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Discovery of the spectroscopic binary nature of the Cepheids X Puppis and XX Sagittarii

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ABSTRACT

We present the analysis of photometric and spectroscopic data of two bright Galactic Cepheids, X Puppis and XX Sagittarii. Based on the available data in the literature as well as our own observations spanning 75 years, we conclude that both Cepheids belong to spectroscopic binary systems. However, the data are not sufficient to determine the orbital periods or other elements for the orbit. This discovery corroborates statements on the high frequency of occurrence of binaries among classical Cepheids, a fact to be taken into account when calibrating the period–luminosity relationship for Cepheids. The photometric data revealed that the pulsation period of X Pup is continuously increasing by $\Delta P = 0.007\,559$ d century^{-1}, likely caused by stellar evolution. The pulsation period of XX Sgr turned out to be very stable over the last ∼100 years.

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

1 INTRODUCTION

Classical Cepheid variable stars are key objects in astronomy because owing to their radial pulsation and its consequences – mainly the famous period–luminosity (*P*–*L*) relationship – they rank among standard candles in establishing the cosmic distance scale and serve as test objects of stellar evolution of intermediate-mass stars.

Companions to Cepheids, however, complicate the situation. On the one hand, 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 and the evolution of binary stars may be quite different from single-star evolution (depending on the separation of the components). On the other hand, the frequency of binaries (and multiple stars) among classical Cepheid variables is considerable: it exceeds 50 per cent for the brightest Cepheids (Szabados 2003a), while among the fainter Cepheids an observational selection effect encumbers the revealing of binarity. Seen in a broader aspect, however, this frequent occurrence of binaries among Cepheids is not surprising and agrees with the general frequency of binary stars in the solar neighbourhood: two-thirds of solar-type stars of F3–G2 spectral type have stellar companions (Abt & Levy 1976).

Depending on the brightness and temperature differences between a Cepheid and its companion (either optical or physical), the observable brightness and colour of the unresolved binary system can differ from the respective value intrinsic to the Cepheid. If values are uncorrected for its contribution, the companion can falsify the luminosity and radius of the Cepheid derived using the Baade–Wesselink method (except for its infrared surface-brightness method implementation).

The orbital motion of a Cepheid in a binary system can even lead to a wrong trigonometric parallax if no allowance is made for binarity. An illustrative example of this adverse effect was shown by Szabados, Kiss & Klagyivik (2011): all negative *Hipparcos* values for Cepheids within 2 kpc were derived solely in the case of Cepheids with known spectroscopic companions.

Cepheids belonging to open clusters are often used for calibrating the *P*–*L* relationship based on independently derived cluster distances (e.g. Turner & Burke 2002; Turner 2010). For these calibrating Cepheids, it is especially important to correct for the luminosity contribution from the companion.

Therefore, it is essential to study Cepheids individually from the point of view of binarity before involving them in any calibration procedure (e.g. of the *P*–*L* or period–radius relationship).

Hot companions to Cepheids can be discovered effectively by ultraviolet spectroscopy: the *IUE* satellite was instrumental in revealing early-type companions (Evans 1992). Radial velocity time-series data (normally in the optical region) obtained during at least two widely differing epochs can lead to the discovery of spectroscopic binaries (see e.g. Szabados 1996). Revealing binarity by means of *astrometry* will be available from the data to be obtained during the ESA *Gaia* space mission from 2013 onwards. Owing to the regular behaviour of Cepheid pulsation, various

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photometric criteria have also been devised for pointing out the presence of Cepheid companions (Szabados 2003b; Klagyivik & Szabados 2009).

In this paper we reveal the *spectroscopic binarity* of two bright Cepheids, X Puppis and XX Sagittarii, by carefully analysing the radial velocity data published for these variable stars. Some new radial velocity data obtained for XX Sgr have also been included in the analysis.

In the case of pulsating variables, like Cepheids, spectroscopic binarity 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 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 using the method of the $O - C$ diagram (Sterken 2005) for both target Cepheids. 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.

2 X PUPPIS

2.1 Accurate value of the pulsation period

The brightness variability of X Pup (HD 60266, $\langle V \rangle = 8.46$ mag) was revealed by Kapteyn (1890). During the time interval elapsed since the discovery (spanning more than 120 yr), the photometric variability was followed first visually then photographically, from the 1950s photoelectrically and in the last decades by CCD photometry. All published observations of this Cepheid radially pulsating in the fundamental mode were re-analysed in a homogeneous manner to determine seasonal moments of the normal maxima. These data are collected in Table 1, the columns of which contain the following pieces of information:

column 1: heliocentric normal maxima;
column 2: epoch number, E, as calculated from equation (1):

$$C = 245\,4845.0497 + 25.970\,068 \times E \qquad (1)$$
$$\pm 0.0926 \pm 0.000\,406$$

(this ephemeris has been obtained by the weighted least-squares fit to the tabulated $O - C$ residuals);
column 3: the corresponding $O - C$ residual as calculated from equation (1);
column 4: weight assigned to the $O - C$ residual (1, 2 or 3 depending on the quality of the light curve leading to the given residual);
column 5: reference to the origin of data, preceded by the name of the observer if different from the author(s) cited.

The $O - C$ residuals have been plotted in Fig. 1 together with the least-squares fitted parabola. This parabolic trend corresponds to a continuous period increase of 5.375×10^{-6} d cycle^{-1}, i.e. $\Delta P = 0.007\,559$ d century^{-1}. This tiny but non-negligible effect 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. Superimposed on this parabolic trend, random fluctuations of the period value are also seen on a time-scale of several years; see the quasi-continuously covered part of the deviations from the parabolic fit to the $O - C$ residuals after JD 244 8000 in Fig. 2. The amplitude of these fluctuations is several tenths of a day, an order of magnitude larger

Table 1. $O - C$ residuals of X Puppis (description of the columns is given in Section 2.1).

JD$_\odot$ 240 0000 +	E	$O - C$	W	Data source
08872	−1771	20	1	Schönfeld (Parenago 1956)
11100.62	−1685	15.13	1	Kapteyn (1890)
14136.7	−1568	12.7	1	Perry (Parenago 1956)
14343.0631	−1560	11.3195	1	Zinner (1932)
14577.1534	−1551	11.6792	1	Parkhurst (1897, 1899, 1903)
14890.4	−1539	13.3	1	Hartwig (Parenago 1956)
14890.8	−1539	13.7	1	Innes (Parenago 1956)
18706.3	−1392	11.6	1	Worsell (Parenago 1956)
19040.869	−1379	8.543	1	Robinson (Parenago 1956)
19638.28	−1356	8.64	1	Hertzsprung (1928)
20001.52	−1342	8.30	1	Payne & Gaposchkin (Parenago 1956)
24545.1	−1167	7.1	1	Bhaskaran (1933)
26725.6293	−1083	6.1632	2	O'Connell (1934)
27115.3559	−1068	6.3388	1	Florya & Kukarkina (1953)
32515.29	−860	4.50	1	Berdnikov, Mattei & Beck (2003)
34877.0978	−769	3.0304	2	Walraven, Muller & Oosterhoff (1958)
35188.9673	−757	3.2591	1	Irwin (1961)
36149.68	−720	3.08	1	Berdnikov et al. (2003)
37369.7691	−673	2.2572	2	Mitchell et al. (1964)
37369.78	−673	2.59	1	Berdnikov et al. (2003)
39368.8181	−596	1.9289	1	Takase (1969)
40875.2311	−538	2.0780	3	Pel (1976)
41653.7755	−508	1.5203	2	Madore (1975)
42017.38	−494	1.54	1	Berdnikov et al. (2003)
42848.4488	−462	1.5705	1	Dean (1977)
43082.33	−453	1.72	1	Berdnikov et al. (2003)
43601.31	−433	1.30	1	Berdnikov et al. (2003)
44120.65	−413	1.24	1	Berdnikov et al. (2003)
44457.6939	−400	0.6714	1	Eggen (1983)
44561.8016	−396	0.8988	1	Berdnikov (2008)
44744.01	−389	1.32	1	Berdnikov et al. (2003)
44898.9264	−383	0.4127	1	Moffett & Barnes (1984)
44977.5009	−380	1.0770	1	Berdnikov (2008)
45704.52	−352	0.9342	1	Berdnikov et al. (2003)
45808.46	−348	0.9940	1	Berdnikov et al. (2003)
47833.64	−270	0.5087	1	Berdnikov et al. (2003)
48145.0626	−258	0.2904	2	*Hipparcos* (ESA 1997)
48716.3278	−236	0.2141	2	*Hipparcos* (ESA 1997)
49806.8990	−194	0.0425	3	Berdnikov (2008)
50118.4982	−182	0.0009	2	Bersier (2002)
50482.0566	−168	−0.0217	2	Bersier (2002)
50560.0343	−165	0.0457	2	Berdnikov (2008)
50819.6483	−155	−0.0409	2	Berdnikov (2008)
50897.3144	−152	−0.2850	2	Berdnikov (2008)
51261.0546	−138	−0.1257	3	Berdnikov (2008)
51650.7613	−123	0.0300	3	Berdnikov (2008)
51962.2826	−111	−0.0896	2	Berdnikov (2008)
52351.9893	−96	0.0661	3	Berdnikov (2008)
52637.6479	−85	0.0540	3	Berdnikov (2008)
52689.5032	−83	−0.0309	3	ASAS (Pojmanski 2002)
52923.1507	−74	−0.1140	3	ASAS (Pojmanski 2002)
53001.1284	−71	−0.0465	3	ASAS (Pojmanski 2002)
53001.1284	−71	−0.0465	3	Berdnikov (2008)
53416.5940	−55	−0.1020	3	ASAS (Pojmanski 2002)
53754.2896	−42	−0.0172	3	ASAS (Pojmanski 2002)
54143.9963	−27	0.1384	3	ASAS (Pojmanski 2002)
54481.6660	−14	0.1973	3	ASAS (Pojmanski 2002)
54845.3282	0	0.2785	3	ASAS (Pojmanski 2002)

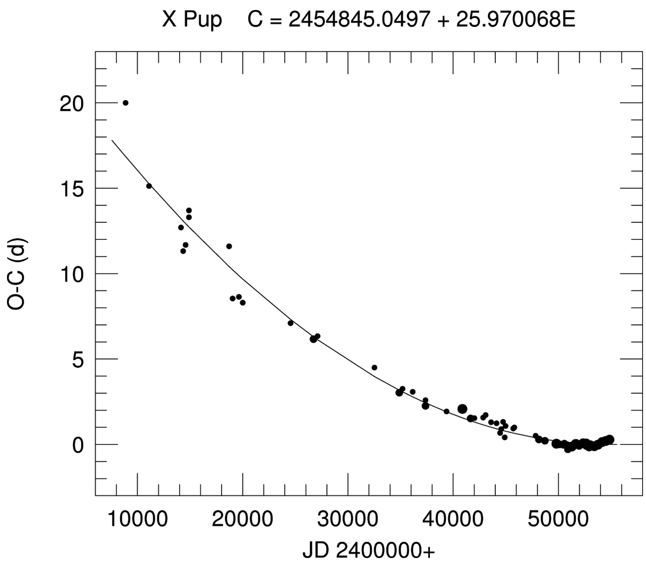

Figure 1. $O - C$ diagram of X Pup based on the residuals listed in Table 1. The pulsation period of X Pup is continuously increasing.

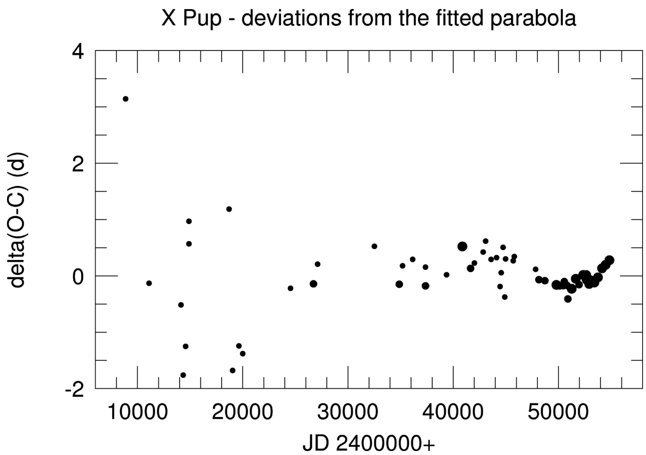

Figure 2. Deviations of the $O - C$ residuals of X Pup from the fitted parabola.

than the periodic light-time effect expected in a binary system (of suitably placed orbital plane) with a Cepheid component.

2.2 Radial velocity data of X Pup

The available radial velocity data include those obtained by Joy (1937), Barnes, Moffett & Slovak (1988), Caldwell et al. (2001), Bersier (2002), Petterson et al. (2005) and Storm et al. (2011). The phase curve was constructed from each data set using the actual value of the pulsation period, taking into account the continuous period variation implied by Fig. 1 (see Section 2.1). Then the mean value of the radial velocity (the γ-velocity) was determined for each data set. These γ-velocities, together with their uncertainties, are listed in Table 2 and also plotted in Fig. 3. The pattern of the data points implies a monotonically changing γ-velocity, which is a sign of the orbital motion in a spectroscopic binary system. The orbital period can be as long as several decades.

The spectroscopic binarity of X Pup has to be confirmed by further observations because the earliest data (obtained by Joy about 80 yr ago) are of low quality. Nevertheless, all radial velocity data have been obtained based on the observed wavelength of metallic lines, therefore one does not expect a noticeable systematic difference between the various data sets.

Table 2. γ-velocities of X Puppis.

Mid-JD 240 0000+	v_γ (km s^{-1})	σ (km s^{-1})	Data source
25590	65.0	2.0	Joy (1937)
44666	67.4	0.5	Caldwell et al. (2001)
45065	66.5	1.5	Barnes et al. (1988)
50523	70.0	0.4	Bersier (2002)
51111	71.5	0.3	Petterson et al. (2005)
54922	71.8	0.2	Storm et al. (2011)

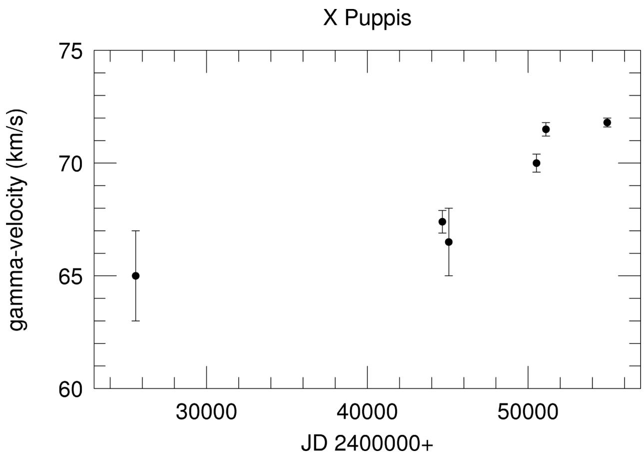

Figure 3. Temporal drift in the γ-velocity of X Puppis.

3 XX SAGITTARII

3.1 Accurate value of the pulsation period

The brightness variability of XX Sagittarii (HD 169315, $\langle V \rangle$ = 8.65 mag) was discovered by Annie Cannon (Pickering 1908). In the first half of the 20th century XX Sgr was occasionally observed, mainly visually; regular photometric data on this Cepheid are available from the last three decades. All photometric data of this single periodic Cepheid pulsating in the radial fundamental mode have been subjected to an $O - C$ analysis, the results of which are summarized in Table 3. The $O - C$ residuals in this table have been obtained by using the following final ephemeris:

$$C = 245\,2814.4629 + 6.424\,267 \times E$$
$$\pm 0.0059 \pm 0.000\,003, \qquad (2)$$

determined from a weighted least-squares fit to all normal maxima listed in Table 3.

The $O - C$ diagram of XX Sgr is plotted in Fig. 4. The pattern of data can be approximated by a constant period but in the last decades a wave-like pattern is seemingly superimposed on the $O - C = 0$ constant line. However, this feature can hardly be attributed to a light-time effect occurring in a binary system due to the orbital motion because the amplitude of the $O - C$ variations is too large.

3.2 Radial velocity data of XX Sgr

For over half a century, the values published by Joy (1937) had been the only existing radial velocity data on XX Sgr. The radial

Table 3. $O - C$ residuals of XX Sagittarii.

JD$_{\odot}$ 240 0000 +	E	$O - C$	W	Data source
19710.2958	−5153	0.0808	1	Zinner (Voûte 1932)
25100.13	−4314	−0.05	1	Zessewitsch (1929)
25485.6503	−4254	0.0192	2	Voûte (1932)
25614.0548	−4234	−0.0616	1	Zacharov (1954)
26185.8675	−4145	−0.0087	1	Parenago (1938)
27117.4641	−4000	0.0692	1	Florya & Kukarkina (1953)
29648.5184	−3606	−0.0377	1	Solov'yov (1948)
31646.3938	−3295	−0.1093	1	Solov'yov (1948)
33117.6109	−3066	−0.0494	2	Eggen, Gascoigne & Burr (1957)
37267.7531	−2420	0.0163	1	Mitchell et al. (1964)
39265.7249	−2109	0.0411	2	Takase (1969)
44019.5564	−1369	−0.0850	2	Berdnikov (2008)
44771.3477	−1252	0.0671	2	Moffett & Barnes (1984)
44944.8381	−1225	0.1023	3	Berdnikov (2008)
48368.8340	−692	−0.0361	3	*Hipparcos* (ESA 1997)
48966.3048	−599	−0.0222	3	Arellano Ferro et al. (1998)
50353.9447	−383	−0.0239	3	Berdnikov (2008)
50893.5982	−299	−0.0089	3	Berdnikov (2008)
51272.6481	−240	0.0093	3	Berdnikov (2008)
51651.6659	−181	−0.0047	3	Berdnikov (2008)
52082.1090	−114	0.0125	3	ASAS (Pojmanski 2002)
52371.1953	−69	0.0068	3	Berdnikov (2008)
52499.6717	−49	0.0021	3	ASAS (Pojmanski 2002)
52814.4674	0	0.0045	3	ASAS (Pojmanski 2002)
52923.6906	17	0.0152	3	*INTEGRAL* OMC
53161.3645	54	−0.0088	3	ASAS (Pojmanski 2002)
53546.8451	114	0.0158	3	ASAS (Pojmanski 2002)
53649.5992	130	−0.0184	3	*INTEGRAL* OMC
53861.6215	163	0.0031	3	ASAS (Pojmanski 2002)
54272.7729	227	0.0014	3	ASAS (Pojmanski 2002)
54645.3666	285	−0.0124	3	ASAS (Pojmanski 2002)
54979.4283	337	−0.0126	3	ASAS (Pojmanski 2002)

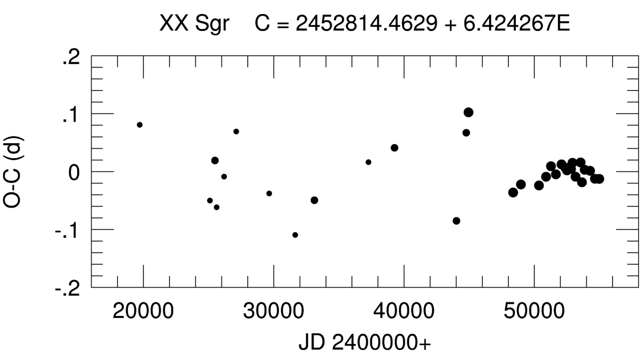

Figure 4. $O - C$ diagram of XX Sgr. The plot can be approximated by a constant period.

velocity survey of Barnes et al. (1988) also included this Cepheid and their two data implied a γ-velocity value different from the one determined using Joy's data. Suspecting a spectroscopic binary nature, we initiated new radial velocity observations (discussed in Section 3.3). In the meantime, however, some more radial velocity data have been published by Berdnikov et al. (2010) and Storm et al. (2011). This latter series of observations resulted in a well-covered and very accurate radial velocity phase curve which confirms the spectroscopic binarity of XX Sgr. However, Storm et al. (2011) did not compare their own measurements with the previous data, thus they missed revealing the binarity of this Cepheid.

Table 4. Log of the FEROS observations of XX Sgr.

Night	Obs. ID.	Mid-exposure JD 240 0000+	Exposure time (s)	$v_{\rm rad}$ (km s^{-1})
Apr 15–16	F1487	55 667.8105	180	−1.98
Apr 16–17	F1645	55 668.8165	180	6.04
Apr 17–18	F1723	55 669.8192	180	15.00
Apr 18–19	F1805	55 670.8533	180	22.48

3.3 FEROS observations

XX Sgr was observed on four consecutive nights during 2011 April, using the FEROS spectrograph on the MPG/ESO 2.2-m telescope in La Silla Observatory, Chile (see Table 4 for details). The Fiber-fed Extended Range Optical Spectrograph (FEROS: Kaufer et al. 1999, 2000) has a total wavelength coverage of 356–920 nm with a resolving power of $R = 48\,000$. Two fibres, with an entrance aperture of 2.7 arcsec, simultaneously recorded star light and sky background. The detector is a back-illuminated CCD with 2948 × 4096 pixels of 15 µm size. Basic data reduction was performed using a pipeline package for reductions (DRS) in the MIDAS environment. The pipeline performs the subtraction of bias and scattered light in the CCD and 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[1] we determined the radial velocities 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). The velocities were determined in the region 500–600 nm, where a number of metallic lines are present and there is a lack of hydrogen lines. We made barycentric corrections to each radial velocity value with the task `rvcorrect`. The estimated uncertainty of the radial velocities is 0.05 km s^{-1}.

3.4 Binarity of XX Sgr

All radial velocity data have been folded on the accurate pulsation period taken from the ephemeris given in equation (2), so the different data series have been correctly phased with respect to each other. The merged radial velocity phase curve is plotted in Fig. 5.

The individual data series are denoted with different symbols: small squares – Joy (1937), corresponding to mid-JD 242 6283; open circles – Barnes et al. (1988), with mid-JD 244 4254; filled circles – Storm et al. (2011) and Berdnikov et al. (2010), with mid-JD 245 4261 and mid-JD 245 4730, respectively; triangles – our FEROS data listed in Table 4, with mid-JD 245 5669.

The earliest radial velocity data by Joy (1937) imply a significantly different γ-velocity from all more recent data, in spite of the uncertainty of his individual data being 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 in instrumental or data-treatment origin between Joy's data 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 radial velocity changes.

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

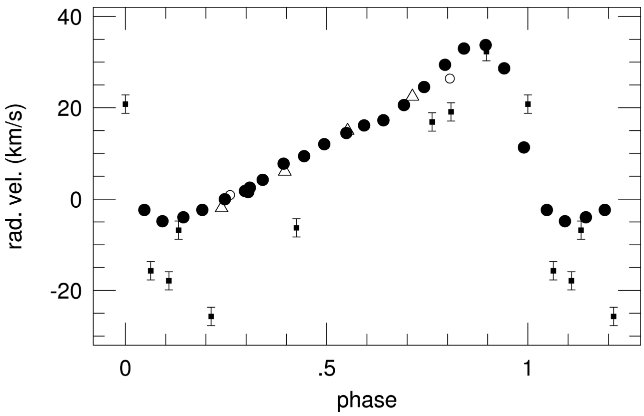

Figure 5. Merged radial velocity phase curve of XX Sgr. There is a striking difference between the γ-velocities valid for the epoch of Joy's (1937) data (denoted as small squares) and more recent data (other symbols, see the detailed list in the text).

The spectroscopic binarity of XX Sgr can barely be suspected from the radial velocity data obtained in the last 25 years, so the orbital period is certainly much longer.

4 CONCLUSIONS

We highlighted the fact that two bright Galactic Cepheids, X Puppis and XX Sagittarii, have a variable γ-velocity, which implies their membership in spectroscopic binary systems. The available radial velocity data are insufficient to determine the orbital period and other elements of the orbit. It is obvious, however, that the orbital period is as long as several decades in both cases. Such long orbital periods are not unprecedented among classical Cepheids, cf. the cases of T Mon and AW Per (see the online data base http://www.konkoly.hu/CEP/orbit.html and its description in Szabados 2003a).

Neither X Pup nor XX Sgr shows any photometric evidence of duplicity based on the criteria discussed by Szabados (2003b) and Klagyivik & Szabados (2009), indicating that the companion cannot be a star much hotter than the Cepheid component in either case. Further spectroscopic observations are necessary to characterize these binary systems.

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 ongoing survey for deducing the binarity of Cepheids from existing radial velocity data covering sufficiently long time intervals.

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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