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On the nature of the break in the X-ray luminosity function of low-mass X-ray binaries.

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Abstract. We analyze a flux-limited sample of persistent and bright (with 2-10 keV fluxes exceeding 1.4×10^{-10} erg s^{-1} cm^{-2}) low-mass X-ray binaries (LMXBs) in our Galaxy. It is demonstrated that the majority of binary systems with X-ray luminosities below $\log L(\mathrm{erg/sec}) \sim 37.3$ have unevolved secondary companions (except for those with white dwarf donors), while systems with higher X-ray luminosity predominantly harbor giant donors. Mass transfer in binary systems with giants significantly shortens their life time thus steepening the X-ray luminosity function of LMXBs at high luminosity. We argue that this is the reason why the LMXB luminosity function constructed in the last years from observations of sources in our and distant galaxies demonstrates a break at $\log L(\mathrm{erg/sec}) \sim 37.3$.

1. Introduction

Binary systems with low-mass secondary companions to a compact star (black hole or neutron star) were discovered in the 1960s at the dawn of X-ray astronomy. All-sky surveys performed by different orbital X-ray observatories (UHURU, HEAO1, Ariel V, etc.) provided us with a relatively large sample of such objects in our Galaxy. The advent of focusing X-ray telescopes with an angular resolution of arcseconds initiated studies of such low-mass X-ray binaries (LMXBs), first in nearby galaxies, like M31 (Trinchieri & Fabbiano 1991; Primini, Forman, & Jones 1993), and then in more distant galaxies (see e.g. reviews in Kim & Fabbiano 2004; Gilfanov 2004).

The accretion luminosity L_x of a persistent (sub-Eddington) LMXB is directly proportional to the mass transfer rate $\dot{M}$ from the secondary star. According to the standard theory of binary star evolution, the persistent mass transfer via the inner Lagrangian point in a close binary is due to an increase of the size of the donor star relative to its Roche lobe. In an LMXB, this can be done either by decreasing the size of the Roche lobe due to loss of the orbital angular momentum (see e.g. Paczynski & Sienkiewicz 1981; Verbunt & Zwaan 1981), or by increasing the radius of the star as a consequence of its nuclear evolution (Webbink, Rappaport, & Savonije 1983; Taam 1983; Ritter 1999). The observed properties of different populations of LMXBs can be used to test the models of binary evolution.

The X-ray luminosity function (LF) is an important characteristic of the LMXB population. In other galaxies it is directly constructed from measured X-ray fluxes down to a luminosity $L_{\mathrm{x}} \sim 10^{37}$ erg/s and can be fitted by a power law $dN/d\log L \propto L^{-0.8...-1.2}$ with a steepening at luminosities exceeding the Eddington limit for accreting neutron stars ($\log L_{\mathrm{x}} > 38.5$) (Kim & Fabbiano 2004). However, recently it became possible to construct the luminosity functions of LMXBs in nearby galaxies, like M31 or Cen A, down to much smaller luminosities of the order of 10^{36} erg/s (Primini, Forman, & Jones 1993; Gilfanov 2004; Voss & Gilfanov 2006, 2007; Voss et al. 2009). Over such a wide luminosity interval the luminosity function of LMXBs can no longer be described by a single power law and demonstrates a characteristic break at $\log L < 37.3$ (Gilfanov 2004). A similar result down to luminosities $L_{\mathrm{x}} \sim 10^{35}$ erg/sec was obtained for galactic LMXBs from all-sky surveys (Grimm, Gilfanov, & Sunyaev 2002; Gilfanov 2004) and the survey of the Galactic bulge (Revnivtsev et al. 2008). The statistical significance of the LF break in the above-mentioned works is high, therefore the existence of the break requires physical explaination. One of the clearest case of the flattening of the LMXB LF at low luminosities can be seen in the work of Revnivtsev et al. (2008), where the LMXB candidates in the bulge of our Galaxy were traced down to luminosities 10^{35} erg/sec, almost unreachable for LMXBs in outer galaxies.

Different explanations have been proposed for the origin of the break in the observed LF of LMXBs. For example, the break in the LF might be caused by the change of the dominant orbital angular momentum loss mechanism from magnetic stellar wind (Verbunt & Zwaan 1981) to gravitational wave emission (see e.g. Paczynski & Sienkiewicz 1981) in the population of LMXBs with low-mass main sequence secondaries (Postnov & Kuranov 2005). It was also noted already quite long ago that the most luminous LMXBs with high mass transfer rates ($\dot{M} > 10^{-8}$ $M_{\odot}$/year), could harbor giant donors (see e.g. Webbink, Rappaport, & Savonije 1983), and this may underly the difference between the low- and high- luminosity sources. The study of the LMXB LF in galaxies using population synthesis methods could potentially be quite powerful (see e.g. Fragos et al. 2008; Kim et al. 2009). However, this approach involves a number of uncertain parameters of binary star evolution, so it is hard to make firm conclusions based on the population synthesis simulations only.

In our paper we make an attempt to identify the main physical reason for the origin of the observed break of the broad band luminosity function of LMXBs.

We show that the break in the LF of LMXBs is probably caused by different types of donor stars: evolved secondaries (giants) at luminosities above the break at $\log L$(erg/sec) ~ 37.3, and main sequence stars at lower luminosities. The correctness of our conclusion might be checked by direct calculations of the LMXB properties using the methods of population synthesis, which we plan to do in the future.

2. A Flux limited sample of persistent LMXBs in the Galaxy

We consider only persistent LMXBs. This selection can be relatively easily done for galactic LMXBs, but in general this can be a difficult task for LMXBs in outer galaxies, since they are typically observed only during short time intervals. Monitoring of X-ray sources in our Galaxy shows that at any particular time there are only a few bright transients (see e.g. Remillard, Levine, & McClintock 2009), whose effect on the instantaneous LF of all galactic LMXBs is rather small.

Moreover, the properties of the observed luminosity distribution of individual variable LMXBs were found to not affect the shape of the instantaneous LF of the galactic sample (Postnov & Kuranov 2005). Therefore the results of our present study can also be applied to the instantaneous sample of LMXBs in distant galaxies.

We study a representative sample of persistent galactic LMXBs with X-ray luminosities $L_{\rm x} > 10^{36}$ erg/s and compare their properties above and below the break. Our goal does not require the sample to be volume limited or complete, because we are not interested in statistics (which was extensively studied in works of other authors), but rather we look for a correspondence of the time averaged X-ray luminosity of sources to some parameters of their binaries.

To select persistent Galactic sources we can analyze any existing X-ray survey. However, such a survey should fulfill the following requirements: 1) it should cover as much as possible of the Galactic plane region, where the majority of the LMXBs are located, 2) it should have an angular resolution of better than $\sim 2-3^{\circ}$ in order to avoid confusion within the Galactic plane, 3) it should be performed in the energy band $\sim 1-20$ keV where Galactic LMXBs emit most of their bolometric luminosity. These requirements significantly shorten the list of usable surveys. In particular, the sky survey of the RXTE observatory (Revnivtsev et al. 2004) does not cover the region of the Galactic plane, and the scans of the RXTE observatory over the Galactic bulge and the Galactic plane (Markwardt et al. 2000) have not (yet) been used to perform a sky survey, rather it is used to measure the fluxes of preselected list of sources. Surveys carried out by the ASCA (Sugizaki et al. 2001; Sakano et al. 2002) and BeppoSAX (Sidoli, Belloni, & Mereghetti 2001) observatories cover only a small fraction of the Galaxy. Even smaller sky areas are covered by the *Chandra* and XMM observatories. The survey of the INTEGRAL observatory (Krivonos et al. 2007) covers the whole Galaxy, but it is done at hard X-ray energies, and is not fully suitable for our purposes (however, we will use it for additional checks of "persistency" of selected sources).

So the persistent X-ray sources detected by UHURU (Forman et al. 1978) turn out to be most suitable for our study; as an additional check of their persistent behavior we have also examined their presence in the INTEGRAL all sky survey (Krivonos et al. 2007). We selected only sources with 2-10 keV fluxes above 1.4×10^{-10} erg s^{-1} cm^{-2} which ensures that their luminosity is not lower than $2-3 \times 10^{36}$ erg/s up to distances of 12 kpc (i.e. up to the further edge of the Galactic bulge). This allows us to conclude that we do not miss brighter sources at least in more than a half of the Galaxy. We also included in our sample the black-hole binary GRS 1915+105, which was not seen by UHURU during its operation time (1971-1973), but now remains persistently bright since its appearance in 1992 (Castro-Tirado, Brandt, & Lund 1992), and excluded the source GX 1+4, which is known to be accreting via a stellar wind (Hinkle et al. 2006) and not via Roche lobe overflow which we consider here. The fluxes assigned to GRS 1915+105 and GS 1826-24 were taken from measurements of the All Sky Monitor of the RXTE observatory averaged over 1996-2009 (see. e.g. `http://xte.mit.edu/asmlc/ASM.html`).

Energy fluxes from the selected sources were calculated from observed UHURU count rates, assuming that the Crab nebula count rate in the energy band 2–10 keV corresponds to the energy flux 2.22×10^{-8} erg s^{-1} cm^{-2} .

In Table 1 we present the list of sources with values of their orbital periods and estimates of their distances and luminosities.

Table 1. The brightest persistent low mass X-ray binaries in the Galaxy with fluxes $> 1.4 \times 10^{-10}$ erg s^{-1} cm^{-2} measured by UHURU (Forman et al. 1978). Orbital periods of systems are adopted from Ritter & Kolb (2003) and Liu, van Paradijs, & van den Heuvel (2007).

Name	L_x (2-10 keV) 10^{37} erg/sec	Dist, kpc	Period,h
Sco X-1	37.4	2.8[1]	18.94
GX 5-1	26.1	9[2]	
GRS 1915+105	26.0	11[3]	739.20
Cyg X-2	19.4	11.6[5]	236.27
GX340+0	18.2	12[4]	
GX 349+2	15.3	8.5[6]	22.5
GX 17+2	14.9	7.5[7]	
GX 9+1	8.7	7.2[7]	
4U1820-30	5.7	8[8]	0.19
Ser X-1	5.5	8.4[9]	12.96
GX 13+1	5.5	6.9[10]	601.7
4U1735-44	4.9	9.1[11]	4.65
GX 3+1	3.4	4.5[12]	
4U1624-49	3.1	15[13]	20.9
4U1636-53	2.4	5.9[10]	3.79
GX 9+9	1.8	5.0[7]	4.20
4U1746-37	1.4	11.0[8]	5.16
4U1705-32	1.18	13[14]	
1A1742-294	0.81	8.5[15]	
4U1254-69	0.79	11[16]	3.93
4U0513-40	0.74	12.1[8]	0.28
4U1823-00	0.61	6.3[17]	3.19
4U1915-05	0.43	8.8[8]	0.83
4U0614+09	0.34	3.2[18]	0.81
4U1702-42	0.32	6.2[19]	
4U1626-67	0.32	8[20]	0.69
GS1826-24	0.31	6.0[21]	2.25[22]
4U1708-40	0.27	8[15]	
4U1543-62	0.26	7.0[8]	0.30
4U1724-30	0.17	9.5[8]	
4U1850-08	0.17	8.2[8]	0.34
4U1812-12	0.09	4.0[19]	
4U1556-60	0.09	4.0[7]	
4U1822-37	0.04*	2.5[23]	5.57

(1) – Bradshaw, Fomalont, & Geldzahler 1999,(2) – Jonker et al. 2000, (3) – Fender et al. 1999, (4) – van Paradijs & White 1995, (5) – Smale 1998, (6) – Wachter & Margon 1996, (7) – Christian & Swank 1997, (8) – Kuulkers et al. 2003, (9) – Ebisuzaki, Sugimoto, & Hanawa 1984, (10) – Bandyopadhyay et al. 1999, (11) – Augusteijn et al. 1998, (12) – Kuulkers & van der Klis 2000, (13) – Xiang, Lee, & Nowak 2007, (14) – in't Zand, Cornelisse, & Méndez (2005), (15) - adopting distance to the Galactic Center, (16) – Courvoisier et al. (1986), (17) – Shahbaz, Watson, & Hernandez-Peralta 2007, (18) – Kuulkers et al. 2010, (19) – Jonker & Nelemans 2004, (20) – Chakrabarty 1998, (21) – Heger et al. 2007, (22) – Mescheryakov et al. 2010, (23)– Mason & Cordova 1982

* – the source belongs to a group of so called accretion disk corona sources, in which we do not see the direct emission of the innermost parts of the accretion flow, therefore the observed X-ray luminosity of such a source is only a part of its intrinsic X-ray luminosity.

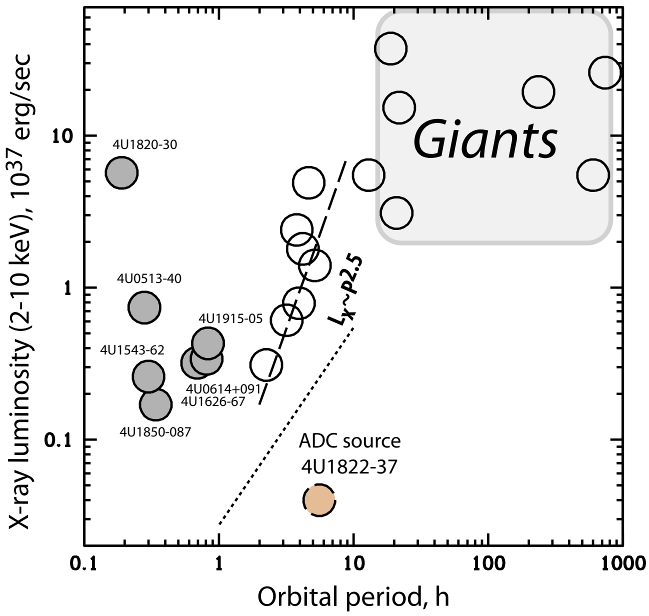

Fig. 1. Positions of the LMXBs from Table 1 on the orbital period – X-ray luminosity diagram. Filled circles denote the positions of peculiar systems: gray circles show the positions of binaries with white dwarf or hydrogen-deficit accretors, the dashed circle shows the position of 4U1822-37 in which we see only a fraction of the total X-ray luminosity due to its nearly edge-on orientation (a so-called accretion disk corona source). The region, occupied by binary systems with a giant donor is shown by the shaded square. The dashed line shows the slope $L_x \propto P^{2.5}$, derived by Iben & Tutukov (1984) for the mass tranfer rate in binaries in which angular momentum loss is driven by a magnetic stellar wind from a main sequence donor. The dotted line shows the boundary of persistency according to the thermal-viscous disk instability for binaries with low-mass main sequence donors $L_x/10^{37}$ erg/sec $\sim 0.025\ P_{\rm hr}^{1.4}$ from eqn.32 of Dubus et al. (1999), where we adopted $M_1 = 1.4 M_\odot$, $M_2 = 0.4 M_\odot$ and $L_x = 0.1 \dot{M} c^2$.

3. Results

From Table 1 and Fig.1 it is clearly seen that all systems with X-ray luminosities exceeding $\sim 5 \times 10^{37}$ erg/s for which we have information about their orbital periods, apparently have large sizes. This (in combination with the assumption that the companion star fills its Roche lobe) means that donor stars in these systems must have large radii and thus are evolved stars (subgiants or giants). In several cases this was shown directly from the observed spectra of the optical counterparts (Sco X-1, Bandyopadhyay et al. 1997; GX 349+2, Bandyopadhyay et al. 1999; Cyg X-2, Casares, Charles, & Kuulkers 1998; GX 5-1, Bandyopadhyay, Shahbaz, & Charles 2003; GRS 1915+105, Greiner et al. 2001; Cir X-1, Jonker, Nelemans, & Bassa 2007).

To the contrary, there are virtually no persistent LMXBs with X-ray luminosities lower than $\sim 10^{37.5}$ erg/s and orbital periods longer than 5-10 hours (see also Ritter & Kolb 2003; Liu, van Paradijs, & van den Heuvel 2007). This is consistent with the assumption that donor stars in these systems are main sequence stars (or degenerate dwarfs, if the orbital period is smaller than $\sim$ 1 hour). For cataclysmic variables with accreting white dwarfs and orbital periods less than $\sim$10 hours (which are much more numerous in the Galaxy and can be found closer to the Sun, so we can study them in much greater details) this statement has been solidly supported by observations (Smith & Dhillon 1998). Therefore, *we conclude from observations that at luminosities $L_x \sim 10^{37.5}$ erg/s there is a transition from LMXBs with predominantly giant donors to binaries with predominantly main-sequence donors.*

4. A simple model of the LMXB luminosity function

Numerous studies have been made in the past to describe the evolution of the LMXB population using specific models of LMXB evolution. They were mostly aimed at understanding the evolution of the total number of galactic LMXBs without distinguishing their X-ray luminosities (see e.g White & Ghosh 1998; Ghosh & White 2001). Attempts to describe the LMXB LF can be found in Webbink, Rappaport, & Savonije (1983), but this work concentrated only on the bright end of the LF and does not consider the effects of magnetic braking on the period/luminosity distribution of binaries. The importance of the magnetic braking for relatively short period systems was emphasized, for example, in papers by Pylyser & Savonije (1988); Cote & Pylyser (1989). In these papers, an indication of transition from a population of bright systems dominated by nuclear evolution of donor stars to a population of systems in which mass transfer is sustained by the magnetic braking can be found. At that time it was impossible to make a quantitative comparison of the model predictions with the observed samples of LMXBs due to the lack of sensitive galactic X-ray surveys. So these studies were mostly focused on the exploration of evolutionary tracks leading to the formation of particular objects, like rotation-powered pulsars (e.g. Kulkarni & Narayan 1988; Naylor & Podsiadlowski 1993; Deloye 2008, and references therein), or ultracompact binaries (e.g Nelemans et al. 2001; Belczynski, Kalogera, & Bulik 2002).

Many papers that appeared later on were devoted to the population synthesis of LMXBs (see e.g. Belczynski, Kalogera, & Bulik 2002; Pfahl, Rappaport, & Podsiadlowski 2003; van der Sluys, Verbunt, & Pols 2005; Fragos et al. 2008), which until now suffer from uncertainties in the binary star evolution (e.g. the treatment of the common envelope stage, parameters of magnetic braking, etc.). Clearly, such detailed studies are very important and must be continued as they may help to constrain values of specific parameters of binary evolution from comparison with observations. However, to understand the observed gross properties of the LMXB LF we can try to use very general assumptions about binary star evolution, as we show below.

Consider an ensemble of binaries that has been formed in a galactic halo over a time period T in the past. Let $\tau(P)$ be the duration of an active LMXB stage of a source within the orbital period range $P, P+dP$. Let $n(P)$ be the number distribution of sources within this period range. Assuming the steady formation of sources over time period T, the luminosity distribution can be written in the form

$$\frac{dN}{dL_x} \propto \frac{\tau(P)}{T} n(P) \frac{dP}{dL_x}.$$

(Note that the first factor τ/T would not appear for a LF constructed from a sample of sources produced in an instantaneous star formation burst; however, this is the case neither for the galactic bulge nor for elliptical galaxies we consider here.)

Clearly, the shape of LF will be determined by the dependence of all three factors in this expression on the X-ray luminosity. Consider these factors separately for bright (with giant donors) and dim (with main-sequence donors) LMXBs.

At luminosities below $L_x \approx 10^{37}$ erg/s ($\dot{M} < 10^{-9}$ $M_\odot$/year), the majority of donor stars in our LMXB sample are main sequence stars with long life times (>Gyr). The stable mass transfer episode is also very long, so the factor τ/T should not strongly depend on L_x. The period distribution $n(P)$ is generally determined by the evolutionary history of binaries which includes as a minimum a supernova explosion to produce the neutron star, a common envelope phase, etc. (or involves dynamical processes in dense stellar clusters), and can be found for example from population synthesis studies. Let us put it in the form $dN/d\log P$ and leave it as it is for a while.

The luminosity of a LMXB due to magnetic stellar wind braking depends on the orbital period as a power law $L_x \propto P^{2.5}$ (see e.g. Iben & Tutukov 1984) or $L_x \propto P^{3.3}$ (Patterson 1984), or $L_x \propto P^{3.8}$ (Cote & Pylyser 1989) so written in the form $d\log P/d\log L_x$ this factor is independent of L_x. So we find

$$n(L_x) \propto \frac{1}{L_x} \frac{dN}{d\log P} \frac{d\log P}{d\log L_x} \sim \frac{1}{L_x} \frac{dN}{d\log P}$$

This would match the observed shape of the LF of dim LMXBs if the factor $dN/d\log P \sim \mathrm{const}(L_x)$. Unfortunately, it is difficult to construct this distribution from observations due to many selection effects. Population synthesis calculations (e.g. Fragos et al. 2008) produce a variable distribution, which only roughly can be considered as constant. Observations suggest that initial orbital periods of binary stars do follow this dependence, i.e. $dN/d\log P$ =const (Popova, Tutukov, & Yungelson 1982), and we shall assume this to hold approximately at all stages of binary evolution.

LMXBs with luminosities higher than $L_x > 10^{37.5}$ erg/s have predominantly giants companions (see above). The duration τ of the mass transfer (and hence the accretion stage) in these systems is significantly smaller than that for systems with main sequence donors, and to a large extent is determined by the mass transfer rate (see e.g. Webbink, Rappaport, & Savonije 1983). Let us assume that the luminosity of LMXB is a powerlaw function of its orbital period $L_x \propto P^\alpha$ (which is true for the magnetic stellar wind braking dominated regime, $\alpha \sim 2.5 - 3.8$, see above, and also holds when nuclear evolution of the giant donor is responsible for its Roche lobe overflow, $\alpha \sim 1$, see Webbink, Rappaport, & Savonije 1983). We also adopted that the duration of the bright LMXB stage is inversely proportional to its luminosity $\tau \propto L_x^{-1}$. This is approximately correct because the total mass, which might be accreted from a late-type giant donor stars does not vary much from system to system (see e.g. Webbink, Rappaport, & Savonije 1983). Combining these we obtain

$$\frac{dN}{dL_x} \propto \frac{1}{L_x P}\frac{dP}{dL_x} \propto \frac{1}{L_x^2}\frac{d\log P}{d\log L_x} \approx L_x^{-2}.$$

Thus *almost independently of the mechanism which drives Roche lobe overflow in luminous LMXBs (with late-type giants) we obtain a slope of the LF similar to the observed one* (Gilfanov 2004; Kim & Fabbiano 2004). The condition for this to be correct is that the donor stars in these LMXBs are short-living giants. We can try to estimate the longest lifetimes of such giants assuming that the maximum mass, which might be accreted from them is $\lesssim 0.6M_\odot$ (e.g. Webbink, Rappaport, & Savonije 1983) and their duty cycle is close to unity. In this case $\tau_{\rm giants} \lesssim 0.6M_\odot/(2\times10^{-9}M_\odot/{\rm year}) \sim 3\times10^8$ years. This means that the list of bright LMXBs in the Galaxy should alter after approximately 30 Myrs.

We would like to note here that the boundary between different types of donors at luminosities above and below $L_x \sim 10^{37}$ erg/sec was also previously noted in numerical simulations of LMXB populations in Fragos et al. (2008); Kim et al. (2009), but the slopes of the LMXB LF above and below this luminosity was found to be not so different. The inability of particular numerical simulations to reproduce the observed break in the X-ray luminosity function of the LMXB population might indicate that we do not (yet) understand all details of the physical processes (e.g. the mode of the angular momentum loss, the common envelope phase, etc.) that shape the LMXB LF. We plan to perform more detailed calculations of the LMXB population in our future work.

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