	0.015		
rms (km/s)	=	0.405		

time-sampling. We plan a detailed follow-up campaign on this object.

4.2.3.3. HD169978 - HR6916 - HIC90797

Little is reported about HD169978 ($m_V = 4.64$, SpT B7.5III) in the literature. With our spectroscopic data, it is easily shown that we are dealing with a single-lined spectroscopic binary with an ultra-short circular orbit of $P_{\rm orb} = 1\overset{\rm d}{.}711529 \pm 0\overset{\rm d}{.}000005$. All the orbital parameters of this system are given in Table 10, and a phase diagram is shown on Fig. 10a. The orbital period of this system is the shortest found in our sample. The components should be very close to each other, so the tidal effects are certainly important. Indeed, we again find evidence for a deformation of the stellar surface, since the photometric measurements are clearly dominated by (twice) the orbital frequency, as can be seen on Fig. 10c.

A search for a first intrinsic frequency in the three residual data sets leads to similar results as for HD69144. Only this time,

Table 11. Overview of the dominant frequency ν_1 in the different data sets for every binary Slowly Pulsating B-star in our sample. A_1 and ϕ_1 denote respectively the corresponding amplitude and phase of the best theoretical approximation of the measurements with a model of the form $A_1 sin[2\pi(\nu_1 t + \phi_1)]$, with t = HJD - 2400000.

Star	ν_1	Data Set	A_1	ϕ_1
HD123515	0.68528c/d	Spectra	(4.34±0.44) km/s	0.477±0.016
		Geneva V	(17.5±0.8) mmag	0.244±0.007
		Hipparcos	(21.6±1.6) mmag	0.188±0.012
HD140873	1.1516c/d	Spectra	(4.03±0.46) km/s	0.769±0.019
		Geneva V	(15.9±1.7) mmag	0.469±0.016
		Hipparcos	(16.0±1.3) mmag	0.440±0.012
HD24587	1.1570c/d	Spectra	(2.07±0.23) km/s	0.850±0.017
		Geneva V	(7.2±0.9) mmag	0.550±0.020
		Hipparcos	(7.9±0.7) mmag	0.561±0.015
HD74560	0.64472c/d	Spectra	(3.25±0.27) km/s	0.390±0.013
		Geneva V	(14.7±0.5) mmag	0.036±0.005
		Hipparcos	(14.7±1.2) mmag	0.008±0.013
HD177863	0.84060c/d	Spectra	(3.81±0.47) km/s	0.682±0.017
		Geneva V	(16.9±0.5) mmag	0.357±0.004
		Hipparcos	(20.7±1.4) mmag	0.370±0.011
HD92287	0.2148c/d	Spectra	(3.70±0.62) km/s	0.058±0.029
		Geneva V	(10.7±0.9) mmag	0.767±0.014
		Hipparcos	(10.6±1.1) mmag	0.802±0.019

the highest peaks in the Scargle periodograms do not even reach the $p_o = 0.01$ level. Some of the line profiles of HD169978 are shown on Fig. 10b. Contrary to HD69144, they do **not** show clear asymmetries, nor moving subfeatures. We therefore conclude that this ellipsoidal variable was misclassified as an SPB.

5. Summary

Two years of intensive photometric and spectroscopic monitoring have revealed the binary nature of (at least) 8 out of 17 target stars. We have found a large variety in the obtained orbits.

Two of the systems, HD123515 and HD140873, are double-lined spectroscopic binaries. On Fig. 1, we clearly see several absorption lines for both the primary and the secondary components, including the SiII-doublet centered at 4130 Å. In both cases, the absorption lines of the secondary are much weaker than the absorption lines of the primary. The HeI-line near 4120 Å appears in the spectra of B type stars or earlier. It is present for the primary components of HD123515 and HD140873, which are classified as respectively a B8III and a B9IV star. For the secondary components, we do not see this He-line, so they are later-type stars. In the spectra of all of the other binaries in our sample, we find no direct signature of the secondary component.

More than half of our binary systems have an eccentric orbit, with an eccentricity between $e \simeq 0.18$ (HD24587) and $e \simeq 0.73$ (HD140873). The orbital periods of the eccentric binaries are longer than those with circular orbits. The orbital periods in our sample range from $P_{\rm orb} \simeq 459$ days (HD24587) down to $P_{\rm orb} \simeq 1.71$ days (HD169978). All three circular binaries (HD92287, HD69144, HD169978) have a very short orbital period of a few days. Due to the tidal force, their surface is no longer spherical symmetric. Hence, (close to) sinusoidal variations with twice the orbital frequency are observed in their photometric measurements. These stars are now classified as ellipsoidal variables.

We here also emphasize that the two SPBs HD53921 and HD55522, which were already described by Aerts et al. (1999), might also be spectroscopic binaries. They have asymmetric line profiles, which points towards pulsation. Their main frequency in the Geneva and Hipparcos photometry coincide. They are respectively 0.6054 c/d and 0.3664 c/d (Aerts et al. 1999). In their radial velocities, very small frequencies due to minor changes in gamma velocity are found. Either these changes are due to beating-effects, either we are dealing with long-period spectroscopic binaries with a very small amplitude. More data with a longer time base is needed to clear this out.

All of the binary systems were classified by Waelkens et al. (1998) as candidate SPBs. After removing the orbit, we find the same first frequency in the radial velocities as in the gathered photometric measurements. Only for HD69144 and HD169978 we did not yet succeed in deriving an intrinsic period, although HD69144 has prominent LPVs. HD169978 should be removed from the candidate SPB list given by Waelkens et al. (1998).

In Table 11, we give an overview of the dominant frequency ν_1 in the different data sets for every confirmed binary SPB in our sample. A_1 and ϕ_1 denote respectively the corresponding amplitude and phase of the best theoretical approximation of the measurements with a model of the form $A_1 sin[2\pi(\nu_1 t + \phi_1)]$, with t = HJD - 2400000.

The HWHM of the central peak in the window function indicates the frequency resolution in the different data sets. Hence, it is a good estimation of the error of ν_1. These values depend mainly on the total time-span of the measurements and to a smaller extent to the number of measurements. For the spectroscopic measurements, the Hipparcos photometry and the Geneva photometry, we find respectively an averaged value of 0.0009 c/d, 0.0015 c/d and 0.0007 c/d. For the previously known SPBs, the uncertainty of the frequency in the Geneva photometry is by far smaller compared to the one obtained for the new SPBs (respectively 0.00009 c/d and 0.003 c/d). ν_1 is therefore given with 5 decimals for the previously known SPBs, and only with 4 decimals for the others.

All the first intrinsic frequencies ν_1 are typical for SPBs. The amplitude A_1 of the corresponding variations in radial velocity ranges between 2 and 5 km/s. In the photometric measurements, the corresponding amplitude reaches 7 up to 20 mmag. The amplitude of the first frequency is of course influenced by the other pulsation frequencies, which were not taken into account yet.

For all cases, the phases ϕ_1 of the Geneva and Hipparcos photometry correspond well. The difference between the spectroscopic phase and the average photometric phase ranges from $\simeq$ 0.26 up to $\simeq$ 0.37 for respectively HD123515 and HD74560.

6. Discussion and future plans

The main goal of our long-term project is to study both the LPVs and the photometric variations of a sample of bright southern SPBs. Most of our targets were found as a by-product of the Hipparcos-mission, since their photometric variability was only discovered by analysing their Hipparcos light curves. After two years of monitoring (candidate) B-type pulsators, a handfull of eccentric binaries with a short orbital period and a pulsating component is found.

Recently, Harmanec et al. (1997) started the SEFONO project: a spectroscopic search for forced nonradial oscillations. They started to monitor known binaries with eccentric orbits and orbital periods shorter than some 30 days, which have early-type primaries. In this way, the pulsational character of some of the components is discovered after the detection of LPVs. Our study can be seen as complementary to the SEFONO project, with a completely different starting point.

In the past, many other authors have tried to find evidence for forced oscillations in binaries. Spica (α Vir, SpT B1III-IV) is one of the first discovered double-lined spectroscopic binaries. It consists of two B stars revolving in an orbit with moderately high eccentricity of about 0.15 and with an orbital period of approximately $4\overset{\mathrm{d}}{.}01$. In two important papers, Smith (1985a, b) reports about high-resolution Reticon observations of the SiIII-triplet at 4552, 4567, 4574 Å. The pattern of moving bumps seen in these spectra can be accounted for by four nonradial pulsation modes. Two of them are related to the orbital motion: (1) a retrograde, tesseral, “quasi-toroidal” mode with a period equal to about 1/12 of the orbital period; (2) an $l = 2$, retrograde, sectoral mode with a period equal to half the orbital period. The latter arises from the tidal distortion of the primary and is the spectroscopic equivalent of the ellipsoidal light variabibity. In our sample, we find three new ellipsoidal variables. For two of them, we see clear LPVs, but no relation with the orbital motion is found (yet).

Mimosa (β Cru, SpT B0.5III) was already a suspect spectroscopic binary for a long time with a suggested orbital period of the order of years. Only recently, Aerts et al. (1998) derived sufficiently accurate orbital parameters. They found an eccentric orbit ($e = 0.38$) with an orbital period of 5.00 years. The system is seen at low inclination and the secondary is a B2V star. In their numerous high-resolution CAT spectra spread over more than 11 years, they only found clear evidence for the presence of the photometric frequency $f_1 = 5.2305468$ c/d (Cuypers 1983) in two observation-runs which are about one orbital period apart. The variations of the spectra near periastron are dominated by $f_3 = 5.472165$ c/d. At all other orbital phases, they find a spurious frequency resulting from a combination of f_1 and $f_2 = 5.958666$ c/d. These findings suggest that the complicated pattern of pulsation frequencies is affected by tidal forces, but their data is not well enough spread in time to make definite conclusions. In our sample, we find 5 binaries with an eccentric orbit. Especially for HD140873 and HD177863, we find an extremely high eccentricity of respectively $e \simeq 0.73$ and $e \simeq 0.60$. Therefore, these systems are very promising candidates to search for frequency changes in function of the orbital phase. The time sampling of our current data set is not suited to do this.

Now that the spectra of our binary targets are shifted to the velocity frame relative to the primary component, we are able to start a thorough analysis of the intrinsic variability for both our binary and single targets. It is our final aim to disentangle the frequency spectrum of the SPBs and to identify the modes. If we succeed in doing so, we will have a better view on the selection of the pulsation modes in this class of g-mode pulsators. Moreover, a well-determined frequency spectrum of identified modes is a fruitful starting point for a successful application of seismological techniques.

Acknowledgements. We are grateful to the Observatoire de Genève and to the European Southern Observatory for the generous awarding of telescope time to make this long-term project possible. P. De Cat acknowledges the financial support of the Belgian Fund for Joint Basic Research under Research Project No. G.0398.98. G. Meeus appreciates the support by the “Flemish Institute for fostering scientific and technological research in the industry” (IWT) under grant IWT/SB/951067. This research has made use of the SIMBAD astronomical database operated at the CDS in Strasbourg, France.

References

Aerts C., De Pauw M., Waelkens C., 1992, A&A 266, 294
Aerts C., De Cat P., Cuypers J., et al., 1998, A&A 329, 137
Aerts C., De Cat P., Peeters E., et al., 1999, A&A 343, 872
Barker E.S., Evans D.S., Laing J.D., 1967, Royal Obs. Bull. 130, 355
Bertiau F.C., Grobben J., 1969, Ric. Astron. Vatican Obs. 8, n. 1
Burki G., Rufener F., Burnet M., et al., 1995, A&A 112, 383

Cuypers J., 1983, A&A 127, 186
Harmanec P., Hadrava P., Yang S., et al., 1997, A&A 319, 867
Heintz W.D., 1978, In: McCormac B.M., Athay R.G., Broecker W.S., et al. (eds.) Double stars. D. Reidel Publishing Company, p. 92
Lindroos K.P., 1985, A&AS 60, 183
Lucy L.B., Sweeney M.A., 1971, ApJ 76, 544
Moore C.E., 1945, A multiplet table of astrophysical interest (revised edition). Contrib. Princeton Univ. no. 20, New Jersey
Petrie R.M., Phibbs P., 1949, Publ. Dominion Astrophys. Obs. 8, 225
Roberts D.H., Lehár J., Dreher J.W., 1987, AJ 93, 968
Rufener F., Bartholdi P., 1982, A&AS 48, 503
Scargle J.D., 1982, ApJ 263, 835
Smith M.A., 1985a, ApJ 297, 206
Smith M.A., 1985b, ApJ 297, 224
Stellingwerf R.F., 1978, ApJ 224, 953
Waelkens C., Rufener, F., 1985, A&A 152, 6
Waelkens C., 1987, In: Cox A.N., Sparks W.M., Starrfield S.G. (eds.) Stellar Pulsation. A memorial to J.P. Cox. Lecture Notes in Physics, Springer-Verlag, p. 75
Waelkens C., 1991, A&A 246, 468
Waelkens C., Aerts C., Kestens E., et al., 1998, A&A 330, 215