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On X-ray pulsations in β Cephei-type variables ⋆
(Research Note)

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ABSTRACT

Context. β Cep-type variables are early B-type stars that are characterized by oscillations observable in their optical light curves. At least one β Cep-variable also shows periodic variability in X-rays.
Aims. Here we study the X-ray light curves in a sample of β Cep-variables to investigate how common X-ray pulsations are for this type of stars.
Methods. We searched the *Chandra* and *XMM-Newton* X-ray archives and selected stars that were observed by these telescopes for at least three optical pulsational periods. We retrieved and analyzed the X-ray data for κ Sco, β Cru, and α Vir. The X-ray light curves of these objects were studied to test for their variability and periodicity.
Results. While there is a weak indication for X-ray variability in β Cru, we find no statistically significant evidence of X-ray pulsations in any of our sample stars. This might be due either to the insufficient data quality or to the physical lack of modulations. New, more sensitive observations should settle this question.

Key words. X-rays: stars – Stars: variables: general– Stars: individual: β Cru, κ Sco, α Vir

1. Introduction

Oscillating stars can be found almost everywhere in the HR diagram. The hottest and most massive oscillating stars are β Cephei-type variables. Born with masses between 8 $M_\odot$ and 18 $M_\odot$, and while still young and burning hydrogen in their cores, these B0–B2 type stars pulsate with periods of a few hours. The physical mechanism that drives these oscillations is understood well and attributed to changes in the opacity inside the star during the pulsation cycle ("κ-mechanism", Dziembowski & Pamiatnykh 1993).

Like other hot massive stars, β Cep-type variables drive stellar winds by their intense UV radiation. Photons that are scattered or absorbed in spectral lines transfer their momentum and thus accelerate the matter to supersonic velocities. This driving mechanism is unstable. It is generally believed that the wind instability results in shocks where part of the wind material is heated to X-ray emitting temperatures (e.g., Feldmeier et al. 1997a).

In β Cep-type variables, the deposition of mechanical energy from stellar pulsations can provide additional heating of the inner wind regions. This idea was put forward to explain the observed excess in the extreme UV spectrum of β CMa (Cassinelli et al. 1996). Recent work on classical Cepheids (Neilson & Lester 2008; Engle et al. 2014) has demonstrated that pulsations may power X-ray emission even from such cool stars. Thus, it seems reasonable to assume that stellar oscillations are closely linked with the X-ray production in β Cep variables.

Recently, it has been found that X-rays from the strongly magnetic β Cep-variable ξ^1 CMa pulsate in phase with the optical light curve[1] (Oskinova et al. 2014). To investigate whether ξ^1 CMa is a unique anomaly or if other β Cep-variables are also X-ray pulsators, we searched the X-ray archives for observations of β Cep-variables. The archival data for a selected sample of variable were analyzed to extract the X-ray light curves (see Figure 1) and study their variability. In this *Research Note* we present the results of this study.

2. Previous investigations of X-ray pulsations in β Cep-variables

Despite being a numerous and astrophysically important class of objects, β Cep-variables have not been studied well in X-rays. The first X-ray survey of six β Cep-type stars was performed with the *Einstein* observatory (Agrawal et al. 1984). No correlation was found between X-ray and pulsational, rotational, or binary properties.

The interest in X-ray properties of β Cep-variables was renewed with the launch of the *Rosat* X-ray observatory. Four

⋆ The scientific results reported in this article are based on observations made by the *Chandra* and *XMM-Newton* X-ray Observatories, data obtained from the *Chandra* and *XMM-Newton* Data Archives, and observations made by the *Chandra* and *XMM-Newton* and published previously in cited articles

[1] http://sci.esa.int/xmm-newton/54101/

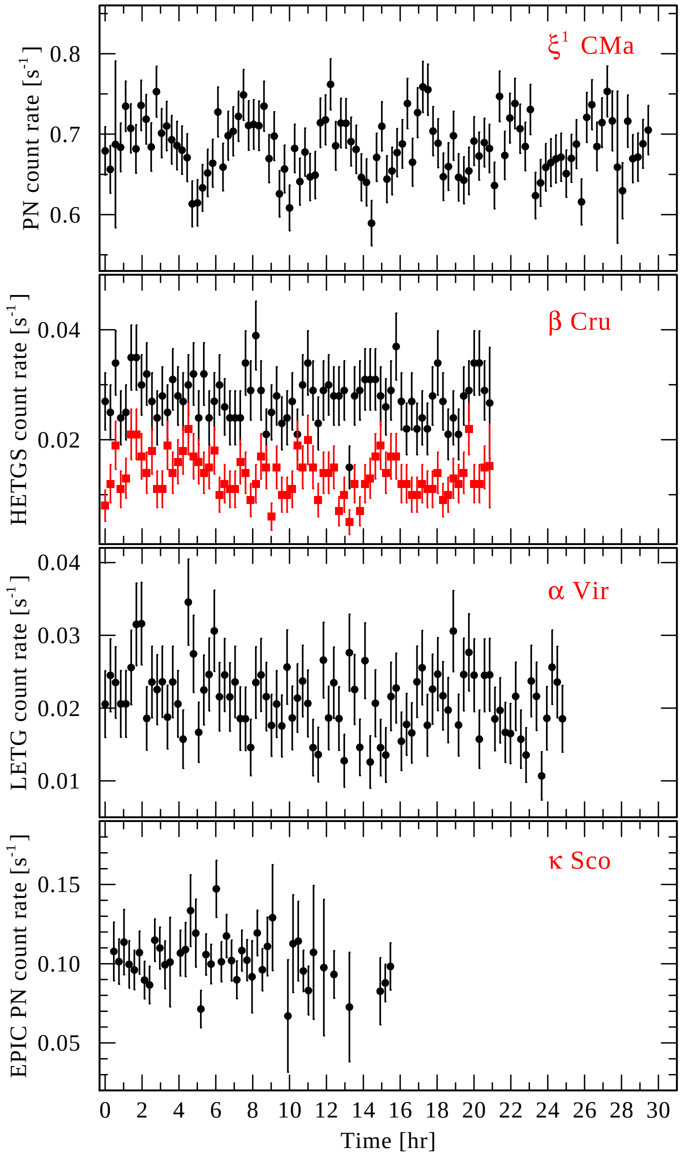

Fig. 1. X-ray light curves in 0.2–10.0 keV band of β Cep-type variables binned by 1000 s. The count rate of ξ^1 CMa is at least an order of magnitude higher than for the other stars. The horizontal axis shows the time after the start of the observation. Vertical bars represent 1σ errors. From top to bottom: the EPIC PN light curve of ξ^1 CMa; the HETG (added +1 and -1 order) light curve of β Cru, where the lower red light curve is in the hard band (1.0-10.0 keV) where the detection of pulsations was claimed by Cohen et al. (2008); LETG (added +1 and -1 order) light curve of α Vir; EPIC PN light curve of κ Sco.

β Cep stars were among the sample of 12 nearby near-main-sequence B-stars observed by *Rosat* (Cassinelli et al. 1994). Timing analysis was performed for all targets, but no variability was found except those attributed to the spacecraft wobble.

Rosat observations of β Cep-variables were further analyzed for the presence of X-ray pulsations by Cohen (2000), who mentions detecting periodic X-ray variability in four β Cephei-type variables. Specifically, for the star β Cephei, it was shown that the hypothesis of a constant source can be rejected with 98% confidence (see Fig. 5 in Cohen 2000). Cohen (2000) reports that the X-ray variability of β Cep is periodic with the same period as stellar pulsational period in the optical.

The binary system β Cep consists of a primary magnetic B2III-type star (Donati et al. 2001) and a secondary B6-B8e type star (Schnerr et al. 2006). The magnetosphere of the primary was studied in detail by Donati et al. (2001). It was predicted that an equatorial disk-like structure would be present around this star. A signature of such a disk was found using interferometry by Nardetto et al. (2011).

The occultations of X-ray emission sites by the disk should lead to observable X-ray variability on the rotational time scale. To test this hypothesis, the more sensitive *XMM-Newton* and *Chandra* observations of β Cep were obtained. However, only limited evidence of a modulation in the X-ray emission was found (Favata et al. 2009). The variability was observed at a 5% level but in anti-phase with the model predictions. Furthermore, Favata et al. (2009) performed a dedicated time analysis of the *XMM-Newton* light curves but did not uncover any periodicity, thus questioning the results of Cohen (2000). It was concluded that “the fact that Cohen (2000) did not perform a period search, but rather assumed the period and fitted the amplitude and phase, makes it likely that the period reported by Cohen (2000) is spurious” (Favata et al. 2009).

An assumed period was also fitted to the X-ray light curve β Cep-variable β Cru obtained with the *Chandra* X-ray observatory (Cohen et al. 2008). These authors applied a Kolmogorov-Smirnov test to the unbinned photon arrival times, as well as a χ^2 fitting of a constant source model to the binned light curve and found no evidence of X-ray variability. However, when a grid of test periods was fitted to the phased photon arrival times, it was found that for the X-ray light curve in the hard band ($h\nu > 1$ keV), the rejection probabilities for some of the assumed periods were quite low. This was the basis for suggesting that the periodic variability is detected with a period $P = 4.588$ h, which is the primary pulsation mode period in β Cru. However, Aerts et al. (2014) give the dominant frequency in β Cru as $5.95867\,\mathrm{d}^{-1}$ (or 4.0277 h). Polarimetric measurements for β Cru did not reveal any magnetic field (Hubrig et al. 2006). We revisit the archival X-ray observations of β Cru in Section 3.1.

Another β Cep-variable that has been studied in X-rays is β Cen. This is a binary system consisting of two β Cep-type stars of nearly equal mass with an orbital period of 357 days (Ausseloos et al. 2006, and references therein). The primary rotates significantly faster ($v \sin i = 190 \pm 20\,\mathrm{km\,s^{-1}}$) than the secondary ($v \sin i = 75 \pm 15\,\mathrm{km\,s^{-1}}$), as is evident from its rotationally broadened lines. The magnetic nature of the secondary, the slower rotating component in β Cen is reported by Alecian et al. (2011).

Sensitive observations of β Cen with *XMM-Newton* are reported by Raassen et al. (2005). The X-ray light curves with different time binnings and energy bands were extracted from data obtained by all *XMM-Newton* instruments and their combinations. Scargle periodograms were produced but no periodicities with high statistical confidence found in any of the data sets. Moreover, no hint of periodicity with the period seen in optical light curves was found even with low statistical confidence. However, when the light curves were compared with the constant source hypothesis, probabilities of 83% (for EPIC PN) and 49% (for EPIC MOS) were determined for the source not being constant.

Oskinova et al. (2011) considered a small sample of β Cep-variables with well known pulsational behavior and existing X-ray observations and searched for correlations between pulsational and X-ray properties. After confirming previous results known from the *Einstein* and *Rosat* works, no clear relations could be found. This could be due to the very limited sample.

The sample of β Cep-variable with X-ray light curves of sufficient quality is very small. It is observationally challenging to

Table 1. *XMM-Newton* and *Chandra* observations of β Cep-variables covering at least three stellar pulsational periods

	Sp	Period[A] [h]	Obs	Counts[B] $P^{-1}_{\rm puls}$	$n_{\rm p}$[C]	X-ray period?	$A_{\rm max}$[D]	Comment[E]	Reference
β Cen	B1III	3.684	XMM	25000	6	no	< 3%	mag	Raassen et al. (2005)
β Cep	B2IIIe	4.572	XMM	2500	9	no	< 6%	mag	Favata et al. (2009)
β Cru	B0.5IV	4.589	CXO	225[F]	4	no	< 26[F]%	non-mag	this work
κ Sco	B1.5III	4.795	XMM	1700	3	no	< 11%	?	this work
α Vir	B1.5IV-V	6.521	CXO	470	3	no	< 21%	?	this work
ξ^1 CMa	B0.5-1IV	5.030	XMM	12800	6	yes	10%	mag	Oskinova et al. (2014)

A – main period of stellar oscillations as listed in the "Catalog of Galactic β Cephei stars" (Stankov & Handler 2005);
B – number of counts per optical pulsation period (EPIC PN for *XMM-Newton*);
C – number of pulsation periods covered by X-ray light curve;
D – amplitude of X-ray pulsations or its upper limit for non-detections;
E – magnetic field presence;
F – in the hard band where the pulsations were suggested by Cohen et al. (2008);

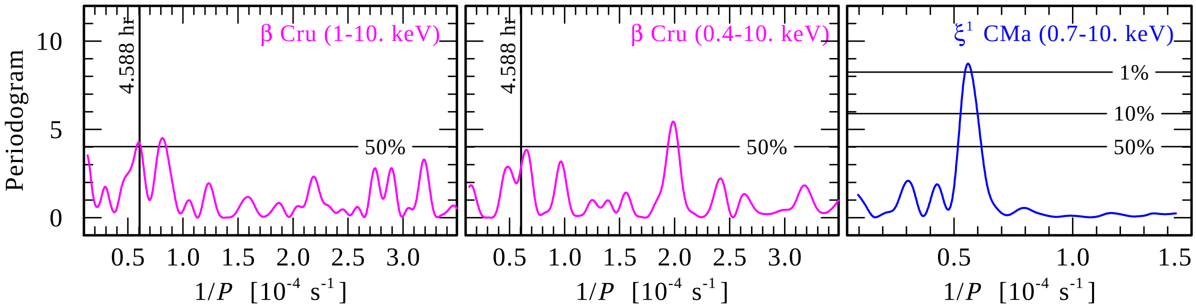

Fig. 2. Power density spectra based on the Fourier transform (Scargle 1982; Horne & Baliunas 1986) of X-ray light curves. The periodogram was calculated from $\nu = 1/P$ to $\nu = N_0/P$ with a spacing P^{-1}, where N_0 is the number of data points. Various false alarm probability levels are marked. From left to right: 1) combined zero and first-order Chandra HETGS light curve of β Cru in hard (1.-10.0 keV) band where pulsations were suggested by Cohen et al. (2008). There is about a 50% probability that this period is spurious. 2) zero-order Chandra's HETGS light curve of β Cru in full (0.2-10.0 keV) band, there is more than a 50% probability that this period is spurious; 3) EPIC PN light curve of ξ^1 CMa in hard band (0.7-10.0 keV).

obtain X-ray light curves of high enough quality to establish periodic variability with high statistical significance. The stellar oscillations periods are typically four to six hours. To confidently detect pulsations in a light curve, the observations should be long enough to cover a number of periods. (In this study we adopt the minimum of three periods.) At the same time, the source should be X-ray bright in order to have enough counts per time bin for a meaningful statistical analysis. In Table 1 we summarize the objects that satisfy the above criteria.

3. Looking for the variability in X-ray light curves of β Cru, κ Sco, and α Vir

3.1. β Cru

We retrieved the archival *Chandra* X-ray observations of β Cru (see Table 2) and analyzed them using the latest calibration. The X-ray light curves were extracted in different energy bands as defined in Cohen et al. (2008): full (0.4-10.0 keV), soft (0.4-1.0 keV), and hard (1.0-10.0 keV). The light curves were binned in the 1000 s and 3600 s bins, and examples of light curves are shown in Fig. 1.

For HETG dispersed photon data, we computed light curves using the ACIS-Grating-Light-Curve (*aglc*) program (used by the Chandra Grating-Data Archive and Catalog processing (TGCat, Huenemoerder et al. 2011)), in order to also produce a curve in the hard band, in addition to the default broad-band curve available from TGCat. Zeroth-order curves (not shown) were created with the CIAO (Fruscione et al. 2006) program, *dmextract*. The program *aglc* computes rates with the explicit exposure records for each CCD, using the user-specified combination of grating types, orders, and bandpasses. For relatively low count-rate systems, such as those analyzed here, with time binning comparable to the dither period and with broad energy ranges spanning all CCDs, chip-to-chip differences and chip gap effects are negligible. Furthermore, for the dispersed photons, there is no concern with light leaks, as there could be for zeroth orders of optically bright objects.

Using the χ^2 test, the X-ray light curves were compared with those expected from the constant source hypothesis. As an example, for the zeroth-order light curve in full band and binned by 1000 s, the probability value is $P \approx 0.168$, which implies that the probability that the observed variability is solely a chance occurrence is less than $\approx 17\%$, which is statistically insignificant. Thus, the null-hypothesis assuming that the source is constant cannot be rejected. On the other hand, for the same light curve but binned into 3000 s, $P \approx 0.0044$, which is statistically significant at the level $\alpha = 0.01$. In the hard band, for the combined zeroth- and first-order light curve, $P \approx 0.06$ is statistically insignificant with $\alpha = 0.05$.

Thus, similar to the case of β Cen, there are marginal indications of source variability. To investigate the presence of periodic modulations further, we constructed Scargle periodograms, with some examples shown in Fig. 2. A peak with a false alarm probability of about 50% is present at the frequency close to the stellar pulsational period. However, this is not the most prominent fea-

Table 2. Log of analysed observations

Object	Telescope	ObsID	Start time	Duration [ks]	Count rate [s^{-1}]
β Cru	CXO/HETG	2575	2002-02-01	75	0.03 (-1+1 order)
κ Sco	XMM	0503500201	2008-03-12	64	0.1 (pn)
α Vir	CXO/LETG	4509	2004-03-09	90	0.02 (-1+1 order)

ture in the periodograms. For comparison, we show in Fig. 2 a periodogram of the ξ^1 CMa in 0.7-10.0 keV (hard) band, where the peak at the stellar pulsation frequency has a false alarm probability less than 1%.

Thus, from reanalysis of the *Chandra* data on β Cru, we must conclude that in the statistical sense, it is likely that the period reported by Cohen et al. (2008) is spurious. Better quality observations are needed to establish whether the periodicity is indeed present in β Cru's X-ray light curve.

3.2. X-ray variability of κ Sco

The spectroscopic binary system, κ Sco, has two B-type components orbiting with a period of 195 d. The primary (B1.5III) is responsible for the pulsational variability (Harmanec et al. 2004) observed photometrically with a main period of 4.797 h (Handler & Schwarzenberg-Czerny 2013).

We retrieved the archival *XMM-Newton* observations of κ Sco (see Table 2) and reprocessed them using the most recent data analysis software (SAS 14.0.0) and calibration files. The source κ Sco has a visual magnitude $m_V = 2.4$, therefore the thickest optical light blocking filter was used in observation. For the *XMM-Newton* detectors operating in full-frame mode and with the thick filter, no optical loading is expected for stars with $m_V > -2$ mag (for the PN camera).

Unfortunately, the observations were affected by the high background from proton flares. The observations were filtered using good time intervals resulting in a useful exposure time of 44 ks. Here, κ Sco is sufficiently isolated without nearby X-ray sources. From the region with radius 25″ and centered on the coordinates of κ Sco, we extracted the EPIC PN light curve in 0.2–10.0 keV energy band and restricting the patterns to single and double events. Background regions were carefully selected on the same CCD. The net light curves with different time binnings were produced using the *epiclccorr* task. As a next step, the X-ray light curves were tested for variability. As an example, in the full band and binned with a 1000 s light curve, the probability value $P \approx 0.83$ is not significant even with $\alpha = 0.1$. Thus, the null hypothesis about the X-ray light curve from κ Sco being constant cannot be rejected. No useful information about the presence of periodic variability could be obtained on the basis of Fourier periodograms, owing to the limited quality of the data.

3.3. X-ray variability of α Vir

Spica (α Vir) is a spectroscopic binary with a period of $\sim$ 4 d in an eccentric orbit. The primary component (B1.5IV-V) is classified as a β Cep-type variable, but its pulsational behavior is not stable (see discussion in Palate et al. 2013).

Spica was observed by *Chandra* LETG for 90180 s in 2005-03-15 (*Chandra* observation identifier 4509). We retrieved the X-ray light curves (see Fig. 1) from the TGCat and tested them for variability. As mentioned above, there is no concern about

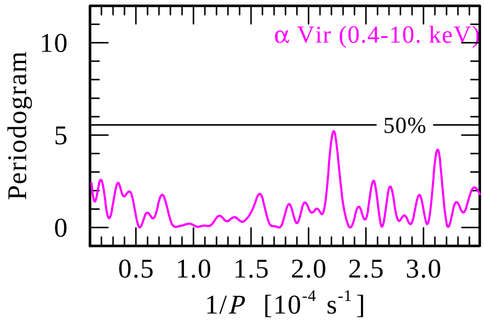

Fig. 3. Power density spectrum based on the Fourier transform (Scargle 1982; Horne & Baliunas 1986) of X-ray light curve (0.4-10.0 keV) of α Vir. The false alarm probability at 50% level is marked.

optical or UV light leakage since we are not using the zeroth-order photons. For extremely high UV flux sources, the LETG coarse support structure acts as a crude disperser, and it can sometimes produce spurious signal for LETG used with HRC-S (Drake 2010), but we see no such evidence in this LETG/ACIS-S spectrum.

Based on the χ^2-test, the chance probability value $P \approx 0.19$ is not significant. We went on to conduct a period search, but all peaks in the Fourier periodogram are statistically insignificant (see Fig. 3). No useful information on the X-ray variability was obtained from other statistical tests either. Moreover, in the case of α Vir with its unstable pulsational behavior in order to reach any conclusions about the correlation between stellar oscillations and X-ray variability, it would be necessary to observe the star simultaneously in X-rays and in optical.

The *Chandra* observations of α Vir lasted for about 25 h, thus covering about a quarter of the orbital period of this binary star. Although no optical eclipses have been observed in this system (Palate et al. 2013), an influence of binarity on the X-ray light curve cannot be excluded a priori.

4. Discussion

Our study of a small sample of X-ray lightmcurves from β Cep-variables did not reveal any periodic variability. However, the X-ray count rate of the only star where the X-ray pulsations are clearly detected, ξ^1 CMa, is much greater than for the other stars considered here. It is important to assess what the upper limit is on an amplitude of modulation that could have been detected in our sample stars with the available data.

We therefore wish to study a star with a periodic signal of relative amplitude A and N counts per pulsational period. The noise level can be approximated as $2\sqrt{N/n_p}$, where n_p is the number of periods. We assume that a significant detection must be a factor 4× higher than the noise level. Thus, we can derive the minimum detectable amplitude for a given observation. The results are shown in Table 1. Only for κ Sco the sensitivity of observations was marginally sufficient to detect a variability on a level of about 10%. The data sets for β Cru and α Vir are not good enough to uncover periodic variability on a level similar to that seen in ξ^1 CMa even if it were present.

While we did not found any periodic pulsations, our analysis showed that some of the sample stars show marginal evidence of X-ray variability. For some β Cep-type variables, such variability has also been previously reported in the literature.

Significant stochastic X-ray variability is expected in the models of X-ray generation in stellar winds (Feldmeier et al. 1997b; Oskinova et al. 2001b). However, the most sensitive X-ray observations of an O-type star (the *XMM-Newton* observations of ζ Puppis with the total exposure time of about 1 Ms) revealed a surprising lack of short time-scale stochastic variability (Nazé et al. 2013).

On the other hand, the evidence is accumulating that the X-ray variability associated with stellar rotation may be present in massive star winds. Berghoefer et al. (1996) observed the supergiant ζ Puppis for 11 days and found modulations with a frequency of $1.44\,\mathrm{d}^{-1}$ in the Hα line profiles, as well as in the X-rays in the 0.9-2.0 keV band. They reported an amplitude of X-ray variability of 6% and suggested that these variations are periodic. This suggestion was not confirmed by later studies based on *ASCA* and *XMM-Newton* observations (Oskinova et al. 2001a; Nazé et al. 2013). Howarth & Stevens (2014) reported the detection of a period $P = 1.780\,\mathrm{d}$ in optical light curves of ζ Puppis and suggested that this period may be due stellar pulsations. While indeed the X-ray modulations on a time scale of a day are present in ζ Puppis, no coherent periodicity in X-ray emission has been confirmed for this object so far.

Periodic modulations of X-ray emission were reported for the O-type dwarf ζ Oph (Oskinova et al. 2001a). However, also in this case, we lack any information on the repeatability of X-ray modulations. Two other O-type stars, ξ Per (Massa et al. 2014) and ζ Ori (A. Pollock, private communication), also show modulations of X-ray emission on a time scale of days. Interestingly, *XMM-Newton* observations of a Wolf-Rayet type star, WR 6 showed that its X-ray light curve changes quasi-periodically (Ignace et al. 2013). We speculate that, similar to WR 6, in the OB-type stars the X-ray variability owing to the rotation has quasi-periodic character.

A small fraction of B-type stars possess strong magnetic fields (e.g., Hubrig et al. 2006; Morel et al. 2014, and references therein). If a magnetic field has a dipole configuration, it can channel the wind toward the magnetic equator, where wind streams from opposite hemispheres collide and produce a strong shock (magnetically confined wind shock (MCWS), Babel & Montmerle 1997; ud-Doula et al. 2014). The MCWS predicts the X-ray variability of magnetic massive stars associated with the stellar rotation due to the occupation of X-ray emitting regions by the cold torus of matter accumulated in the equatorial plane (Donati et al. 2001, 2002). Such X-ray modulations on a rotational time scale are sometimes observed (e.g., Gagné et al. 1997; Pillitteri et al. 2014); however, this is not ubiquitous behavior among magnetic massive stars – some of these well-known objects, such as τ Sco, do not show any evidence of X-ray variability over the stellar rotation period (Ignace et al. 2010).

The data sets that we consider in this paper do not cover long enough time intervals to test the X-ray light curves for modulations due to stellar rotation or orbital motion. Thus, it is not clear what the true nature is of X-ray variability observed in some of our sample stars.

However, in none of our sample stars, β Cru, κ Sco, or α Vir, do we find statistically significant evidence for periodic X-ray variability. Up to now, the unambiguous presence of X-ray pulsations with the same period and in phase with the optical light curve has only been detected in the magnetic star ξ^1 CMa. It remains to be seen whether this object is exceptional or if new, better quality observations will reveal similar properties in other β Cep-variables.

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References

Aerts, C., Simón-Díaz, S., Groot, P. J., & Degroote, P. 2014, A&A, 569, A118
Agrawal, P. C., Singh, K. P., Riegler, G. R., & Stern, R. A. 1984, MNRAS, 208, 845
Alecian, E., Kochukhov, O., Neiner, C., et al. 2011, A&A, 536, L6
Ausseloos, M., Aerts, C., Lefever, K., Davis, J., & Harmanec, P. 2006, A&A, 455, 259
Babel, J. & Montmerle, T. 1997, A&A, 323, 121
Berghoefer, T. W., Baade, D., Schmitt, J. H. M. M., et al. 1996, A&A, 306, 899
Cassinelli, J. P., Cohen, D. H., Macfarlane, J. J., et al. 1996, ApJ, 460, 949
Cassinelli, J. P., Cohen, D. H., Macfarlane, J. J., Sanders, W. T., & Welsh, B. Y. 1994, ApJ, 421, 705
Cohen, D. H. 2000, in Astronomical Society of the Pacific Conference Series, Vol. 214, IAU Colloq. 175: The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat, 156
Cohen, D. H., Kuhn, M. A., Gagné, M., Jensen, E. L. N., & Miller, N. A. 2008, MNRAS, 386, 1855
Donati, J., Babel, J., Harries, T. J., et al. 2002, MNRAS, 333, 55
Donati, J., Wade, G. A., Babel, J., et al. 2001, MNRAS, 326, 1265
Drake, J. 2010, Chandra News, 17, 21
Dziembowski, W. A. & Pamiatnykh, A. A. 1993, MNRAS, 262, 204
Engle, S. G., Guinan, E. F., Harper, G. M., Neilson, H. R., & Remage Evans, N. 2014, ApJ, 794, 80
Favata, F., Neiner, C., Testa, P., Hussain, G., & Sanz-Forcada, J. 2009, A&A, 495, 217
Feldmeier, A., Kudritzki, R., Palsa, R., Pauldrach, A. W. A., & Puls, J. 1997a, A&A, 320, 899
Feldmeier, A., Puls, J., & Pauldrach, A. W. A. 1997b, A&A, 322, 878
Fruscione, A., McDowell, J. C., Allen, G. E., et al. 2006, in Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference, Vol. 6270, SPIE Conference Series
Gagné, M., Caillault, J.-P., Stauffer, J. R., & Linsky, J. L. 1997, ApJ, 478, L87
Handler, G. & Schwarzenberg-Czerny, A. 2013, A&A, 557, A1
Harmanec, P., Uytterhoeven, K., & Aerts, C. 2004, A&A, 422, 1013
Horne, J. H. & Baliunas, S. L. 1986, ApJ, 302, 757
Howarth, I. D. & Stevens, I. R. 2014, MNRAS, 445, 2878
Hubrig, S., Briquet, M., Schöller, M., et al. 2006, MNRAS, 369, L61
Huenemoerder, D. P., Mitschang, A., Dewey, D., et al. 2011, AJ, 141, 129
Ignace, R., Gayley, K. G., Hamann, W.-R., et al. 2013, ApJ, 775, 29
Ignace, R., Oskinova, L. M., Jardine, M., et al. 2010, ApJ, 721, 1412
Massa, D., Oskinova, L., Fullerton, A. W., et al. 2014, MNRAS, 441, 2173
Morel, T., Castro, N., Fossati, L., et al. 2014, The Messenger, 157, 27
Nardetto, N., Mourard, D., Tallon-Bosc, I., et al. 2011, A&A, 525, A67
Nazé, Y., Oskinova, L. M., & Gosset, E. 2013, ApJ, 763, 143
Neilson, H. R. & Lester, J. B. 2008, ApJ, 684, 569
Oskinova, L. M., Clarke, D., & Pollock, A. M. T. 2001a, A&A, 378, L21
Oskinova, L. M., Ignace, R., Brown, J. C., & Cassinelli, J. P. 2001b, A&A, 373, 1009
Oskinova, L. M., Nazé, Y., Todt, H., et al. 2014, Nature Communications, 5, 4024
Oskinova, L. M., Todt, H., Ignace, R., et al. 2011, MNRAS, 416, 1456
Palate, M., Koenigsberger, G., Rauw, G., Harrington, D., & Moreno, E. 2013, A&A, 556, A49
Pillitteri, I., Wolk, S. J., Goodman, A., & Sciortino, S. 2014, A&A, 567, L4
Raassen, A. J. J., Cassinelli, J. P., Miller, N. A., Mewe, R., & Tepedelenlioǧlu, E. 2005, A&A, 437, 599
Scargle, J. D. 1982, ApJ, 263, 835
Schnerr, R. S., Henrichs, H. F., Oudmaijer, R. D., & Telting, J. H. 2006, A&A, 459, L21
Stankov, A. & Handler, G. 2005, ApJS, 158, 193
ud-Doula, A., Owocki, S., Townsend, R., Petit, V., & Cohen, D. 2014, MNRAS, 441, 3600