Identification of two new HMXBs in the LMC: a ~2013 s pulsar and a probable SFXT

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ABSTRACT
We report on the X-ray and optical properties of two high-mass X-ray binary systems located in the Large Magellanic Cloud (LMC). Based on the obtained optical spectra, we classify the massive companion as a supergiant star in both systems. Timing analysis of the X-ray events collected by XMM-Newton revealed the presence of coherent pulsations (spin period ~2013 s) for XMMU J053108.3-690923 and fast flaring behaviour for XMMU J053320.8-684122. The X-ray spectra of both systems can be modelled sufficiently well by an absorbed power-law, yielding hard spectra and high intrinsic absorption from the environment of the systems. Due to their combined X-ray and optical properties we classify both systems as SgXRBs: the 19th confirmed X-ray pulsar and a probable supergiant fast X-ray transient in the LMC, the second such candidate outside our Galaxy.

Key words: galaxies: individual: Large Magellanic Cloud – X-rays: binaries – stars: neutron – pulsars: individual:

1 INTRODUCTION
X-ray binaries (XRBs) are close binary systems composed of a compact object and an optical companion star that is usually undergoing nuclear burning. They can be classified into different categories based on the type of the compact star (i.e. black hole, neutron star, white dwarf) or the optical companion (low-mass or high-mass star). For black-hole (BH) or neutron-star (NS) binaries it has been shown that the number of low-mass X-ray binaries within a galaxy scales with the galaxy’s mass (Gilfanov 2004) while the number of high-mass X-ray binaries (HMXBs) is proportional to the recent star formation rate of the galaxy. HMXBs can be divided into two categories depending on the luminosity class of the donor star (for a detailed review see Reig 2011): Supergiant X-ray binaries (SgXRBs) for luminosity class I-II stars and Be/X-ray Binaries (BeXRBs) when the optical companion is a dwarf, sub-giant or giant OB star.

It has been established that HMXBs show strong aperiodic variability (Belloni & Hasinger 1990). On the one hand, BeXRB systems are transient systems exhibiting periodic Type-I outbursts near the NS periastron passage and sporadically major Type-II outbursts associated with periods of increased accretion probably due to the formation of warped Be-disks (Okazaki et al. 2013). Wind-fed systems like SgXRBs, on the other hand, have a fairly constant luminosity with typical hourly variability as a result of clumped stellar wind accretion (e.g. Oskinova et al. 2012; Martínez-Núñez et al. 2014).

The standard classification is challenged by newly discovered systems that do not seem to fit into this scheme. Within the last decade a new population of HMXBs (Bird et al. 2016), which is demographically different to the previously studied HMXB population, has been discovered by the International Gamma-ray Astrophysics Laboratory (INTEGRAL). This new population of HMXB systems is usually characterized by large obscuration, while it exhibits extreme flaring activity on timescales of a few hours. Both properties led to their identification as supergiant fast X-ray transients (SFXT) (Negueruela et al. 2006; Sidoli 2017). It has been proposed that the SFXT phenomenon is fairly common (Ducci et al. 2014), but the detection of the entire population in the Galaxy is hindered by their transient properties and the large Galactic absorption. Given the above observational biases, it is no surprise that only one extragalactic SFXT has been detected so far (IC 10 X-2, Laycock et al. 2014).

In the case of the Magellanic Clouds (MCs) all but one of the known XRB systems (i.e. LMC X-2 is low-mass X-ray binary Smale et al. 2003) are HMXBs in nature (e.g. Antoniou et al. 2010; Antoniou & Zezas 2016). The Small Magellanic Cloud (SMC) alone harbours about 120 HMXBs of which 64 are confirmed BeXRB pulsars and only one is a confirmed SgXRB (Haberl & Sturm 2016; Vasilopoulos et al. 2017; Maravelias et al. 2014). The population of BeXRBs was shown to be associated with the recent star formation history of the galaxy that peaks at ~40 Myr.
Table 1. X-ray observations log

| Observation Target/Observatory | ObsID | Date (MJD) | Instrument | Mode a | Mode b | Net Exp [ks] | Net counts/s | Lx [erg s⁻¹] |
|-------------------------------|-------|------------|------------|--------|--------|-------------|--------------|-------------|
| XMMU J053108.3-690923         | 0690744601 | 2012-10-10 | EPIC-pn    | ff-thin | 40     | 0.20±0.03   | 6.4          |
| XMM-Newton                    | 0690744601 | 2012-10-10 | EPIC-MOS1  | ff-medium | 41     | 0.071±0.002 |             |
|                              | 0690744601 | 2012-10-10 | EPIC-MOS2  | ff-medium | 41     | 0.073±0.002 |             |
| Swift                         | 00032616001 |         | XRT        | pc      | 4      | <0.0025     | <0.8         |
|                              | 00045434001 |         | XRT        | pc      | 2      | <0.027      | <8.8         |
|                              | 00045434003 |         | XRT        | pc      | 1.3    | <0.015      | <4.8         |
|                              | 00045436002 |         | XRT        | pc      | 1.4    | <0.007      | <2.3         |
|                              | 00045436004 |         | XRT        | pc      | 0.8    | <0.008      | <2.6         |
|                              | 00045463001 |         | XRT        | pc      | 2.5    | <0.006      | <1.95        |
|                              | 00032616002 |         | XRT        | pc      | 0.8    | 0.015±0.005 | 4.9          |
|                              | 00032616003 |         | XRT        | pc      | 0.8    | <0.017      | 5.2          |
| XMMU J053320.8-684122         | 0690743801 | 2012-04-27 | EPIC-pn    | ff-thin | 26     | 0.137±0.004 | 2.8          |
| XMM-Newton                    | 0690743801 | 2012-04-27 | EPIC-MOS1  | ff-medium | 28     |          |             |
|                              | 0690743801 | 2012-04-27 | EPIC-MOS2  | ff-medium | 28     | 0.040±0.002 |             |
| Swift                         | 00045431001 |         | XRT        | pc      | 2.0    | 0.013±0.003 | 3.5          |
|                              | 00032310001 |         | XRT        | pc      | 2.9    | 0.021±0.003 | 5.7          |
|                              | 00045431003 |         | XRT        | pc      | 0.3    | <0.04      | <11.         |
|                              | 00032310002 |         | XRT        | pc      | 1.0    | <0.006      | <1.6         |
|                              | 00045566001 |         | XRT        | pc      | 2.6    | <0.009      | <2.5         |
|                              | 00045566002 |         | XRT        | pc      | 1.2    | <0.009      | <2.5         |
|                              | 00032310003 |         | XRT        | pc      | 0.2    | <0.15      | <40.         |

a Instrument setup modes. For XMM-Newton a full-frame (ff) mode with thin or medium filter was used. For Swift/XRT photon counting (pc) observation mode was used.

b To convert Swift/XRT count rates to luminosities we used the spectral parameters obtained from the fit to the XMM-Newton data. The conversion factor is 3.25×10³⁵ erg s⁻¹ (c/s⁻¹)⁻¹ for XMMU J053108.3-690923 (see case I in Table 1) and 2.73×10³⁵ erg s⁻¹ (c/s⁻¹)⁻¹ for XMMU J053320.8-684122.

2 OBSERVATIONS

2.1 X-ray data

The two targets were serendipitiously discovered in X-rays by Swift and XMM-Newton. XMMU J053320.8-684122 was firstly identified as a HMXB candidate following a Swift/XRT detection (Swift J053321.3-684121: Sturm et al. 2012) during a Swift/UVOT survey observation of the LMC (PI: S. Immler) performed on 2012 March 13. It was later serendipitously detected during two XMM-Newton pointings, performed on April 27 and August 23 of 2012, as part of the LMC survey. Additional Swift/XRT observations that were analysed for the current work is presented in Table 1.

XMM-Newton/EPIC (Strüder et al. 2001; Turner et al. 2001) data were processed using the latest XMM-Newton data analysis software SAS, version 16.1.0. Observations were inspected for high background flaring activity by extracting the high-energy light curves (7.0 keV < E < 15 keV) for both MOS and PN detectors with a bin size of 100 s. Event extraction was performed with SAS task eventselect using the standard filtering flags (#XMEA_EP & & PATTERN<4 for EPIC-pn and #XMEA_EM & & PATTERN<12 for EPIC-MOS1 and EPIC-MOS2).

1 Science Analysis Software (SAS): http://xmm.esac.esa.int/sas/
Table 2. Optical counterparts

| X-ray  | XMMU J053108.3-690923 | XMMU J053320.8-684122 |
|--------|-----------------------|-----------------------|
| [M2002]\(^a\) | LMC 150004            | LMC 157075            |
| V      | 13.68±0.01            | 12.72±0.01            |
| B      | 13.76±0.01            | 12.63±0.01            |
| U      | 12.89±0.01            | 11.67±0.01            |
| R      | 13.6±0.01             | 12.71±0.01            |
| [AAVSO]\(^b\) | -                     | -                     |
| g'     | 13.654±0.047          | 12.548±0.010          |
| r'     | 13.769±0.077          | 12.792±0.040          |
| i'     | 13.872±0.066          | 12.968±0.083          |

\(^a\) Catalogue number and photometric magnitudes from Massey (2002), typical photometric uncertainties are below 0.01 mag.
\(^b\) AB magnitudes using Sloan filters (Henden et al. 2015)

EPIC-MOS). Circular regions with a radius of 20″ and 50″ were used for the source and background extraction to maximize the number of extracted photons. For the spectral analysis the SAS tasks rmfgen and arfgen were used to create the redistribution matrix and ancillary file. The grouped spectra were binned to achieve a minimum signal-to-noise ratio of five for each bin. For the timing analysis the event arrival times were corrected to the solar-system barycentre by using the SAS task barycen.

The Swift/XRT data were analysed following standard procedures described in the Swift data analysis guide\(^2\) (Evans et al. 2007). We used the xrtpipe to generate the Swift/XRT products. Because of the low luminosity of the systems in most observations, we only performed a simple source detection and position determination using a sliding-cell detection algorithm implemented by XIMAGE\(^3\). For non-detections we estimated the 3σ upper limits using a Bayesian method introduced by Kraft et al. (1991).

2.2 Optical data

Based on the accurate X-ray positions as determined by XMM-Newton we identified the most probable counterpart in the LMC field. A high-mass star is located within the X-ray error circle of each system (see Table 2). We consider these as the most likely counterparts, since it is very unlikely to find low-mass X-ray binary systems in the LMC (Gilfanov 2004) due to its recent star formation history and its total mass (Harris & Zaritsky 2009; Antoniou & Zezas 2016). The X-ray detected systems are not background Active Galactic Nuclei (AGN), given their large X-ray variability (AGN have typical normalized excess variance <1, Lanzuisi et al. 2014) and their hard X-ray spectra (see §3). In Fig. 1 we present a finding chart for each system. The images were constructed using J, H and K publicly available VISTA images\(^4\).

Optical spectra were obtained using ESO’s Fibre-fed Extended Range Optical Spectrograph (FEROS, Kaufer et al. 1999) mounted on the ESO/MPG 2.2 m telescope at La Silla (Chile). Observations were performed using the MPE high-energy group internal observing time. Observations were scheduled around full moon periods when observing conditions were not optimal for photometric observations with GROND (Greiner et al. 2008), that is the telescope’s main instrument. The targets were observed during non-photometric nights during 2014 November 7, with ∼1 h of total exposure for each target. Reduction of the FEROS spectra was performed with the ESO Data Reduction System (DRS), provided to the FEROS users\(^5\).

\(^2\) http://www.swift.ac.uk/analysis/xrt/
\(^3\) https://heasarc.gsfc.nasa.gov/xanadu/ximage/ximage.html
\(^4\) http://horus.roe.ac.uk/vsa/index.html
\(^5\) www.eso.org
3 RESULTS

In the following subsections, we present our results on the X-ray position, spectral and temporal properties of the two HMXB systems as well as report on the optical properties of their donor stars.

3.1 X-ray positions

X-ray positions were determined by performing a maximum-likelihood source detection analysis on the XMM-Newton/EPIC images. Fifteen images were created from the three EPIC cameras in five energy bands: 1 $\rightarrow$ (0.2 – 0.5) keV, 2 $\rightarrow$ (0.5 – 1.0) keV, 3 $\rightarrow$ (1.0 – 2.0) keV, 4 $\rightarrow$ (2.0 – 4.5) keV, 5 $\rightarrow$ (4.5 – 12.0) keV (Watson et al. 2009; Sturm et al. 2013). Source detection was performed simultaneously on all the images using the SAS task edetect_chain. Astrometric boresight corrections were performed using a catalogue of background AGN with known redshifts or selected using ALLWISE mid-infrared colour selection criteria (Mateos et al. 2012; Secrest et al. 2015) with the task eposcorr accounting for a linear shift. The inferred shifts in right ascension and declination were applied to the attitude file of the pointings and the data reprocessed. For XMMU J053108.3-690923 we derived boresight corrected positional coordinates of R.A. = 05h31m08s33 and Dec. = $-69^\circ 09'23.5''$ (J2000), with a 1σ statistical uncertainty of 0.1". From the two observations of XMMU J053320.8-684122 we derived error-weighted mean of the position to R.A. = 05h33m20s87 and Dec. = $-68^\circ 41'22.6''$ (J2000) with a 1σ statistical uncertainty of 0.5". The positional error is usually dominated by systematic astrometric uncertainties. Following Sturm et al. (2013) we added a systematic error of 0.5" in quadrature. We note, however, that subsequent analysis of XMM-Newton observations of the SMC with the newest SAS version has re-
duced the systematic uncertainty to 0.33'' (Maitra et al., in prep). Our analysis provides an improved X-ray position for both candidates. For XMMU J053320.8-684122, the improved position is consistent with the one reported by Sturm et al. (2012) confirming the initially reported counterpart (i.e. blue supergiant Sk-68 122; Sanduleak 1970) as the true optical companion.

3.2 X-ray temporal properties

Both systems exhibit strong variability during the XMM-Newton observations (see Fig. 2). XMMU J053108.3-690923 shows periodic bursts every ~2000 s. In order to compute the X-ray variability from the XMM-Newton/EPIC light-curve we compared the highest count rate with the 5% percentile of the count rate distribution. We infer an X-ray variability factor of about 10. XMMU J053320.8-684122 remained at a lower luminosity level (~0.035 counts s⁻¹) for the first ~22 ks of the exposure (obsid: 0690743801). During the last ~8 ks the light curve shows three consecutive bursts separated by ~2200 s reaching a maximum count rate of ~0.45 counts s⁻¹. By comparing the highest count rate recorded by XMM-Newton/EPIC with the lower 5% percentile of the total X-ray light curve, we find an X-ray variability factor of at least 30.

To further investigate the X-ray variability we used the fast Fourier transform (van der Klis 1988) and constructed the power density spectra for the two systems (see Fig. 3). The power spectra are normalized such that their integral over a range of frequencies gives the square of the root mean square (RMS). The power density spectra were grouped using a geometrical rebinning (Papadakis & Lawrence 1993). The spectra of both systems are dominated by white noise at high frequencies (≥ 10 – 30 mHz), while they can be well described by a power-law at lower frequencies. The power spectrum of XMMU J053108.3-690923 shows additional features at 0.5 mHz, 1 mHz, and 1.5 mHz that are related to the pulsar’s spin-period and its harmonics. In order to estimate the significance of these features and better determine the period and its uncertainty we used an epoch folding technique (EF: Davies 1990; Larsson 1996). We used the combined EPIC-pn and EPIC-MOS barycentric corrected arrival times to search for a periodic signal. We applied an EF method, while implementing the Rayleigh Z² test (Timmer & Koenig 1995; Emmanoulopoulos et al. 2013). For XMMU J053108.3-690923 a clear period of 2013.5 s was found, while the periodogram shows peaks at the multiples of this period (see Fig. 4). To estimate the uncertainty of the derived period we used two approaches. First, we analytically estimated the uncertainty to be ~4-10 s using equation (14) of Buccheri et al. 1983. Then, we performed a numerical estimation by bootstrapping the event arrival times and by performing the EF method to the bootstrapped samples. An uncertainty of ~3 s was derived from the distribution of the derived periods. The pulse-profile of the system is single peaked (Fig. 5). We also investigated the hardness ratio (HR) evolution along the spin phase of the system by using two different energy bands (0.3-2.0, 2.0-10.0 keV). The HR is defined as $R_{\text{hard}} - R_{\text{soft}} / (R_{\text{hard}} + R_{\text{soft}})$, with $R_{\text{hard/soft}}$ denotes the background-subtracted count rates in the hard and soft energy band. The spin phasefolded light-curves of the system, for the complete energy range of XMM-Newton as well as the soft and hard energy bands, are plotted together with the spin phase resolved HR in Fig. 5.

For XMMU J053320.8-684122 any periodicity search is hampered by the three late flares that dominate the statistics. Thus, we searched for periodic signal only in the first 22 ks of the exposure. No significant period was derived from the periodicity search.

![Figure 4](http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/)  
**Figure 4.** Results of period search for XMMU J053108.3-690923. Epoch folding (EF) method (Rayleigh $Z^2$ test) was applied to the combined XMM-Newton/EPIC events (obsid:0690744601). The significance of the derived period was estimated by applying the EF method on simulated light curves (Timmer & Koenig 1995; Emmanoulopoulos et al. 2013).

![Figure 5](http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/)  
**Figure 5.** From top to bottom we present the phase folded pulse profile of XMMU J053108.3-690923 in the 0.3-10 keV , 2.0-10.0 keV and 0.3-2.0 keV bands and the hardness ratio between the two sub-bands.

3.3 X-ray spectral properties

X-ray spectral analysis was performed using the XSPEC fitting package, version 12.9.1 (Arnaud 1996). We fitted the time-averaged X-ray spectra of both systems with an absorbed power-law model. X-ray absorption was modeled using the tbabs⁶ code (Wilms et al. 2000). Commonly referred to as tbnew, this model is now included in the latest release of XSPEC. The code is available through: [http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/](http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/)
Table 3. Results of the X-ray spectral modelling

| Component | Parameter | Value | units |
|-----------|-----------|-------|-------|
|           |           |       |       |
| XMMU J053108.3-690923 | CASE I: constant*TBabs*TBvarabs*(powerlaw+bbodyrad) | | |
| Component | Parameter | Value | units |
| TBabsa | nH | 0.0618 (fixed) | 10^{22}cm^{-2} |
| TBvarabs | nH | 2.3±0.7 | 10^{22}cm^{-2} |
| powerlaw | Γ | 0.8±0.8 | 0.3±0.3 |
|         | norm | 1.3±0.3 | 10±12 erg cm^{-2} s^{-1} |
| bbodyrad | kT | 1.75±0.5 | keV |
|         | norm | 0.01±0.01 | - |
|         | R | 0.5±0.1 | km |
| Observed Fluxa | | 1.87±0.4 | 10^{-2}erg cm^{-2} s^{-1} |
| Luminositya | | 6.4±3.0 | 10^{39} erg s^{-1} |
| χ^2_red/DOF | | 0.99/252 | |
| XMMU J053320.8-6841122 | CASE II: constant*TBabs*TBvarabs1*(partcov*TBvarabs2)*powerlaw | | |
| Component | Parameter | Value | units |
| TBabsa | nH | 0.0618 (fixed) | 10^{22}cm^{-2} |
| TBvarabs1 | nH | 3.2±0.5 | 10^{22}cm^{-2} |
| partial covering | partcov | 0.52±0.01 | - |
| TBvarabs2 | nH | 18±3.0 | 10^{22}cm^{-2} |
| powerlaw | Γ | 1.3±0.20 | 10^{-2}erg cm^{-2} s^{-1} |
|         | norm | 3.1±0.04 | 10^{-12} erg cm^{-2} s^{-1} |
| Observed Fluxa | | 1.87±0.06 | 10^{-12} erg cm^{-2} s^{-1} |
| Luminositya | | 9.4±0.3 | 10^{39} erg s^{-1} |
| χ^2_red/DOF | | 1.00/252 | |
| XMMU J053320.8-684122 | constant*TBabs*TBvarabs*powerlaw | | |
| Component | Parameter | Value | units |
| TBabsa | nH | 0.0609 (fixed) | 10^{22}cm^{-2} |
| TBvarabs | nH | 0.6±0.18 | 10^{22}cm^{-2} |
| powerlaw | Γ | 0.9±0.12 | 0.3±0.3 |
|         | norm | 0.94±0.06 | 10^{-12} erg cm^{-2} s^{-1} |
| Observed Fluxa | | 0.85±0.05 | 10^{-12} erg cm^{-2} s^{-1} |
| Luminositya | | 2.8±0.1 | 10^{39} erg s^{-1} |
| χ^2_red/DOF | | 1.03/65 | |

a Contribution of Galactic foreground absorption, column density fixed to the weighted average value of (Dickey & Lockman 1990).
b Absorbed flux of the fitted model in the 0.3-10.0 keV energy band.
c Unabsorbed Luminosity of the fitted model in the 0.3-10.0 keV energy band, for a distance of 50 kpc (Pietrzyński et al. 2013).

2000) with atomic cross sections adopted from Verner et al. (1996). For the modeling we used two absorption components, one to describe the Galactic foreground absorption and another to account for the column density of both the interstellar medium of the LMC and the intrinsic absorption of the sources. For the Galactic photo-electric absorption we used a fixed column density (Dickey & Lockman 1990) with abundances taken from Wilms et al. (2000).

For XMMU J053320.8-684122 the X-ray spectrum was adequately described by an absorbed power-law model ($\chi^2_{\text{red}} \sim 1.03$). For XMMU J053108.3-690923 the absorbed power-law model yielded an acceptable goodness of fit with reduced $\chi^2 \sim 1.1$, but failed to describe the data in terms of residual distribution (Andrae et al. 2010). The introduction of an additional spectral component reduces the structures in the residuals. Such a component is commonly seen in the spectra of HMXB systems below 10 keV and is usually referred to as “soft excess” (Hickox et al. 2004). For HMXB systems observed at low luminosities this soft excess can have two different origins. It can be due to the NS hot spot (CASE I) and can therefore be modelled by a black-body component with typical size of 1 km radius (La Palombara & Mereghetti 2006; Bartlett et al. 2013; Vasilopoulos et al. 2013; Sidoli et al. 2017b). Alternatively, it can be associated with X-ray absorption from the clumpy wind of a supergiant star (CASE II). In this case, it can be modelled by a partial-covering absorption component (Tomsick et al. 2009). Often, it is difficult to distinguish between the two cases (e.g. Fornasini et al. 2017).

In the case of XMMU J053108.3-690923, both models for the soft excess provide equally good fits (CASE I: 0.99 vs CASE II: 1.01) and identical residual structure. It is thus impossible to statistically distinguish between the two scenarios. In the case of XMMU J053320.8-684122, any additional component would result in over-fitting the data and would not constrain any of the physical parameters of the system.

![Figure 6](image1.png)  
Figure 6. EPIC spectra of XMMU J053108.3-690923 from April 2012 (black: pn, red: MOS2) together with the best-fit model (solid lines) composed of absorbed power-law and black-body components (CASE I in Table 3). The power-law (dash-dotted lines) and black-body (dotted lines) contributions are also indicated. The bottom panel shows the fit residuals.

![Figure 7](image2.png)  
Figure 7. EPIC spectra of XMMU J053320.8-684122 from April 2012 (black: pn, red: MOS2) together with the best-fit power-law model (solid lines). The bottom panel shows the fit residuals.
The X-ray spectra along with the data-to-model residual plots for both systems are given in Table 3. Interestingly, the intrinsic absorption of both systems is larger than that of the typical BeXRB pulsars located in the LMC (e.g. Vasilopoulos et al. 2014, 2016; Haberl et al. 2017). Moreover, by comparing the two systems, XMMU J053108.3-690923 is both brighter and exhibits higher intrinsic absorption.

From our temporal analysis (see §3.2 and Fig. 2), we find that XMMU J053108.3-690923 and XMMU J053320.8-684122 reached a maximum luminosity of $1.1 \times 10^{36} \text{ erg s}^{-1}$ and $8.5 \times 10^{35} \text{ erg s}^{-1}$ respectively during the two XMM-Newton observations.

### 3.4 Optical properties of donor stars

The reduced optical spectra of the two massive stars (see Table 2) that are interpreted as the companion stars of the corresponding HMXB systems XMMU J053108.3-690923 and XMMU J053320.8-684122, have been classified using the criteria described in Evans et al. (2004, 2015), which take into account the lower metallicity of the LMC massive stars (compared to massive Galactic stars).

#### 3.4.1 Spectral classification

The optical companion of XMMU J053108.3-690923 is consistent with a B0e spectral class, as absorption lines HeII 4686Å and 4541Å are weak but present, while the HeII 4200Å line is very weak or absent. The optical companion of XMMU J053320.8-684122 is consistent with B0.5e spectral class, as absorption lines HeII 4200Å and 4541Å are absent, while the HeII 4686Å line is clearly present (but weak). Figure 8 shows part of the optical spectra obtained for the two stars with the main lines marked.

#### 3.4.2 H-alpha line profiles

In Fig. 8 we show the H-alpha line region for the two stars. The narrow nebular emission lines and cosmic rays have been subtracted from the spectra. Both profiles are double peaked. Simultaneous fits with Gaussian profiles were performed and the results are summarised in Table 4. Usually, the profiles of supergiants of this type are expected to show P-Cygni profiles in the Balmer lines. However the absence of P-Cygni signature does not prove that a star is not a supergiant, as the profile is variable and goes through phases with no P-Cygni signature (e.g. Grundstrom et al. 2007; Negueruela et al. 2006).

#### 3.4.3 Luminosity Classification

The luminosity class of the systems was determined using a combination of spectroscopic and hybrid spectro-photometric criteria.

Spectroscopically, the spectra of both XMMU J053108.3-690923 and XMMU J053320.8-684122 show clear SiIII lines (4553Å, 4568Å, 4575Å), NIII 4097Å, and OII lines (4640Å, 4643Å, 4650Å, 4699Å, 4705Å), that indicate a supergiant luminosity class (Hendry et al. 2008). The equivalent width of the Balmer H$_{\alpha}$ line is $\approx 1.06\AA$ for the case of XMMU J053108.3-690923 and $\approx 1.17\AA$ for XMMU J053320.8-684122. Both values are consistent with a supergiant luminosity class given the spectral type of the objects (see e.g. Cananzi et al. 1993).

Classification based on photometric or spectrophotometric criteria requires an estimate of the absolute magnitude of the systems, which can be derived from the apparent magnitudes of the objects given in Table 2, corrected for the distance modulus of the LMC of $m_{B}=18.49 \text{ mag}$ (Pietrzynski et al. 2013) and for interstellar extinction. As an indication of the interstellar absorption in the direction of XMMU J053108.3-690923 and XMMU J053320.8-684122, we used the values provided by Haschke et al. (2011). By averaging the provided values around a 10' area around the two systems we derived $E(B-V)$ values of 0.076 and 0.086 for XMMU J053108.3-690923 and XMMU J053320.8-684122, respectively. Given the spectral class of the two stars (B0-B0.5) one would expect a (B-V)$_{0}$ colour of $\approx -0.2$. Comparing with the actual B-V colours from Table 2, reddensions of $0.28 \text{ mag}$ for XMMU J053108.3-690923 and $0.11 \text{ mag}$ for XMMU J053320.8-684122 are inferred. For the case of XMMU J053320.8-684122 the two reddening estimates are consistent, while in the case of XMMU J053108.3-690923, the actual reddening of the star is significantly higher than expected according to Haschke et al. (2011), probably indicating the presence of absorption related to the system itself, or, alternatively the colour of the star may be affected by the contribution of a circumstellar disk. Adopting the first set of E(B-V) values, and applying the corresponding extinction correction, we derive, $M_{V} = -5.07$ and $M_{V} = -6.05$ for XMMU J053108.3-690923 and XMMU J053320.8-684122 respectively. For the second set E(B-V) estimates the corresponding absolute magnitudes of $M_{V} = -5.70$ and $M_{V} = -6.11$ for XMMU J053108.3-690923 and XMMU J053320.8-684122 respectively, assuming that the observed B-V colour is only due to reddening and not to the contribution from a possible disk.

Given these values for the absolute magnitudes of the two donor stars and the values for the equivalent widths of the H$_{\alpha}$ line mentioned earlier, we can apply the hybrid luminosity class criteria appropriate for Magellanic Cloud metallicity (see Table 3 of Evans et al. 2004). Note that the ranges given in this paper refer to a distance modulus of 19.2 (for the SMC). After taking this into account, XMMU J053108.3-690923 can be assigned a hybrid luminosity class of (II), while XMMU J053320.8-684122 is clearly of luminosity class (Ib), with the parentheses indicating that these are not truly morphological luminosity classes, but are based on both spectroscopic and photometric criteria.

Using only photometric criteria, based on the expected range of absolute magnitudes for BO-B0.5 spectral types of different luminosity classes (e.g. Wegner 2006; Urbania et al. 2017), both XMMU J053108.3-690923 and XMMU J053320.8-684122 are consistent with luminosity class I supergiants.

To summarize, all classification criteria indicate that XMMU J053108.3-690923 is a BO II-IB bright giant or supergiant and XMMU J053320.8-684122 is a B0.5 Ib supergiant. For XMMU J053108.3-690923 there is indication of either heavy local reddening, or of contribution of a circum-stellar disk component (even present in supergiant systems; Menneick et al. 2017).

### 3.4.4 Masses of donor stars

For both systems we can use their combined spectro-photometric properties to estimate the masses of the donor stars. For this purpose we can use the Modules for Experiments in Stellar Astrophysics (MESA; Paxton et al. 2011) Isochrones and Stellar Tracks (MIST Choi et al. 2016; Dotter 2016). We compared the photometric properties of the systems with the MIST curves produced for the LMC metallicity taking into account the effect of rotation.
Figure 8. FEROS spectra of XMMU J053108.3-690923 and XMMU J053320.8-684122. Intensities have been normalised according to the underlying continuum flux and arbitrarily shifted for plotting purposes. Lines that have been used for the spectral classification are marked with vertical dashed red lines.

Figure 9. Colour-magnitude diagram of the MESA evolutionary models for the LMC metallicity (Choi et al. 2016; Dotter 2016). Stellar tracks for different mass-ranges are overplotted with coloured solid lines. The position of XMMU J053108.3-690923 (squares) and XMMU J053320.8-684122 (circles) in the diagram are marked using both their corrected (filled symbols) and uncorrected (open symbols) colour and magnitude values. For XMMU J053108.3-690923 the two corrected values correspond to the case of local extinction (brighter) or disk contribution (see text for details).

Table 4. H-alpha profile characteristics

|             | XMMU J053320.8-684122 |         |         |
|-------------|------------------------|---------|---------|
|             | $\lambda_{\text{central}}$ (Å) | FWHM (Å) | EW      |
| Red         | 6555.8±0.1             | 4.1±0.4 | -0.44±0.03 |
| Blue        | 6566.9±0.1             | 7.8±0.2 | -1.35±0.04 |
|             |                        |         |         |
| XMMU J053108.3-690923 |            |         |         |
|             | $\lambda_{\text{central}}$ (Å) | FWHM (Å) | EW      |
| Red         | 6556.34±0.06           | 4.8±0.2 | -0.51±0.02 |
| Blue        | 6567.50±0.03           | 7.1±0.1 | -2.06±0.02 |

on stellar models. This is presented in Fig. 9. In both systems, the $(B-V)_0$ colour of the star (i.e. its temperature) is better determined by its spectral class than by its photometric properties. The photometric color is affected by the uncertainties in interstellar and circumstellar reddening and the possible contribution from a circumstellar disk. Therefore, we used $B - V \approx -0.2$ as the de-reddened colour of the donor. Regarding the absolute magnitude, we use the values calculated earlier, with the clarification that in the case of XMMU J053108.3-690923 the absolute magnitude can have an uncertainty of the order of 0.5 mag in B. This is a result of the different interpretations that are possible for the observed large B-V value. If it is caused by high local or circumstellar absorption, then the corresponding extinction needs to be taken into account in the derivation of $M_B$ (leading to the brighter value of $M_B$). This interpretation is supported by the high absorption of the X-ray spectrum. If, on the other hand, the high B-V value is due to
a disk component, which is expected to contribute mostly to the red and infrared, \( M_b \) is not expected to be affected appreciably. In this case, we only correct for the known interstellar extinction in the region from Haschke et al. (2011). Interestingly, the ratio between \( E(B-V) \) and the equivalent width of the \( H_\alpha \) line is consistent with the expected relation for BeXRB systems (Riquelme et al. 2012), thus supporting this interpretation.

Taking into account all these uncertainties, and according to Fig. 9, we estimate that the mass of XMMU J053108.3-690923 is in the range 12-18 \( M_\odot \) and of XMMU J053320.8-684122 around 18-22 \( M_\odot \). We note that the upper limits on these ranges are mainly driven from our assumption on the expected color of the donor star that was assumed \( B - V \approx -0.2 \), but could be as low as -0.25.

4 DISCUSSION

We have presented a detailed study of the X-ray spectral and temporal properties of two newly discovered HMXB systems in the direction of the LMC. Below we summarize the results of our study and discuss the properties of the systems in the context of quasi-spherical accretion in the subsonic regime.

4.1 XMMU J053108.3-690923: a \( \sim 2013 \) s pulsar with a bright giant (or supergiant Ib) companion

Timing analysis of the \textit{XMM-Newton} data revealed the presence of coherent pulsations with a period of \( \sim 2013 \) s. The phase resolved hardness ratio of the system (see Fig. 5) reveals a week correlation between its luminosity and hardness ratio (harder when brighter), which is in agreement with the general trend of accreting XRB pulsars in the MCs (e.g. Vasilopoulos et al. 2014; Sturm et al. 2014; Koliopanos & Vasilopoulos 2017). The optical companion of the system was identified as a B0e II-Ib with a mass in the range of 12-18 \( M_\odot \) (see § 3.4).

From all the available X-ray observations we can set a lower limit on the long-term (i.e. not due to pulsations) X-ray variability of the system (factor of 8; see Table 1). This is relatively low compared to pulsating HMXBs located in the MCs (Haberl & Sturm 2016, for SMC systems). The small long-term variability of the system can be a result of the nature of the donor star (i.e. supergiant). BeXRBs can exhibit variability in their X-ray light curves on timescales of months to years that can be connected to the activity of the donor star and changes of its decretion disk (e.g. Reig et al. 2010). Very long optical variations related to modulations of the Be disk size is present in most of the SMC pulsars (Rajoelimanana et al. 2011). Similarly, analysis of optical monitoring data of SMC BeXRB pulsars obtained by OGLE\(^7\), have revealed optical periodicities that can be interpreted as orbital period or non-radial pulsations of the Be star (Schmidke et al. 2013; McBride et al. 2017). In many cases, orbital periods of individual BeXRB systems in both the LMC and SMC have been inferred from their OGLE optical light-curves\(^8\) (e.g. Vasilopoulos et al. 2016, 2017; Sturm et al. 2014; Boon et al. 2017). It is therefore atypical for BeXRB systems not to exhibit some sort of optical variability due to the presence of a disk around the massive star. We

\(^7\) OGLE: Optical Gravitational Lensing Experiment (Udalski et al. 2015)

\(^8\) The OGLE-IV I band photometric data are publicly available online through the OGLE real time monitoring of X-ray variables web page (Udalski 2008); http://ogle.astrouw.edu.pl/ogle4/xrom/xrom.html

analysed the available OGLE data of XMMU J053108.3-690923 (Udalski, A.: private communication) using the Lomb-Scargle periodogram (Scargle 1982; Horne & Baliunas 1986). The OGLE-IV light curve of XMMU J053108.3-690923 reveal no long-term modulation or periodic signal that could be interpreted as orbital period (see also van Jaarsveld et al. 2017). Due to the above, we interpret the measured pulsations as the NS spin period, and classify the system as a SgXRB pulsar, the 2\(^{nd}\) known in the LMC. In this scenario the long-term X-ray variability of the system is easily explained in terms of orbital modulation due to an eccentric orbit (e.g. Haberl 1991).

The X-ray spectrum of the system can be satisfactorily described by (i) an absorbed power law plus black-body component or by (ii) a partial-covered absorbed power law (see §3.3). In the first scenario, the black-body component has a temperature of \( \sim 1.75 \) keV and a size of \( \sim 0.5 \) km, and can be explained by the presence of a hot spot at the NS magnetic pole. In the second interpretation, the high X-ray absorption can be associated with the presence of a clumpy wind originating from the supergiant star. Another physical alternative for explaining the presence of a partial-covering absorber is that the NS is covered by a dense shell of material or an accretion curtain. In this scenario, any changes in the HR with pulse profile may be explained by variations in the covering fraction with pulse phase, if the covering material is locked with the NS rotation period. To investigate this possibility, we used the best-fit model to create simulated spectra for different values of the covering fraction. The minimum observed HR (\( \sim -0.57 \) at phase \( \sim 0.5 \)) can be reproduced by a covering factor of 0.33, whereas the maximum observed HR (\( \sim -0.74 \) at phase \( \sim -1 \)) requires a covering factor of 0.8. Nevertheless, this interpretation makes it difficult to explain such high absorptions from ionized gas as it would require very high densities and the resulting optical depth would probe much higher accretion rates than the one inferred from the observed X-ray luminosity.

4.2 XMMU J053320.8-684122: A probable SFXT in the LMC

Timing analysis of the X-ray events collected by \textit{XMM-Newton} (obsid: 0690743801) did not reveal the presence of any statistically significant periodic signal. During the first 22 ks of the \textit{XMM-Newton} observation, the X-ray luminosity of the system shows small variations around a mean value of \( L_{X,\text{obs}} \sim 1.4 \times 10^{34} \) erg s\(^{-1}\). Towards the end of the observation the system’s luminosity increased rapidly (within \( \sim 0.5 \) ks) by a factor of \( \sim 13 \), while three subsequent flares appear to occur every \( \sim 2200 \) s (see Fig. 2). We propose that this indicates the onset of fast bright X-ray flares which have been detected in HMXB systems with supergiant companions (Negueruela et al. 2006). This is also consistent with the quasi-periodic flaring activity observed in other galactic SFXT (e.g. IGR J11215-5952 & IGR J16418-4532: Sidoli et al. 2017b, 2012).

Following this scenario the low X-ray luminosity of XMMU J053320.8-684122 prior to the three flares may be the result of quasi-spherical settling accretion in a wind-fed HMXB (Shakura et al. 2012; see also Shakura & Postnov 2017 for a recent review). The optical counterpart of XMMU J053320.8-684122, which has been identified as a B0.5e Ib star with a mass of \( 18 \sim 22 M_\odot \) (see Fig. 9), is also compatible with the classification of the system as an SFXT.

The X-ray spectrum of the system can be described well by an absorbed power-law model, but due to low photon statistics we were not able to test more complex models. Nevertheless, the high value of intrinsic column density that is required to model
the system’s X-ray spectrum is in favour of a dense environment expected in a wind-fed accreting system. It is typical for the X-ray spectrum of wind-fed systems to exhibit large intrinsic absorption. Obscured HMXBs are naturally explained by a compact object orbiting inside a cocoon of dust and/or cold gas formed by a strong and clumpy stellar wind of the companion (Chaty 2008b; Blay et al. 2012). Typical SgXRBs show larger persistent luminosities and higher absorption (N\textsubscript{H}>10\textsuperscript{22} cm\textsuperscript{-2}) indicating a stronger wind, while SXFTs are known to show lower intrinsic absorption values (10\textsuperscript{21} < N\textsubscript{H} < 10\textsuperscript{22} cm\textsuperscript{-2}). The latter is consistent with the XMMU J053320.8-684122 scenario that XMMU J053320.8-684122 is most probably an SFXT system.

4.2.1 Quasi-spherical accretion onto an NS

By adopting the scenario of quasi-spherical accretion onto a slowly rotating NS, we provide rough estimates for the physical properties of XMMU J053320.8-684122.

In the scenario of quasi-spherical accretion, the stellar wind material that is being gravitationally captured by the orbiting NS can either fall supersonically towards the NS magnetosphere (supersonic regime) or it can form a quasi-static shell of hot plasma above it (subsonic regime) (Shakura et al. 2012). The latter is relevant for systems with L\textsubscript{X} \lesssim 4\times10\textsuperscript{36} erg s\textsuperscript{-1}, whereas the supersonic regime settles in for higher X-ray luminosities. Thus, the quasi-spherical accretion model is applicable to both persistent and SXFT systems with slowly rotating pulsars.

As the X-ray luminosity of XMMU J053320.8-684122 never exceeds 4\times10\textsuperscript{36} erg s\textsuperscript{-1} for the duration of the XMM-Newton observation (obsid: 0690743801), it is reasonable to assume that accretion takes place in the subsonic regime. The entry of accreting material into the magnetosphere determines the X-ray luminosity from the NS\textsuperscript{9} and is being regulated by the plasma cooling processes. These lead effectively to a lower radial plasma velocity (v_\text{r}) than the free-fall velocity at a given radius r (v_\text{ff} = \sqrt{2GM_{\text{NS}}/r}) and can be incorporated into the dimensionless factor f = v_\text{r}/v_\text{ff} \lesssim 1.

For L\textsubscript{X} \gtrsim 10\textsuperscript{35} erg s\textsuperscript{-1}, which is relevant to XMMU J053320.8-684122, Compton cooling dominates over the radiative cooling due to free-free emission and f is given by (Shakura & Postnov 2017):

\begin{equation}
    f_c(v) \approx 0.22 \zeta^{7/11} M_{16}^{11/11} P_{30}^{-2/11},
\end{equation}

where \zeta \leq 1, M = 10\textsuperscript{16} M_\odot g s\textsuperscript{-1} is the accretion rate inferred from the X-ray luminosity, and \mu = 10\textsuperscript{9} \mu_\odot G cm\textsuperscript{3} is the NS magnetic moment. The X-ray luminosity of the non-flaring state can be then derived (Shakura et al. 2014):

\begin{equation}
    L_{X,\text{low}} \approx \frac{5 \times 10^{32} \text{erg s}^{-1}}{f_c(v)} \left( \frac{M}{10\textsuperscript{16} M_\odot} \right)^{s-2/3} \left( \frac{v_\text{w}}{10\textsuperscript{3} \text{km s}^{-1}} \right)^{-1} \left( \frac{P_{\text{orb}}}{10\textsuperscript{3} \text{d}} \right)^{4/3},
\end{equation}

where s = 2.76 is the power law index of mass-luminosity relation for massive stars (see Vitrichenko et al. 2007), v_\text{w} is the terminal wind velocity of massive stars (typically 1000 km s\textsuperscript{-1}), v_\text{w} is the wind velocity at the NS Bondi radius, and P_\text{orb} is the orbital period. Hence, we adopt M = 18M_\odot as an reference value (see Fig. 9).

An estimate of v_\text{w} can be obtained, if one matches the mean duration of the observed X-ray flares (t_\text{fl} \sim 2.2 \times 10\textsuperscript{3} s) with the free-fall timescale from the outer radius of the plasma shell (i.e., the Bondi radius):

\begin{equation}
    v_w = \left( \frac{2GM_{\text{NS}}}{r_\text{tr}} \right)^{1/3} = \frac{570}{1.4} \left( \frac{M_{\text{NS}}}{10\textsuperscript{3} M_\odot} \right)^{1/3} \left( \frac{t_{\text{fl}}}{10\textsuperscript{3} \text{d}} \right)^{-1/3} \text{km s}^{-1},
\end{equation}

By substituting eqs. (1), (3) and the measured mean X-ray luminosity (i.e., L_{X,\text{low}} \approx 1.4 \times 10\textsuperscript{35} erg s\textsuperscript{-1}) into eq. (3), we find that P_{\text{orb}} \sim 10 \text{ d. Interestingly, the derived orbital period is similar to those of supergiant and SXFT systems (e.g. Drave et al. 2012).}

The torques acting on the quasi-static plasma shell above the magnetosphere can either spin-up or spin-down the NS. Because of the short relaxation time (∼10\textsuperscript{9} yr – see also Siddoli et al. 2017a), it is reasonable to assume that the NS is at an equilibrium state, where its spin period remains constant with time and is given by (Shakura & Postnov 2017):

\begin{equation}
    P_{\text{eq}} \approx 1000 \mu_{30}^{12/11} M_{16}^{-4/11} \left( \frac{P_{\text{fl}}}{10 \text{ d}} \right) \left( \frac{v_w}{10\textsuperscript{3} \text{km s}^{-1}} \right)^{4} \text{s}
\end{equation}

Using the estimated values for the wind velocity and the orbital period, we find P_{\text{eq}} \sim 200 \text{s for } \mu_{30} = 1. Below we list other parameters of the shell that we can estimate:

- Bondi radius: R_\text{B} = 2GM_{\text{NS}}/v_\text{w} \sim 10\textsuperscript{11} cm
- Alfvén radius (Shakura et al. 2012; Shakura & Postnov 2017):

\begin{equation}
    R_\Lambda \approx \frac{300}{1 - \frac{1}{\Gamma} \frac{\mu_{30}^2}{G M_{\text{NS}}^3}} \times \frac{f_{c}(v_{w})^{2}}{\Gamma^{7/11}} \sim 2 \times 10\textsuperscript{8} \text{cm},
\end{equation}

where \Gamma ≈ 5/3 is the adiabatic index.

- Temperature of the plasma at Alfvén radius:

\begin{equation}
    T(R_\Lambda) = \frac{\Gamma}{1 - \frac{1}{\Gamma} \frac{\mu_{30}^2}{G M_{\text{NS}}^3}} \approx 2.5 \times 10\textsuperscript{8} \text{K}
\end{equation}

where \mu ≈ 0.60 for ionized gas for the LMC chemical composition (Rolleston et al. 2002) and R is the gas constant. The derived temperature is sufficiently low to allow the entry of matter through the magnetosphere via the interchange instability (see Shakura et al. 2012).

- Mass of the plasma shell (Shakura et al. 2014):

\begin{equation}
    M_\text{sh} \approx \frac{2}{3} \frac{M}{f_c(v)} t_{\text{fl}}(R_\text{B}) \approx 2 \times 10\textsuperscript{15} \text{g.}
\end{equation}

- Plasma density at Alfvén radius (Shakura et al. 2012):

\begin{equation}
    \rho(R_\Lambda) \approx \frac{3M_\text{sh}}{8\pi R_\Lambda^3} \left( \frac{R_\text{B}^3}{R_\Lambda^3} - 1 \right)^{1/2} \approx 8 \times 10\textsuperscript{-13} \text{g cm}^{-3},
\end{equation}

where a density profile of \rho(R) \propto R^{-3/2} was assumed.

In the Compton cooling regime, the ratio of the flaring to the non-flaring luminosity can be estimated as L_{X,\text{fl}}/L_{X,\text{low}} \approx 1/f_c(v) \propto L_{X,\text{low}}^{-4/11}. Using the mean low luminosity of XMMU J053320.8-684122 in the 0.3-10 keV and equation (1), we find L_{X,\text{fl}}/L_{X,\text{low}} ≈ 7. Following this, we made a comparison of our results with those derived for other known SXFT systems. Recently, Shakura et al. (2014) computed the mean dynamic range of INTEGRAL detected flares from SXFT systems by using long-term INTEGRAL archival data in hard X-rays (17-50 keV) (Paizis & Sidoli 2014). This is illustrated in Fig. 10 (black crosses). XMMU J053320.8-684122 is well modeled by an absorbed power-law in the 0.3-10 keV band. The X-ray spectrum of accreting NS exhibits a cutoff above 10 keV, thus it is not straightforward to extrapolate the luminosity of accreting NS in different energy bands. Nevertheless, we can estimate an expected range for its hard X-ray luminosity assuming an upper (i.e. 50 keV) and lower (i.e. 0 keV).
10 keV) limit for the cutoff energy. If we assume a cutoff power law with photon index 0.92 (see Table 3) and variable cutoff energy, the non-flaring luminosity of XMMU J053320.8-684122 in the 17-50 keV band ranges between ~1 and 4 times its luminosity in the 0.3-10.0 keV band. The variability of the system in the soft and X-rays is expected to be the same, assuming no significant change in its spectral properties during the flares. The location of XMMU J053320.8-684122 in the $L_{X,low}$ vs $L_{X,flare}/L_{X,low}$ diagram, shown as a striped band in Fig. 10, is in agreement with the theoretical predictions (dashed and dotted lines). We caution the reader that our estimates for the time-averaged luminosities are limited to a single XMM-Newton observation.

In principle, similar estimates can be performed for XMMU J053108.3-690923 by assuming that the observed spin-period corresponds to the equilibrium one (see eq. (4)). However, the estimates will suffer from large uncertainties due to the following reasons: No fast bright flares have been detected, thus no flare duration and amplitude can be determined. Subsequently, no wind velocity or orbital period can be estimated. We note that $P_{\text{spin}}$ has a strong dependence on the wind velocity (see also Shakura et al. 2014). Finally, the nature of the donor star is less certain than in the XMMU J053320.8-684122 system.

5 CONCLUSIONS

We present a detailed analysis of two SgXRBS in the LMC, raising the number of LMC SgXRBS systems to five. We study the X-ray timing and spectral properties of the compact objects as well as the optical properties of the donor stars.

The first system XMMU J053108.3-690923, displays a long period of quiescence followed by three subsequent flares of high dynamic range. The spectrum is consistent with an absorbed power-law with a moderate value of absorption column density. The optical companion is identified as B0.5e Iib with a mass of 18 M⊙. The above properties are indicative of the SFXT nature of the system.

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Figure 10. Comparison of the mean dynamic flare range of other known SFXT systems. Values for the known systems (black crosses) refer to the INTEGRAL/IBIS energy range (17-50 keV) and were obtained from Paizis & Sidoli (2014). For XMMU J053320.8-684122 (striped band) we used the XMM-Newton derived rates in the 0.3-10 keV energy range and extrapolated to the 17-50 keV band by assuming a power law with photon index 0.92 with different cutoff energies (10 & 50 keV). Overplotted are the expected dependencies of $L_{X,\text{flare}}/L_{X,\text{low}}$ on the non-flaring luminosity in two regimes of plasma cooling in the shell: radiative cooling (black dotted line) (see Shakura et al. 2014) or Compton cooling (red dashed line), as described in the text.
