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

László Szabados, Aliz Derekas, Csaba Kiss, and Péter Klagyivik

1 Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, H-1121 Budapest, Konkoly Thege Miklós út 15-17, Hungary

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 nor other elements for the orbit. This discovery corroborates 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. The photometric data revealed that the pulsation period of X Pup is continuously increasing with $\Delta P = 0.007559\,\text{d/century}$ likely caused by stellar evolution.

The pulsation period of XX Sgr turned out to be very stable in the last $\sim 100$ years.

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

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

Depending on the brightness and temperature differences between the Cepheid and its (either optical or physical) companion, the observable brightness and colour of the unresolved binary system can differ from the respective value intrinsic to the Cepheid. If uncorrected for its contribution, the companion can falsify the luminosity and radius of the Cepheid derived by using the Baade-Wesselink method (except 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 for this adverse effect was shown by Szabados, Kiss, & Klagyivik (2011): all negative Hipparcos values for Cepheids within 2 kpc were solely derived 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 the 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 (of e.g., $P$-$L$ or period-radius relationship).

Hot companions to Cepheids can be effectively discovered 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 discovery of spectroscopic binaries (see e.g., Szabados).
Revealing binarity by means of astrometry will be available from the data to be obtained during the ESA Gaia space mission from 2013 on. Owing to the regular behaviour of Cepheid pulsation, various photometric criteria have also been devised for pointing out the presence of Cepheid companions (Szabados 2003b; Klagyivik & Szabados 2009).

In this paper we reveal spectroscopic binarity of two bright Cepheids, X Puppis and XX Sagittarii, by carefully analysing the radial velocity data published on 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 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 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, ⟨V⟩ = 8.46 mag.) was revealed by Kapteyn (1890). During the time interval elapsed since the discovery (spanning more than 120 years) 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 whose columns contain the following pieces of information:

- Column 1: Heliocentric normal maxima;
- Col. 2: Epoch number, E, as calculated from Eq. 1:
  \[ C = 2454845.0497 + 25.970068 \times E \pm 0.0926 \pm 0.000406 \]
  (this ephemeris has been obtained by the weighted least squares fit to the tabulated \( O − C \) residuals);
- Col. 3: the corresponding \( O − C \) residual as calculated from Eq. 1;
- Col. 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);
- Col. 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 \( 5.375 \times 10^{-6} \) d/cycle, i.e., \( \Delta P = 0.007559 \) d/century. 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 2 448 000 in Fig. 2. The amplitude of these fluctuations is several tenths of a day, an order of magnitude larger 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), Caldwell et al. (2001), Barnes, Moffett & Slovak (1988), Bersier (2002), Petterson et al. (2003), 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...
Table 1. $O-C$ residuals of X Puppis (description of the columns is given in Sect. 2.1)

| JD $\odot$ | $E$ | $O-C$ | $W$ | Data source               |
|------------|-----|-------|-----|---------------------------|
| 008872     | 0   | −1771 | 20  | Schönfeld (Parenago 1956)  |
| 11100.62   | 0   | −1685 | 15.12 | Kaptyn (1980)            |
| 14316.7    | 0   | −1568 | 12.7 | Perry (Parenago 1956)     |
| 14343.0631 | 0   | −1560 | 11.395 | Zinner (1932)          |
| 14577.1534 | 0   | −1551 | 11.6792 | Parkhurst (1897, 1899, 1903) |
| 14890.4    | 0   | −1539 | 13.3 | Hartwig (Parenago 1956)   |
| 14908.9    | 0   | −1539 | 13.7 | Innes (Parenago 1956)     |
| 18706.3    | 0   | −1392 | 11.6 | Worsell (Parenago 1956)   |
| 19040.869  | 0   | −1379 | 8.543 | Robinson (Parenago 1956)  |
| 19638.28   | 0   | −1356 | 8.64 | Hertzsprung (1928)       |
| 20001.52   | 0   | −1342 | 8.30 | Payne & Gaposchkin (1956) |

| Data source               |
|---------------------------|
| Schönfeld (Parenago 1956)  |
| Kaptyn (1980)             |
| Perry (Parenago 1956)     |
| Zinner (1932)            |
| Parkhurst (1897, 1899, 1903) |
| Hartwig (Parenago 1956)   |
| Innes (Parenago 1956)     |
| Worsell (Parenago 1956)   |
| Robinson (Parenago 1956)  |
| Hertzsprung (1928)       |
| Payne & Gaposchkin (1956) |

Table 2. $\gamma$-velocities of X Puppis

| Mid-JD | $v_{\gamma}$ (km/s) | $\sigma$ (km/s) | Data source |
|--------|----------------------|-----------------|-------------|
| 2 400 000+ |                      |                 |             |
| 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 $\gamma$-velocity of X Puppis by Fig. 1 (see Sect. 2.1). Then the mean value of the radial velocity (the $\gamma$-velocity) was determined for each data set. These $\gamma$-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 $\gamma$-velocity which is a sign of the orbital motion in a spectroscopic binary system. The orbital period can be as long as several decades.

Spectroscopic binarity of X Pup has to be confirmed by further observations because the earliest data (obtained by Joy about 80 years 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.

3 XX SAGITTARI

3.1 Accurate value of the pulsation period

The brightness variability of XX Sagittarii (HD169315, $(V) = 8.65$ 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 whose results are summarized in Table 3. The $O-C$ residuals in this table have been obtained by using the following final ephemeris:

$$C = 2 452 814.4629 + 6.424 267 \times E$$

(2)
The pattern of data can be approximated by a constant period

\[ O - C \approx \text{constant} \]

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

The pattern of data can be approximated by a constant period in the last decades a wave-like pattern is seemingly superimposed on the \( O - C \approx 0 \) 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.

### Table 3. \( O - C \) residuals of XX Sagittarii

| JD \(_{2400000}\) | \( E \) | \( O - C \) | \( W \) | Data source |
|-----------------|-------|------------|------|------------|
| 19710.2958      | -513  | 0.00808    | 1    | Zinner (Voûte 1972) |
| 25100.13        | -424  | -0.05      | 1    | Zessewitsch (1992) |
| 2548.503        | -425  | 0.0192     | 2    | Voûte (1932) |
| 25614.0548      | -424  | -0.0616    | 1    | Zacharov (1954) |
| 26185.8675      | -415  | -0.0087    | 1    | Parenago (1938) |
| 27177.4641      | -400  | 0.0692     | 1    | Flora & Kukarkin (1953) |
| 29648.5184      | -306  | -0.0377    | 1    | Solov'yov (1948) |
| 31646.3938      | -329  | -0.1093    | 1    | Solov'yov (1948) |
| 33117.6109      | -306  | -0.0494    | 2    | Egen et al. (1957) |
| 37267.7531      | -242  | 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    | Moffet & Barnes (1984) |
| 44944.8381      | -1225 | 0.1023     | 3    | Berdnikov (2008) |
| 48368.8340      | -692  | -0.0361    | 3    | Hipsros (ESA 1997) |
| 48966.3048      | -585  | -0.0222    | 3    | Arellano Ferro et al. (1998) |
| 50353.947      | -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) |
| 53649.5902      | 130   | -0.0184    | 3    | INTEGRAL OMC |
| 53861.6215      | 163   | 0.0301     | 3    | ASAS (Pojmanski 2002) |
| 54272.7729      | 227   | 0.0014     | 3    | ASAS (Pojmanski 2002) |
| 54643.6666      | 285   | -0.0124    | 3    | ASAS (Pojmanski 2002) |
| 54979.4283      | 337   | -0.0126    | 3    | ASAS (Pojmanski 2002) |

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

| Night   | Obs. ID. | Mid-exposure time (s) | Exposure JD 2400000+ | \( v_{\text{rad}} \) (km/s) |
|---------|----------|-----------------------|----------------------|-----------------------------|
| 15-16 Apr. | F1487   | 55,667.8105            | 180                  | -1.98                        |
| 16-17 Apr. | F1645   | 55,668.8165            | 180                  | 6.04                         |
| 17-18 Apr. | F1723   | 55,669.8192            | 180                  | 15.00                        |
| 18-19 Apr. | F1805   | 55,670.8533            | 180                  | 22.48                        |

### 3.2 Radial velocity data of XX Sgr

Over half century the values published by [Loy (1937)] had been the only existing radial velocity data on XX Sgr. The radial velocity survey of [Barnes et al. (1988)] also included this Cepheid, and their two data implied a \( \gamma \)-velocity value different from the one determined Joy’s data. Suspecting the spectroscopic binary nature we initiated new radial velocity observations (discussed in Sect. 2.3). 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 to reveal the binarity of this Cepheid.

### 3.3 FEROS observations

XX Sgr was observed on four consecutive nights in April, 2011, 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 entrance aperture of 2′′, 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 \texttt{midas} environment. The pipeline performs the subtraction of bias and scattered light in the CCD, orders extraction, flatfielding 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 \texttt{IRAF}, we determined the radial velocities with the task \texttt{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 lack of hydrogen lines. We determined in the region 500-600 nm where a number of metallic lines are present and lack of hydrogen lines. We made barycentric corrections to each radial velocity value with the task \texttt{rvcorrect}. The estimated uncertainty of the radial velocities is 0.05 km s\(^{-1}\).

\(^1\) \texttt{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.
3.4 Binarity of XX Sgr

All radial velocity data 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 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 2 426 283; open circles - Barnes et al. (1988) with mid-JD 2 444 254; filled circles - Storm et al. (2011) and Berdnikov et al. (2010), with mid-JD 2 454 261 and mid-JD 2 454 730, respectively; triangles: our FEROS data listed in Table 4, with mid-JD 2 455 669.

The earliest radial velocity data by Joy (1937) imply a significantly different γ-velocity than all more recent ones 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 radial velocity changes.

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

4 CONCLUSIONS

We pointed out 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 on-line 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 (2004) indicating that the companion cannot be a star much hotter than the Cepheid component in either case. Further spectroscopic observations are necessary to characterise 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 on-going survey for pointing out binarity of Cepheids from the existing radial velocity data covering sufficiently long time interval.

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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REFERENCES

Abt H. A., Levy S. G. 1976, ApJS, 30, 273
Arellano Ferro A., Rojo Arellano E., Gonzalez-Bedolla S., Rosenzweig, P. 1998, ApJS, 117, 167
Barnes T. G. III, Moffett T. J., Slovak M. H. 1988, ApJS, 66, 43
Berdnikov L. N. 2008, VizieR On-line Data Catalog: II/285
Berdnikov L., Mattei J A., Beck S. J. 2003, J. AAVSO, 31, 146
Berdnikov L., Kniazev A. Yu., Usenko I. A., Kovtyukh V. V., Kravtsov V. V. 2010, AstL, 36, 490
Bersier D. 2002, ApJS, 140, 465
Bhaskaran T. P. 1933, J. Observateurs, 16, 95
Caldwell J. A. R., Coulson I. M., Dean J. F., Berdnikov L. N. 2001, JAD, 7, No. 4
Dean J. F. 1977, MNASSA, 36, 3
Eggen O. J. 1983, AJ, 88, 998
Eggen O. J., Gascoigne S. C. B., Burr E. J. 1957, MNRAS, 117, 406

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)
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