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Low-mass X-ray binaries in the bulge of the Milky Way

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Abstract. We study the population of low-mass X-ray binaries (LMXBs) in the Galactic bulge using the deep survey of this region by the IBIS telescope aboard the INTEGRAL observatory. Thanks to the increased sensitivity with respect to previous surveys of this field, we succeeded to probe the luminosity function (LF) of LMXBs down to $\sim 7\times10^{34}$ erg s^{-1} in the 17–60 keV energy band. The slope $d\log N/d\log L = -0.96\pm0.20$ measured in the 10^{35}–10^{37} erg s^{-1} range confirms that the LMXB LF flattens below $L_{\rm x}\lesssim 10^{37}$ erg s^{-1} with respect to higher luminosities. We discuss the origin of the observed LF flattening. We demonstrate that the spatial distribution of persistent LMXBs in the Galactic Center/Galactic bulge region is consistent with a model of stellar mass distribution that includes the nuclear stellar disk component in the innermost degree of the Galaxy. The spatial distribution of transient LMXBs detected in the Galactic Center region indicates an increased fraction of transient sources in the innermost degree of the Galaxy with respect to outer regions.

Key words. ISM: general – Galaxies:general – Galaxies: stellar contents – X-rays:diffuse background

1. Introduction

Low-mass X-ray binaries (LMXBs) are binary systems with a compact object that accretes matter from a low mass optical companion star filling its Roche lobe (see e.g van den Heuvel 1975). Ways of formation and evolution of LMXBs are important and not yet fully understood questions of X-ray astronomy (see discussions of these issues in e.g. Webbink, Rappaport, & Savonije 1983; Lipunov et al. 2007; Belczynski et al. 2008).

The shape of the luminosity function (LF) of LMXBs may provide important information about their long term evolution. In particular, Postnov & Kuranov (2005) noted that the observed shape of the LMXB LF (assuming that the X-ray luminosity of the compact object is directly proportional to the mass transfer rate in the binary system) depends on the distribution of the masses of optical donor stars in LMXBs, which is in turn intimately related to the mechanism of removal of the angular momentum of the binary system. They suggested that the flattening of the LMXB LF at luminosities $L_{\rm x} < 2\times10^{37}$ erg s^{-1} found in a number of studies (Primini, Forman, & Jones 1993; Gilfanov 2004; Voss & Gilfanov 2006, 2007) might correspond to the transition from the magnetic stellar wind braking to the gravitational wave braking mechanism of removal of the binary system angular momentum (Postnov & Kuranov 2005). Confirmation of this idea would provide additional evidence for the action of gravitational braking mechanisms in LMXBs and enable one to select those binary systems effectively emitting gravitational waves for the next generation of gravitational wave detectors. It is therefore interesting and important to check the presence of the break in the LMXB LF and to continue the LF to lower luminosities.

Using LF as a tool for studying populations of X-ray sources in nearby galaxies is only possible with instruments that have good sensitivity and angular resolution. First attempts of estimating the LF of bright X-ray binaries were done with the Einstein/HEAO2 observatory (see e.g van Speybroeck et al. 1979; Trinchieri & Fabbiano 1991) more than twenty years ago. Studying LMXB LF in galaxies has now become quite common due to the unprecedented capabilities of the *Chandra* X-ray Observatory. However, even this powerful observatory does not allow one to probe the faint end ($L_{\rm x} < 10^{36-37}$ erg s^{-1}) of the LMXB LF in the majority of nearby galaxies. This is only feasible for the nearest galaxies, like M31 (Trinchieri & Fabbiano 1991; Primini, Forman, & Jones 1993; Voss & Gilfanov 2007).

The Milky Way is a unique galaxy where we can detect X-ray objects with the lowest possible luminosities. However, because of the large angular size of the Galaxy and the different and often poorly known distances to Galactic X-ray sources, it is not easy to construct the LF of LMXBs in the Milky Way. First of all, one needs to cover a large fraction of the sky. However, focusing X-ray telescopes usually have small fields of view (∼10 arcmin)

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and thus cannot cover a considerable part of the Galaxy within a reasonable time. Even the region of maximal concentration of Galactic LMXBs – the Galactic bulge – is too large for focusing X-ray telescopes.

The Galactic Center/Galactic bulge region is most suitable for studying Galactic LMXBs because the majority of sources are spatially concentrated and are located at nearly the same distance from the Sun. Skinner (1993) reconstructed the surface density map of X-ray sources in the Galactic bulge region using a compilation of observational campaigns by different observatories. The population of Galactic bulge X-ray sources was also studied with the exceptionally wide field-of-view ART-P coded-mask telescope aboard the *GRANAT* observatory (Grebenev, Pavlinsky, & Sunyaev 1996).

Grimm, Gilfanov, & Sunyaev (2002) used data of the All-Sky Monitor (ASM) of the *RXTE* observatory in the 2–10 keV energy band to construct the luminosity function of Galactic LMXBs with luminosities $L_{\rm x} \gtrsim 10^{36}$ erg s^{-1}. Later, Gilfanov (2004) studied the populations of LMXBs in the Milky Way and nearby galaxies and showed that the LMXB LF has a break at a luminosity $L_{\rm x} \sim 2 \times 10^{37}$ erg s^{-1}, below which it significantly flattens. Similar flattening of the LMXB LF was found by Primini, Forman, & Jones (1993) for the population of sources in the M31 galaxy. Recent studies of a number of galaxies performed with the *Chandra* observatory confirmed such a break in the LMXB LF in the M31 galaxy (Kong et al. 2003; Voss & Gilfanov 2007) and indicated the presence of a break for the Cen A galaxy (Voss & Gilfanov 2006). No breaks, however, were detected by Kim et al. (2006) in the LF of sources in NGC3379 and NGC4278.

In order to make a significant improvement in the statistical study of LMXBs in our Galaxy and independently measure the faint end of the LMXB LF, one needs a large field-of-view instrument with increased (in comparison with previous ones) sensitivity. It is also necessary to use a hard X-ray energy band to avoid contamination by large numbers of nearby, soft X-ray emitting stars, as was the case with the ROSAT all-sky survey (e.g. Voges et al. 1999). This is exactly what is provided by the coded-mask telescopes of the INTEGRAL observatory (Winkler et al. 2003). Deep observations of the Galaxy performed with INTEGRAL/IBIS over five years of its operation have allowed us to increase the sensitivity to point sources by an order of magnitude in comparison with the RXTE/ASM survey. This allows us to probe the faint end of the LF of Galactic LMXBs for the first time.

2. Sample of sources and data analysis

To avoid problems with unknown source distances and consequently unknown source luminosities, we do not use here the whole INTEGRAL survey of the Milky Way and restrict ourselves to the Galactic Center/Galactic bulge region where LMXBs are strongly concentrated (see e.g Skinner 1993; Grebenev, Pavlinsky, & Sunyaev 1996; Grimm, Gilfanov, & Sunyaev 2002; Lutovinov et al. 2005).

The INTEGRAL observatory has spent a lot of time observing the Galactic Center (Galactic bulge) region over the first five years of its operations (see e.g Revnivtsev et al. 2004; Kuulkers et al. 2007). Among the INTEGRAL instruments, the IBIS telescope best meets the requirements of the present study: it has good sensitivity for detecting point sources and a wide field of view ($\sim 28^\circ \times 28^\circ$). Due to the hard energy band of IBIS (> 17 keV), it is less sensitive to sources that have high luminosities in the standard 2–10 keV energy band (since such sources have very soft spectra that do not continue to hard X-rays), but it is very effective in detecting low-luminosity objects (which typically have hard spectra). The sensitivity achieved by now with respect to point sources in the Galactic Center region is typically 0.5 mCrab in the 17–60 keV energy band (see e.g. Krivonos et al. 2007b).

For the present study we selected all sources detected by INTEGRAL in the Galactic Center (Galactic bulge) region listed in the catalog of Krivonos et al. (2007b) and added INTEGRAL/IBIS data that became available since the publication of this catalog. These additional data allowed us to increase the accuracy of source flux measurements and to add one newly detected source, IGR J17586–2129, to the sample.

We only considered those sources located within the elliptical region around the Galactic Center with axes $|l| < 10.7^\circ, |b| < 5.1^\circ$ and having fluxes higher than 0.64 mCrab in the 17–60 keV energy band, which typically ensures the source detection with statistical significance more than 8σ. This conservative detection threshold prevents any problems with possible systematical uncertainties in the image reconstruction and with variations of the sensitivity over the region of our interest.

Due to the anticipated concentration of LMXBs in the Galactic bulge, we assume that all sources that are not known to be high-mass X-ray binaries, cataclysmic variables or extragalactic sources, are LMXBs. It is possible that a detailed study of some faint sources (typically with luminosities $L < 10^{35}$ erg s^{-1}) from our sample will reveal their non-LMXB nature. Therefore, we are probably somewhat overestimating the faint end of the LMXB LF.

From the preliminary source list we have filtered out:

1. **HMXBs**. High-mass X-ray binaries (HMXBs) are young objects, which in our Galaxy are concentrated to the regions of recent star formation – the spiral arms. The spatial distribution of Galactic HMXBs has been studied by Grimm, Gilfanov, & Sunyaev (2002) in soft X-rays and by Lutovinov et al. (2005, 2007) in hard X-rays (> 20 keV) with the INTEGRAL observatory. Due to the low star-formation rate in the Galactic bulge we can anticipate that HMXBs should not be a dominant population of bright X-ray sources there. However, we might detect some HMXBs located in the Galactic disk, projected on the bulge in the sky plane. We excluded from our analysis all sources

that are known or supposed to be HMXBs, for example so-called supergiant fast X-ray transients (SFXTs) and X-ray pulsars. These sources include EXO 1722−363, IGR J17407−2808, XTE J1743−363, IGR J17544−2619, IGR J17391−3021 (XTE J1739−302), AX J1749.1−2733, AX J1749.2−2725 and IGR J18027-2016. Note that most of them have a transient nature.

Table 1. List of known or likely LMXB sources (persistent and transients) in the Galactic bulge region detected by INTEGRAL on the time-average map. The 1 mCrab flux in the 17–60 keV energy band for a Crab-like spectrum corresponds to an energy flux of $\sim 1.4 \times 10^{-11}$ erg s^{-1} cm^{-2} and to a luminosity 1.1×10^{35} erg s^{-1} for a distance of 8 kpc. Fluxes in the 2–10 keV energy band reported for some sources in the last column were obtained from RXTE/ASM measurements or adopted from the literature if a reference is given. The hard X-ray fluxes of the sources SLX 1744−299 and SLX 1744−300, which are not resolvable with INTEGRAL/IBIS, were calculated from their measured summed flux by assuming their flux ratio to be 2:1 (Sidoli et al. 1999)

#	Name	Flux, mCrab 17-60 keV	Flux, mCrab 2-10 keV
1	GRS 1758-258	59.07 ± 0.07	25
2	GX 1+4	54.14 ± 0.08	11
3	GX 5-1	48.14 ± 0.07	972
4	GX 354-0	37.57 ± 0.08	99
5	1E 1740.7-2942	31.79 ± 0.07	10
6	4U 1724-30	17.14 ± 0.07	25
7	A1742-294	13.71 ± 0.07	18[1]
8	GX9+1	16.50 ± 0.09	532
9	SLX 1735-269	11.21 ± 0.07	14
10	GX3+1	9.93 ± 0.07	300
11	SLX1744-299	5.47 ± 0.07	9.0[1]
12	1E1742.8-2853	6.29 ± 0.07	
13	1E1743.1-2843	5.20 ± 0.07	8.1[2]
14	SLX 1737-282	3.94 ± 0.07	5.4[3]
15	SLX1744-300	2.73 ± 0.07	5.1[1]
16	IGR J17254-3257	1.72 ± 0.08	3.5
17	IGR J17475-2253	1.09 ± 0.08	
18	IGR J17353-3539	0.88 ± 0.08	
19	IGR J17505-2644	0.81 ± 0.07	
20	IGR J17585-3057	0.81 ± 0.07	
21	IGR J17586-2129	0.73 ± 0.08	
22	IGR J17448-3231	0.70 ± 0.07	
Transients detected on the averaged map			
1	GRS 1741.9-2853	3.17 ± 0.07	
2	SAX J1747.0-2853	3.30 ± 0.07	
3	KS 1741-293	4.95 ± 0.07	
4	XTE J1739-285	2.21 ± 0.07	
5	GRS 1747-313	1.53 ± 0.07	
6	IGR J17464-3213	22.07 ± 0.07	
7	SLX 1746-331	0.69 ± 0.07	
8	IGR J17353-3257	1.12 ± 0.07	
9	MXB 1730-33	4.20 ± 0.08	
10	IGR J17331-2406	1.01 ± 0.08	
11	XTE J1720-318	1.73 ± 0.08	
12	IGR J17597-2201	4.62 ± 0.08	
13	XTE J1817-330	7.01 ± 0.09	
14	4U 1746-37	2.77 ± 0.09	
15	4U 1705-32	2.30 ± 0.09	
16	IGR J17091-3624	4.75 ± 0.10	

[1] - Sidoli et al. (1999), [2] - Porquet et al. 2003, [3] - in't Zand et al. 2002

2. **Extragalactic**. We also excluded extragalactic sources. Within the region of our study there are only two known extragalactic sources – active galactic nuclei GRS 1734−292 and IGR J17488−3253. According to the all-sky averaged AGN number-flux function in hard X-rays (Krivonos et al. 2007b) we should detect ~ 2 AGNs above the adopted flux limit of 0.64 mCrab within the area of our study (~ 171 sq. deg). This indicates that most likely we already know of all the extragalactic sources with fluxes of > 0.64 mCrab within the considered field. The probability that there are additional 2 or more unidentified extragalactic sources in this region is $\sim$0.14 and we do not expect unknown extragalactic sources to considerably contribute to the measured number-flux function of sources within the bulge region.
3. **Other sources** We removed cataclysmic variables, detected in the considered region. We removed from our sample the source IGR J17402−3656, which is associated with the nearby open star cluster NGC 6400 and may be composed of multiple point sources; the source IGR J17456−2901, which is similarly associated with the collective emission of the nuclear stellar cluster (Bélanger et al. 2006; Krivonos et al. 2007a); and the source IGR J17475−2822 representing the emission of the molecular cloud Sgr B2 (Revnivtsev et al. 2004b).

2.1. Transients

A significant fraction of Galactic LMXBs are transients. During outbursts their luminosities can change by more than 6–7 orders of magnitude (e.g. Tanaka & Shibazaki 1996). The "on" state of bright X-ray transients typically lasts several weeks, but due to their extreme brightness at that time they may still be detected on a sky map averaged over several years even if they were undetectable most of the time.

It is usually considered that the observed X-ray brightness variations of LMXB transients are caused by a developed mass transfer instability in the accretion disk (e.g. Meyer & Meyer-Hofmeister 1984; Lasota 2001). In this case, the X-ray luminosity observed from such a source at any given time does not provide us information about the global mass transfer rate in the binary system, which is of interest for us. The global mass transfer rate could be determined by averaging the X-ray luminosity of a transient source over a period that is much longer than the accretion disk mass accumulation time; however, this time scale might be too long (e.g. Chen, Shrader, & Livio 1997) to be testable by available X-ray observations. The inclusion of transient sources with their fluxes averaged over some arbitrary period (not related to any physically motivated time scale) might distort the true distribution of mass transfer rates, in which we are interested.

Therefore, in our analysis we treated the transient sources in two ways: 1) we included all sources detected at

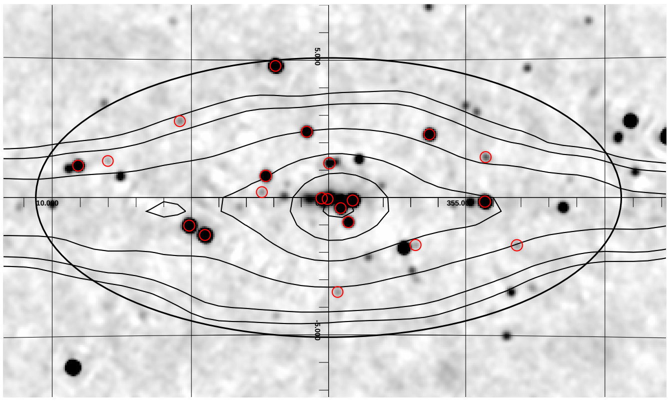

Fig. 1. Map of the Galactic Center region in the 17–60 keV energy band obtained by INTEGRAL/IBIS. The ellipse encloses the region of our study. Sources used in the analysis of the LMXB LF are marked by circles. Contours are isophotes of the 4.9μm surface brightness of the Galaxy (COBE/DIRBE) demonstrating the bulge/disk structure of the inner Galaxy.

the 5-year averaged INTEGRAL/IBIS map of the Galactic Center, and 2) we filtered out all transient sources from our sample. In the latter case, we adopted the following selection criterium for separating transient sources from persistent ones: a transient should have the ratio of maximal 3-day averaged flux to the all-time mean flux of more than 5.0. We note that transient nature is difficult to ascertain for weaker sources because they become detectable only after accumulating a large part of the total exposure time. Therefore, our resulting sample of transient sources is likely significantly incomplete at low fluxes.

The final list of accepted sources is presented in Table 1. The map of the Galactic bulge region with the sources from Table 1 is presented in Fig. 1.

2.2. Distances to the sources

The distances to the majority of our sources are unknown. However, assuming that LMXBs are distributed in the Galactic bulge similarly to ordinary stars, we can calculate the density distribution of LMXBs in the bulge and predict the spread of values of the flux to luminosity conversion coefficient for our sources. This determines the typical systematic error we are making in estimating source luminosities by assuming that all sources are at the same, 8 kpc, distance from the Sun.

To this end, we adopted a mass model of the Galaxy consisting of the Galactic bulge, Galactic disk and nuclear stellar disk (e.g. Launhardt, Zylka, & Mezger 2002). We did not consider the nuclear stellar cluster, which is important in the innermost $\sim 10'$ of the Galaxy, because its size is smaller than the angular resolution of INTEGRAL/IBIS.

The stellar density in the bulge was assumed to follow model G3 from Dwek et al. (1995). We adopted the mass of the bulge to be $1.3 \times 10^{10} M_\odot$ (Dwek et al. 1995).

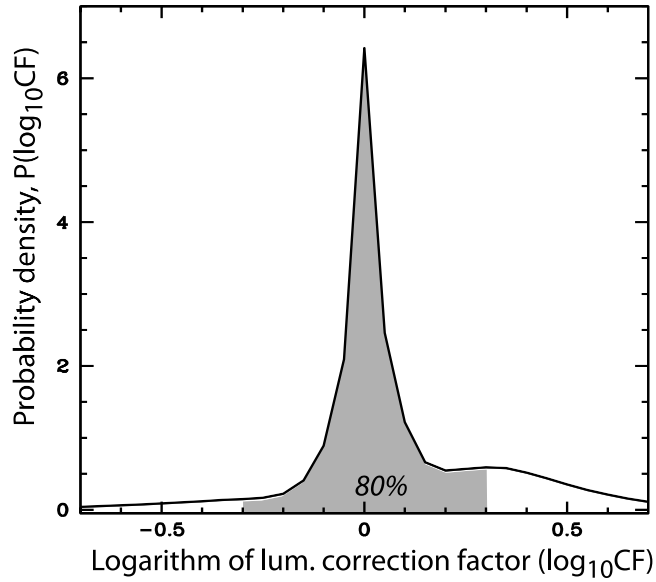

Fig. 2. Probability density of the luminosity correction factor (the probability density is normalized so that $\int P(\log_{10} CF) d(\log_{10} CF) = 1$). Eighty per cent of sources in the studied region of the Galaxy are expected to fall into the interval shown in gray.

The stellar density in the Galactic disk:

$$\rho_{\rm disk}(r,z) = \rho_{0,\rm disk} \exp\left[-\left(\frac{r_m}{r}\right)^3 - \left(\frac{r}{r_{\rm disk}}\right) - \left(\frac{|z|}{z_{\rm disk}}\right)\right],$$

where $r_{\rm disk} = 2.2$ kpc, $r_{\rm m} = 2.5$ kpc, $z_{\rm disk} = 130$ pc (Revnivtsev & Sazonov 2007). The total mass of the Galactic stellar disk was taken to be $2.5 \times 10^{10} M_\odot$.

The nuclear stellar disk (NSD) was assumed to have the density distribution (r and z are measured in parsecs)

$$\rho_{\rm NSD} = \rho_d r^{-\alpha} e^{-|z|/z_d},$$

where $z_d = 45$ pc. At $r < 120$ pc the slope $\alpha = 0.1$ and the normalization constant $\rho_d = 300 M_\odot/{\rm pc}^3$. At 120 pc $< r <$ 220 pc, $\alpha = 3.5$, and at $r > 220$ pc, $\alpha = 10$ (Launhardt, Zylka, & Mezger 2002), and we adjust the constant ρ_d so that the density distribution is continuous. The total adopted mass of the NSD is $1.4 \times 10^9 M_\odot$. In reality this quantity is uncertain by some 50% (Launhardt, Zylka, & Mezger 2002).

Based on this model, we determined the distribution of stars over the distance from the Sun in the region of our study (ellipse $|l| < 10.7°$, $|b| < 5.1°$). The ratio $(D/8\,{\rm kpc})^2$ defines the luminosity correction factor CF. The probability density of this correction factor can be calculated from the probability density $P(D)$ of the source distance, which can be found by integrating the distribution of stellar mass $\rho_*(l,b,D)$ in a given direction (l,b) over the solid angle Ω of our study:

$$P(D) = \frac{\int_\Omega \rho_*(l,b,D) D^2 d\Omega}{\int_\Omega \int_{\rm D=0}^{D=\infty} \rho_*(l,b,D) D^2 d\Omega dD}.$$

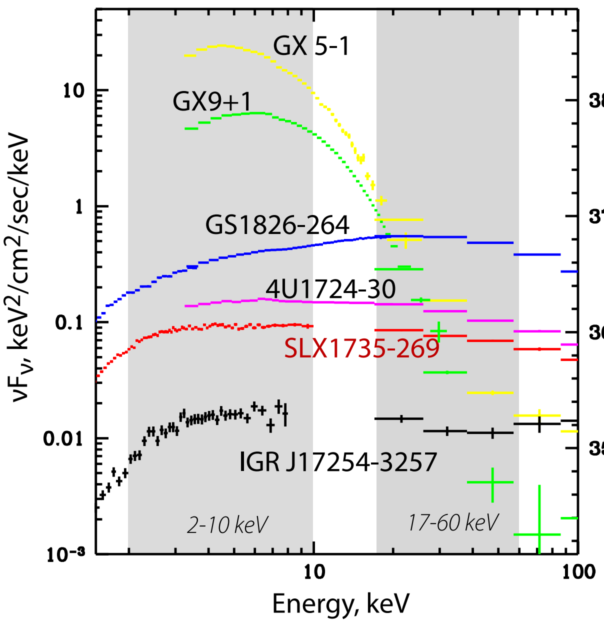

Fig. 3. Typical broadband spectra of LMXBs. The right axis shows the logarithm of the luminosity, assuming a distance of 8 kpc to all sources.

The probability density of CF is presented in Fig. 2. It turns out that for 80% of sources $\log_{10} CF < 0.3$. Therefore, assuming that all bulge sources are located at the same distance (8 kpc) from the Sun we can predict the luminosities of most sources to within a factor 2, this uncertainty being comparable to expected variations in source fluxes.

2.3. Spectral corrections

Previously, for constructing the luminosity function of LMXBs in galaxies one usually used instruments operating in the standard X-ray energy band, 2–10 keV, or similar bands (Grimm, Gilfanov, & Sunyaev 2002; Gilfanov 2004). The INTEGRAL/IBIS sky survey is done in the hard X-ray band, 17–60 keV. Therefore, to compare the LMXB LF derived here with those reported before we should take into account the spectral shapes of LMXBs in the broad energy range 1–100 keV.

It is well-known that the brightest LMXBs emit most of their luminosity in the standard X-ray band (∼2–10 keV), while less luminous objects emit similar amounts of energy in the standard and hard X-ray (∼10–100 keV) bands. Bright LMXBs usually have spectra with an exponential cutoff at energies of ∼6–10 keV (e.g. Rappaport et al. 1969; Toor et al. 1970; Mitsuda et al. 1984; Pavlinsky, Grebenev, & Sunyaev 1994) and essentially do not continue into the hard X-ray band (e.g. Gilfanov et al. 1993). In contrast, dim LMXBs are characterized by a power-law spectral shape between 2 and 60 keV (Mitsuda et al. 1989; Grebenev et al. 1991; Barret et al. 1991; Zhang et al. 1996; Barret et al. 2000). We can therefore expect that the LMXB LF constructed in the 17–60 keV energy band should strongly differ from that derived in the standard X-ray band.

To demonstrate this, we constructed the broadband spectra of Galactic bulge sources with different luminosities using all available instruments – INTEGRAL/IBIS, RXTE/PCA, Swift/XRT, ASCA/GIS. This allowed us to cover the wide energy range 1–100 keV (see Fig. 3). The LMXB GS 1826−24 formally lies outside the elliptical region of our study, but since its distance from the Sun is similar to those of bulge sources (e.g. in 't Zand et al. 1999) and its broadband spectrum has very high statistics this spectrum is also shown in the figure.

One can see dramatic changes in the broadband behavior of source spectra at a threshold luminosity of $\sim$ few $\times\, 10^{37}$ erg s^{-1}. At high luminosities, most of the energy is emitted below 17 keV. At low luminosities, the spectral shape in the 2–60 keV band is close to a power law with photon index $\Gamma \sim$1.9–2 and similar fluxes are emitted at 2–10 keV and 17–60 keV.

The time-averaged fluxes of most of the brightest sources in the 2–10 keV band are directly measured by the All-Sky Monitor aboard RXTE and we present these measurements in Table 1. Based on these data and Fig. 3, we adopted the following spectral correction factors for the subsequent analysis:

$$\frac{L_{2-10\ \mathrm{keV}}}{L_{17-60\ \mathrm{keV}}} = \begin{cases} 40 & \text{if } L_{2-10\ \mathrm{keV}} > 2\times10^{37}\ \mathrm{erg\ s^{-1}} \\ 1.25 & \text{if } L_{2-10\ \mathrm{keV}} < 2\times10^{37}\ \mathrm{erg\ s^{-1}} \end{cases}$$

In comparing below the LMXB LFs in the 2–10 keV and 17–60 keV energy bands, we mostly used direct RXTE/ASM measurements to determine the 2–10 keV luminosities for sources with $L_{2-10\ \mathrm{keV}} \gtrsim 10^{36}$ erg s^{-1}, and assumed that those sources with luminosities below this RXTE/ASM completeness limit are in the hard spectral state.

It is important to note that the spectral correction factors introduced above may not be applicable to rare, extremely luminous LMXBs such as the Galactic source GRS 1915+105, which is more powerful that any source in our Galactic bulge sample and is apparently in a highly unusual spectral state.

3. Results

3.1. Luminosity function of faint LMXBs

The luminosity functions of all and only persistent LMXBs detected by INTEGRAL/IBIS in the Galactic bulge region are shown in Fig. 4. These LFs are defined so as to give the number of sources within the studied region containing $1.65 \times 10^{10} M_\odot$ of stars.

It can be seen that the LF of weak LMXBs ($L_{17-60\ \mathrm{keV}} < 10^{36.5}$ erg s^{-1}) is relatively flat. The LF of all LMXBs can be approximated by the function $L_{35} dN/dL_{35} = (12 \pm 4)\, L_{35}^{-(0.13\pm0.13)}$ in the range $10^{34.7}$ erg s^{-1} $< L_{17-60\ \mathrm{keV}} < 10^{36.5}$ erg s^{-1}, and the LF of peristent sources can be approximated by the function

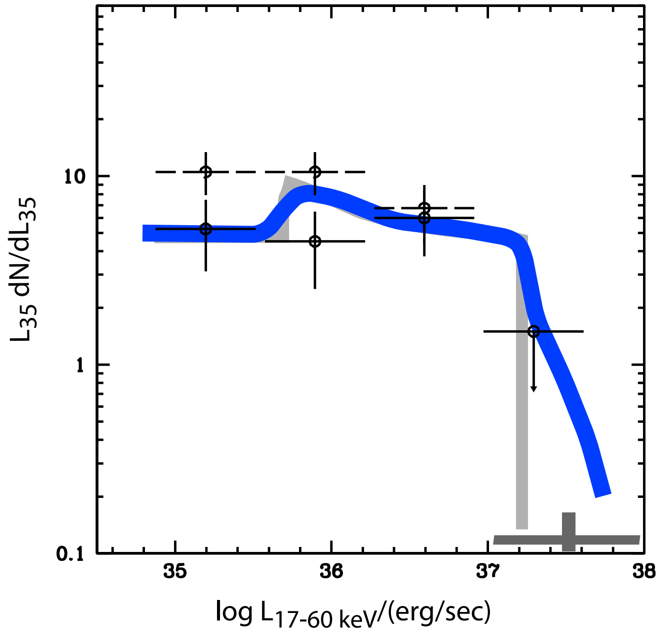

Fig. 4. Luminosity function of LMXBs detected by INTEGRAL/IBIS in the Galactic bulge region. The LF of persistent sources is shown by solid crosses, and that of all sources (including transients) by dashed crosses. The thick gray cross represents an estimate of the number of LMXBs with extremely high luminosities based on the one such source in the Galaxy, GRS 1915+105 ($L_{17-60\ \mathrm{keV}} \sim 5 \times 10^{37}$ erg s^{-1}). This estimate takes into account that the bulge region covered by the present study contains only 16% of the total stellar mass of the Galaxy. The thick gray line is the analytic model of the LMXB LF from Gilfanov (2004) normalized to $1.65 \times 10^{10} M_\odot$ – the stellar mass within the considered region, recalculated into the 17–60 keV energy band using the introduced spectral correction factors and multiplied by an additional factor of 0.4. The thick blue line is the same LF model convolved with the distribution of luminosity correction factor, which is important for sources in our sample due to unknown values of exact distances (see Fig.2)

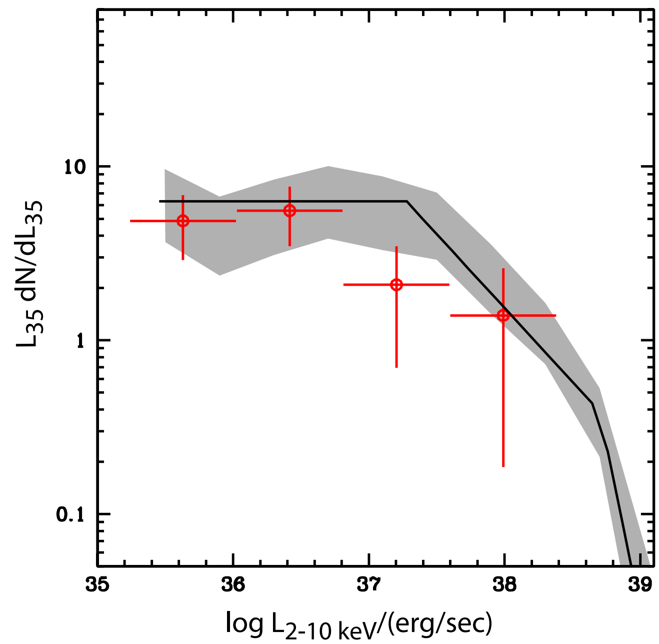

Fig. 5. Luminosity function of persistent sources in the 2–10 keV energy band. The solid line shows the analytic form of the LMXB LF from Gilfanov (2004) rescaled to $1.65 \times 10^{10} M_\odot$ – the stellar mass within the region studied here, and multiplied by 0.4. The shaded area represents the spread of LF between different galaxies (Gilfanov 2004)

$L_{35}dN/dL_{35} = (4.7 \pm 2.2)L_{35}^{(0.04\pm0.2)}$. Here, $L_{35}-$ is the hard X-ray (17–60 keV) luminosity in units of 10^{35} erg s^{-1}.

There are no objects with $L_{17-60\ \mathrm{keV}} > 10^{37}$ erg s^{-1} in our sample. Consequently, there is an abrupt drop in the number density of very bright sources as can be seen in Fig. 4. In fact, there is only one non-transient (but strongly variable) source in the whole Milky Way that has a higher luminosity: GRS 1915+105 with $L_{17-60\ \mathrm{keV}} \sim 5 \times 10^{37}$ erg s^{-1} (this value was calculated from the time averaged flux of the source of 261 mCrab in the energy band 17–60 keV from Krivonos et al. 2007b, assuming a 11 kpc source distance, Harlaftis & Greiner 2004). Since such ultraluminous sources can be easily detected with INTEGRAL throughout the Galaxy, we can estimate their expected number in the Galactic bulge region studied here by taking into account that this region contains 16% of the total stellar mass of the Galaxy. This estimate is shown in Fig. 4 by the thick gray cross.

In order to compare the 17–60 keV LF derived here with the analytic approximation of the 2–10 keV LF presented by Gilfanov (2004), we recalculated the last one into the 17–60 keV energy band using the spectral correction factors described above. This predicted LF, rescaled to the stellar mass contained in the considered region ($1.65 \times 10^{10} M_\odot$), is shown in Fig. 4 by the thick gray line. It was additionally multiplied by a factor of 0.4 in order to match the normalization of the LF measured with INTEGRAL in the Galactic bulge. We note that a similar indication of underabundance of LMXBs in the Milky Way as compared to other galaxies was previously reported by Gilfanov (2004).

As is apparent from Fig. 4, transient sources provide a significant contribution to the LMXB LF. If we describe the LF by the function $L_{35}dN/dL_{35} = const$ in the luminosity range $10^{34.7}$–$10^{36.5}$ erg s^{-1}, the normalization increases by a factor of ~ 1.7 after adding the transient sources.

In Fig. 5 we present the luminosity function of persistent LMXBs in the standard X-ray band (2–10 keV), which we constructed using direct RXTE/ASM source flux measurements for brighter sources (see Table 1) and our assumed spectral correction factors for weaker sources.

We should note that, despite the low star-formation rate in the Galactic bulge, some bulge HMXBs may be present in our sample. This can be especially important at the lowest luminosities because the LF of HMXBs is much steeper than that of LMXBs below $\sim 2\times10^{37}$ erg s^{-1}(see e.g. Grimm, Gilfanov, & Sunyaev 2002; Gilfanov 2004). For example, even for a star formation rate as low as $\dot{M}_* = 0.03 M_\odot$/year, the number of faint HMXBs will be comparable to that of all similarly faint sources in the region of our study. Therefore, the true number of faint LMXBs will be even lower than suggested by the derived luminosity function.

Summarizing all of the above, we can conclude that irrespective of the inclusion of transient sources the shape of the LF of Galactic bulge LMXBs is broadly compatible with the LMXB LF averaged over nearby galaxies (Gilfanov 2004), which exhibits a significant flattening at luminosities $L_{2-10\ \mathrm{keV}} < 2\times10^{37}$ erg s^{-1}.

3.2. Possible interpretations of the break in the LF

The flattening of the LMXB LF at luminosities $L_\mathrm{x}\sim10^{37}$ erg s^{-1} could be due to various reasons: i) a break in the distribution over mass transfer rates from the companion star, ii) a change of the correspondence between the mass transfer rate in the binary system and the mass accretion rate onto the compact object, possibly associated with the spectral state transition. We now briefly comment on each of these possibilities.

3.2.1. State transition

It is somehow surprising that the break in the LMXB LF occurs almost exactly at the (broadband) luminosity at which the sources experience a spectral state transition. At high luminosities, practically all sources are in the so-called soft/high spectral state and emit most of their luminosity in the optically thick regime. At low luminosities, the sources are in the so-called low/hard spectral state, emit in the optically thin regime and have hard spectra.

It is usually assumed that in the soft/high spectral state the X-ray luminosity is directly proportional to the mass accretion rate in the binary system (e.g. Shakura & Syunyaev 1973). The dependence of X-ray luminosity on mass accretion rate in the low/hard state is not clear. In the framework of the radiatively inefficient accretion flow models (Ichimaru 1977; Torbett 1984; Narayan & Yi 1994; Blandford & Begelman 1999), the accretion flow X-ray luminosity in the hard state may be a non-linear function of the mass accretion rate at the outer edge of the accretion flow: $L_\mathrm{x}\propto\dot{M}^\beta$, where $\beta>1$. Some observational data favor such a dependence (e.g. Gallo et al. 2006).

In this case, even if the distribution of mass transfer rates in binary systems has no peculiarities at the rates corresponding to X-ray luminosities $\sim$ few $\times10^{37}$ erg s^{-1}, one would still observe a break in the X-ray luminosity function due to the change in the $L_\mathrm{x}-\dot{M}$ relation. If the underlying distribution of mass transfer rates has the slope $d\log N/d\log\dot{M}=-\alpha$ and $L_\mathrm{x}\propto\dot{M}^\beta$, then the resulting slope of the LF will be $\gamma=(\alpha+\beta-1)/\beta$. Assuming that the true mass transfer rate distribution has the slope $\alpha=1.8$–2.0, as seen at luminosities $\log L_\mathrm{x}\sim$37.5–38.5 (Gilfanov 2004), and that $\beta=3.3$ (Beckert & Duschl 2002), the slope of the LF will be $\gamma\sim1.2-1.3$. Such a flattening of the LF is significant but not strong enough to explain the observed behavior of the LF.

The majority of the considered X-ray sources are likely accreting neutron stars. They have solid surfaces and the simple advection dominated model, in which the accreted mass flows under the black hole horizon without creation of the X-ray emission, is not directly applicable to them. However, some other mechanisms of reducing the X-ray emissivity of the accretion system might be considered (see e.g. Torbett 1984; Blandford & Begelman 1999).

3.2.2. Change of the binary braking mechanism

Following Postnov & Kuranov (2005), the break in the LMXB LF can be interpreted as the luminosity at which the mass transfer rate in the binary systems starts to driven by the gravitational braking mechanism rather than by magnetic stellar wind braking.

If this is indeed the case, we can anticipate that the majority of such faint LMXBs should have very small masses of optical companions ($M_\mathrm{opt}\lesssim0.2-0.4M_\odot$, see Postnov & Kuranov 2005) and short orbital periods ($<2-3$ hours), and be very faint in the optical and near-infrared spectral bands: the observable brightness of sources could be as low as $m_R>20$ even without any interstellar extinction (see estimates of the optical brightness of compact binary systems in van Paradijs & McClintock 1994). These predictions can be directly checked when accurate localizations of such X-ray sources will be achieved with the help of X-ray telescopes. Positional accuracy of the order of few arcseconds or less is necessary in this case, because the spatial density of such faint optical objects ($m_R>20-22$) is very high in the direction of the Galactic bulge.

3.3. Distribution of LMXBs in the Galactic Center region

3.3.1. Persistent sources

An extensive study of LMXB distributions in the Milky Way and in other galaxies showed that their number density closely traces the stellar mass distribution (e.g. Gursky & Schreier 1975; Skinner 1993; Grebenev, Pavlinsky, & Sunyaev 1996; Grimm, Gilfanov, & Sunyaev 2002; Gilfanov 2004). A rough comparison of the surface density of LMXBs in the Galactic bulge region with that of stars was previously done by Skinner (1993) based on archival observations with different instruments and by Grebenev, Pavlinsky, & Sunyaev (1996) based on a smaller sample of sources detected with the ART-P

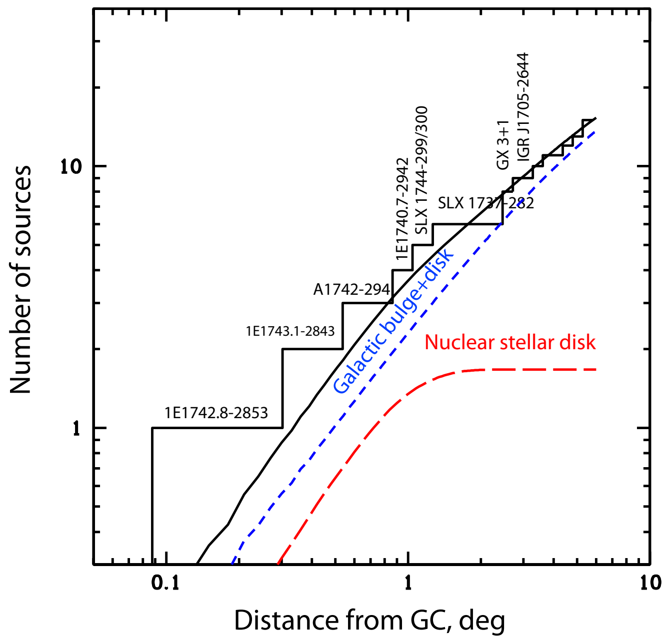

Fig. 6. Cumulative number of persistent LMXBs in the Milky Way bulge seen by INTEGRAL/IBIS within the circular region of a given projected radii. The solid curve shows the number of sources predicted by the Galaxy mass model described above and the LMXB LF of Gilfanov (2004) (multiplied by 0.4). The contributions of the Galactic bulge and nuclear stellar disk components are indicated by the short- and long-dashed lines, respectively. For the model curve we assumed the luminosity limit of 10^{35} erg s^{-1}. Positions of sources in the central region of the bulge are labeled.

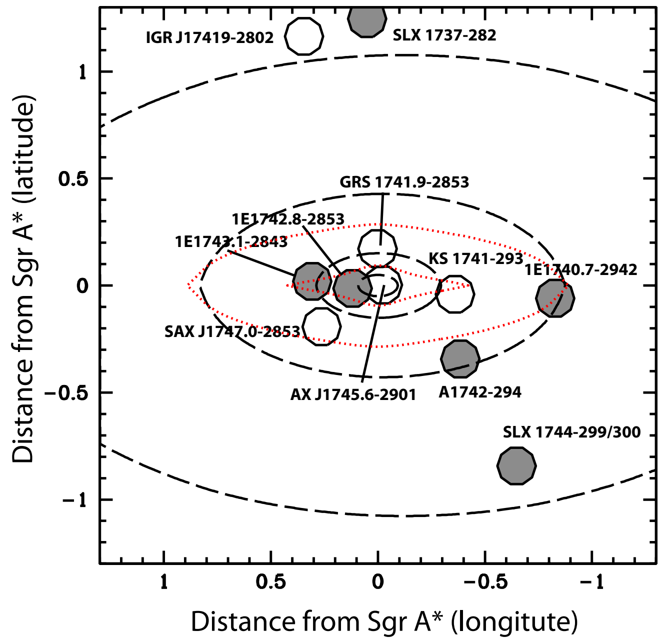

Fig. 7. Positions of all sources detected by IBIS/ISGRI within the inner 1.3° around the center of the Galaxy (Sgr A*). Dashed (black) curves are contours of the *iso* surface density of the stellar mass in the model of the Galaxy, which includes the bulge, the nuclear stellar disk and nuclear stellar cluster (which is important only within ∼10 ′ around Sgr A*). Dotted curves are *iso* surface density contours of the nuclear stellar disk component only. Filled (gray) circles show positions of persistent sources, open circles – positions of transient ones.

telescope aboard the *GRANAT* observatory. Now, using the sample of sources detected by INTEGRAL over five years of its operation we can make a somewhat better comparison.

The cumulative angular distribution of the number of persistent LMXBs detected by INTEGRAL in the Galactic bulge region as a function of projected angular distance from the Galactic Center is shown in Fig. 6 by the histogramm. The solid curve in this figure shows the cumulative stellar mass within given projected radii. To match the number of observed sources at distances < 5.1° from the Galactic Center with the galactic mass model described above (the total stellar mass contained in this region is $\approx 1.2 \times 10^{10} M_{\odot}$) and the average LMXB LF of Gilfanov (2004), the latter was multiplied by a factor of 0.4.

Interestingly, the radial distribution of sources shows an indication on an excess of the number of LMXBs inside the innermost ∼ 2° with respect to that expected from the distribution of stars in the Galactic bulge (note that a similar effect was previousely observed by Skinner 1993). The excess itself has low statistical significance – instead of the predicted ∼ 1 source within the innermost 0.6° around Sgr A* we see three sources, but it is consistent with the presence of LMXBs from the so-called nuclear stellar disk (e.g. Launhardt, Zylka, & Mezger 2002) (its contribution is shown by the long-dashed line). This allows us to tentatively suggest that at least the innermost sources, namely 1E1742.9−2853 and 1E1743−2843, reside in the nuclear stellar disk.

In order to visualize the distribution of sources in the innermost region of the Galaxy (see Fig. 7), we present the positions of detected LMXBs within 1.3° around Sgr A* with overlayed contours of *iso* surface density of stars in the region for the different components of the Galactic stellar population.

It is necessary to note that the best-fit LF normalization for the Galactic bulge population of LMXBs is ≈ 0.4 of the average over a number of nearby galaxies (Gilfanov 2004). Nevertheless, the Galactic bulge normalization is within the spread of best-fit values obtained for different galaxies (Gilfanov 2004).

3.3.2. Transients

Using the large time span of the INTEGRAL observations we have the ability to effectively determine the "transientness" of sources and study these transient sources separately. In particular, it is interesting to analyze their spa-

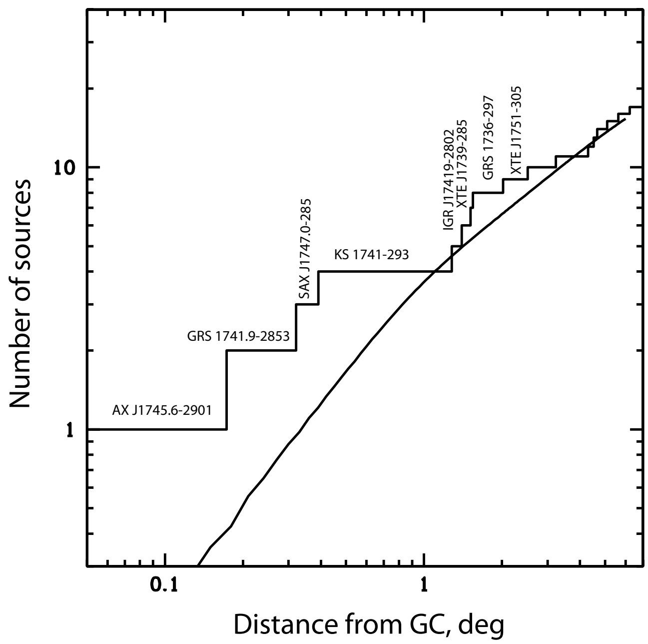

Fig. 8. Cumulative number of transient LMXB sources in the Galactic Center region, as seen by INTEGRAL/IBIS. The solid line represents the adopted mass model of the Galaxy normalized to the number of sources within 5.1° of the Galactic Center. The positions of sources in the innermost region of the bulge are labeled.

Table 2. List of transients seen by INTEGRAL/IBIS over the period 2003–2007

#	Dist from Sgr A*, deg	Name
1	0.02	AX J1745.6-2901
2	0.17	GRS 1741.9-2853
3	0.33	SAX J1747.0-2853
4	0.36	KS1 741-293
5	1.27	IGR J17419-2802
6	1.36	XTE J1739-285
7	1.51	GRS 1736-297
8	2.02	XTE J1751-305
9	2.54	GRS 1747-313
10	3.22	IGR J17464-3213
11	4.29	SLX 1746-331
12	4.48	IGR J17353-3257
13	4.67	XTE J1807-294
14	5.11	MXB 1730-33
15	5.64	IGR J17331-2406
16	6.18	XTE J1720-318
17	7.14	A 1744-361
18	7.68	IGR J17597-2201
19	7.95	XTE J1817-330
20	8.10	4U 1746-37
21	8.56	XTE J1818-245
22	8.57	4U 1705-32
23	8.68	4U 1745-203
24	10.60	IGR J17098-3628
25	10.66	IGR J17091-3624

tial distribution in view of the predictions of some theories that the densest central regions of galactic bulges might contain increased numbers of transients due to their enhanced dynamical formation (e.g. Voss & Gilfanov 2007).

The list of transient sources detected by INTEGRAL within the region of our study is presented in Table 2 along with their distances from the Galactic Center. The cumulative number of these sources as a function of their distance from the Galactic Center is shown in Fig. 8. The cumulative mass of stars within the considered region, normalized to the number of transients at $< 5.1°$ is shown by a solid line. One can note that there is a slight indication that transient sources are more concentrated towards the Galactic Center than the persistent ones, but the statistical significance of this effect is low. We should note that a similar effect was observed by Skinner (1993), since the majority of the sources considered in that work were transients detected with different instruments over a long period. If the effect of the increased surface density of transient sources in the center of the Galaxy is real, this might be related to the mechanism of dymanical formation of LMXBs proposed by Voss & Gilfanov (2007).

4. Conclusions

We analyzed the luminosity function and spatial distribution of low-mass X-ray binaries in the central part of our Galaxy (Galactic bulge) using data from the INTEGRAL observatory in the 17–60 keV energy band and found that:

1. No sources in the considered region demonstrate hard X-ray (17–60 keV) luminosities higher than $L_{17-60\ \mathrm{keV}} \sim 10^{37}$ erg s^{-1}. This happens because: a) sources with high bolometric luminosities have soft spectra with only a small portion of the bolometric luminosity emitted in the hard X-ray band, b) those sources with hard spectra do not have high bolometric luminosities. In fact, in our Galaxy there is only one source with hard X-ray luminosity as high as $L_{17-60\ \mathrm{keV}} \sim 5\times10^{37}$ erg s^{-1} – GRS 1915+105, which is pecular in many respects.
2. The luminosity function of persistent LMXBs is fairly flat at the faint end ($L_{17-60} \lesssim 10^{37}$ erg s^{-1}): the slope is $d\log N/d\log L = -0.96\pm0.20$. The shape of the LF of the Galactic bulge LMXBs in the standard X-ray band is consistent with that of the LMXB LF averaged over several nearby galaxies (Gilfanov 2004) and thus confirms the presence of the break at $L_{\mathrm{x}} \sim 10^{37}$ proposed earlier by Primini, Forman, & Jones (1993) and Gilfanov (2004).
3. The origin of the observed break in the LF is not clear. One of the possibilities is that it is connected with a change of the mechanism of removal of the angular momentum of the binary system: from magnetic stellar wind braking to graviational braking (see Postnov & Kuranov 2005). We propose that some additional flattening of the LMXB LF might be provided by the change of the mass accretion rate–X-ray lumi-

nosity relation expected in radiatively inefficient accretion flow models.
4. The cumulative angular distribution of the persistent LMXBs in the Galactic center region traces the cumulative number of stars in the model consisting of the Galactic bulge and nuclear stellar disk components. The data favor (though with low statistical significance) the presence of the nuclear stellar disk component in the distribution of LMXBs.
5. The cumulative angular distribution of the transient LMXBs slightly differs from that of the persistent sources, indicating some increase of the fraction of transient sources in the innermost regions of the Galaxy. However, the statistical significance of this increase is low.

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