A TESS search for donor-star pulsations in High-Mass X-ray Binaries

Gavin Ramsay, 1 Pasi Hakala, 2 Philip A. Charles 3
1 Armagh Observatory & Planetarium, College Hill, Armagh, BT61 9DG, UK
2 Finnish Centre for Astronomy with ESO (FINCA), Quantum, FI-20014 University of Turku, Finland
3 School of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK

Accepted 2022 August 3. Received 2022 August 3; in original form 2022 June 29

ABSTRACT

Ground-based optical photometry of the counterparts of High-Mass X-ray Binaries (HMXBs) has revealed the presence of periodic modulations on timescales of ~0.3-0.5 d. More recent space-based observations (Corot and TESS) of OB and Be stars have shown that pulsations caused by p and g modes are common in early type stars. We have therefore undertaken a systematic search for variability in the optical counterparts of 23 HMXBs (mostly neutron star systems, but including one black hole, Cyg X-1) using TESS data primarily in 2 min cadence mode. After removing the orbital period modulation in four systems, we find that all 23 sources show evidence for quasi-periodic variability on periods shorter than ~1 d. We compare their power spectra with those from observations of other OB and Be type stars. In two systems, V725 Tau and HD 249179 (which may not be a HMXB), we find evidence for an outburst, the former being simultaneous with an X-ray flare. We search for changes in the power spectra over the outburst duration, and compare them with outbursts seen in other Be systems.

Key words: stars: emission line Be – stars: circumstellar matter – stars: early type – stars: oscillations – X-rays: binaries

1 INTRODUCTION

High-Mass X-ray Binaries (HMXBs) are intense X-ray sources consisting of a compact star, either a neutron star (NS) or a black hole (BH), and a giant or supergiant companion star which is close to filling its Roche Lobe. Accretion onto the primary takes place in the form of an accretion disc and/or via a stellar wind from the hot companion. They have orbital periods ranging from days to months and many have a high binary eccentricity which can cause short duration X-ray outbursts on the orbital cycle as the companion star passes through periastron (Type I outbursts). Longer duration outbursts lasting several orbital cycles (Type II outbursts) are seen less frequently (see Okazaki & Negueruela (2001) for an overview of the outburst models). For a detailed review of HMXBs see Lewin & van der Klis (2006).

The optical light curves of HMXBs over an interval of days and weeks can be complex, and is a combination of the ellipsoidal modulation of the secondary star with the effect of a tilted and precessing accretion disc (e.g. Gerend & Boynton (1976)). On shorter timescales, observations by Gutierrez-Soto et al. (2011) of two HMXBs revealed short period modulations which were identified as being due to nonradial pulsations from the companion star in V635 Cas (0.30 d) and GSC 03588-00834 (0.45 d). Observations using wide-field imaging surveys, such as OGLE IV, have allowed the discovery of short period photometric modulations in other HMXBs, e.g. Schmidtke et al. (2014, 2016, 2019). If the nature of these periodic signals can be effectively modelled they can give insight into the internal structure of the companion star in HMXBs.

The discovery of pulsations from the secondary star in some HMXBs is not especially surprising since they are OB stars with spectral types ranging from supergiants (e.g. HDE 226868 the optical companion to Cyg X-1) to dwarfs (e.g. V490 Cep), which have previously shown pulsations. The slowly pulsating B-type stars (SPBs) display high-order g-modes (with periods ≥ 6 hr) whilst the β Cep stars can show lower-order p modes (periods ~ 1–8 hr) and g-modes (see De Cat et al. (2010) for a review of observations made using Corot). More recently, Labadie-Bartz et al. (2022) made an analysis of 432 classical Be stars observed by TESS during its first year of operation. Almost all of these stars showed significant variability and their power spectra could be classified, with 85 percent showing closely spaced frequencies in their power spectra.

The launch of satellites such as Corot and TESS have provided a golden opportunity to search for pulsations in stars of all types, including X-ray binaries. Although none were known in the original 115 square degree Kepler field (Borucki et al. 2010), the prototypical LMXB Sco X-1 was observed when Kepler was repurposed as K2 with fields along the ecliptic being observed for 2 month blocks (see Scaringi et al. (2015); Hakala et al. (2015); Hynes et al. (2016)). TESS was launched in April 2018 and although it does not go as deep as Kepler, it does provide high signal-to-noise photometry of sources down to V ~ 13–14 (see Ricker et al. (2015) for more details). In its initial 2 year mission it observed ~3/4 of the whole sky, with a gap along the ecliptic plane and an additional section of the northern hemisphere. Given that some HMXBs are optically bright, this provides an opportunity to search for short period pulsations, of the type identified by Gutierrez-Soto et al. (2011) and Schmidtke et al. (2014, 2016, 2019).

In this paper we present observations of the optical light curve of 23 HMXBs and identify those which show evidence for short periodic, likely pulsation, variations. We have not attempted to do a full frequency analysis of the light curves, but rather determine how common pulsations are in the donor-stars of HMXBs. Further, we
2 THE HMXB SAMPLE

As we are searching for periodic variability on a timescale ≤1 d, we restrict our sample to include HMXBs which have TESS 2 min cadence data or a calibrated light curve made using full-frame image data (see §3 for further details). We cross-matched all stars observed in Cycles 1–4 with the HMXB catalogue of Liu et al. (2006), finding 23 sources which are detailed in Table 1. Four of our sample have supergiant donor stars, while more than half the sample have Be type donors. Although HD 49798 is classed as HMXB in Liu et al. (2006) this appears to be a sdO/WD binary and have therefore not included it in this study. HD 141926 is included in the catalogue of candidate Herbig Ae/Be stars (Vieira et al. 2003) and hence its evolutionary state will differ from other stars in this sample. In §4.2 we note that HD 249179 might not be an HMXB; however, for reasons outlined there we decided to retain this source as part of our study.

For further insight as to the nature of the donor stars in these 23 HMXBs, we use the Gaia EDR3 parallaxes (Gaia 2021) to infer their distances. In practise we use a routine in the STILTS package (Taylor 2006) and use a scale length L=1.35 kpc, which is appropriate for stellar populations in the Milky Way in general. From these distances we determine their absolute magnitudes in the Gaia G band (a very broad optical filter), $M_G$, using the mean Gaia $G$ magnitude. The other key observables are the blue ($BP$) and red ($RP$) filtered magnitudes, which are derived from the Gaia Prism data. We then deredden the ($BP - RP$), $M_G$ values using the 3D-dust maps derived from Pan-STARRS1 data (Green et al. 2019) and the relationship between $E(B-V)$, $E(BP - RP)$, $A_G$ and $E(BP - RP)$ outlined in Andrae et al. (2018). For those stars just off the edge of the Pan-STARRS1 field of view (stars with $\delta < -30^\circ$) we take the nearest reddening distance relationship. We include the distances to our targets and $M_G$, ($BP - RP$), in Table 1.

The nearest HMXB in our sample is $\mu^2$ Cru which is only 120 pc distant (we note that although $\mu^2$ Cru is bright, $T_{\text{mag}}$=5.3, there is another star 35.3 $^\circ$ distant which is $T_{\text{mag}}$=4.2, so some contamination in the light curve will be present). In contrast, V490 Cep (1H 2138+579) is ~9 kpc distant, although with a large uncertainty. We show the dereddened $M_G$, and ($BP - RP$), values for our sample in Figure 1, where the size of the symbols reflect the binary orbital period (if known). To give context, we also show the apparent $M_G$ and ($BP - RP$) values for stars within 50 pc and assume they show negligible reddening. What is immediately striking is the spread in position of our sample HMXBs in the Gaia HRD. Cyg X-1, the one system which we know has a BH primary is near the upper part of the distribution. Those sources close to Cyg X-1 are V662 Cas (a NS primary with a very slow rotation period of 2.78 hr (Hall et al. 2000)) and CI Cam the nature of whose primary remains controversial.

3 THE TESS DATA

TESS, launched on 18th April 2018, has four telescopes, each with an aperture of 10.5 cm that cover a 24° × 90° sector of sky for ~27 d. In the prime mission, the majority of the sky was observed apart from a strip along the ecliptic plane. In the first year of the extended mission, the southern ecliptic hemisphere was observed for a second time, whilst in the second year those regions not observed in the prime mission were covered with a second observation of northern fields.

The TESS camera detectors have 21″ × 21″ pixels, with the PSF covering more than 2x2 pixels, which can make blending an issue especially in crowded fields. For the first two years, ~20,000 predefined targets were observed in each sector with a 2 min cadence, with a 20 s cadence being introduced in year 3. In years 1 and 2, full-frame images with a cadence of 30 min are available, with the cadence increasing to 10 min in year 3. All of our targets, with the exception of HD 109857 (which has 30 min cadence in sectors 11–12 and 10 min in sectors 38–39), were observed in 2 min cadence.

We downloaded the calibrated light-curves with 2 min cadence of our targets from the MAST data archive. We used the data values for PDCSAP_FLUX, which are the Simple Aperture Photometry values, SAP_FLUX, after the removal of systematic trends common to all stars on that Chip. Each photometric point is assigned a QUALITY flag which indicates if the data has been compromised to some degree by instrumental effects. For HD 109857, we obtained calibrated light-curves from full-frame images using the TESS-SPOC pipeline.

1 The sources in this paper were on the 2 min cadence list thanks to their inclusion on the following Guest Investigator programs: G011060/PI Paunzen; G011155/PI Huber; G011204/PI Pepper; G011224/PI Redfield; G011268/PI Scarioni; G011281/PI Silvotti; G022020/PI Dorn-Wallenstein; G022062/PI Prsa; G022071/II Scarioni; G022172/II Labadie-Bartz; G022184/II Coley; G03156/PI Pope; G03186/II Labadie-Bartz; G03221/PI Barlow; G04067/II Wisniewski; G04074/II Bowman; G04103/II Huber.

2 following the guidelines of Bailer-Jones (2015); Astraatmadja & Bailer-Jones (2016) and Gaia (2018), which is based on a Bayesian approach.

3 https://archive.stsci.edu/tess/
### Table 1. Properties of HMXBs observed by TESS in 2 min cadence mode.

| Name            | Other Name | TIC     | $T_{\text{sec}}$ | Sectors | Spectral Type | $P_{\text{orb}}$ (d) | Distance$^2$ (kpc) | $MG_v^3$ | $(BP - RP)_v^5$ | Primary | Power Spectra Type |
|-----------------|------------|---------|------------------|---------|---------------|----------------------|--------------------|-----------|----------------|---------|-------------------|
| GP Vel          | Vela X-1   | 191450569 | 6.3              | 8.9     | B0.5v         | 8.96                 | 2.0$^{+0.1}_{-0.1}$ | -5.8      | 0.2            | NS      | Mid               |
| Hen 3-640       | 1A 1118-615 | 468095832 | 10.7             | 10.37,38| O9.5v         | 24.0                 | 3.0$^{+0.2}_{-0.2}$ | -2.0      | 0.9            | NS      | Mid/Low           |
| V801 Cas        | 2S 1145-619  | 324288119 | 8.7              | 10.37,38| B0.2IIIe      | 187.5                | 2.1$^{+0.1}_{-0.1}$ | -4.0      | 0.0            | NS      | Mid               |
| BZ Cru          | IH 1249-637 | 413936219 | 5.2              | 11.37,38| B0.5IHe       | 0.44$^{+0.03}_{-0.03}$ | -3.4      | 0.4            | NS      | Mid               |
| $\mu^2$ Cru     | IH 1255-567 | 261862960 | 5.3              | 11.37,38| B3Ve          | -0.12$^{+0.00}_{-0.00}$ | -0.4      | -0.2           | Mid     |                   |
| HD 141926       | IH 1555-552 | 84513533  | 8.0              | 12.39   | B2IIIb        | -1.4$^{+0.1}_{-0.1}$ | 2.7       | 0.5            | Isolated |                   |
| V884 Sco        | 4U 1700-37  | 347468930 | 6.1              | 12      | O6.5Iaf       | 3.41                 | 1.6$^{+0.2}_{-0.2}$ | -5.3      | 0.1            | Mid     |                   |
| HDE 226868      | Cyg X-1    | 102604645 | 7.9              | 14      | O9.7 Iab      | 5.6                  | 2.2$^{+0.1}_{-0.1}$ | -4.3      | 0.7            | BH      | Mid               |
| GSC 03588-0034  | SAX 2103.5+4545 | 273066197  | 13.0             | 16      | B0Ve          | 12.68                | 7.4$^{+0.2}_{-0.2}$ | -2.3      | 0.7            | NS      | Mid               |
| V490 Cep        | IH 2138+579 | 341320747 | 13.0             | 16      | B1-B2Ve       | 9.6                  | 2.8       | 0.6            | NS      | Mid               |
| BD +53 2790     | 4U 2206+543 | 328546890 | 9.6              | 16      | O9.5Ve        | 9.57                 | 3.3$^{+0.1}_{-0.1}$ | -4.1      | -0.2           | NS      | Mid/Low           |
| V662 Cas        | 2S 0114+650 | 54469882  | 9.8              | 18      | B0.5b         | 11.6                 | 5.1$^{+0.1}_{-0.1}$ | -4.5      | 0.8            | NS      | Mid               |
| V635 Cas        | 4U 0115+634 | 54527515  | 13.3             | 18      | B0.2Ve        | 24.3                 | 7.6$^{+0.2}_{-0.2}$ | -1.7      | 1.3            | Isolated |                   |
| BQ Cam          | EXO 0331+530 | 354185144 | 13.0             | 18      | O8.5Ve        | 34.25                | 7.0$^{+0.2}_{-0.2}$ | -1.8      | 1.5            | NS      | Mid               |
| X Per           | 4U 0352+309 | 94471007  | 6.0               | 18      | B0Ve          | 250.3                | 0.61$^{+0.03}_{-0.03}$ | -3.2      | 0.3            | NS      | Mid               |
| CI Cam          | XTE J0421+560 | 418090700 | 9.9              | 19      | sgB[e]       | 19.41                | 4.7$^{+0.1}_{-0.1}$ | -4.0      | 0.9            | Isolated |                   |
| LS V +44 17     | RX J0409.9+4431 | 410336237 | 10.0             | 19      | B0.2Ve        | 150.0                | 2.6$^{+0.1}_{-0.1}$ | -2.8      | 0.5            | NS      | Mid               |
| V420 Aur        | EXO 051910+3737.7 | 143681075 | 7.0              | 19      | B0IVpe        | 1.41                 | -4.2      | 0.1            | Isolated |                   |
| HD 109835$^4$   | IH 1253-761 | 360632151 | 6.5              | 11,12,38,39| B8V          | 0.2$^{+0.00}_{-0.00}$ | -0.3      | 0.1            | Isolated |                   |
| V725 Tau        | 1A 0355+262 | 75078662  | 8.2               | 43-45   | O9/B0IIIVe     | 111.0                | 1.9$^{+0.1}_{-0.1}$ | -3.7      | 0.5            | NS      | Isolated          |
| IGR J06074+2205 |            | 45116246  | 11.8             | 43      | B0.5Ve        | 6.9$^{+0.1}_{-0.1}$ | -3.8      | -0.1           | Isolated |                   |
| BD+47 3129      | RX J2030.5+4751 | 187940144 | 8.7              | 41      | B0.5VIIIe     | 2.39$^{+0.1}_{-0.1}$ | -3.9      | 0.2            | Isolated |                   |
| HD 249179       | 4U 0548+29  | 78499882  | 9.2               | 43-45   | B3Ve          | 1.68$^{+0.1}_{-0.1}$ | -2.0      | -0.3           | Mid     |                   |

1 Magnitude in the TESS pass-band; 2 From Gaia EDR3; 3 De-reddened; 4 Data taken in 30 min cadence.

---

**Figure 2.** Upper Panel: A nine day section of TESS 2 min cadence data of V635 Cas from sector 18. There is a clear modulation on a period of 0.30 d. Middle Panel: The TESS 2 min cadence data of HDE 226868 (Cyg X-1) obtained in sector 14. A high amplitude modulation is seen on the orbital period (5.6 d) and half the orbital period. Lower Panel: The light curve of HDE 226868 detrended to remove the signature of the orbital period.
(Caldwell et al. 2020), again from the MAST data archive\(^4\). We removed those points which did not have QUALITY=9 and normalised each light-curve by dividing the flux of each point by the mean flux of the star in that sector.

As an example of the light curves obtained by TESS, we show in Figure 2 V635 Cas, which has a clear short-period modulation with the same period (0.3 d) as found by Gutierrez-Soto et al. (2011), and HDE 226868 (the optical counterpart to Cyg X-1). The latter displays the signature of the 5.6 d orbital period through the well-known ellipsoidal modulation of the donor star (hence its appearance as peaks every 2.8 d). Even though Cyg X-1 is an extremely luminous (≥10\(^{37}\) erg s\(^{-1}\)) X-ray source, the donor is an OB1 star, so the effects of X-ray heating are small. (As a benefit to the reader we show one sector of TESS data for each of our targets in Fig. A1 to A4).

Four sources showed evidence of orbital modulations (GP Vel, V884 Sco, HDE 226868 and V662 Cas). We detrended these light curves using the flatten routine in the Lightkurve python package (Lightkurve Collaboration 2018) to search for shorter period variability. After some trial and error we chose a window length for the filter of 1 d: we acknowledge that the resulting detrended light curves could contain features which are a result of this choice of window length. Nevertheless, we show in the lower panel of Figure 2 the detrended light curve of HDE 226868, which reveals significant short period variability in the light curve (we show the normalised and detrended light curves for GP Vel, B884 Sco and V662 Cas in Figure B1). In sector 44, X Per shows a prominent sinusoidal variation on a timescale of ∼15 d (see Fig. A3) which is much shorter than its orbital period of 250 d. We also removed the 15 d trend in X Per to search for shorter period variability.

To search for periodic variations in the light curves, we used the generalised Lomb Scargle periodogram (LS, Zecharis & Kürster 2009; Press et al. 1992), obtaining a power spectrum for each sector the star was observed. We show the power spectra obtained for each sources in Figures 4 to 6 with the periods of the most prominent peaks shown in Table 2 on a sector-by-sector basis.

In their study of 432 classical Be stars made using TESS data Labadie-Bartz et al. (2022) classified them based on their power spectra. The classifications include low frequency (>2 d) signals which dominate and are typical of g mode pulsations; frequency groups in the mid frequency range (0.16–2 d) closely spaced groups (p and g modes); high frequency (0.06–0.16 d) signals dominate (p and g modes); and single isolated frequencies – sources can have more than one classification. We made an assessment of the power spectra shown in Figures 4 to 6 and classified them based on the criteria of Labadie-Bartz et al. (2022). We find that 13/23 (57 percent) have mid frequency spectra; 8/23 (35 percent) have isolated spectra and 2/23 (9 percent) show both mid and low frequency spectra. In comparison, Labadie-Bartz et al. (2022) find that 32 percent of Be stars show isolated frequencies and 85 percent show frequency groups. Hen 3-640 was included in both this study and that of Labadie-Bartz et al. (2022), with us classifying the power spectra as mid/low and Labadie-Bartz et al. (2022) indicating it shows low-frequency trends and isolated signals (including at high frequencies). Given the element of uncertainty in classifying the power spectra of the HMXB in our sample, the light curves analysed here appear to be broadly similar to the classical Be stars reported in Labadie-Bartz et al. (2022).

In Figure 3 we show the same Gaia HRD as we showed in Figure 1 but here we have colour coded the symbols representing those sources with mid frequency signals in red; isolated signals in blue and those showing mid and low frequency signals in green.

We now comment on some specific sources. GSC 03588-00834 (SAX J2103+4545) shows two eclipses in its TESS light curve separated by 16.6 d. Given this is longer than the orbital period, this suggests that one of two relatively bright stars (G=13.9, G=14.3) within 21 arcsec (the TESS pixel size) is the source of the eclipses. The light curve also shows evidence of two dip-like features which may be related to the orbital period. Using a Weighted Wavelet Z-Transform (Foster 1996) to search for evidence of short period variations we found evidence for a period which drifts in the three sectors of data between 0.33–0.45 d which is similar to the period reported by Gutierrez-Soto et al. (2011). However, once we take into account the dilution of the two spatially nearby stars this increases to 1.2 percent. We conclude that it is likely that a quasi-periodic signal on a timescale similar to that reported by Gutierrez-Soto et al. (2011) is present at times in GSC 03588-00834.

We noted earlier that X Per shows a modulation on a timescale of ∼15 d in sector 44 whose signature we removed before obtaining a LS power spectrum. In Figure 5 we see that power is concentrated at periods near 0.33–0.45 d in sectors 18 and 43, but in sector 44 the peak in the power spectrum is shifted to an isolated peak at ∼0.3 d (there is no evidence for an X-ray outburst at this time). In Figure 4 we show the power spectra of Hen 3-640: in sector 10, peaks are seen between periods of 0.5–1.1 d but in sectors 37 and 38 there is a clear modulation in a period ∼3 d. Similarly, in Figure 4 we find that BZ Cru shows enhanced power between 0.6–0.8 d in sectors 37 and 38 compared to sector 11. For two sources, V725 Tau and HD 249179, we discuss their power spectra in greater detail in §7.

4 OUTBURSTS

TESS has been used to observe supernovae prior to their detection in ground-based transient surveys (e.g. Fausnaugh et al. (2021))

\(^4\) https://archive.stsci.edu/hlsp/tess-spoc
Figure 4. The LS power spectra of the TESS light curves of our HMXB sample, each labelled with the sector where the data originated.
Figure 5. Figure 4 continued.
Figure 6. Figure 5 continued.
4.1 V725 Tau

V725 Tau (1A 0535+262/HD 245770) is a prototypical transient X-ray pulsar which has been observed to show many X-ray outbursts, including a recent giant outburst (peaking at $1.2 \times 10^{38}$ erg s$^{-1}$) in November 2020 (e.g. Kong et al. (2021)). Since then, observations made using MAXI showed a weaker outburst around 2021 June 20 (the field was not being observed by TESS) and an even weaker X-ray outburst a few months later, starting on October 13 (MJD = 59500). In Figure 7 (left) we show the simultaneous TESS and X-ray (MAXI) light curves of V725 Tau during this much weaker outburst. The increase in optical flux suggests an outburst amplitude of ∼0.2 mag (there are no significant issues of dilution from nearby bright stars).

Figure 7 indicates there was a clear periodic (∼0.5 d) signal in all three sectors (43–45) of TESS data. To investigate this further, we detrended each of these sectors so as to remove the large outburst variation, and show the resulting light curve in Figure C1: it appears like a typical multi-periodic pulsation where modes come and go on a quasi-period of ∼6.4 d, causing a change in the amplitude of the main pulsation. We applied a shifted time window version of the epoch folding periodogram (Davies 1990) to search for the evolution of the pulsations over the TESS observations. Firstly, long term variations were removed, after which we moved a 2 d wide time window in steps of 0.05 d through the observations and carried out the epoch folding analysis with 30 phase bins for each step. We show the resulting trailed periodogram in the upper left hand panel of Figure 7. There is no apparent change in the amplitude of the ∼0.5 d period during or immediately after the optical outburst. However, it is clear that we detect at least three epochs of increased pulsation amplitude, separated by ∼30 d. An Analysis of Variance (AoV) periodogram (Schwarzenberg-Czerny 1996) using the full detrended light curve finds a peak in the power spectrum at 13.6 d: this is half of the reported period of ∼28 d determined using radial velocities (Hutchings et al. 1978). Given the orbital period is 111 d, it is unclear what the origin of the 28 d period is due to.

4.2 HD 249179

4U 0548+29 (Forman et al. 1978) was associated with the B5ne star HD 249179 by Wackerling (1970) and classed as an HMXB in the catalogue of Liu et al. (2006). However, Torrejón & Orr (2001) made pointed observations of HD 249179 using BeppoSax and found no evidence for X-ray emission, concluding that HD 249179 was not in fact the optical counterpart of 4U 0548+29. Nevertheless, we have retained HD 249179 in this study as a potential HMXB, since Be stars are known to undergo long intervals of weak or no X-ray emission, as a result of their highly eccentric orbits (Okazaki & Negueruela 2001).

In Figure 7 (right hand panels) we show the light curve of HD 249179 during sector 45: in the second half, after a slight decline in flux, there is a rapid increase of ∼0.1 mag (this increases to ∼0.14 mag once dilution from nearby bright stars is taken into account). We believe this is the first recorded optical outburst from HD 249179.

The detrended light curve of HD 249179 (Figure C2) shows a quasi-periodic signal on a period of ∼0.28 d. This light curve also highlights how the amplitude of the short period modulation increases by a factor of ∼3 at the same time as the start of the optical outburst. This is also demonstrated in the sliding epoch folding periodogram shown in the upper right hand panel of Figure 7. In addition there is some evidence that after the peak of the outburst has been reached, most of the power is transferred from the initial 0.28 d period to twice that (i.e. from 3.6 d$^{-1}$ to 1.7 d$^{-1}$ in frequency). We speculate that material has been ejected from this Be star to its disc.

Table 2. The principal periods determined for our targets on a sector-by-sector basis (indicated by the square brackets) using the LS periodogram.

| Object       | Periods (d) |
|--------------|-------------|
| GP Vel       | [10] 1.066 [37] 3.06 [38] 3.05, 1.072 |
| Hen 3-640    | [10] 0.665, 0.357, 0.464 [37] 0.358, 0.463, 0.661 [38] 0.463, 0.358, 0.375 |
| V801 Cen     | [11] 0.339, 0.104, 0.969 [37] 0.725, 0.637, 0.694 [38] 0.636, 0.359, 0.725 |
| BZ Cru       | [11] 1.614, 0.935, 0.989, 0.336 [37] 0.918, 1.005, 0.337, 0.106 [38] 1.598, 0.930, 0.337, 0.893 |
| µ² Cru       | [12] 0.904, 0.953, 0.419 [39] 0.904, 0.407, 0.415 |
| HD 141926    | [12] 0.729, 0.763, 0.614 |
| V884 Sco     | [13] 0.661, 0.597, 0.578 |
| HDE 226868   | [14] 0.448, 0.102 |
| GSC 03588-00834 | [16] 1.970, 0.538 [17] 1.963, 1.772 |
| V490 Cep     | [16] 1.120, 0.981, 0.647 [17] 0.998, 0.834, 0.791 |
| BD +53 2790  | [18] 0.497, 0.352, 0.572 [24] 0.687, 0.741, 0.791 [25] 0.594, 0.613, 0.578 |
| V662 Cas     | [18] 0.3003 [24] 0.3003 [25] 0.3010 |
| V635 Cas     | [18] 0.419, 0.755 [19] 0.420, 0.756 |
| BQ Cam       | [18] 0.574, 0.277 [43] 0.575, 0.277 [44] 0.277, 0.529 |
| X Per        | [19] 0.406 |
| CI Cam       | [19] 0.385, 0.460 |
| LS V +44 17  | [19] 0.672, 1.446 |
| V420 Aur     | [19] 0.568, 0.284 [12] 0.569, 0.285 [38] 0.571, 0.454, 0.285 [39] 0.570, 0.284, 0.453 |
| HD 109857    | [43] 0.468 [44] 0.469 [45] 0.468 |
| V725 Tau     | [43] 1.225 |
| IGR J06074+2205 | [43] 0.434 [44] 0.435 |
| BD +47 3129  | [43] 0.283 [44] 0.490, 0.283 [45] 0.282 |
| HD 249179    | [43] 0.283 [44] 0.490, 0.283 [45] 0.282 |
Figure 7. Lower panels: An outburst of V725 Tau (left hand panel) which started on 2021 Oct 13 (day zero corresponds to MJD=59473.68) during TESS sector 44, together with the MAXI X-ray data (blue dots). The right hand panel shows an outburst of HD 249179 during TESS sector 45 (day zero corresponds to MJD=59525.54). Upper panels: Sliding periodograms of the TESS light curves (V725 Tau, left hand panel, HD 249179, right hand panel) where the colour intensity is scaled to reflect the amplitude of the power.

5 DISCUSSION

We now discuss pulsations from isolated early type stars and previous observations of outbursts from Be type stars.

5.1 Pulsations from early type stars

Bowman (2020) gives an overview of observations of High-Mass stars including β Cep and SPB stars. TESS observations of nearly 100 OB stars, coupled with high resolution optical spectroscopy, were presented by Burssens et al. (2020), who found that many of them showed pulsations and concluded that if the modes of pulsation could be determined then asteroseismic modelling would be possible. They identified a group of pulsators which show periods of a few days, such as SPBs which were likely due to coherent g mode pulsations. Furthermore β Cep stars show periods of a few tenths of a day, which are likely due to coherent p mode pulsations. In addition, there are a group of stars which appear to be hybrid pulsators, showing both g and p mode pulsations. Sharma et al. (2022) presented TESS observations of 119 B type stars which were members of the Sco-Cen association and found pulsations in 2/3 of the stars they sampled. Although they initially applied a cut-off at 0.4 d where stars were likely to be SPB if the main periods were <0.4 d and β Cep if >0.4 d, they conclude that it was not always possible to separate these stars purely on this criterion. Indeed there were stars which appeared to be hybrids showing power in both frequency ranges.

However, based on these criteria, we find that 42% of our sample were hybrids, 33% were SPBs and 25% were β Cep stars. This compares with 23% hybrids, 28% SPBs and 40% β Cep stars as we have estimated from Table 1 of Sharma et al. (2022). Given the indirect nature of the comparison, and that the Sharma et al. (2022) study covers all B spectral sub-types, whilst our sample is more concentrated on earlier sub-types or even giant/sub-giants, there is not a large difference in the fractions of types in these two studies.

5.2 Outbursts

Optical outbursts have been seen from many Be stars with timescales ranging from days, weeks to years (e.g. Labadie-Bartz et al. (2018)). The outburst causes material to be expelled from the star and forms (or maintains) an excretion disc. Much of this material is eventually returns onto the star (see Rivinius et al. (2013) for details).

Using TESS observations we have detected optical outbursts from V725 Tau and HD 249179. V725 Tau is a bona fide HMXB with a neutron star as its primary. In contrast, there is some doubt that HD 249179 is an HMXB, but rather an isolated Be star (Torrejón & Orr 2001). The outburst from V725 Tau showed no change in the period or amplitude of the short period modulation which is likely due to p-mode oscillations in the donor star. In contrast, we have
found evidence that the period changes slightly during the outburst of HD 249179, with strong evidence that the amplitude increases significantly at the time where the outburst starts.

The outburst which we detected in HD 249179 is very similar to the outburst seen in HD 49330 (B0.5IVe) made using CoRoT data (Huat et al. 2009). They found that the amplitudes of the p-modes (short period) and g-modes (long period) were directly correlated with the outburst: the amplitude of the p-modes decreased just before the outburst and increased after the start of outburst. This is almost identical to our findings for HD 249179. Indeed, there is evidence that the combination of pulsation modes actually cause outbursts from Be stars (e.g. Baade et al. 2017), with the increase in the amplitude of the pulsations during the outburst has been explained by stochastically excited waves (e.g. Baade et al. 2018; Neiner et al. 2020). More detailed work would be needed to identify the modes in HD 249179 before a similar study could be undertaken on the TESS outburst data.

It is not clear whether HD 249179 is a binary system. Unfortunately, there are no radial velocity data for it in Gaia DR3, presumably since it is in the Galactic plane (b = 1.9°) where blending of the RVS spectra can be a serious issue. Studies on the multiplicity of early type stars (see Sana 2017 for an overview) suggest the multiplicity fraction of B4–9 type stars in the Milky Way is ~1/5. It is therefore a matter of speculation of whether the outburst seen in HD 249179 is due to tidal interaction of a companion star.

6 CONCLUSIONS

We have shown that each of the 23 optical counterparts to the HMXBs in this survey show clear evidence of quasi-periodic modulations with periods in the range ∼0.1–1 d which fully supports the earlier ground based observations of HMXBs by Gutierrez-Soto et al. (2011) and Schmidtke et al. (2014, 2016, 2019). Many other massive stars, including Be stars, also show quasi-periodic pulsations with similar periods. To be able to derive fundamental parameters of the stars it is essential to identify the modes in the power spectrum. This is not normally achievable just from broad band photometry, but generally must be combined with high resolution spectra (e.g. Aerts et al. 2019). However, this will be much more difficult to achieve for HMXBs where an accretion disc will make it difficult to separate the disc and stellar pulsation emission. Observations of massive eclipsing binaries (e.g. Southworth et al. 2020) show that tidal forces can affect the pulsation frequencies. Given that some HMXBs, primarily those with Be donor stars, have a non-negligible eccentricity (e.g. Vela X-1 has e ~0.09) it is possible that a more detailed study of the pulsation spectrum as a function of their orbital period may reveal some dependency on the orbital phase. Finally, in Cycle 5, the cadence of TESS full frame images will be 200 s which will allow many more HMXBs and early type stars to be searched for pulsations.

7 ACKNOWLEDGMENTS

This paper includes data collected by the TESS mission, for which funding is provided by the NASA Explorer Program. This work presents results from the European Space Agency (ESA) space mission Gaia. Gaia data is being processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for the DPAC is provided by national institutions, in particular the institutions participating in the Gaia MultiLateral Agreement (MLA). The Gaia mission website is https://www.cosmos.esa.int/gaia. The Gaia archive website is https://archives.esac.esa.int/gaia. This research has made use of MAXI data provided by RIKEN, JAXA and the MAXI team. Armagh Observatory & Planetaryarium is core funded by the Northern Ireland Executive through the Dept for Communities. We thank the anonymous referee for a detailed review of the manuscript.

DATA AVAILABILITY

The TESS data are available from the NASA MAST portal5 and MAXI data are available from the the Riken MAXI portal.6

REFERENCES

Aerts, C., et al., 2019, A&A, 624, A75
Andrae, R., et al., 2018, A&A, 616, A8
Astraatmadja, T. L., & Bailer-Jones, C. A. L., 2016, ApJ, 833, 119
Baade, D., et al., 2017, Second BRITE-Constellation Science Conference: Small Satellites - Big Science, eds Zwintz, K., Poretti, E., Polish Astro Soc, arXiv:1611.01113
Baade, D., et al., 2018, A&A, 610A, 70
Bailer-Jones, C. A. L., 2015, PASP, 127, 994
Borucki W. J., et al., 2010, Sci, 327, 977
Bowman, D. M., 2020, FrASS, 7, 70
Bursens, S., et al., 2020, A&A, 639, A81
Caldwell, D. A., 2020, RNAAS, 4, 201
Court, J. M. C., et al., 2019, MNRAS, 488, 4149
Davies R. S., 1990, MNRAS, 244, 93
De Cat, P., Uytterhoeven, K., Gutiérrez-Soto, J., Degroote, P., Simón-Díaz, S., 2010, Proc IAU Symposium, Volume 272, 433
Fausnaugh, M. M., et al., 2021, ApJ, 908, 51
Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H. Giacconi, R., 1978, ApJS, 38, 357
Foster, G., 1996, AJ, 112, 1709
Gaia Collaboration, Luri, X., Brown, A. G. A., et al., 2018, A&A, 616, A9
Gaia Collaboration, Brown, A.G.A., et al., 2021, A&A, 649, A1
Gerend, D., Boynton, P. E., 1976, ApJ, 209, 562
Green, G. M., et al., 2019, ApJ, 887, 93
Gutiérrez-Soto, J., Reig, P., Fabregat, J., Fox-Machado, L., 2011, Proc IAU Symposium, 272, 119, 505
Hakala, P., Ramsay, G., Barclay, T., Charles, P., 2015, MNRAS, 453, L6
Hall, T. A., Finley, J. P., Corbet, R. H. D., Thomas, R. C., 2000, ApJ, 536, 450
Huat, A.-L., et al., 2009, A&A, 506, 95
Hutchings, J. B., Bernard, J. E., Crampton, D., Cowley, A.P., 1978, ApJ, 223, 350
Hynes, R. I., et al., 2016, MNRAS, 459, 3596
Kong, L. D., et al., 2021, ApJL, 917, L38
Labadie-Bartz, J. et al., 2018, AJ, 155, 53
Labadie-Bartz, J., Carciofi, A. C., de Amorim, T. H., Rubio, A., Luiz, A., Ticiani dos Santos, P., Thomson-Paressant, K., 2022, AJ, 163, 226
Lewin, W. H. G., van der Klis, M., et al., 2018, Astrophysics Source Code Library, 1812.0135
Liu Q.Z., van Paradijs J., van den Heuvel E.P.J., 2006, A&A, 455, 1165
Neiner, C., Lee, C., Mathis, S., Saio, H., Lovekin, C. C., Auguston, K. C., 2020, A&A 644, A9
Okazaki, A. T., Negueruela, I., 2001, A&A, 377, 160
Okazaki, A. T., Negueruela, I., 2001, A&A, 377, 160

5 https://archive.stsci.edu/
6 http://maxi.riken.jp
APPENDIX A: LIGHT CURVES

The light curves of all the HMXB in our sample where we indicate the TESS sector the originated. For most cases we show the first sector of data where more than one sector of data was obtained.

APPENDIX B: DETRENDED LIGHT CURVES

For sources showing high amplitude variations in their light curve over the orbital period we detrended the signature of the orbital period to search for short period pulsations. In Figure 2 we show the original and detrended light curve of HDE 226868 (Cyg X-1). Here we show the original and detrended light curves of GP Vel, V884 Sco and V662 Cas.

APPENDIX C: LIGHT CURVES

The light curves of V725 Tau and HD 249179 which have been detrended to remove the signature of the outburst. The time of the optical outbursts are indicated for each source.
Figure A1. The light curves of the TESS light curves of the HMXBs in our sample where we indicate which sector the data originated.
Figure A2. Figure A1 continued.
Figure A3. Figure A2 continued.
Figure A4. Figure A3 continued.
Figure B1. The original and detrended light curves of GP Vel; V884 Sco and V662 Cas.
Figure C1. The TESS light curve of V725 Tau which has been detrended to remove the outburst and long-term variations. The resulting curve has a prominent signal at ~0.48 d.
Figure C2. The TESS light curve of HD249179 which has been detrended to remove the outburst and long-term variations. The resulting curve has a prominent signal at ≈0.28 d.