Period–luminosity relation for persistent LMXBs in the near-infrared

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ABSTRACT
We study 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 optical and near-infrared spectral energy distribution of LMXBs can be adequately described by a simple model of an accretion disc and a secondary star reprocessing X-ray emission of a central compact object. This gives us an evidence that using an X-ray luminosity and an absolute infrared magnitude of a persistent LMXB one can make reliable estimate of its orbital period. Using a sample of well-known LMXBs, we have constructed a correlation of $L_X$, $P_{orb}$ and $M_K$ values which can be approximated by a straight line with the RMS scatter at the level of $\sim 0.3$ mag. Such a correlation, being to some extent an analogous to the correlation, found by van Paradijs & McClintock (1994), might be helpful for future population studies especially in the light of forthcoming surveys of the Galaxy in X-ray and infrared spectral domains.

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

1 INTRODUCTION

Low-mass X-ray binaries are binary systems with compact objects (neutron stars or black holes) accreting matter from a low-mass secondary companion. First such systems were discovered about 50 years 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]). 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 a host galaxy (e.g. the age of its stellar population). In order to reach these goals one needs: (1) to better 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 with the latter item is the lack of measurements of orbital periods for the majority of known LMXBs. This is mainly caused by the fact that the orbital modulation of the X-ray emission is rarely observed due to geometrical reasons (small companion star covers insignificant fraction of the sky for the compact object, therefore very few known LMXBs demonstrate eclipses and/or dips), whereas the detection of the optical or infrared (IR) modulation of LMXBs emission is challenging due to extreme faintness of these objects.

However, it is sometimes possible to estimate the 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. [1970] 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 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 stationary accretion flow with a constant incident X-ray flux. A transient-like behaviour might lead to the large variations of X-ray flux or/and the accretion flow structure and thus to the deviations from any possible correlation. One might also expect significant deviations if the central X-ray emis-
sion of the source is hidden from an observer due to the very large inclination angle of the binary system (so called Accretion Disc Corona/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, thus shifting observational methods to longer wavelengths. Due to the fact that reliable measurements of LMXBs absolute magnitude in the infrared spectral bands can be done for much 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, spectral energy distribution (SED) of sources at these wavelengths might be contaminated by optically thin synchrotron emission, sometimes observed in the far end of NIR up to radio range in persistent (Migliari et al. 2010) and especially often in transient LMXBs (see e.g. Corbel & Fender 2002; Russell et al. 2006; Russell, Fender, & Jonker 2007; Shahbaz et al. 2008; Russell & Fender 2008). This issue is to be carefully explored before we are able to construct reliable period–luminosity relation for the $K$ band.

In this paper we show that the general shape of SED of persistent LMXBs in the optical–NIR spectral range can be reasonably well described in the framework of a model, where the optical–NIR emission comes from the reprocessing of the central X-ray flux in the accretion disc and the secondary star. This gives us an evidence that there is a physical connection between the main properties of the binary and its infrared luminosity. We present the correlation of an 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 which harbour neutron stars as a compact object in order to reduce the uncertainties related with the mass of the compact object.

2 LMXBS SPECTRAL ENERGY DISTRIBUTION IN THE OPTICAL AND NIR

In order to check the validity of our approach to interpretation of the LMXB luminosity in optical and NIR spectral domains, we have studied broad band spectral energy distribution of the three binary systems, Cyg X-2, Sco X-1, and 4U0614+091, which can be considered as illustrative. These three systems cover wide range of orbital periods, from 0.81 to 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 an optically thin emission can be seen at different 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 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 the 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) state.

For calculation of 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 2011) when all surface elements in a binary system (which comprises an accretion disc and a secondary star) emit black body radiation with the local temperature defined by X-ray irradiation and internal heating. Shape of the star was assumed to be of Roche lobe geometry.

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

\[ T^4 = T^4_{\text{in}} + \frac{\eta_0 L_{\text{X}} \cos \theta}{4 \pi \sigma \varepsilon d^2}, \]  

where $L_{\text{X}}$ – luminosity of the central X-ray source, $\theta$ – angle between X-ray source direction and surface normal, $d$ – distance from X-ray source to the surface element, $\sigma$ – Stefan-Boltzmann constant, $\eta_0$ – fraction of reprocessed X-ray emission. Temperature of the part of the star not illuminated by a compact object was taken following de Jong, van Paradijs, & Augusteijn (1996) as $T_{\text{out}} = 5800(L/L_{\odot})^{1/4}(R/R_{\odot})^{-1/2} \text{K}$ and mass–luminosity and mass–radius relation from Tout et al. (1996). For the fraction of X-ray emission reprocessed and reradiated from the surface of the secondary star we assume $\eta_0 = 0.6$ (see e.g. London, McClay, & 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 geometrically thin accretion disc:

\[ T^4_d = \frac{3GM_1 L_{\text{X}}}{8\pi \varepsilon c^2 \sigma R^3} + \frac{\eta_4 L_{\text{X}}}{3\pi \sigma \epsilon R^2} \left( \frac{H}{R} \right)_{\text{out}} (n-1). \]

We use $M_1 = 1.4 M_{\odot}$ and $\epsilon = 0.1$, – mass of the compact object and accretion efficiency, respectively, for NS LMXB.

The fraction of the flux, intercepted by the accretion disc, was calculated assuming a shape of the intercepting surface as disk with height being a function of its radius: $H \propto R^n$, we assume $n = 9/7$ (Vrtilek et al. 1990). We note here that 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 (2011). We assume ratio of height of the intercepting surface to its radius at the outer edge of the disc $(H/R)_{\text{out}} = 0.1$. Parameter $\eta_4$ – the effective fraction of emission, reprocessed in the accretion disc–corona system (ratio of X-ray flux thermalised in optically thick disc to the incident X-ray flux) is not yet accurately known, different authors estimate its value from less than 0.1 (de Jong, van Paradijs, & Augusteijn 1996) up to ~0.5 (Vrtilek et al. 1991). In our work we adopt the value $\eta_4 = 0.25$.

The accretion disc radius around the compact object was taken to be equal to the tidal radius as estimated by Paczynski (1977). More detailed description of our model can be found in Mescheryakov, Revnivtsev, & Filippova (2011). We would like to note here that our ability to pre-
Table 1. Parameters of the three binary systems, for which we have calculated optical–NIR SEDs. Orbital periods were adopted from Revnivtsev et al. (2011). See the text for other parameters, common for these systems.

| System     | Distance (kpc) | Period (day) | Inclination | Extinction (mag) |
|------------|----------------|--------------|-------------|------------------|
| Cyg X-2    | 11.6 ± 0.3     | 3.14         | 62.5°       | 1.34             |
| Sco X-1    | 28.0 ± 0.3     | 8.0          | 68°         | 0.91             |
| 4U0614+091 | 18.94          | 1.4          | 38°         | 0.34             |

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

| Filter | Vega mag | $A_V$ | Vega mag corr. |
|--------|----------|-------|----------------|
| U      | 15.0     | 2.05  | 12.9           |
| B      | 15.3     | 1.77  | 13.5           |
| V      | 14.8     | 1.34  | 13.5           |
| R      | 14.0     | 1.00  | 13.0           |
| J      | 13.39    | 0.38  | 13.01          |
| H      | 13.15    | 0.24  | 12.92          |
| K      | 13.05    | 0.15  | 12.90          |

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 circular aperture with the radius of 6 arcsec (for Spitzer/MIPS at 24 μm) and used 9 arcsec aperture due to larger FWHM of the instrument PSF at these wavelengths) centered at the object and subtracting the background counts, collected in an appropriate field nearby.

Another set of photometric measurements was extracted from 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 the interstellar extinction assuming the Rieke & Lebofsky (1985) reddening law.

Data at these long wavelengths are important for additional check for the presence of optically thin synchrotron emission, sometimes seen in 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. Model of the broadband SED, constructed assuming the above mentioned parameters is shown by solid curve. 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. Accurate position of the modelled SED with respect to Y-axis depends on the source distance, the fraction of emission reprocessed in 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 well describes the SED of Cyg X-2 up to ∼4 μm, and 2) at longer wavelengths we observe the indication of some additional emission component which is likely the optically thin synchrotron emission.
of non-thermal electrons. Polarization measurements, indicating that at these wavelengths the source might have a contribution from 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 spectral energy distribution at long wavelength end, while in the optical the changes are inessential (see e.g. McNamara et al. 2005). It 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 non-thermal population of electrons. In addition to that it was shown that in the NIR Sco X-1 sometimes exhibits polarization, exceeding the one induced by the 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 the Rayleigh–Jeans type SED in 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 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.

3.3 4U0614+091

We have adopted photometric measurements of 4U0614+091 from Migliari et al. (2010). It is clearly seen (and it was mentioned in Migliari et al. 2010) that the source demonstrates optically thin component at mid-infrared wavelengths and its contribution to $K$ band can be comparable to that of the optically thick mechanism, considered by our model. For that reason we have calculated $K$ magnitude of 4U0614+091 from $J$ band measurement by Migliari et al. (2010), using the model of optically thick emission (see Fig. 3), and used this value in the subsequent work.
Table 3. Photometric measurements of Sco X-1. We have assumed its interstellar extinction to be $A_V = 0.91$.

| Filter | Vega mag | $A_\lambda$ | 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$^6$| 0.15       | 11.84          |
| $K$    | 11.98$^6$| 0.10       | 11.88          |

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

4 $M_K – \Sigma_K$ RELATION OF PERSISTENT LMXBS

4.1 Model

Broad band spectral energy distributions, shown in the previous section, provide us support that we adequately understand 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 both on X-ray luminosity of the central source and on the size of the binary system. van Paradijs & McClintock (1994) showed that the luminosity of the system in optical $V$ band scales approximately as a 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 temperatures of matter that gives the main contribution to optical emission lie in particular range of temperatures ($T \approx 10000–30000$ K). For these temperatures the surface brightness of a black body emitter scales as $S_V \propto T^{2/3}$. For our case of the NIR $K$ band the scalings should be different.

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

$$T_{\text{H}} = 7200 \alpha^{-0.002} \left( \frac{M_1}{M_\odot} \right)^{0.03} \left( \frac{R}{10^{10} \text{ cm}} \right)^{-0.08} \text{ K} \quad (3)$$

Here $\alpha$ is the standard Shakura-Sunyaev viscosity parameter.

For the temperature range $T > T_{\text{H}}$ the $K$ spectral band ($\lambda \approx 2.2$ $\mu$m) lies almost at the Rayleigh-Jeans part of the disc blackbody spectrum, therefore the disc surface brightness should scale as $S_K \propto T^{2/3}$. As the outer disc temperature dominated by irradiation scales as $T_{\text{out}} \propto R_{\text{out}}^{-1/2}$ (see Eq. 2), having in mind $R_{\text{out}} \propto a$ and $a \propto P_4^{1/3}$ (from Kepler’s law) as well as $L_K \propto S_K R_{\text{out}}^2$, the total IR luminosity of the accretion disc should be proportional to $L_K \propto L_K^{2.25} P_4$.

It is worth noting, that the above relations are simplistic, e.g. the noticeable viscous heating in the disc or contribution from the secondary star are expected to modify them. Therefore in order to understand more correct dependencies 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 of 2–750 h and X-ray luminosities of $1 \times 10^{35}$–$4 \times 10^{36}$ 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 then ~6 h ($M < 0.6 M_\odot$) the secondary star is not evolved and obey mass–radius relation for a main sequence star Tout et al. (1996). For the orbital periods larger than ~6 h (i.e. for the giant companions) we have fixed the companion masses at 0.6 $M_\odot$ value. This assumption in fact does not influence our results strongly, and is supported by the cases when masses of the donor giants are known, because they do not exceed this value, e.g. Sco X-1 $M_2 \sim 0.4 M_\odot$ (Steeghs & Casares 2002), Cyg X-2 $M_2 \sim 0.6 M_\odot$ (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. 3). Additional shift can be caused by 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, which have the disc temperature at outer radius not lower than $T_H \approx 6500$ K (see Eq. 5). This selection was applied because we are interested only in persistent LMXBs, while LMXBs with lower outer disc temperatures should be subject to disc thermonuclear instability (see e.g. Lasota 2001 for 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 the inclination of $i = 0^\circ$ is $M_{K,\text{model},i=0} = 2.62 - 0.73 \log(L_X/L_{\text{Edd}}) - 2.29 \log(P(h))$; for the inclination of $i = 70^\circ$: $M_{K,\text{model},i=70} = 3.71 - 0.70 \log(L_X/L_{\text{Edd}}) - 2.32 \log(P(h))$. For both cases the rms scatter of the data points from the approximation is $\sim 0.03$. Here we adopted Eddington luminosity for 1.4 $M_\odot$ neutron star $L_{\text{Edd}} = 2 \times 10^{38}$ erg/s.

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

4.2 Sample of known LMXBs

Having in hand physically motivated value of $\Sigma_K$, on which the LMXB luminosity should depend, we constructed $\log \Sigma_K - M_K$ 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 $K$ 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 $K$ band and $\log \Sigma_K$ for known binaries from Table 4 is shown in Fig. 5.

We have used linear least squares 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 binaries.

The best-fitting approximation of this relation for all considered binaries is $M_K = (2.78 \pm 0.24) - (2.60 \pm 0.11) \log \Sigma_K$ ($1\sigma$ confidence intervals). In order to estimate the confidence intervals here (and below) we assumed the uncertainties of data points corresponding to the unity value of the resulted $\chi^2/\text{d.o.f}$. Confidence intervals then were calculated as usual from interval of parameter which 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 $\Sigma_K$ is proportional to the IR luminosity $L_K$ of the system, whereas absolute brightness is $M_K = -2.5 \log L_K + \text{const}$), which is
Table 4. Persistent LMXBs which were used to illustrate $\Sigma_K - M_K$ 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 Uhuru catalog. 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 3 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 remaining sources were taken from 3D Galaxy extinction map by Marshall et al. (2006) if not indicated another reference. Magnitude of 4U0614+091 in the K band was recalculated from $J$ measurement of Migliari et al. (2010) taking into account $J - K$ colours from the discussed model (see the text).

| Name     | $\log L_X$ (2-10 keV) | $d$ kpc | $P$ h | $m_K^{corr}$ | $A_K$ mag |
|----------|-----------------------|---------|-------|--------------|-----------|
| Sco X-1  | 38.3                  | 2.8 ± 0.3 | 18.94 | 11.88        | 0.1       |
| Cyg X-2  | 38.3                  | 11.6 ± 0.3 | 236.27 | 12.9         | 0.15      |
| GX 349+2 | 38.2                  | 8.53     | 22.5  | 14.1         | 0.45      |
| GX 13+1  | 37.7                  | 7 ± 1.5  | 601.7 | 10.5         | 1.8       |
| 4U1624-49 | 37.5                | 15.0 ± 2.9 | 20.9  | 15.9         | 2.4       |
| 4U1735-44 | 37.7                | 9.110    | 4.65  | 16.6         | 0.16      |
| 4U1636-53 | 37.4                | 5.9      | 3.79  | 15.9         | 27.3      |
| 4U0614+091 | 36.5               | 3.2      | 0.81  | 16.9         | 0.22      |

(1) – Bradshaw, Fomalont, & Geldzahler (1999), (2) – Smale (1998), (3) – Galactic Center distance, (4) – Wachter & Margon (1996), (5) – Bandopadhyay et al. (1999), (6) – Bandopadhyay 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)

Compatible with the results of the fit. Fixing this coefficient we obtain:

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

RMS scatter of the observed points from the fitted straight line for our sample of sources is $\sim0.3$ mag. Note, that this value is approximately a lower limit for any $M_K = f(L_X, P)$ model which does not take into account explicitly the binary system inclination and the time variability of its flux.

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 $i = 0^\circ$. The best fit was calculated minimizing the root mean square residual on logarithmic scale:

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

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

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

5 SUMMARY

In our paper we studied 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 where all the surface elements in a binary system (comprising an accretion disc and a secondary star) emit black body 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 the clear relation between $\Sigma_K$ 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 orbital period and absolute NIR magnitude of a binary system, hence one may consider it to be effectively the period–luminosity relation in the NIR.

In some cases, however, we do see a significant emission excess in the NIR with the 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 an adequate usage of the presented $\Sigma_K - M_K$ relation. Extremely red colour indexes are not consistent with the colour of an optically thick regions in the binary systems considered in this work.

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

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Approximation of LMXB colors with models, described in the text. Upper plot shows $V-K$ color, lower plot – $J-K$ color. Lower panels on each plot represent residuals from the adopted model.

Figure 6. Approximation of LMXB colors with models, described in the text. Upper plot shows $V-K$ color, lower plot – $J-K$ color. Lower panels on each plot represent residuals from the adopted model.

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