

Discovery of the spectroscopic binary nature of six southern Cepheids

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ABSTRACT

We present the analysis of photometric and spectroscopic data of six bright Galactic Cepheids: GH Carinae, V419 Centauri, V898 Centauri, AD Puppis, AY Sagittarii, and ST Velorum. Based on new radial velocity data (in some cases supplemented with earlier data available in the literature), these Cepheids have been found to be members in spectroscopic binary systems. V898 Cen turned out to have one of the largest orbital radial velocity amplitude ($> 40 \text{ km s}^{-1}$) among the known binary Cepheids. The data are insufficient to determine the orbital periods nor other orbital elements for these new spectroscopic binaries.

These discoveries corroborate the statement on the high frequency of occurrence of binaries among the classical Cepheids, a fact to be taken into account when calibrating the period-luminosity relationship for Cepheids.

We have also compiled all available photometric data that revealed that the pulsation period of AD Pup, the longest period Cepheid in this sample, is continuously increasing with $\Delta P = 0.004567 \text{ d/century}$, likely to be caused by stellar evolution. The wave-like pattern superimposed on the parabolic $O - C$ graph of AD Pup may well be caused by the light-time effect in the binary system. ST Vel also pulsates with a continuously increasing period. The other four Cepheids are characterised with stable pulsation periods in the last half century.

Key words: stars: variables: Cepheids – binaries: spectroscopic

1 INTRODUCTION

Classical Cepheid variable stars are primary distance indicators because owing to the famous period-luminosity ($P-L$) relationship they rank among standard candles in establishing the cosmic distance scale.

Companions to Cepheids, however, complicate the situation. The contribution of the secondary star to the observed brightness has to be taken into account when involving any particular Cepheid in the calibration of the $P-L$ relationship. Binaries among Cepheids are not rare at all: their frequency exceeds 50 per cent for the brightest Cepheids, while among the fainter Cepheids an observational selection effect encumbers revealing binarity (Szabados 2003a).

It is essential to study Cepheids individually from the point of view of binarity before involving them in any calibration procedure (of e.g. $P-L$ or period-radius relationship). This attitude is especially important if Cepheid-related relationships are calibrated us-

ing a small sample. However, a deep observational analysis of individual Cepheids can only be performed in the case of their Galactic representatives. When dealing with extragalactic Cepheids, unrevealed binarity is one of the factors that contribute to the dispersion of the $P-L$ relationship. A detailed list of physical factors responsible for the finite width of the $P-L$ relationship around the ridge line approximation is given by Szabados & Klagyivik (2012).

The orbital period of binaries involving a supergiant Cepheid component cannot be shorter than about a year. Spectroscopic binaries involving a Cepheid component with orbital periods longer than a decade are also known (see the on-line data base on binaries among Galactic Cepheids: <http://www.konkoly.hu/CEP/orbit.html>). Therefore, a first-epoch radial velocity curve, especially based on data obtained in a single observational season, is usually insufficient for pointing out an orbital effect superimposed on the radial velocity changes due to pulsation.

Table 1. Basic data of the programme stars and the number of spectra

Star	$\langle V \rangle$ (m)	P (d)	Mode of pulsation	No. of obs.
GH Car	9.18	5.725532	first overtone	27+43
V419 Cen	8.19	5.507123	first overtone	26
V898 Cen	8.00	3.527310	first overtone	33+4
AD Pup	9.91	13.596919	fundamental	33
AY Sgr	10.55	6.569667	fundamental	22
ST Vel	9.73	5.858316	fundamental	27

In the case of pulsating variables, like Cepheids, spectroscopic binarity (SB) manifests itself in a periodic variation of the γ -velocity (i.e., the radial velocity of the mass centre of the Cepheid). In practice, the orbital radial velocity variation of the Cepheid component is superimposed on the radial velocity variations of pulsational origin. To separate the orbital and pulsational effects, knowledge of the accurate pulsation period is essential, especially when comparing radial velocity data obtained at widely differing epochs. Therefore, the pulsation period and its variations have been determined with the method of the $O - C$ diagram (Sterken 2005) for each target Cepheid. Use of the accurate pulsation period obtained from the photometric data is a guarantee for the correct phase matching of the (usually less precise) radial velocity data.

In this paper we point out spectroscopic binarity of six bright Galactic Cepheids by analysing radial velocity data. The structure of this paper is as follows. The new observations and the equipments utilized are described in Section 2. Section 3 are devoted to the results on the six new SB Cepheids: GH Carinae, V419 Centauri, V898 Centauri, AD Puppis, AY Sagittarii, and ST Velorum, respectively. Basic information on these Cepheids are found in Table 1. Finally, Section 4 contains our conclusions.

2 NEW OBSERVATIONS

2.1 Spectra from Siding Spring Observatory

We performed a radial velocity (RV) survey of Cepheids with the 2.3 m ANU telescope located at Siding Spring Observatory, Australia. The main aim of the project was to detect Cepheids in binary systems by measuring changes in the mean values of their RV curve which can be interpreted as the orbital motion of the Cepheid around the center of mass in a binary system (change of γ -velocity). The target list was compiled to include Cepheids with single-epoch radial velocity phase curve or without any published radial velocity data. Several Cepheids suspected members in spectroscopic binaries were also put on the target list. On 64 nights between October 2004 and March 2006 we monitored 40 Cepheids with pulsation periods between 2 and 30 days. (V898 Cen was observed in July 2009, too).

Medium-resolution spectra were taken with the Double Beam Spectrograph using the 1200 mm^{-1} gratings in both arms of the spectrograph. The projected slit width was $2''$ on the sky, which was about the median seeing during our observations. The spectra covered the wavelength ranges 4200–5200 Å in the blue arm and 5700–6700 Å in the red arm. The dispersion was 0.55 Å px^{-1} , leading to a nominal resolution of about 1 Å .

All spectra were reduced with standard tasks in IRAF¹. Re-

duction consisted of bias and flat field corrections, aperture extraction, wavelength calibration, and continuum normalisation. We checked the consistency of wavelength calibrations via the constant positions of strong telluric features, which proved the stability of the system. Radial velocities were determined only for the red arm data with the task *fxcor*, applying the cross-correlation method using a well-matching theoretical template spectrum from the extensive spectral library of Munari et al. (2005). Then, we made barycentric corrections to every single RV value. This method resulted in a $1\text{-}2 \text{ km s}^{-1}$ uncertainty in the individual radial velocities, while further tests have shown that our absolute velocity frame was stable to within $\pm 2\text{-}3 \text{ km s}^{-1}$. This level of precision is sufficient to detect a number of Cepheid companions, as they can often cause γ -velocity changes well above 10 km s^{-1} .

2.2 FEROS observations in ESO

V898 Centauri was observed on four consecutive nights in April, 2011, using the *FEROS* (Fiber-fed Extended Range Optical Spectrograph) instrument on the MPG/ESO 2.2 m telescope in La Silla Observatory, Chile (see Table 10). The *FEROS* has a total wavelength coverage of 356–920 nm with a resolving power of $R = 48\,000$ (Kaufer et al. 1999, 2000). Two fibres, with entrance aperture of $2''7$, simultaneously recorded star light and sky background. The detector is a back-illuminated CCD with 2948×4096 pixels of $15 \mu\text{m}$ size. Basic data reduction was performed using a pipeline package for reductions (DRS), in MIDAS environment. The pipeline performs the subtraction of bias and scattered light in the CCD, orders extraction, flat-fielding and wavelength calibration with a ThAr calibration frame (the calibration measurements were performed at the beginning of each night, using the ThAr lamp).

After the continuum normalization of the spectra using IRAF we determined the radial velocities with the task *fxcor*, as in the case of the SSO spectra (see Sect. 2.1). The velocities were determined in the region 500–600 nm where a number of metallic lines are present and hydrogen lines are lacking. We made barycentric corrections to each RV value with the task *rvcorrect*. The estimated uncertainty of the radial velocities is 0.05 km s^{-1} .

2.3 CORALIE observations from La Silla

GH Car was among the targets during multiple observing campaigns between April 2011 and May 2012 using the fiber-fed high-resolution ($R \sim 60000$) echelle spectrograph *CORALIE* mounted at the Swiss 1.2 m Euler telescope at ESO La Silla Observatory, Chile. The instrument’s design is described in Queloz et al. (2001); recent instrumental updates are found in Wilson et al. (2008).

The spectra are reduced by the efficient online reduction pipeline that performs bias correction, cosmetics removal, and flat-fielding using tungsten lamps. ThAr lamps are used for the wavelength calibration. The reduction pipeline directly determines the RV through cross-correlation (Baranne et al. 1996) using a mask that resembles a G2 spectral type. The RV stability of the instrument is excellent and for non-pulsating stars the RV precision is limited by photon-noise, see e.g., Pepe et al. (2002). However, the precision achieved for Cepheids is lower due to line asymmetries.

which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

¹ IRAF is distributed by the National Optical Astronomy Observatories,

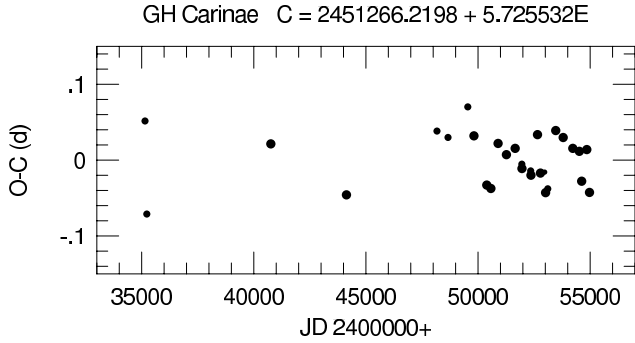


Figure 1. $O - C$ diagram of GH Car based on the values listed in Table 2. The pulsation period of GH Car is constant

We estimate a typical precision of $\sim 0.1 \text{ km s}^{-1}$ (including systematics due to pulsation) per data point for our data. The radial velocity data are listed in Table 4.

3 RESULTS

3.1 GH Carinae

Accurate value of the pulsation period The brightness variability of GH Car (HD 306077, $\langle V \rangle = 9.18$ mag.) was revealed by Oosterhoff (Hertzsprung 1930). This Cepheid pulsates in the first overtone mode, therefore it has a small pulsational amplitude and nearly sinusoidal light (and velocity) curve.

In the case of Cepheids pulsating with a low amplitude, the $O - C$ diagram constructed for the median brightness is more reliable than that based on the moments of photometric maxima (Derekas et al. 2012). Therefore we determined the accurate value of the pulsation period by constructing an $O - C$ diagram for the moments of median brightness (the mid-point between the faintest and the brightest states) on the ascending branch of light curve since it is this phase when the brightness variations are steepest during the whole pulsational cycle.

All published observations of GH Car covering half a century were re-analysed in a homogeneous manner to determine seasonal moments of the chosen light curve feature. The relevant data listed in Table 2 are as follows:

Column 1: Heliocentric moment of the median brightness on the ascending branch;

Col. 2: Epoch number, E , as calculated from Eq. 1:

$$C = 2451266.2198 + 5.725532 \times E \quad (1)$$

$$\pm 0.0038 \pm 0.00004$$

(this ephemeris has been obtained by the weighted least squares fit to the tabulated $O - C$ differences);

Col. 3: the corresponding $O - C$ value as calculated from Eq. 1;

Col. 4: weight assigned to the $O - C$ value (1, 2, or 3 depending on the quality of the light curve leading to the given difference);

Col. 5: reference to the origin of data, preceded by the name of the observer if different from the author(s) cited.

The plot of $O - C$ values shown in Fig. 1 can be approximated with a constant period. The scatter of the points in the figure reflects the observational error and uncertainties in the analysis of the data.

Binarity of GH Car There are no published radial velocity data for this bright Cepheid. The phase diagram of our RV observations is plotted in Fig. 2. The observational data have been folded on the

Table 2. $O - C$ values of GH Carinae (see the description in Sect. 3.1)

JD _⊙ 2400000 +	E	$O - C$	W	Data source
35148.8988	-2815	+0.0516	2	Walraven et al. (1958)
35228.9336	-2801	-0.0711	2	Irwin (1961)
40759.8900	-1835	+0.0214	3	Pel (1976)
44132.1611	-1246	-0.0458	3	Berdnikov (2008)
48168.7453	-541	+0.0383	2	<i>Hipparcos</i> (ESA 1997)
48661.1326	-455	+0.0299	2	<i>Hipparcos</i> (ESA 1997)
49542.9049	-301	+0.0702	2	Berdnikov (2008)
49817.6922	-253	+0.0320	3	Berdnikov (2008)
50390.1805	-153	-0.0329	3	Berdnikov (2008)
50573.3930	-121	-0.0374	3	Berdnikov (2008)
50894.0822	-65	+0.0220	3	Berdnikov (2008)
51266.2270	0	+0.0072	3	Berdnikov (2008)
51655.5715	68	+0.0155	3	Berdnikov (2008)
51953.2783	120	-0.0053	2	ASAS (Pojmanski 2002)
51958.9981	121	-0.0111	3	Berdnikov (2008)
52348.3311	189	-0.0142	2	ASAS (Pojmanski 2002)
52359.7765	191	-0.0199	3	Berdnikov (2008)
52651.8321	242	+0.0336	3	Berdnikov (2008)
52783.4687	265	-0.0171	3	ASAS (Pojmanski 2002)
52972.4125	298	-0.0158	1	<i>INTEGRAL</i> OMC
53012.4642	305	-0.0429	3	Berdnikov (2008)
53109.8033	322	-0.0378	2	ASAS (Pojmanski 2002)
53464.8631	384	+0.0390	3	ASAS (Pojmanski 2002)
53796.9347	442	+0.0298	3	ASAS (Pojmanski 2002)
54226.3353	517	+0.0155	3	ASAS (Pojmanski 2002)
54518.3336	568	+0.0116	3	ASAS (Pojmanski 2002)
54621.3538	586	-0.0278	3	ASAS (Pojmanski 2002)
54850.4167	626	+0.0139	3	ASAS (Pojmanski 2002)
54970.5964	647	-0.0426	3	ASAS (Pojmanski 2002)

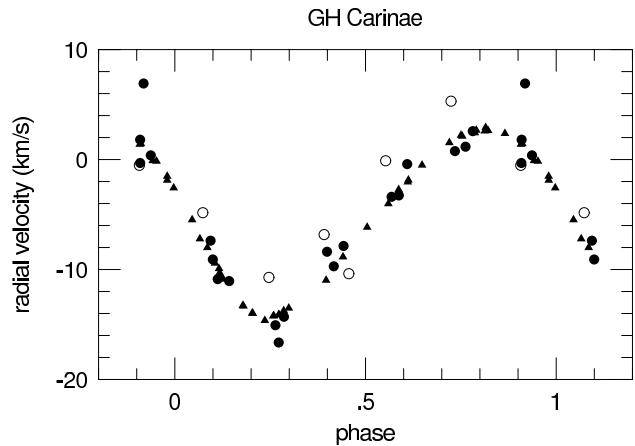


Figure 2. Radial velocity phase curve of GH Carinae. Filled circles represent data from 2004-2005, open circles denote data from 2006, while the *CORALIE* data obtained in 2011-2012 are marked as triangles

period given by the ephemeris in Eq. 1. The zero phase has been arbitrarily chosen at JD 2400000 (similarly to all phase curves in this paper). Figure 2 clearly shows a vertical shift between the mean values valid for 2004-2005 and 2006. For the first season, the γ -velocity (the mean RV averaged over a pulsational cycle) was -4.6 km s^{-1} , while one year later it became -3.5 km s^{-1} , while the *CORALIE* data result in the value of -5.3 km s^{-1} for the γ -velocity. Though the difference is small, homogeneity of the data

Table 3. New RV values of GH Carinae from the SSO spectra. This is only a portion of the full version available online only

JD _⊙ 2 400 000 +	v_{rad} (km s ⁻¹)
53364.2431	-8.4
53367.2163	6.9
53368.2542	-9.1
53369.2434	-16.6
53451.0951	-3.4

Table 4. New *CORALIE* velocities of GH Carinae. This is only a portion of the full version available online only

JD _⊙ 2 400 000 +	v_{rad} (km s ⁻¹)
55652.8343	-9.9
55653.8063	-13.7
55654.6963	-8.9
55655.6685	-2.0
55656.6753	2.4

and the identical treatment is a guarantee that the shift is not an artifact of the analysis. The individual data are listed in Tables 3–4.

Spectroscopic binarity of GH Car has to be verified by further observations.

3.2 V419 Centauri

Accurate value of the pulsation period The brightness variability of V419 Cen (HD 100148, $\langle V \rangle = 8.19$ mag.) was revealed by O’Leary & O’Connell (1937). This Cepheid also pulsates in the first overtone mode, so the $O - C$ diagram was also constructed for the moments of the median brightness on the ascending branch, similarly to the case of GH Car (see Sect. 3.1).

The $O - C$ diagram of V419 Cen based on the $O - C$ values listed in Table 5 is shown plotted in Fig. 3. The plot can be approximated by a constant period by the ephemeris for the moments of median brightness on the ascending branch:

$$C = 2\,452\,357.3949 + 5.507\,123 \times E \pm 0.0053 \pm 0.000\,005 \quad (2)$$

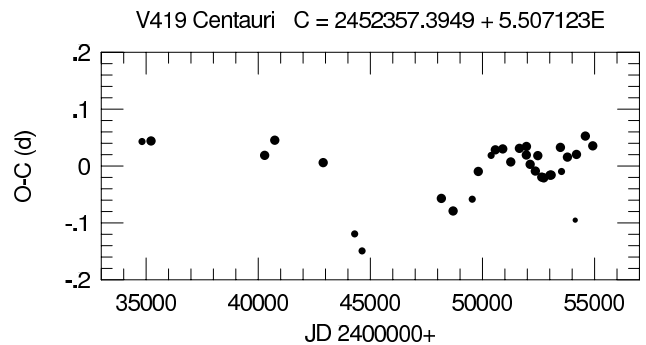
However, a parabolic pattern indicating a continuously increasing period cannot be excluded. For the proper phasing of the RV data it is important that the $O - C$ differences are about zero for each epoch when radial velocity data were obtained.

Binarity of V419 Cen All RV data (including the new ones listed in Table 6) have been folded on the accurate pulsation period taken from the ephemeris given in Eq. 2, so the different data series have been correctly phased with respect to each other. The merged RV phase curve is plotted in Fig. 4. The individual data series are denoted with different symbols: filled squares - radial velocities from 1952 by Stibbs (1955); empty triangles - data by Lloyd Evans (1980) from 1969-1970; filled and empty circles - our 2004-2005 and 2006 data, respectively.

Variability in the γ -velocity is striking. Systematic errors can be excluded. Although our 2006 data are shifted to a larger value of the γ -velocity, similarly to the case of GH Car (see Sect. 3.1), other new spectroscopic binaries and dozens of Cepheids in our sample

Table 5. $O - C$ values of V419 Centauri (see the description in Sect. 3.1)

JD _⊙ 2 400 000 +	E	$O - C$	W	Data source
34817.2512	-3185	+0.0431	2	Walraven et al. (1958)
35219.2722	-3112	+0.0441	3	Irwin (1961)
40285.8001	-2192	+0.0188	3	Stobie (1970)
40737.4108	-2110	+0.0454	3	Pel (1976)
42896.1636	-1718	+0.0060	3	Dean (1977)
44300.3547	-1463	-0.1193	2	Berdnikov (2008)
44630.7521	-1403	-0.1492	2	Eggen (1985)
48166.4174	-761	-0.0569	3	<i>Hipparcos</i> (ESA 1997)
48689.5720	-666	-0.0790	3	<i>Hipparcos</i> (ESA 1997)
49543.1967	-511	-0.0583	2	Berdnikov (2008)
49813.0946	-462	-0.0095	3	Berdnikov (2008)
50385.8636	-358	+0.0187	2	Berdnikov (2008)
50573.1155	-324	+0.0285	3	Berdnikov (2008)
50903.5445	-264	+0.0301	3	Berdnikov (2008)
51261.4846	-199	+0.0072	3	Berdnikov (2008)
51647.0071	-129	+0.0311	3	Berdnikov (2008)
51955.3943	-73	+0.0194	3	ASAS (Pojmanski 2002)
51960.9164	-72	+0.0344	3	Berdnikov (2008)
52126.0927	-42	+0.0030	3	ASAS (Pojmanski 2002)
52357.3861	0	-0.0088	3	Berdnikov (2008)
52467.5557	20	+0.0183	3	ASAS (Pojmanski 2002)
52643.7458	52	-0.0195	3	Berdnikov (2008)
52731.8585	68	-0.0208	3	ASAS (Pojmanski 2002)
53012.7265	119	-0.0160	3	Berdnikov (2008)
53062.2908	128	-0.0158	3	ASAS (Pojmanski 2002)
53475.3737	203	+0.0328	3	ASAS (Pojmanski 2002)
53524.8954	212	-0.0096	2	<i>INTEGRAL</i> OMC
53789.2626	260	+0.0157	3	ASAS (Pojmanski 2002)
54136.1005	323	-0.0951	1	<i>INTEGRAL</i> OMC
54191.2873	333	+0.0204	3	ASAS (Pojmanski 2002)
54587.8324	405	+0.0527	3	ASAS (Pojmanski 2002)
54918.2426	465	+0.0355	3	ASAS (Pojmanski 2002)

**Figure 3.** $O - C$ diagram of V419 Cen. The plot can be approximated by a constant period but a parabolic pattern indicating a continuously increasing period cannot be excluded

with non-varying γ -velocities indicate stability of the equipment and reliability of the data reduction. Another piece of evidence in favour of the intrinsic variability of the γ -velocity is that both Stibbs (1955) and Lloyd Evans (1980) used the same spectrograph during their observations.

To have a clearer picture, the γ -velocities (together with their uncertainties) are listed in Table 7 and also plotted in Fig. 5. The last two points (which are the most accurate ones), i.e., the shift between 2004-2005 and 2006 data implies an orbital period of several

Table 6. New RV values of V419 Centauri from the SSO spectra. This is only a portion of the full version available online only

JD _⊙ 2 400 000 +	v_{rad} (km s ⁻¹)
53369.2636	-1.8
53451.1179	-4.8
53452.0995	3.9
53453.1895	-1.5
53454.1215	-7.9

Table 7. γ -velocities of V419 Centauri

Mid-JD 2 400 000+	v_{γ} (km s ⁻¹)	σ (km s ⁻¹)	Data source
34129	-16.40	1.3	Stibbs (1955)
40550	-11.70	1.5	Lloyd Evans (1980)
53474	-5.53	0.3	present paper
53800	-0.96	0.5	present paper

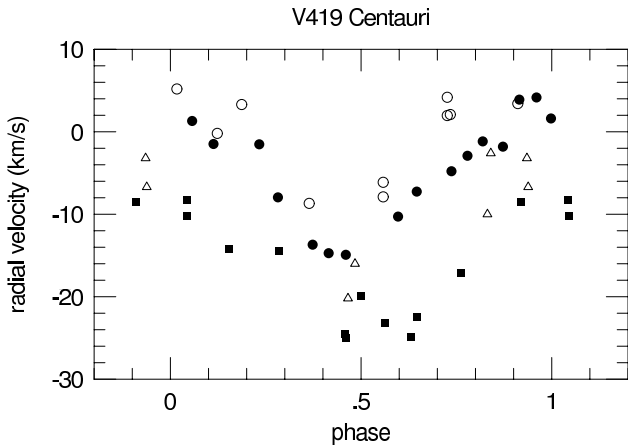
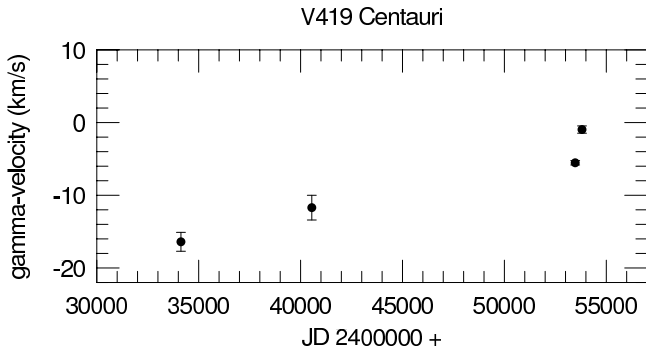

Figure 4. Merged RV phase curve of V419 Cen. There is a striking difference between the γ -velocities valid for the epoch of Stibbs' (1955) and Lloyd Evans' (1980) data (denoted as filled squares and empty triangles, respectively) and our recent data (denoted by circles, see the text)

Figure 5. Temporal shift in the γ -velocity of V419 Cen

Table 8. $O - C$ values of V898 Centauri (description of the columns is given in Sect. 3.1)

JD _⊙ 2 400 000 +	E	$O - C$	W	Data source
47955.2823	-1247	+0.0023	3	<i>Hipparcos</i> (ESA 1997)
48311.5410	-1146	+0.0027	3	<i>Hipparcos</i> (ESA 1997)
48692.4782	-1038	-0.0096	3	<i>Hipparcos</i> (ESA 1997)
51260.3772	-310	+0.0077	3	Berdnikov (2008)
51648.3705	-200	-0.0031	3	Berdnikov (2008)
51958.7588	-112	-0.0181	3	Berdnikov (2008)
52353.8561	0	+0.0205	3	Berdnikov (2008)
52650.1280	84	-0.0016	3	Berdnikov (2008)
53006.4034	185	+0.0155	3	Berdnikov (2008)
53140.4565	223	+0.0308	2	<i>INTEGRAL</i> OMC
53718.7991	387	-0.1055	1	<i>INTEGRAL</i> OMC

years instead of several decades suggested by the whole pattern of the plot.

3.3 V898 Centauri

Accurate value of the pulsation period The brightness variability of V898 Cen (HD 97317, $\langle V \rangle = 8.00$ mag.) was revealed by Strohmeier et al. (1964). This is also a low amplitude Cepheid pulsating in the first overtone mode. The first reliable photometric data were only obtained during the *Hipparcos* space astrometry mission (ESA 1997). Later on Berdnikov and his co-workers followed the photometric behaviour of V898 Cen (Berdnikov 2008).

The $O - C$ diagram of V898 Cen was constructed for the moments of median brightness on the ascending branch (see Table 8). The weighted least squares fit to the $O - C$ values resulted in the ephemeris:

$$C = 2\,452\,353.8356 + 3.527\,310 \times E \pm 0.0052 \pm 0.000\,008 \quad (3)$$

The $O - C$ diagram of V898 Cen plotted in Fig. 6 indicates constancy of the pulsation period.

Binarity of V898 Cen The Cepheid variable V898 Cen has been neglected from the point of view of spectroscopy, as well. A spectral type of F3III has been assigned to it in the SIMBAD data base which is atypical of a Cepheid (and probably erroneous). Cepheids are supergiants of Ia or Ib luminosity class and their short period representatives have a late F spectral type. Ironically there is a single RV data, -2.4 ± 2.4 km s⁻¹ (which is an average of two measurements) published by Nordström et al. (2004) in their catalog of 14000 *dwarf* stars of F and G spectral types. However, the epoch of these particular observations has remained unknown. Therefore, our data provide a first epoch RV phase curve.

It became obvious already in the first observing season that an orbital effect is superimposed on the RV variations of pulsational origin (see the left part of Fig. 7). Therefore several spectra of V898 Cen have been taken in 2009 and 2011, as well. Our individual RV data are listed in Tables 9 and 10. Based on these data, the RV phase curve has been constructed using the 3.527310 d pulsation period appearing in Eq. 3. The wide scatter in this phase curve plotted in Fig. 8 corresponds to a variable γ -velocity. The data series has been split into seven segments, denoted by different symbols in Fig. 8: empty circles - Dec. 2004; filled circles - March 2005; empty squares - May-June 2005; filled square - Dec. 2005;

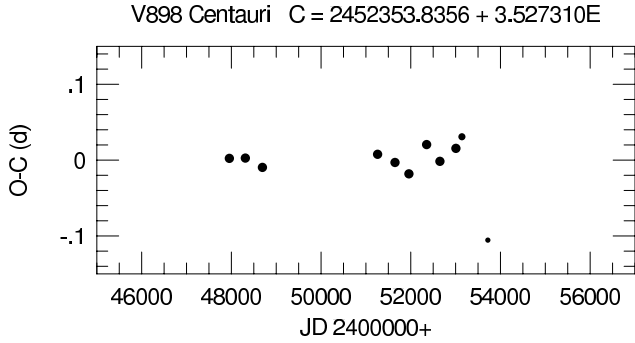


Figure 6. $O - C$ diagram of V898 Cen. The plot can be approximated by a constant period

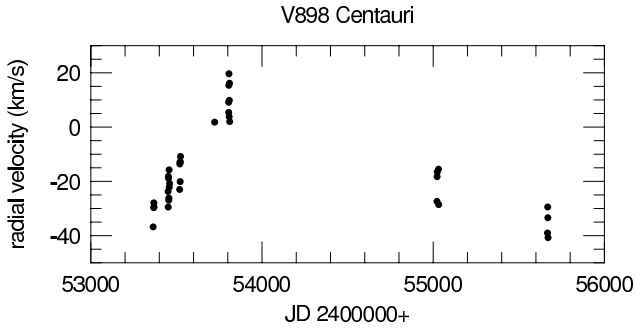


Figure 7. Merged RV curve of V898 Cen

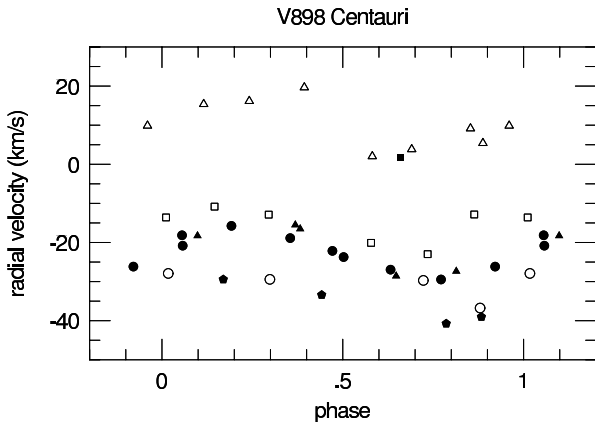


Figure 8. Radial velocity phase curve of V898 Cen. Various symbols refer to different observational runs (see the text)

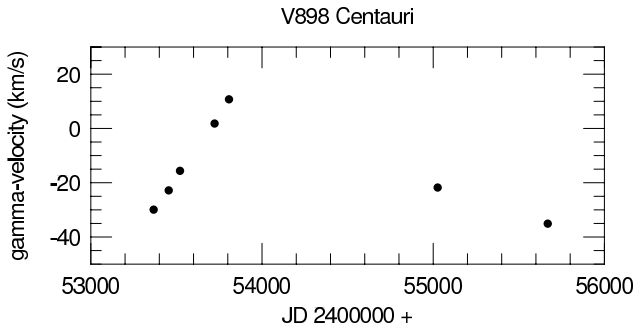


Figure 9. Temporal drift in the γ -velocity of V898 Centauri

Table 9. New RV values of V898 Centauri from the SSO spectra. This is only a portion of the full version available online only

JD _⊙ 2 400 000 +	v_{rad} (km s ⁻¹)
53364.2485	-36.8
53367.2225	-29.7
53368.2618	-27.9
53369.2529	-29.4
53451.1003	-23.7

Table 10. New FEROS velocities of V898 Centauri

JD _⊙ 2 400 000 +	v_{rad} (km s ⁻¹)
55667.5948	-39.02
55668.6044	-29.44
55669.5644	-33.40
55670.7789	-40.74

empty triangles - March 2006; filled triangles - July 2009; filled pentagons - April 2011.

The γ -velocities determined from each data segment are listed in Table 11 and are plotted in Fig. 9. This latter plot implies that V898 Cen is a new spectroscopic binary and the orbital period is about 2000 or 3000 days, depending on whether the most negative value of the γ -velocity occurred before or after our measurements in 2011. The pattern of the points implies a non-sinusoidal shape of the orbital velocity phase curve, with much steeper ascending branch than descending one. This is a strong indication of an eccentric orbit, however far more seasons of observations are needed before attempting to derive accurate orbital elements from the γ -velocity variations. The most important feature of Fig. 9 is the large amplitude of the orbital velocity variations: it exceeds 40 km s⁻¹. The ‘recorder’ among the known binary systems involving a Cepheid component has been the system of SU Cygni with a peak-to-peak orbital amplitude of 60 km s⁻¹ (see the on-line data base of Cepheids in binary systems described by Szabados 2003a).

The orbital motion of the Cepheid component around the center of mass in the binary system may cause a light-time effect in the $O - C$ diagram of the given variable star. In the case of V898 Cen the wave-like pattern characteristic of the light-time effect cannot be detected yet (see Fig. 6).

To provide reliable values for the physical properties of this bright Cepheid, our FEROS spectra were analysed in detail. The parameters T_{eff} , $\log g$, $[M/H]$, and $v \sin i$ were determined by search-

Table 11. γ -velocities of V898 Centauri

Mid-JD 2 400 000+	v_{γ} (km s ⁻¹)	σ (km s ⁻¹)	Data source
53367.7	-29.9	0.5	present paper
53455.5	-22.8	0.4	present paper
53521.4	-15.6	0.5	present paper
53723.3	1.8	0.6	present paper
53807.5	10.7	0.4	present paper
55026.3	-21.8	0.5	present paper
55669.2	-35.1	0.5	present paper

ing for the best fitting model in the synthetic spectrum library of Munari et al. (2005) using a standard χ^2 procedure. To derive the parameters and their errors we applied the following method: The model spectra were ordered according to their calculated χ^2 value, then we selected all with number less than $1.05 \chi_{\min}^2$ and adopted the means and the standard deviations of this sample as values and errors of the parameters.

The best fitting values are as follows:

$$\begin{aligned} T_{\text{eff}} &= 5950 \pm 380 \text{ K}, \\ \log g &= 1.2 \pm 0.7, \\ [M/H] &= -0.4 \pm 0.2 \\ v \sin i &= 2 \pm 2. \end{aligned}$$

The effective temperature obtained by us corresponds to an F9 spectral type supergiant star, a typical value of a short-period Cepheid. Note, however, that these values are preliminary ones. The large number of SSO spectra of all 40 target Cepheids will be analysed for obtaining physical properties with smaller uncertainties.

3.4 AD Puppis

Accurate value of the pulsation period The brightness variability of AD Pup (HD 63446, $\langle V \rangle = 9.91$ mag.) was revealed by Hertzsprung (Wesselink 1935). This is the longest period Cepheid in this paper and it has been frequently observed from the 1950s. Long-period Cepheids are usually fundamental pulsators and they oscillate with a large amplitude. In their case, the $O - C$ analysis is based on the moments of brightness maxima.

The $O - C$ differences of AD Puppis are listed in Table 12. These values have been obtained by the following ephemeris:

$$C = 2\,451\,935.3031 + 13.596\,919 \times E \quad (4)$$

$$\pm 0.0065 \pm 0.000\,040$$

which contains the constant and linear terms of the weighted parabolic fit to the $O - C$ values. The parabolic nature of the $O - C$ diagram is clearly seen in Fig. 10.

This parabolic trend corresponds to a continuous period increase of $(1.7 \pm 0.09) \times 10^{-6}$ d/cycle, i.e., $\Delta P = 0.004567$ d/century. This tiny but non-negligible period increase has been caused by stellar evolution: while the Cepheid crosses the instability region towards lower temperatures in the Hertzsprung-Russell diagram, its pulsation period is increasing. Continuous period variations (of either sign) often occur in the pulsation of long-period Cepheids (Szabados 1983).

The pattern of fluctuations around the fitted parabola shows a wavy nature with a characteristic period of about 50 years as if it were a light-time effect.

Binarity of AD Pup The earlier RV data by Joy (1937) imply a significantly different γ -velocity (66.5 km s^{-1}) than our recent ones (74.0 km s^{-1}) in spite of the uncertainty of his individual data as large as 4 km s^{-1} . Because the zero point of Joy's system is reliable, as discussed by Szabados (1996), there is no systematic difference of instrumental or data treatment origin between Joy's and the more recent observational series. The only plausible explanation for the shift in the γ -velocity is the orbital motion in a binary system superimposed on the pulsational RV changes. The shift in the γ -velocity is obvious in the phase diagram of the radial velocities of AD Puppis plotted in Fig. 11 where Joy's data are denoted with empty squares, while our data are represented with filled circles. The γ -velocity of AD Pup did not change noticeably during the interval of our observations. Our RV data (listed in Table 13 have been folded with the period as given in the ephemeris in Eq. 4.

Table 12. $O - C$ values of AD Puppis (description of the columns is given in Sect. 3.1 but the first column contains the moments of brightness maxima)

JD _⊙ 2 400 000 +	<i>E</i>	<i>O - C</i>	<i>W</i>	Data source
34614.2663	-1274	+1.4380	1	Walraven et al. (1958)
35212.4702	-1230	+1.3775	2	Irwin (1961)
40881.6304	-813	+0.6224	3	Pel (1976)
41656.4884	-756	+0.4561	3	Madore (1975)
44552.3367	-543	+0.1606	2	Eggen (1983)
45694.4366	-459	+0.1193	2	Berdnikov (2008)
47924.3692	-295	+0.1572	2	<i>Hipparcos</i> (ESA 1997)
48400.1048	-260	+0.0006	3	<i>Hipparcos</i> (ESA 1997)
48767.2244	-233	+0.0034	2	<i>Hipparcos</i> (ESA 1997)
49814.2750	-156	+0.0913	3	Berdnikov (2008)
50806.7186	-83	-0.0402	2	Berdnikov (2008)
51269.0641	-49	+0.0100	3	Berdnikov (2008)
51649.8321	-21	+0.0643	3	Berdnikov (2008)
51935.3197	0	+0.0166	3	ASAS (Pojmanski 2002)
51962.5484	2	+0.0515	3	Berdnikov (2008)
52234.5236	22	+0.0883	3	ASAS (Pojmanski 2002)
52343.2076	30	-0.0031	3	Berdnikov (2008)
52411.1912	35	-0.0041	3	ASAS (Pojmanski 2002)
52642.3572	52	+0.0143	3	Berdnikov (2008)
52723.9484	58	+0.0240	3	ASAS (Pojmanski 2002)
52995.8827	78	+0.0199	3	Berdnikov (2008)
53050.3131	82	+0.0626	3	ASAS (Pojmanski 2002)
53254.2231	97	+0.0189	3	<i>INTEGRAL</i> OMC
53444.5663	111	+0.0052	3	ASAS (Pojmanski 2002)
53770.8223	135	-0.0649	3	ASAS (Pojmanski 2002)
53852.4136	141	-0.0551	3	ASAS (Pojmanski 2002)
54178.8427	165	+0.0480	3	ASAS (Pojmanski 2002)
54532.3418	191	+0.0272	3	ASAS (Pojmanski 2002)
54831.3885	213	-0.0583	3	ASAS (Pojmanski 2002)

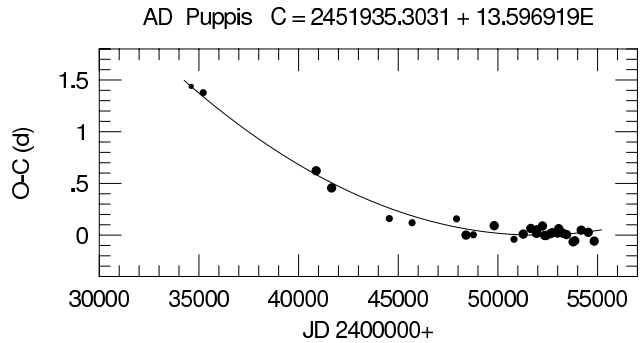


Figure 10. $O - C$ diagram of AD Pup. The plot can be approximated by a parabola indicating a continuously increasing pulsation period

Table 13. New RV values of AD Puppis from the SSO spectra. This is only a portion of the full version available online only

JD _⊙ 2 400 000 +	v_{rad} (km s^{-1})
53304.2658	103.1
53306.2580	71.8
53307.2487	70.0
53308.2504	72.9
53309.1650	59.7

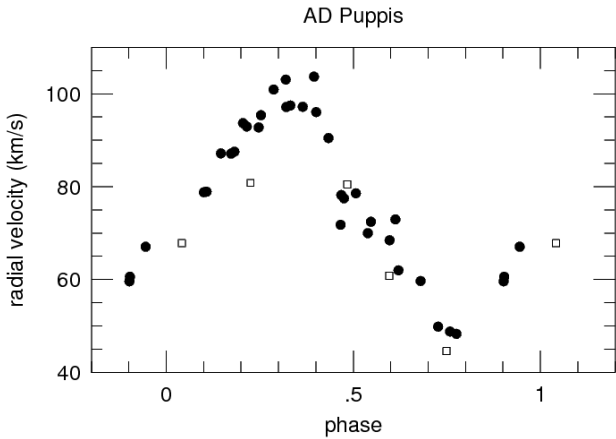


Figure 11. Merged RV phase curve of AD Pup. There is an obvious shift between the γ -velocities valid for the epoch of Joy's (1937) data (denoted by empty squares) and our data (filled circles)

Joy's data have been phased with the same period but a proper correction has been applied to correct for the phase shift due to the parabolic $O - C$ graph.

The smaller value of the γ -velocity determined from Joy's (1937) data is in a qualitative agreement with the with the wave-like pattern superimposed on the fitted parabola in Fig. 10. In this particular case the light-time effect interpretation implies a 50-year-long orbital period.

3.5 AY Sagittarii

Accurate value of the pulsation period The brightness variability of AY Sgr (HIP 90110, $\langle V \rangle = 10.55$ mag.) was revealed by Henrietta Leavitt (Pickering 1904). Hoffmeister (1923) determined the pulsation period to be 6.74426 days from his unpublished visual observations made in 1917-1918. Interestingly enough, this period is about 3% longer than the value deduced from the $O - C$ diagram (see Table 14 and Fig. 12). Such a strong period change, if it really happened, is unprecedented among classical Cepheids.

AY Sgr is a fundamental mode pulsator, so its $O - C$ diagram has been constructed based on the moments of brightness maxima. The tabulated $O - C$ values have been calculated by using the ephemeris:

$$C = 2\,452\,449.4622 + 6.569\,667 \times E \pm 0.0044 \pm 0.000\,004 \quad (5)$$

based on applying a weighted linear least squares fit to the $O - C$ differences.

As is seen in Fig. 12, the pulsation period of AY Sgr has remained practically constant over decades.

Binarity of AY Sgr Our new RV data are listed in Table 15. The first epoch RV phase curve of AY Sgr by Joy (1937) has been followed by our one 25 000 days later. The merged RV phase curve in Fig. 13 shows a significant increase in the γ -velocity during eight decades: at JD 2 427 640 $v_\gamma = -22.4$ km s⁻¹, while at JD 2 453 550 $v_\gamma = -15.5$ km s⁻¹ indicating the membership of AY Sgr in a spectroscopic binary system. During the two observing seasons covered by our spectroscopic observations, no shift in the γ -velocity is apparent. Nevertheless, the larger amplitude of the phase curve based on Joy's data may be the consequence of the

Table 14. $O - C$ values of AY Sagittarii (description of the columns is given in Sect. 3.1 but the first column contains the moments of brightness maxima)

JD _⊙ 2 400 000 +	<i>E</i>	<i>O - C</i>	<i>W</i>	Data source
21425.45	-4722	-2.04	-	Hoffmeister (1923)
27051.2394	-3866	0.1098	1	Florya & Kukarkina (1953)
34960.9601	-2662	-0.0485	3	Walraven et al. (1958)
36813.6830	-2380	+0.0283	3	Weaver et al. (1960)
40781.6694	-1776	-0.0642	3	Pel (1976)
43908.8993	-1300	+0.0042	2	Harris (1980)
48330.3254	-627	+0.0444	2	<i>Hipparcos</i> (ESA 1997)
49946.4248	-381	+0.0057	2	Berdnikov (2008)
50905.5915	-235	+0.0010	3	Berdnikov (2008)
51273.5280	-179	+0.0027	3	Berdnikov (2008)
51647.9618	-122	-0.0010	3	Berdnikov (2008)
52088.1177	-55	-0.0128	3	ASAS (Pojmanski 2002)
52449.4780	0	+0.0158	3	ASAS (Pojmanski 2002)
52843.6666	60	+0.0244	3	ASAS (Pojmanski 2002)
52909.3756	70	+0.0367	3	<i>INTEGRAL</i> OMC
53093.2519	98	-0.0377	3	Berdnikov (2008)
53165.5436	109	-0.0123	3	ASAS (Pojmanski 2002)
53559.7519	169	+0.0160	3	ASAS (Pojmanski 2002)
53861.9333	215	-0.0073	3	ASAS (Pojmanski 2002)
54341.5068	288	-0.0195	3	ASAS (Pojmanski 2002)
54650.3169	335	+0.0163	2	<i>INTEGRAL</i> OMC
54742.2598	349	-0.0162	3	ASAS (Pojmanski 2002)
54985.3351	386	-0.0186	3	ASAS (Pojmanski 2002)

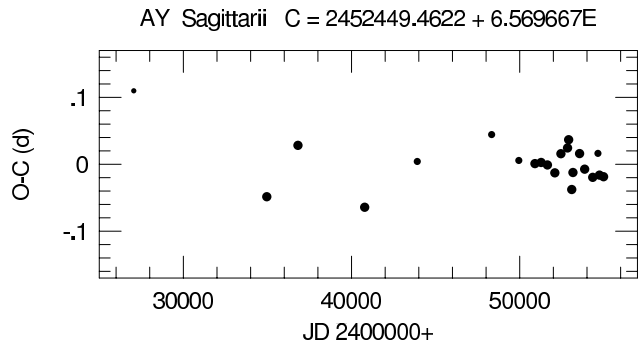


Figure 12. $O - C$ diagram of AY Sgr. The plot can be approximated by a constant period

Table 15. New RV values of AY Sagittarii from the SSO spectra. This is only a portion of the full version available online only

JD _⊙ 2 400 000 +	v_{rad} (km s ⁻¹)
53451.2048	-12.9
53452.2318	-6.1
53453.2541	5.3
53454.2702	-29.7
53455.2032	-32.7

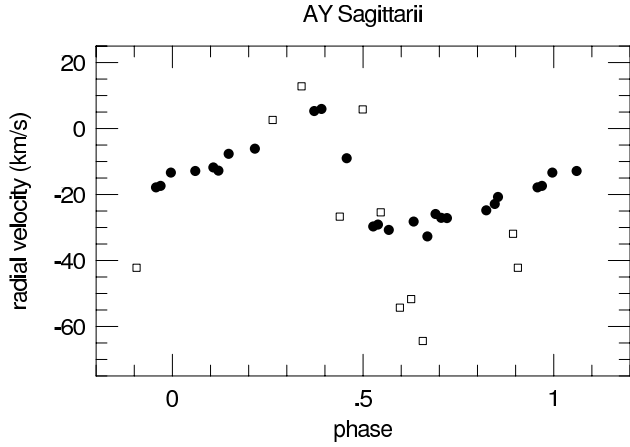


Figure 13. Merged RV phase curve of AY Sgr. There is a striking difference between the γ -velocities valid for the epoch of Joy's (1937) data (denoted as empty squares) and our recent data (filled circles)

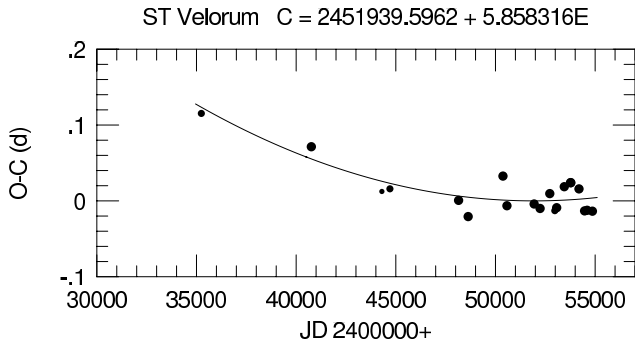


Figure 14. $O - C$ diagram of ST Vel. The plot can be approximated by a parabola indicating a continuous period increase

orbital motion in the binary system during his five-year-long observational interval.

3.6 ST Velorum

Accurate value of the pulsation period The brightness variability of ST Vel (CD -50° 3533), $\langle V \rangle = 9.73$ mag.) was suspected by Kapteyn (Gill & Innes 1903) and it was reported as a new variable by Cannon et al. (1909). Being a Cepheid that pulsates in the fundamental mode, the $O - C$ diagram in Fig. 14 has been constructed for the moments of brightness maxima listed in Table 16. The final ephemeris obtained by a weighted parabolic least squares fit is:

$$C = 2\,451\,939.5962 + 5.858\,316 \times E \pm 0.0025 \pm 0.000\,006 \quad (6)$$

The second order term omitted from Eq. 6 results in a continuous increase in the pulsation period amounting to $(3.04 \pm 0.58) \times 10^{-8}$ d/cycle, i.e., 16.36 s/century.

Binarity of ST Vel The available RV data – those by Pont et al. (1994) and our new ones listed in Table 17 – have been plotted in Fig. 15. When folding the data into a phase curve, the period of 5.858316 day given in the Eq. 6 was used but due to the parabolic pattern of the $O - C$ graph, a tiny correction was applied when plotting the data by Pont et al. (1994). It is noteworthy that our own data show an excessive scatter that can be explained in terms of the variation in the γ -velocity. This effect is clearly seen in Fig. 16

Table 16. $O - C$ values of ST Velorum (description of the columns is given in Sect. 3.1 but the first column contains the moments of brightness maxima)

JD _⊙ 2 400 000 +	<i>E</i>	<i>O - C</i>	<i>W</i>	Data source
35243.5109	-2850	+0.1153	2	Walraven et al. (1958) + Irwin (1961)
40762.0007	-1908	+0.0714	3	Pel (1976)
44300.3645	-1304	+0.0124	1	Berdnikov (2008)
44704.5918	-1235	+0.0159	2	Eggen (1985)
48149.2664	-647	+0.0007	3	<i>Hipparcos</i> (ESA 1997)
48629.6270	-565	-0.0207	3	<i>Hipparcos</i> (ESA 1997)
50375.4585	-267	+0.0327	3	Berdnikov (2008)
50574.6022	-233	-0.0064	3	Berdnikov (2008)
51939.5921	0	-0.0041	3	ASAS (Pojmanski 2002)
52238.3603	51	-0.0100	3	ASAS (Pojmanski 2002)
52724.6201	134	+0.0096	3	ASAS (Pojmanski 2002)
52976.5052	177	-0.0129	2	<i>INTEGRAL</i> OMC
53070.2422	193	-0.0090	3	ASAS (Pojmanski 2002)
53451.0604	258	+0.0187	3	ASAS (Pojmanski 2002)
53767.4149	312	+0.0241	3	<i>INTEGRAL</i> OMC
53779.1313	314	+0.0239	3	ASAS (Pojmanski 2002)
54189.2053	384	+0.0158	3	ASAS (Pojmanski 2002)
54470.3755	432	-0.0132	3	ASAS (Pojmanski 2002)
54599.2593	454	-0.0124	3	ASAS (Pojmanski 2002)
54862.8823	499	-0.0136	3	ASAS (Pojmanski 2002)

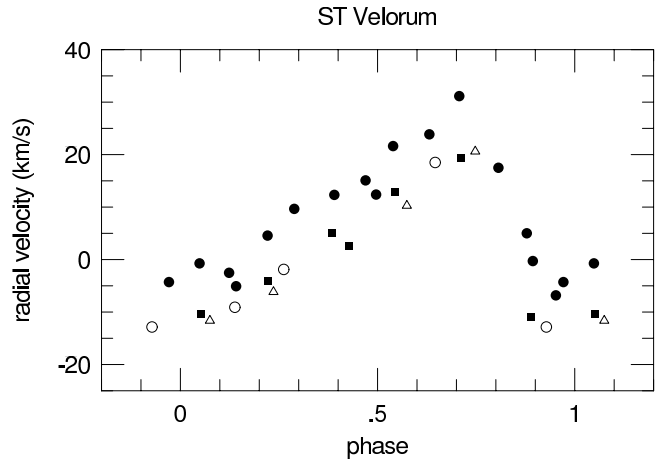


Figure 15. Merged RV phase curve of ST Vel. Triangles represent radial velocities obtained by Pont et al. (1994), our data are split into three parts: those from 2004 (empty circles), from 2005 (filled circles), and 2006 (filled squares)

Table 17. New RV values of ST Velorum from the SSO spectra. This is only a portion of the full version available online only

JD _⊙ 2 400 000 +	v_{rad} (km s ⁻¹)
53310.2539	-12.9
53312.2108	-1.9
53364.2096	-9.1
53367.1854	18.5
53450.9950	-6.8

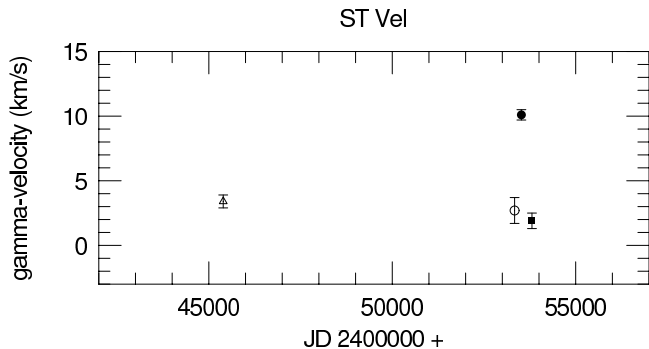


Figure 16. Temporal variations in the γ -velocity of ST Velorum. The symbols are consistent with those used in Fig. 15

Table 18. γ -velocities of ST Velorum

Mid-JD 2 400 000+	v_γ (km s^{-1})	σ (km s^{-1})	Data source
45392	3.4	0.5	Pont et al. (1994)
53335	2.7	1.0	present paper
53520	10.1	0.4	present paper
53808	1.9	0.6	present paper

where the annual γ -velocities listed in Table 18 have been plotted. The pattern of the points in this figure implies that the orbital period can be several hundred days, which is rather short among the spectroscopic binaries containing a Cepheid component.

4 CONCLUSIONS

We pointed out that six southern Galactic Cepheids, GH Carinae, V419 Centauri, V898 Centauri, AD Puppis, AY Sagittarii, and ST Velorum have a variable γ -velocity which implies their membership in spectroscopic binary systems. The available RV data are insufficient to determine the orbital period and other elements of the orbit. We can only state that the orbital period of V419 Cen is several years, for V898 Cen it is 2000-3000 days, for AD Pup about 50 years, and for ST Vel several hundred days.

The value of the orbital period for spectroscopic binary systems involving a Cepheid component is often unknown: according to the on-line data base (Szabados 2003a) the orbital period has been determined for about 20% of the known SB Cepheids. Majority of the known orbital periods exceeds a thousand days.

Our finding confirms the previous statement by Szabados (2003a) about the high percentage of binaries among classical Cepheids and the observational selection effect hindering the discovery of new cases.

Radial velocity data obtained prior to ours were instrumental in discovering binarity of V419 Cen, AD Pup, AY Sgr, and ST Vel, while the spectroscopic binary nature of GH Car and V898 Cen has been discovered from our observations alone.

A companion star may have various effects on the photometric properties of the Cepheid component. Various pieces of evidence of duplicity based on the photometric criteria are discussed by Szabados (2003b) and Klagyivik & Szabados (2009). As to our targets, there is no obvious sign of companion from photometry alone. This indicates that the companion star cannot be much hotter than the Cepheid component in either case. Nevertheless, weak

evidence of anomalous photometric behaviour was reported for GH Car by Madore & Fernie (1980) (abnormal phase shift between the light curves in different photometric bands) and for V419 Cen by Onnembo et al. (1985) (anomalous behaviour when determining its physical parameters with the CORS method). The strange spectral type of F3III for V898 Cen appearing in the SIMBAD data base may be wrong because an F9 spectral type has been deduced from our spectra. Further spectroscopic observations are necessary to characterise these binary systems. In addition, accurate future photometric observations can be instrumental in confirming the interpretation of the wavy pattern superimposed on the parabolic $O - C$ graph of AD Pup in terms of a light-time effect.

Regular monitoring of the radial velocities of a large number of Cepheids will be instrumental in finding more long-period spectroscopic binaries among Cepheids. Quite recently Evans et al. (2012) reported on their on-going survey for pointing out binarity of Cepheids from the existing RV data covering sufficiently long time interval. Radial velocity data to be obtained with the Gaia astrometric space probe (expected launch: October 2013) will certainly result in revealing new spectroscopic binaries among Cepheids brighter than 13-14th magnitude (Eyer et al. 2012).

When determining the physical properties (luminosity, temperature, radius, etc.) of individual Cepheids, the effects of the companion on the observed parameters (apparent brightness, colour indices, etc.) have to be corrected for. This type of analysis, however, should be preceded by revealing the binarity of the given Cepheid.

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Table 6. New RV values of V419 Centauri from the SSO spectra.

Table 9. New RV values of V898 Centauri from the SSO spectra.

Table 13. New RV values of AD Puppis from the SSO spectra.

Table 15. New RV values of AY Sagittarii from the SSO spectra.

Table 17. New RV values of ST Velorum from the SSO spectra.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 3. New RV values of GH Carinae from the SSO spectra.

Table 4. New CORALIE velocities of GH Carinae.