Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **421,** 2846–2853 (2012) doi:10.1111/j.1365-2966.2012.20511.x

Period–luminosity relation for persistent low-mass X-ray binaries in the near-infrared

Mikhail G. Revnivtsev,[1★] Ivan Yu. Zolotukhin[2,3,4] and Alexander V. Meshcheryakov[1]

[1]*Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia*
[2]*Observatoire de Paris-Meudon, LERMA, UMR 8112, 61 Av. de l'Observatoire, 75014 Paris, France*
[3]*Sternberg Astronomical Institute, Moscow State University, Universitetskij pr. 13, 119992 Moscow, Russia*
[4]*Observatoire de Paris, VO–Paris Data Centre, 61 Av. de l'Observatoire, 75014 Paris, France*

Accepted 2012 January 6. Received 2011 December 2; in original form 2011 July 21

ABSTRACT

We study the relations between the X-ray luminosity, orbital period and absolute near-infrared magnitude of persistent low-mass X-ray binaries (LMXBs). We show that often the optical and near-infrared spectral energy distributions of LMXBs can be adequately described by a simple model of an accretion disc and a secondary star reprocessing X-ray emission from a central compact object. This gives us evidence that one can make a reliable estimate of the orbital period of a persistent LMXB using an X-ray luminosity and an absolute infrared magnitude. Using a sample of well-known LMXBs, we have constructed a correlation of L_X, P_{orb} and M_K values that can be approximated by a straight line with root-mean-square scatter at the level of ∼0.3 mag. Such a correlation, being to some extent analogous to the correlation found by van Paradijs & McClintock, might be helpful for future population studies, especially in the light of forthcoming surveys of the Galaxy in the X-ray and infrared spectral domains.

Key words: infrared: stars – X-rays: binaries.

1 INTRODUCTION

Low-mass X-ray binaries (LXMBs) are binary systems with compact objects (neutron stars or black holes) accreting matter from a low-mass secondary companion. The first such systems were discovered about 50 yr ago (Giacconi et al. 1962) and presently more than a hundred of them are known in our Galaxy (e.g. Liu, van Paradijs & van den Heuvel 2007) and hundreds of them in external galaxies (see e.g. Fabbiano 2006; Evans et al. 2010). The population of low-mass X-ray binaries provides us with tools to study different physical mechanisms that define the population features (e.g. the energy-transfer efficiency during the common-envelope stage of the binary, the gravitational wave emission influence, the average magnetic field strength in old neutron stars) and also some properties of the host galaxy (e.g. the age of its stellar population). In order to reach these goals, one needs (1) better to understand the laws of formation and evolution of LMXBs and (2) to gather a clear sample of LMXBs with known parameters (orbital periods, X-ray luminosities, etc).

One of the major obstacles in doing the latter is the lack of measurements of orbital periods for the majority of known LMXBs. This is mainly caused by the fact that orbital modulation of the X-ray emission is rarely observed for geometrical reasons (a small companion star covers an insignificant fraction of the sky for a compact object, therefore very few known LMXBs demonstrate eclipses and/or dips), whereas detection of the optical or infrared (IR) modulation of LMXB emission is challenging because of the extreme faintness of these objects.

However, it is sometimes possible to estimate LMXB orbital periods indirectly, making use of the fact that their optical and IR emission originates mainly from reprocessing of the central X-ray emission by the outer accretion disc (see e.g. McClintock et al. 1979; van Paradijs & McClintock 1994). The efficiency of this approach was demonstrated by van Paradijs & McClintock (1994), who showed that the absolute optical magnitude of LMXBs had a very clear correlation with their X-ray luminosity and orbital period. It should be kept in mind, however, that this method is physically justified for *persistent* LMXBs, which possess a stationary accretion flow with a constant incident X-ray flux. A transient-like behaviour might lead to large variations of X-ray flux or/and accretion-flow structure and thus to deviations from any possible correlation. One might also expect significant deviations when the central X-ray emission of a source is hidden from the observer due to the very large inclination angle of the binary system (so-called accretion-disc corona or ADC sources like 4U1822–37).

Unfortunately, the majority of LMXBs in the Galaxy (either transient or persistent) reside in the Galactic plane and thus suffer from severe dust extinction reaching $A_V \sim 10$–30 mag, making them completely unobservable in the optical domain and thus shifting observational methods to longer wavelengths. Due to the fact that reliable measurements of LMXB absolute magnitude in the infrared

★E-mail: revnivtsev@iki.rssi.ru

spectral bands can be made for many more sources, it is then reasonable to calibrate diagnostics similar to that of van Paradijs & McClintock (1994) in the IR, in particular, in the *K* spectral band.

However, the spectral energy distribution (SED) of sources at these wavelengths might be contaminated by optically thin synchrotron emission, sometimes observed at the far end of the NIR and up to the radio range in persistent (Migliari et al. 2010) and especially in transient (see e.g. Corbel & Fender 2002; Russell et al. 2006; Russell, Fender & Jonker 2007; Russell & Fender 2008; Shahbaz et al. 2008) LMXBs. This issue needs to be carefully explored before we are able to construct a reliable period–luminosity relation for the *K* band.

In this paper we show that the general shape of the SED of *persistent* LMXBs in the optical–NIR spectral range can be reasonably well described in the framework of a model in which the optical–NIR emission comes from the reprocessing of the central X-ray flux in the accretion disc and the secondary star. This provides evidence that there is a physical connection between the main properties of the binary and its infrared luminosity. We present a correlation of the absolute magnitude of LMXBs with their X-ray luminosity and orbital period similar to the one found in the *V* band by van Paradijs & McClintock (1994). In this work we consider only persistent LMXBs to be sure that their accretion-disc structure does not change much at different epochs. We consider only LMXBs that harbour neutron stars as a compact object, in order to reduce the uncertainties related to the mass of the compact object.

2 LMXB SPECTRAL ENERGY DISTRIBUTION IN THE OPTICAL AND NIR

In order to check the validity of our approach to interpretation of the LMXB luminosity in the optical and NIR spectral domains, we have studied the broad-band spectral energy distribution of three binary systems, Cyg X-2, Sco X-1 and 4U0614+091, which can be considered as illustrative. These three systems cover a wide range of orbital periods, from 0.81–236.27 h, and have more or less reliable distance, interstellar extinction and in two cases (Cyg X-2 and Sco X-1) inclination estimates. Their parameters, adopted in this study for spectral modelling, are presented in Table 1.

It is important to keep in mind that in some cases a considerable contribution from optically thin emission can be seen in different

Table 1. Parameters of the three binary systems for which we have calculated optical–NIR SEDs. Orbital periods were adopted from Ritter & Kolb (2003). Cyg X-2 and Sco X-1, being members of the so-called ‘Z sources’, were assumed to have Eddington luminosity, whereas the luminosity of 4U0614+091 is taken from Revnivtsev et al. (2011). See the text for other parameters common for these systems.

	Cyg X-2	Sco X-1	4U0614+091
Distance(kpc)	$11.6 \pm 0.3^{(1)}$	$2.8 \pm 0.3^{(2)}$	$3.2^{(3)}$
$P_{\rm orb}$	236.27	18.94	0.81
M_1	$1.71^{(4)}$	1.4	1.4
q	$0.34^{(4)}$	$0.3^{(5)}$	$0.04^{(6)}$
$\log L_{\rm x}$(erg/sec)	38.3	38.3	36.5
Inclination	$62.5^{(7)}$	$38^{(5)}$	$60^{(8)}$
A_V	$1.34^{(9)}$	$0.91^{(10)}$	$2^{(11)}$

(1) Smale (1998), (2) Bradshaw, Fomalont & Geldzahler (1999), (3) Kuulkers et al. (2010), (4) Casares et al. (2010), (5) Steeghs & Casares (2002), (6) Werner et al. (2006), (7) Orosz & Kuulkers (1999), (8) inclination is unknown, fixed at given value, (9) McClintock et al. (1984), (10) Vrtilek et al. (1991), (11) Migliari et al. (2010).

states of X-ray binaries (see e.g. Russell et al. 2006). In particular, detection of polarized infrared emission of some X-ray binaries, exceeding levels expected from interstellar scattering, hints at a synchrotron origin of some fraction of their infrared flux (see e.g. Shahbaz et al. 2008).

Therefore, in order to test the applicability of our model that accounts for optically thick emission, we have intentionally selected X-ray binaries at different spectral states, namely high/soft (Sco X-1 and Cyg X-2) and low/hard (4U0614+091) states.

For calculation of the spectral energy distribution of LMXBs, we adopt a simple model (see e.g. Tjemkes, van Paradijs & Zuiderwijk 1986; O'Brien et al. 2002; Mescheryakov, Revnivtsev & Filippova 2011b), when all surface elements in a binary system (which comprises an accretion disc and a secondary star) emit blackbody radiation with local temperature defined by X-ray irradiation and internal heating. The shape of the star was assumed to follow Roche-lobe geometry.

The temperature of the illuminated side of the star was calculated taking into account heating due to the incident X-ray flux:

$$T_\star^4 = T_{\star,0}^4 + \frac{\eta_\star L_{\rm X} \cos\theta_\star}{4\pi\sigma d^2}, \qquad (1)$$

where $L_{\rm X}$ is the luminosity of the central X-ray source, $\theta_\star$ the angle between the X-ray source direction and the surface normal, d the distance from the X-ray source to the surface element, σ the Stefan-Boltzmann constant and $\eta_\star$ the fraction of reprocessed X-ray emission. The temperature of the part of the star not illuminated by a compact object was taken following de Jong, van Paradijs & Augusteijn (1996) as $T_{\star,0} = 5800(L/{\rm L}_\odot)^{1/4}(R/{\rm R}_\odot)^{-1/2}$ K and the mass–luminosity and mass–radius relation were taken from Tout et al. (1996). For the fraction of X-ray emission reprocessed and reradiated from the surface of the secondary star, we assume $\eta_\star = 0.6$ (see e.g. London, McCray & Auer 1981).

For the effective temperature of the disc surface element we used the common relation, which includes viscous heating and heating by X-ray irradiation in the outer parts of a geometrically thin accretion disc:

$$T_{\rm d}^4 = \frac{3GM_1L_{\rm X}}{8\pi\epsilon c^2\sigma R^3} + \frac{\eta_{\rm d} L_{\rm X}}{4\pi\sigma R^2}\left(\frac{H}{R}\right)_{\rm out}(n-1). \qquad (2)$$

We use $M_1 = 1.4\,{\rm M}_\odot$ and $\epsilon = 0.1$ to denote the mass of the compact object and the accretion efficiency, respectively, for a neutron star (NS) LMXB.

The fraction of the flux intercepted by the accretion disc was calculated assuming the shape of the intercepting surface to be a disc with height that is a function of its radius: $H \propto R^n$, where we assume $n = 9/7$ (Vrtilek et al. 1990). We note here that the intercepting surface is not necessarily the optically thick accretion disc itself; it might be the corona that intercepts the X-ray flux and redirects it to the optically thick accretion disc (see e.g. Jimenez-Garate, Raymond & Liedahl 2002; Mescheryakov, Shakura & Suleimanov 2011a). We assume the ratio of the height of the intercepting surface to its radius at the outer edge of the disc to be $(H/R)_{\rm out} = 0.1$. Parameter $\eta_{\rm d}$, the effective fraction of emission reprocessed in the accretion disc–corona system (ratio of X-ray flux thermalized in the optically thick disc to the incident X-ray flux), is not yet accurately known; different authors estimate values from less than 0.1 (de Jong et al. 1996) up to ∼0.5 (Vrtilek et al. 1991). In our work we adopt the value $\eta_{\rm d} = 0.25$.

The accretion disc radius around the compact object was taken to be equal to the tidal radius as estimated by Paczynski (1977). A more detailed description of our model can be found in Mescheryakov et al. (2011b). We note here that our ability to predict the absolute magnitude of LMXBs with accuracy better than 0.5–0.8 mag (i.e. within a factor of 2 in the flux) mostly depends on the accuracy of our knowledge of the binary system inclination and the fraction of reprocessed X-ray emission (for fixed disc radius and shape of the X-ray intercepting surface).

3 DATA

In this work we consider only *persistent* LMXBs, which means that their optical, IR and X-ray fluxes do not vary by large factors. This is essential for the present work, because here we use measurements of brightness of sources in the optical, IR and X-ray energy bands, not obtained simultaneously.

The distribution of X-ray fluxes of bright (with fluxes greater than ∼50 mCrab, i.e. enough to be detected by the All-Sky Monitor (ASM) of the *Rossi X-ray Timing Explorer* (*RXTE*) observatory in all single measurements) persistent LMXBs was analysed by Postnov & Kuranov (2005). It was shown there that typical long-term root-mean-square flux deviations do not exceed ∼20–30 per cent of their mean values. Long-term variations of the optical emission of persistent LMXBs were studied in a number of works, in particular for sources Sco X-1 (McNamara et al. 2005), Cyg X-2 (O'Brien et al. 2004) and 4U0614+091 (Hakala, Charles & Muhli 2011) considered in our paper. It was demonstrated that the long-term variations of their apparent optical magnitudes do not typically exceed ∼0.1–0.3 mag (i.e. ∼10–30 per cent flux variation).

Based on this evidence, we assume an additional ∼10–30 per cent systematic flux uncertainty due to the non-simultaneous nature of the measurements we use while analysing X-ray and optical luminosity correlations.

To construct broad-band spectral energy distributions of our test objects, we have used their multi-colour photometry from the literature and also new publicly available data from the *Spitzer* instruments IRAC (Fazio et al. 2004) and MIPS (Rieke et al. 2004) and the *Wide-field Infrared Survey Explorer* (*WISE*: Wright et al. 2010).

Mid-infrared photometric measurements were obtained from the analysis of *Spitzer* basic calibrated data images. For each source we have determined the flux by summing counts in a circular aperture with a radius of 6 arcsec (for *Spitzer*/MIPS at 24 μm we have used a 9-arcsec aperture due to the larger full width at half-maximum (FWHM) of the instrument point spread function (PSF) at these wavelengths) centred on the object and subtracting the background counts, collected in an appropriate field nearby.

Another set of photometric measurements was extracted from the preliminary data release of the *WISE* satellite (Wright et al. 2010). Conversion of magnitudes into physical fluxes was achieved by using the coefficients presented in Cutri et al. (2011).

All photometric measurements were corrected for interstellar extinction assuming the Rieke & Lebofsky (1985) reddening law.

Data at these long wavelengths are important as an additional check for the presence of optically thin synchrotron emission, sometimes seen in the SEDs of LMXBs (see e.g. Migliari et al. 2010).

3.1 Cyg X-2

Photometric measurements of Cyg X-2 used in this work are given in Table 2. A model of the broad-band SED constructed assuming the above-mentioned parameters is shown by the solid curve on Fig. 1. The model is not fitted to the data, but presented as it is, making use of the parameters described in the text and in Table 1. The accurate position of the modelled SED with respect to the *y*-axis depends on the source distance, the fraction of emission reprocessed in the thermal disc and the binary system inclination.

It is clear from Fig. 1 that the adopted model adequately describes the shape of the broad-band spectral energy distribution of the source, except for its long wavelength range (8 and 24 μm). We make the following conclusions from this comparison: (1) the model describes the SED of Cyg X-2 well up to ∼4 μm and (2) at longer wavelengths we observe indications of some additional emission component, which is likely the optically thin synchrotron

Table 2. Photometric measurements of Cyg X-2. We have assumed its interstellar extinction to be $A_V = 1.34$.

Filter	Vega mag	A_λ	Vega mag corr.
U	15.0$^{(1)}$	2.05	12.9
B	15.3$^{(1)}$	1.77	13.5
V	14.8$^{(1)}$	1.34	13.5
R	14.0$^{(2)}$	1.00	13.0
J	13.39$^{(3)}$	0.38	13.01
H	13.15$^{(3)}$	0.24	12.92
K	13.05$^{(3)}$	0.15	12.90
Spitzer			
λ (μm)	Flux (mJy)		
4.5	1.4		
8.0	0.8		
24	8.5		

(1) Orosz & Kuulkers (1999), (2) USNO B1, (3) 2MASS.

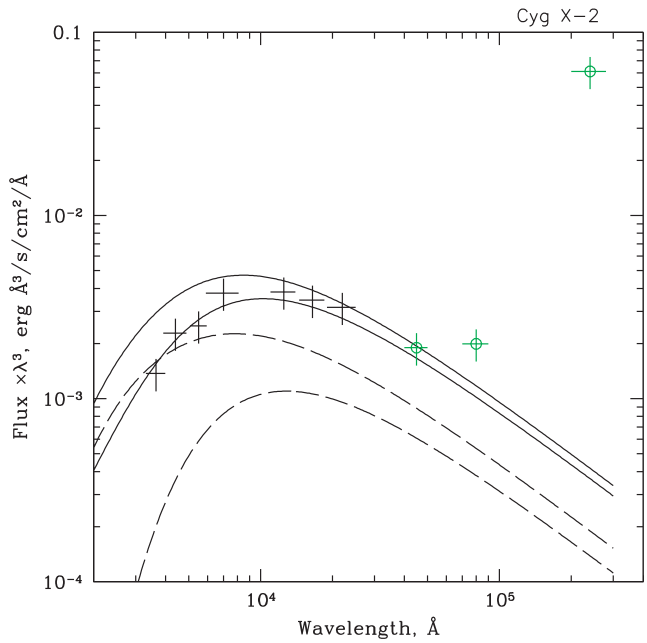

Figure 1. Extinction-corrected spectral energy distribution of Cyg X-2 in the optical and IR with a simple model of its emission (see text). The model is not fitted to the data, but presented as it is, making use of the parameters described in the text and in Table 1. The dashed line represents the contribution of the secondary star. Two sets of curves represent SEDs during maximum and minimum contribution of the secondary star to the total brightness of the binary. Due to possible time variations of the optical/NIR emission of the source, we have assumed a 0.2-mag uncertainty of all photometric measurements. Open circles denote measurements obtained using *Spitzer* data.

emission of non-thermal electrons. Polarization measurements, indicating that at these wavelengths the source might have a contribution from a synchrotron component, were presented by Shahbaz et al. (2008).

3.2 Sco X-1

A set of Sco X-1 photometric measurements in the optical and infrared, obtained at different epochs with different instruments, is presented in Table 3. It is clearly seen that Sco X-1 exhibits significant variations of its SED at the long-wavelength end, while in the optical the changes are inessential (see e.g. McNamara et al. 2005). This is not surprising because the source is known to be strongly variable at radio wavelengths (e.g. Pandey et al. 2007), which means that it sometimes displays a spectral component emerging from a non-thermal population of electrons. In addition to this, it was shown that in the NIR Sco X-1 sometimes exhibits polarization exceeding that induced by interstellar dust scattering (Shahbaz et al. 2008; Russell & Fender 2008), which can also be attributed to the emission caused by non-thermal electrons. Finally, yet another spectral component (different from the optically thick emission considered by our model) can be found in the presence of hard X-ray tails, often observed from Sco X-1 (e.g. D'Amico et al. 2001; Paizis et al. 2006) and likely to be related to the emission of energetic non-thermal electrons in the accretion flow (see e.g. Migliari et al. 2007).

However, in spite of these complications we note that one set of NIR measurements (namely those of Willis et al. 1980) does show a Rayleigh–Jeans type SED in the NIR, suggesting that the contribution of an additional component attributable to non-thermal electrons at that epoch was small or negligible. We will therefore use this K-magnitude estimate in our subsequent work. Importantly, the $J - K$ colour can be used as an indicator of a presumably synchrotron component in the SED. In particular, our model (see Fig. 2) predicts $J - K \sim -0.15$ mag for the source (see below), while the brightest NIR measurements reach $J - K = 0.6$ mag. The faintest NIR estimates give $J - K = -0.19$ mag, which is reasonably compatible with the predictions of our model.

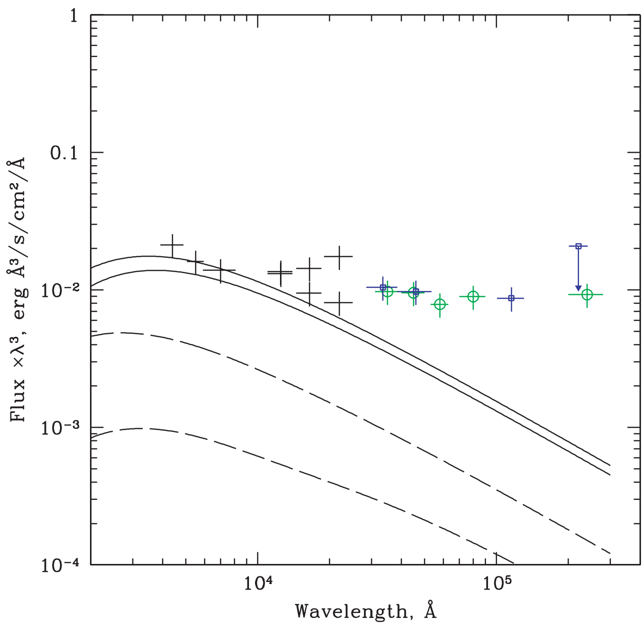

Figure 2. The same as Fig. 1, but for Sco X-1. Open circles denote measurements obtained using *Spitzer* data, open squares measurements from *WISE* data.

Table 3. Photometric measurements of Sco X-1. We have assumed its interstellar extinction to be $A_V = 0.91$.

Filter	Vega mag	A_λ	Vega mag corr.
B	12.38[(1)]	1.78	11.04
V	12.40[(2)]	0.91	11.49
R	12.3[(3)]	0.68	11.62
J	11.90[(4)]	0.25	11.65
H	11.54[(4)]	0.15	11.39
K	11.15[(4)]	0.10	11.05
J	11.94[(5)]	0.25	11.69
H	11.99[(5)]	0.15	11.84
K	11.98[(5)]	0.10	11.88
Spitzer			
λ (μm)	Flux (mJy)		
3.5	9.3		
4.5	7.1		
5.8	4.5		
8.0	3.7		
24	1.3		
WISE			
3.35	10.4		
4.60	7.0		
11.5	2.5		
22.0	<3.0		

(1) McNamara et al. (2005), (2) McNamara et al. (2003), (3) USNO B1, (4) 2MASS, (5) Willis et al. (1980).

3.3 4U0614+091

We have adopted photometric measurements of 4U0614+091 from Migliari et al. (2010). It is clearly seen (and was mentioned in Migliari et al. 2010) that the source demonstrates an optically thin component at mid-infrared wavelengths and its contribution to the K band can be comparable to that of the optically thick mechanism considered by our model. For this reason, we have calculated the K magnitude of 4U0614+091 from J-band measurements by Migliari et al. (2010), using the model of optically thick emission (see Fig. 3), and used this value in subsequent work.

4 M_K–Σ_K RELATION OF PERSISTENT LMXBS

4.1 Model

Broad-band spectral energy distributions, shown in the previous section, help us to understand adequately the physical processes responsible for the observational appearance of LMXBs in the optical and NIR spectral domains.

According to this model, the absolute optical and NIR magnitude of LMXBs depend on both the X-ray luminosity of the central source and the size of the binary system. van Paradijs & McClintock (1994) showed that the luminosity of the system in the optical V band scales approximately as the square root of its X-ray luminosity and as a power of 2/3 of its orbital period. Note that these indexes are theoretically expected for V-band photometry if the temperature of the matter that gives the main contribution to the optical

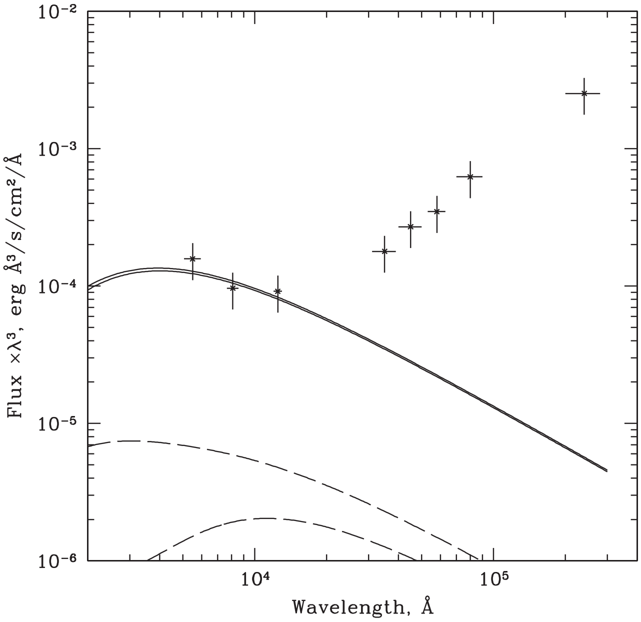

Figure 3. The same as Fig. 1, but for 4U0614+091.

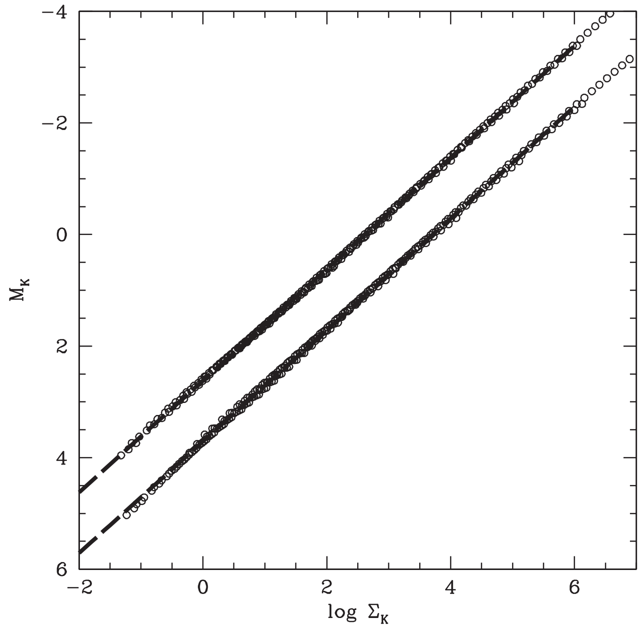

Figure 4. Absolute NIR magnitudes of modelled binaries versus their orbital period and X-ray luminosity, combined into Σ_K quantity. The upper points represent absolute brightness for binaries with orbital plane inclination $i = 0°$, in this case $\Sigma_K = (L_X/L_{Edd})^{0.29}P(\mathrm{h})^{0.92}$. The lower points show absolute brightness for binaries with inclination $i = 70°$, in this case $\Sigma_K = (L_X/L_{Edd})^{0.28}P(\mathrm{h})^{0.93}$. Dashed lines show the best linear fit to the points.

emission lies in a particular range ($T \approx 10\,000$–$30\,000$ K). For these temperatures, the surface brightness of a blackbody emitter scales as $S_V \propto T^{\simeq 2}$. For our case of the NIR K band, the scalings should be different.

In persistent LMXBs, we expect that the effective temperature of the accretion disc is above the hydrogen recombination limit everywhere. The effective temperature at which a hot disc becomes thermally unstable is, according to Dubus, Hameury & Lasota (2001), given by

$$T_H = 7200\alpha^{-0.002}\left(\frac{M_1}{M_\odot}\right)^{0.03}\left(\frac{R}{10^{10}\,\mathrm{cm}}\right)^{-0.08}\ \mathrm{K}. \qquad (3)$$

Here α is the standard Shakura–Sunyaev viscosity parameter.

For the temperature range $T > T_H$, the K spectral band ($\lambda \approx 2.2$ μm) lies almost at the Rayleigh–Jeans part of the disc blackbody spectrum; therefore the disc surface brightness should scale as $S_K \propto T^{\simeq 1}$. As the outer disc temperature dominated by irradiation scales as $T_{out} \propto L_X^{1/4}R_{out}^{-1/2}$ (see equation 2), having in mind $R_{out} \propto a$ and $a \propto P^{2/3}$ (from Kepler's law) as well as $L_K \propto S_K R_{out}^2$, the total IR luminosity of the accretion disc should be proportional to $L_K \propto L_X^{0.25}P^1$.

It is worth noting that the above relations are simplistic, e.g. noticeable viscous heating in the disc or contributions from the secondary star are expected to modify them. Therefore in order to understand more correct dependences between the absolute NIR magnitude of LMXBs, their X-ray luminosity and accretion disc size (i.e. orbital period), we have calculated a set of LMXB models for the range of orbital periods 2–750 h and X-ray luminosities 1×10^{35}–4×10^{38} erg s^{-1}.

While varying the orbital period, we have assumed that the secondary star fills its Roche lobe. We assumed that at orbital periods less than ∼6 h ($M < 0.6\,M_\odot$) the secondary star is not evolved and obeys the mass–radius relation for a main-sequence star (Tout et al. 1996). For orbital periods larger than ∼6 h (i.e. for the giant companions) we have fixed the companion masses at the value $0.6\,M_\odot$. This assumption in fact does not influence our results strongly and is supported by cases in which the masses of the donor giants are known, because they do not exceed this value, e.g. Sco X-1 has $M_2 \sim 0.4\,M_\odot$ (Steeghs & Casares 2002) and Cyg X-2 has $M_2 \sim 0.6\,M_\odot$ (Orosz & Kuulkers 1999).

After we have fixed the radius of the accretion disc (at the value of the tidal radius) and the shape of the disc (i.e. power-law index n in the law $H \propto R^n$), the main parameter, which can significantly shift the correlation up or down on the absolute magnitude axis, is the inclination angle of the binary system (this effect is illustrated in Fig. 4). An additional shift can be caused by a different value of the fraction of emission reprocessed in the accretion disc–corona system. We have assumed it to be 0.25 above.

Among all models covering the above-mentioned parameter space we have accepted only those that have a disc temperature at the outer radius not lower than $T_H \approx 6500$ K (see equation 3). This selection was applied because we are interested only in persistent LMXBs, while LMXBs with lower outer disc temperatures should be subject to disc thermal–viscous instability (see e.g. Lasota 2001 for a review).

The obtained absolute NIR magnitudes were fitted as a linear combination of log P and log L_X parameters. We have minimized the root-mean-square deviations from the modelled M_K values. The best-fitting relation for LMXBs with inclination $i = 0°$ is $M_{K,\mathrm{model},i=0} = 2.62 - 0.73\log(L_X/L_{Edd}) - 2.29\log P(\mathrm{h})$, while for an inclination of $i = 70°$ we have $M_{K,\mathrm{model},i=70} = 3.71 - 0.70\log(L_X/L_{Edd}) - 2.32\log P(\mathrm{h})$. For both cases the rms scatter of the data points from the approximation is ∼0.03. Here we adopted an Eddington luminosity for a 1.4-$M_\odot$ neutron star of $L_{Edd} = 2 \times 10^{38}$ erg s^{-1}.

Following the idea of van Paradijs & McClintock (1994), we construct the quantity Σ_K in such a way that it is proportional to the NIR luminosity L_K of the binary (but not to its absolute magnitude $M_K = -2.5\log L_K + \mathrm{const}$). Therefore, using the average values of the obtained best-fitting parameters we obtain a Σ_K for the near-infrared K band of $\Sigma_K = (L_X/L_{Edd})^{0.29}P(\mathrm{h})^{0.92}$. For such a parametrization, the absolute brightness $M_K = -2.5\log\Sigma_K +$ const. Note that the derived scaling is quite similar to our simplest theoretical estimates above.

4.2 Sample of known LMXBs

Having in hand a physically motivated value of Σ_K, on which the LMXB luminosity should depend, we constructed the $\log\Sigma_K$–M_K relation for the list of known LMXBs with NIR brightness measurements.

We have compiled a sample of all known LMXBs with measured values of their brightness in the *K* band (see Table 4). We have selected only binaries with neutron stars in order to reduce possible additional scatter due to compact object mass uncertainties.

The relationship between absolute magnitude in the *K* band and $\log\Sigma_K$ for known binaries from Table 4 is shown in Fig. 5.

We have used a linear least-squares method to fit this dependence without taking into account measurement uncertainties because of the possible physical dispersion of the absolute NIR magnitude values due to the unknown inclinations of the binaries.

The best-fitting approximation of this relation for all binaries considered is $M_K = (2.78 \pm 0.24) - (2.60 \pm 0.11)\log\Sigma_K$ (1σ confidence intervals). In order to estimate the confidence intervals here (and below) we assumed that uncertainties of data points are such that they provide $\chi^2 =$ d.o.f. (degrees of freedom). Confidence intervals were then calculated as usual from the interval of parameters that gives $\Delta\chi^2 = 1$.

Note that if our parametrization of this relationship is correct, then the coefficient in front of $\log\Sigma_K$ should be equal to 2.5 (because the constructed value Σ_K is proportional to the IR luminosity L_K of the system, whereas the absolute brightness is $M_K = -2.5\log L_K +$ const), which is compatible with the results of the fit. Fixing this coefficient we obtain

$$M_K = (2.66 \pm 0.11) - 2.5\log\Sigma_K.$$

The root-mean-square scatter of the observed points from the fitted straight line for our sample of sources is $\sim$0.3 mag. Note that this value is approximately a lower limit for any $M_K = f(L_X, P)$ model, which does not explicitly take into account the binary system inclination and the time variability of its flux.

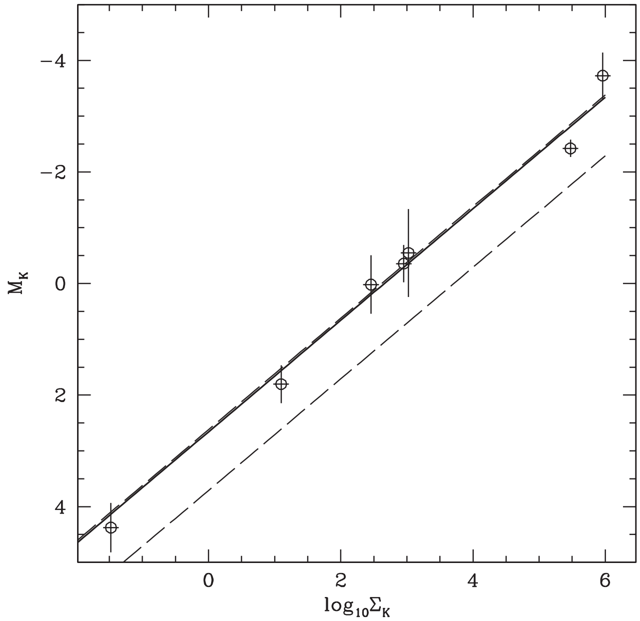

Figure 5. Correlation between absolute NIR magnitude of persistent LMXBs and the combination of their X-ray luminosity with the orbital period, $\Sigma_K = (L_X/L_{Edd})^{0.29}P(h)^{0.92}$. Crosses denote the positions of known persistent LMXBs, while dashed lines show the best-fitting correlations calculated from our modelling, the lower line for inclination $i = 70°$ and the upper line for $i = 0°$. The solid line shows the correlation $M_K = 2.66 - 2.5\log\Sigma_K$.

As a useful application we also present here the approximation of $V-K$ and $J-K$ colours obtained with our model as a function of P(h) and L_X for orbital plane inclination $i = 0°$. The best fit was calculated by minimizing the root-mean-square residual on a logarithmic scale:

$$\log(V-K+1.12) = -0.27\log L_X/L_{Edd} + 0.34\log P(h) - 0.75,$$

Table 4. Persistent LMXBs that were used to illustrate the Σ_K–M_K correlation plotted in Fig. 5. Literature references are given where necessary. X-ray luminosity L_X is taken from Revnivtsev et al. (2011), who calculated it using the X-ray flux from the *Uhuru* catalogue (Forman et al. 1978) and the distance estimates available from the literature; orbital periods *P* are adopted from Ritter & Kolb (2003). Values of A_K for three sources with detailed SED analysis in this paper were calculated from A_V values assuming $A_K = 0.11A_V$. Values of A_K for the remaining sources were taken from the 3D Galaxy extinction map by Marshall et al. (2006) if another reference is not indicated. The magnitude of 4U0614+091 in the *K* band was recalculated from the *J* measurement of Migliari et al. (2010), taking into account $J-K$ colours from the model discussed (see the text).

Name	$\log L_X$ (2–10 keV) ($\mathrm{erg\,s^{-1}}$)	*d* (kpc)	*P* (h)	m_K^{corr} (Vega mag)	A_K (mag)
Sco X-1	38.3	2.8 ± 0.3[1]	18.94	11.88	0.1
Cyg X-2	38.3	11.6 ± 0.3 [2]	236.27	12.9	0.15
GX 349+2	38.2	8.5[3]	22.5	14.1[4]	0.45
GX 13+1	37.7	7 ± 1[5]	601.7	10.5[6]	1.8[7]
4U1624-49	37.5	15.0 ± 2.9[8]	20.9	15.9[9]	2.4
4U1735-44	37.7	9.1 [10]	4.65	16.6[8][9]	0.16
4U1636-53	37.4	5.9	3.79	15.9[11]	0.27[11]
4U0614+091	36.5	3.2	0.81	16.9	0.22

(1) Bradshaw et al. (1999), (2) Smale (1998), (3) Galactic Center distance, (4) Wachter & Margon (1996), (5) Bandyopadhyay et al. (1999), (6) Bandyopadhyay et al. (2002), (7) Charles & Naylor (1992), (8) Xiang, Lee & Nowak (2007), (9) Wachter et al. (2005), (10) Augusteijn et al. (1998), (11) Russell et al. (2011).

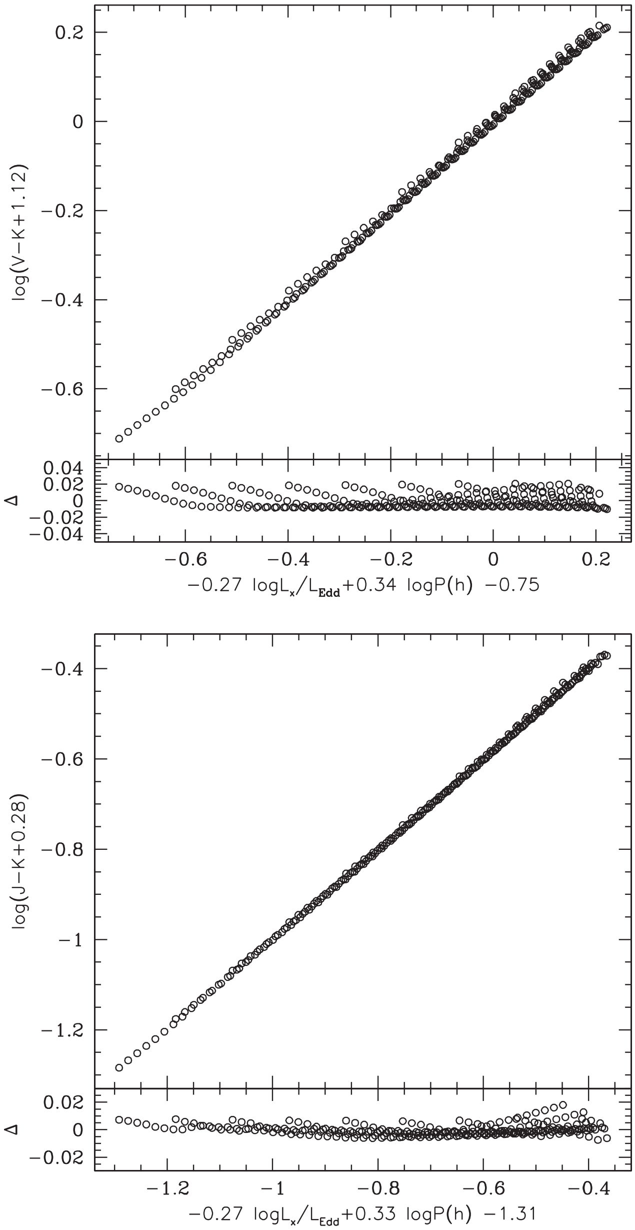

Figure 6. Approximation of LMXB colours with models described in the text. The upper plot shows $V - K$ colour, the lower plot $J - K$ colour. The lower panels on each plot represent residuals from the adopted model.

$$\log(J - K + 0.28) = -0.27 \log L_X/L_{Edd} + 0.33 \log P(h) - 1.31.$$

Residuals of these fits do not typically exceed 0.02–0.04 on a logarithmic scale (see Fig. 6).

5 SUMMARY

In our paper we studied the relations between the X-ray luminosity, orbital period and absolute NIR magnitude of persistent low-mass X-ray binaries.

We have demonstrated that LMXB spectral energy distribution in the optical–NIR spectral range can often be adequately described by a simple model in which all the surface elements in a binary system (comprising an accretion disc and a secondary star) emit blackbody radiation with the local temperature, which is itself defined by the illuminating X-ray flux. According to this model we can construct the quantity $\Sigma_K = (L_X/L_{Edd})^{0.29} P(h)^{0.92}$ on which the infrared luminosity of LMXBs depends almost exclusively. Therefore we were finally able to define a clear relation between Σ_K and the absolute magnitude of LMXBs in the K-band M_K:

$$M_K = (2.66 \pm 0.11) - 2.5 \log \Sigma_K.$$

Due to the fact that for the majority of persistent LMXBs we do have estimates of their X-ray luminosities, the essence of this relation is that it connects the orbital period and absolute NIR magnitude of a binary system; hence one may consider it effectively to be the period–luminosity relation in the NIR.

In some cases, however, we do see a significant emission excess in the NIR with respect to the prediction of this model, suggesting the presence of an additional spectral component (likely optically thin synchrotron emission from non-thermal electrons). We therefore recommend checking colours in the NIR spectral bands against expected values using the formula we give for adequate usage of the presented Σ_K–M_K relation. Extremely red colour indexes are not consistent with the colour of optically thick regions in the binary systems considered in this work.

We propose that the presented period–magnitude relation can be widely used in forthcoming surveys of the Galaxy in the X-ray and NIR spectral domains.

ACKNOWLEDGMENTS

This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France and NASA/ IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. IYZ and AVM were supported by Russian state contract No. 02.740.11.0575. MGR and AVM acknowledge support by grants of the President of Russian Federation MD-1832.2011.2, RFBR 10-02-00492, 12-02-00186, program P19 of Presidium of the Russian Academy of Sciences/RAS and program OFN17 of the Division of Physical Sciences of the RAS. MGR is supported by the Dynasty foundation.

REFERENCES

Augusteijn T., van der Hooft F., de Jong J. A., van Kerkwijk M. H., van Paradijs J., 1998, A&A, 332, 561
Bandyopadhyay R. M., Shahbaz T., Charles P. A., Naylor T., 1999, MNRAS, 306, 417
Bandyopadhyay R. M., Charles P. A., Shahbaz T., Wagner R. M., 2002, ApJ, 570, 793
Bradshaw C. F., Fomalont E. B., Geldzahler B. J., 1999, ApJ, 512, L121
Casares J., González Hernández J. I., Israelian G., Rebolo R., 2010, MNRAS, 401, 2517
Charles P. A., Naylor T., 1992, MNRAS, 255, 6p
Corbel S., Fender R. P., 2002, ApJ, 573, L35
Cutri R. M. et al., 2011, Explanatory Supplement to the WISE Preliminary Data Release Products, available at http://wise2.ipac.caltech.edu/docs/release/prelim/expsup/wise_prelrel_toc.html
D'Amico F., Heindl W. A., Rothschild R. E., Gruber D. E., 2001, ApJ, 547, L147
de Jong J. A., van Paradijs J., Augusteijn T., 1996, A&A, 314, 484
Dubus G., Hameury J.-M., Lasota J.-P., 2001, A&A, 373, 251
Evans I. N. et al., 2010, ApJS, 189, 37
Fabbiano G., 2006, ARA&A, 44, 323
Fazio G. G. et al., 2004, ApJS, 154, 10
Forman W., Jones C., Cominsky L., Julien P., Murray S., Peters G., Tananbaum H., Giacconi R., 1978, ApJS, 38, 357

Giacconi R., Gursky H., Paolini F. R., Rossi B. B., 1962, Phys. Rev. Lett., 9, 439
Hakala P. J., Charles P. A., Muhli P., 2011, MNRAS, 416, 644
Jimenez-Garate M. A., Raymond J. C., Liedahl D. A., 2002, ApJ, 581, 1297
Kuulkers E. et al., 2010, A&A, 514, 65
Lasota J.-P., 2001, New Astron. Rev., 45, 449
Liu Q. Z., van Paradijs J., van den Heuvel E. P. J., 2007, A&A, 469, 807
London R., McCray R., Auer L. H., 1981, ApJ, 243, 970
Marshall D. J., Robin A. C., Reylé C., Schultheis M., Picaud S., 2006, A&A, 453, 635
McClintock J. E., Canizares C. R., Cominsky L., Li F. K., Lewin W. H. G., van Paradijs J., Grindlay J. E., 1979, Nat, 279, 47
McClintock J. E., Remillard R. A., Petro L. D., Hammerschlag-Hensberge G., Proffitt C. R., 1984, ApJ, 283, 794
McNamara B. J. et al., 2003, AJ, 125, 1437
McNamara B. J., Norwood J., Harrison T. E., Holtzman J., Dukes R., Barker T., 2005, ApJ, 623, 1070
Mescheryakov A. V., Shakura N. I., Suleimanov V. F., 2011a, Astron. Lett., 37, 311
Mescheryakov A. V., Revnivtsev M. G., Filippova E. V., 2011b, Astron. Lett., 37, 892
Migliari S. et al., 2007, ApJ, 671, 706
Migliari S. et al., 2010, ApJ, 710, 117
O'Brien K., Horne K., Hynes R. I., Chen W., Haswell C. A., Still M. D., 2002, MNRAS, 334, 426
O'Brien K., Horne K., Gomer R. H., Oke J. B., van der Klis M., 2004, MNRAS, 350, 587
Orosz J. A., Kuulkers E., 1999, MNRAS, 305, 132
Paczynski B., 1977, ApJ, 216, 822
Paizis A. et al., 2006, A&A, 459, 187
Pandey M., Rao A. P., Ishwara-Chandra C. H., Durouchoux P., Manchanda R. K., 2007, A&A, 463, 567
Postnov K. A., Kuranov A. G., 2005, Astron. Lett., 31, 7
Revnivtsev M., Postnov K., Kuranov A., Ritter H., 2011, A&A, 526, A94
Rieke G. H., Lebofsky M. J., 1985, ApJ, 288, 618
Rieke G. H. et al., 2004, ApJS, 154, 25
Ritter H., Kolb U., 2003, A&A, 404, 301
Russell D. M., Fender R. P., 2008, MNRAS, 387, 713
Russell D. M., Fender R. P., Hynes R. I., Brocksopp C., Homan J., Jonker P. G., Buxton M. M., 2006, MNRAS, 371, 1334
Russell D. M., Fender R. P., Jonker P. G., 2007, MNRAS, 379, 1108
Russell D. M., O'Brien K., Muñoz-Darias T., Casella P., Gandhi P., Revnivtsev M. G., 2011, A&A, preprint (arXiv:1109.1839)
Shahbaz T., Fender R. P., Watson C. A., O'Brien K., 2008, ApJ, 672, 510
Smale A. P., 1998, ApJ, 498, L141
Steeghs D., Casares J., 2002, ApJ, 568, 273
Tjemkes S. A., van Paradijs J., Zuiderwijk E. J., 1986, A&A, 154, 77
Tout C. A., Pols O. R., Eggleton P. P., Han Z., 1996, MNRAS, 281, 257
van Paradijs J., McClintock J. E., 1994, A&A, 290, 133
Vrtilek S. D., Raymond J. C., Garcia M. R., Verbunt F., Hasinger G., Kurster M., 1990, A&A, 235, 162
Vrtilek S. D., Penninx W., Raymond J. C., Verbunt F., Hertz P., Wood K., Lewin W. H. G., Mitsuda K., 1991, ApJ, 376, 278
Wachter S., Margon B., 1996, AJ, 112, 2684
Wachter S., Wellhouse J. W., Patel S. K., Smale A. P., Alves J. F., Bouchet P., 2005, ApJ, 621, 393
Werner K., Nagel T., Rauch T., Hammer N. J., Dreizler S., 2006, A&A, 450, 725
Willis A. J. et al., 1980, ApJ, 237, 596
Wright E. L. et al., 2010, AJ, 140, 1868
Xiang J., Lee J. C., Nowak M. A., 2007, ApJ, 660, 1309

This paper has been typeset from a TEX/LATEX file prepared by the author.