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Properties of the Galactic population of cataclysmic variables in hard X-rays

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ABSTRACT

We measure the spatial distribution and hard X-ray luminosity function of cataclysmic variables (CVs) using the INTEGRAL all-sky survey in the 17–60 keV energy band. The vast majority of CVs detected by INTEGRAL are intermediate polars of luminosity in the range 10^{32}–10^{34} erg s^{-1}. The scale height of the Galactic disk population of intermediate polars is found to be 130^{+93}_{-46} pc. The CV luminosity function measured with INTEGRAL in hard X-rays is compatible with that previously determined at lower energies (3–20 keV) using a largely independent sample of sources detected by RXTE (located at $|b| > 10°$ as opposed to the INTEGRAL sample, which is strongly concentrated to the Galactic plane). The cumulative 17–60 keV luminosity density of CVs per unit stellar mass is found to be $(1.3 \pm 0.3) \times 10^{27}$ erg s^{-1} $M_{\odot}^{-1}$, which is comparable to that of low-mass X-ray binaries in this energy band. Therefore, faint but numerous CVs are expected to provide an important contribution to the cumulative hard X-ray emission of galaxies.

Key words. stars: binaries: close – stars: binaries: general – stars: novae, cataclysmic variables – stars: luminosity function, mass function – stars: white dwarfs – X-rays: binaries

1. Introduction

The sky far less studied in hard X-rays (>20–50 keV) than at lower energies because of the difficulties in detecting hard X-ray photons from rapidly decreasing photon flux from cosmic sources with increasing energy. The most extensive catalogs contain only about ~400 hard X-ray sources (Krivonos et al. 2007b; Bird et al. 2007; Tueller et al. 2007). As a result, basic properties of different populations of hard X-ray sources, such as number density, luminosity function and spatial distribution are poorly known. Therefore, any sample of hard X-ray sources with well-defined statistical properties (such as that of Krivonos et al. 2007b) is invaluable because it allows a robust analysis of the parameters of source populations.

The lack of information about Galactic populations of hard X-ray sources has increased the difficulty in interpreting the results of some hard X-ray observations. For example, early experiments detected unresolved hard X-ray emission from the Galaxy, in particular from its central region, this was proposed to be truly diffuse emission originating from interaction of low-energy cosmic rays with the interstellar medium (e.g. Stecker 1977; Mandrou et al. 1980; Sacher & Schoenfelder 1984; Skibo & Ramaty 1993). However, the INTEGRAL observatory (Winkler et al. 2003) resolved most of the Galactic hard X-ray emission at energies below ~100 keV into a number of luminous discrete sources (Lebrun et al. 2004). Furthermore, the remaining unresolved emission – the so-called Galactic ridge X-ray emission (GRXE) – was shown to follow closely the stellar mass distribution in the Galaxy, suggesting that it might be composed of a large number of fainter stellar-type sources (Krivonos et al. 2007a).

For the stellar origin of the GXRE to be correct, the space density of faint Galactic hard X-ray sources must be sufficiently high to provide the required luminosity density. According to the luminosity function of CVs in the Solar neighborhood measured in the 3–20 keV energy band (Sazonov et al. 2006), most of the GRXE at energies above several keV is expected to be produced by cataclysmic variables (CVs) (Sazonov et al. 2006; Revnivtsev et al. 2006). At hard X-rays (~20–100 keV), the main contribution to the GRXE is expected to originate in intermediate polars, a subclass of magnetic CVs (Revnivtsev et al. 2006; Krivonos et al. 2007a), whose hard X-ray spectra were individually measured with INTEGRAL (see e.g. Revnivtsev et al. 2004a,b; Barlow et al. 2006) and found to agree with the spectral shape of the GRXE (Krivonos et al. 2007a). Nonetheless, it is still important to measure the cumulative luminosity density of CVs directly at energies higher than 20 keV.

To directly estimate the luminosity function and cumulative luminosity density of faint Galactic hard X-ray sources, we analyze results of the INTEGRAL all-sky survey (Krivonos et al. 2007b). Apart from low and high mass X-ray binaries, the INTEGRAL catalog contains Galactic sources of other types, mostly CVs. The only non-CV faint Galactic sources in the INTEGRAL catalog are the symbiotic stars RT Cru and IGR J10109−5746/CD-57 3057 and the peculiar stars Gamma Cas and Eta Carinae. Because of the small number of such sources, we do not consider them here and focus instead on studying the properies of CVs detected in hard X-rays.

2. The sample of sources

We selected all INTEGRAL sources from the catalog of Krivonos et al. (2007b) that were identified to be CVs. This sample is ideal for our analysis because it is based on an all-sky survey and represents serendipitous observations of CVs (none of the sample sources were deeply observed by INTEGRAL

Table 1. CVs from the INTEGRAL all-sky survey (Krivonos et al. 2007b). Distance estimates enclosed in parentheses were estimated by either assuming an absolute K-band brightness of the binary system or using the period–luminosity relation. Observed K-magnitudes are adopted from the 2MASS survey (Skrutskie et al. 2006).

Name	$l^{\rm II}$	$b^{\rm II}$	Type	Orb. per. (h)	$F_{17-60\ {\rm keV}}$	D, pc	m_K	$\log L_{\rm hx}$	$1/V_{\rm gen}$
V709 Cas	120.04	–3.45	IP	5.34	3.91	230[1]	12.51	32.54	1.09×10^{-8}
GK Per	150.95	–10.10	IP	47.9	1.82	470[2]	10.06	32.80	5.08×10^{-9}
V1062 Tau	178.08	–10.31	IP	9.90	3.67	1100[3]	13.24	33.87	2.86×10^{-10}
IGR J14536-5522	319.74	3.46	IP		1.20	(347)[4]	12.70	32.38	1.74×10^{-8}
IGR J15094-6649	315.92	–7.49	IP		1.05	(496)[4]	13.48	32.64	8.20×10^{-9}
NY Lup	332.44	7.02	IP	9.86	4.10	690[5]	12.52	33.51	7.08×10^{-10}
IGR J16167-4957	349.70	7.33	IP		1.45	(546)[4]	13.76	32.86	4.27×10^{-9}
IGR J16500-3307	359.87	8.74	IP		1.12	(552)[4]	13.71	32.76	5.75×10^{-9}
V2400 Oph	359.86	8.74	IP	3.42	2.64	(331)[6]	13.02	32.55	7.10×10^{-9}
IGR J17195-4100	346.98	–2.11	IP		1.92	(217)[4]	11.69	32.18	3.26×10^{-8}
IGR J17303-0601	17.90	15.01	IP	15.4	3.54	3300[7]	12.48	34.81	3.47×10^{-11}
V2487 Oph	6.64	7.77			1.14	8000–27 000[8]	14.40	35.1–36.1	
V1223 Sgr	4.96	–14.35	IP	3.36	6.40	510[9]	12.64	33.44	8.49×10^{-10}
V1432 Aql	28.98	–15.50	IP	3.36	2.32	230[1]0	13.69	32.31	2.16×10^{-8}
V2069 Cyg	87.11	–5.68	IP	7.48	1.03	(1854)[7]	13.73	33.58	3.65×10^{-10}
IGR J21335+5105	94.36	–0.40	IP	7.19	3.15	(995)[7]	13.45	33.88	4.20×10^{-10}
SS Cyg	90.56	–7.11	DN	6.60	2.89	166[11]	8.29	32.12	3.87×10^{-8}

Notes: (1) – Bonnet-Bidaud et al. (2001), (2) – Slavin et al. (1995), (3) – Patterson (1994), (4) – distance was calculated assuming K-band absolute magnitude $M_K = 5$, (5) – de Martino et al. (2006), (6) based on period–hard X-ray luminosity correlation, (7) – Sazonov et al. (2006), based on Gänsicke et al. (2005), (8) – Hernanz & Sala (2002), (9) – Beuermann et al. (2004), (10) – Watson et al. (1995), (11) – Bitner et al. (2007).

intentionally). We selected only those sources detected at a confidence level higher than 5σ significance in the all-time averaged map of the sky. The resulting sample, consisting of 15 intermediate polars, one dwarf nova, and one classical Nova that is likely an accreting white dwarf binary (V2487 Oph), is presented in Table 1.

2.1. Source distances

Accurate distance estimates were not available for more than half of the sources in our sample, which presented a serious obstacle in constructing a CV luminosity function.

If the spectral type of the secondary star and the apparent brightness of a binary system are known, one can usually attempt to estimate its distance (e.g. Barnes & Evans 1976; Beuermann 2006; Knigge 2006). However, in the case of intermediate polars (IPs, which represent the majority of our sample), the accuracy of this method is significantly affected by the fact that the optical light of an IP is produced not only by the secondary star (see e.g. Knigge 2006), but also by the accretion disk (see e.g. Beuermann et al. 2004) and white dwarf surface (e.g. Bonnet-Bidaud et al. 2001; Eisenbart et al. 2002; Belle et al. 2003). Detailed spectroscopic information allows one in some cases to determine the contribution of the light of the companion star to the optical brightness of the binary (e.g. Watson et al. 1995; Bonnet-Bidaud et al. 2001; Gänsicke et al. 2005), but this information is not available for all CVs in our sample.

To demonstrate the importance of the contribution of the accretion disk to the near-infrared (NIR) emission of our IPs, we selected those sources with available distance estimates (Table 2). Assuming that the secondary stars in these binary systems are main sequence stars, which is not always true (see. e.g. Beuermann et al. 1998), but is true for the majority of our sample (see Table 2), we can relate their absolute brightness to their sizes. In this case the is still uncertainty in the estimate of the radii of companion stars depending on whether the star is closer to being a zero age main sequence star or a terminal age main sequence star, although it typically does not exceed a factor of 1.5 in radius.

The orbital period (P) of these systems can be used to estimate the radius of the secondary star (R_2) under the assumption that the star fills its Roche lobe:

$$R_2/R_\odot \approx 0.234\cdot(M_2/M_\odot)^{1/3}P^{2/3}.$$

Assuming the mass–radius relation $R\approx 0.91\cdot M^{0.75}$ for the late-type main sequence stars in CVs (e.g. Warner 1995; Smith & Dhillon 1998), we can write $R_2/R_\odot \approx 0.081\cdot P^{1.18}$ (Smith & Dhillon 1998), where the orbital period P is measured in hours. In Fig. 1, we compare the expected dependence using Baraffe et al. (1998) of the absolute K-band brightness of the secondary star on the binary system period with the measured values for our CVs of known distances. We see that while for some sources the observed and predicted K-band absolute magnitudes agree to within one magnitude, other sources are significantly brighter in the near-infrared than expected.

This deviation results from the unaccounted contribution of emission from the accretion disk in the binary system. Indeed, our sources demonstrate a good correlation of absolute K-band brightness with hard X-ray luminosity (see Fig. 1, middle panel). The linear fit to the observed correlation gives:

$$M_K \approx 12.81 - 2.63\log L_{\rm hx,30},$$

where $L_{\rm hx,30}$ is the source hard X-ray (17–60 keV) luminosity[1] in units of 10^{30} erg s^{-1}.

This correlation is caused partly by the direct contribution of accretion disk emission to the optical and near-infrared light of the binary. Another contributor to this correlation is the dependence of the mass accretion rate in IPs on the orbital period due to enhanced magnetic stellar wind braking in binaries

[1] Due to the relatively narrow range of spectral shapes of IPs in the hard X-ray energy band (see e.g. Suleimanov et al. 2005), the hard X-ray luminosity might be considered a proxy of the source bolometric luminosity or mass accretion rate.

Table 2. Sources in our sample with available information on distances (we excluded here the IP with a giant companion GK Per and dwarf nova SS Cyg due to unclear correlation of its measured NIR brightness with the mass tranfer rate in the binary system, set by the orbital period).

Name	D, pc	Orb. period, h	Sp. type	$F_{\rm hx}$ mCrab	$\log L_{\rm hx}$	m_K	M_K
V709 Cas	230[1]	5.34		3.91	32.54	12.51	5.70
V1062 Tau	1100[2]	9.90		3.67	33.87	13.24	3.03
NY Lup	690[3]	9.86	K0-4V[3]	4.10	33.51	12.53	3.33
IGR J17303-0601	3300[4]	15.4	G0-4V[5]	3.54	34.81	12.49	–0.11
V1223 Sgr	510[6]	3.36	M4V[6]	6.40	33.45	12.64	4.10
V1432 Aql	230[7]	3.36	M4V[7]	2.32	32.31	13.70	6.89

(1) – Bonnet-Bidaud et al. (2001), (2) – Patterson (1994), (3) – de Martino et al. (2006), (4) – Sazonov et al. (2006), based on Gänsicke et al. (2005), (5) – Gänsicke et al. (2005), (6) – Beuermann et al. (2004), (7) – Watson et al. (1995).

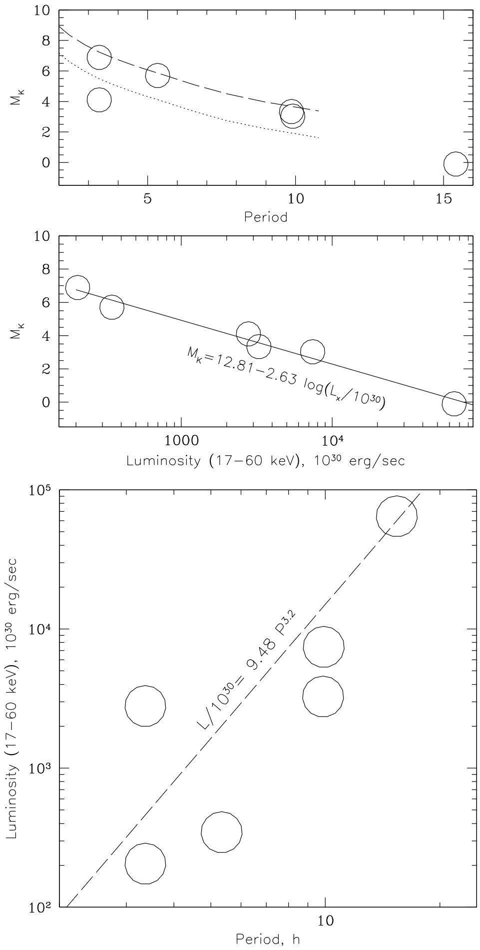

Fig. 1. *Upper panel* – dependence of the absolute K-band brightness of IPs on their orbital period. Circles are measurements for sources from our sample. The dashed line shows the theoretical estimate of M_K based on Baraffe et al. (1998). The dotted line is the same estimate shifted by 1.75 mag, which is equivalent to assuming that the secondary star contributes only 1/5 of the total near-infrared brightness of an IP or that the star is slightly evolved and approximately twice larger that a main sequence star of the same mass. *Middle panel* – absolute K-band brightness of IPs as a function of their hard X-ray luminosity. An empirical fit is shown by the solid line. *Lower panel* – correlation of the hard X-ray (17–60 keV) luminosity of IPs with their orbital period. The dashed line shows the empirical dependence $L_{\rm x} \propto P^{3.2}$.

with higher mass companion stars (Skumanich 1972; Rappaport et al. 1983; Patterson 1984; Postnov & Kuranov 2005). If no allowance is made for X-ray luminosity, the absolute near-infrared brightness and distance of an IP can therefore be underestimated significantly.

On the other hand, we can use the P–$L_{\rm hx}$ correlation calibrated on our 6 CVs with known distances to predict hard X-ray luminosities and distances for other CVs from the INTEGRAL sample. The power-law slope of the empirical fit to the observed luminosity (mass-accretion rate) – orbital period correlation (Fig. 1, lower panel),

$$L_{\rm hx,30} \approx 9.48 \cdot P^{3.2},$$

agrees with previous empirical (see e.g. Patterson 1984) and theoretical estimates (e.g. Postnov & Kuranov 2005), indicating that this dependence is physically motivated.

We used the above empirical correlation to estimate the distances to those sources in our sample with measured orbital periods. For the remaining systems we estimated their distance by assuming that $M_K = 5$. Although this assumption is certainly inaccurate, though reasonable, it should not affect our analysis dramatically. For example, if instead of $M_K = 5$ we had assumed $M_K = 3$ or $M_K = 7$, the resulting value of the cumulative luminosity density of CVs would have changed by less than a factor of 1.5. Nevertheless, we keep in mind that since distances are not known with adequate accuracy for all sources in the sample, all properties of the Galactic CV population estimated below contain systematic uncertainties in addition to purely statistical ones.

3. Spatial distribution

Cataclysmic variables are not uniformly distributed about the Sun. Being relatively old stellar systems, they are concentrated towards the Galactic plane: $\rho_{\rm CV} \propto \exp(-z/h)$, where z is the height above the Galactic plane. Our current understanding of the CV population suggests that the long period systems are typically younger than the short period systems and so-called period bouncers, and consequently have different spatial distributions with respect to the Galactic plane (e.g. Pretorius et al. 2007a; Pretorius et al. 2007b). However, since the majority of sources in our sample are long period systems, we expect that their distribution scale hight is about 120–150 pc (e.g. Patterson 1984; Thomas & Beuermann 1998; Ak et al. 2008). We do not consider the Galactocentric dependence of the CV distribution, since it only becomes important at distances larger than 1.5–2 kpc from the Sun and all of our sources apart from one are located closer (we exclude this source, IGR J17303−0601, from the following determination of the scale height of the CV spatial density distribution).

Using our INTEGRAL sample of sources derived from an all-sky survey, we estimate the scale height of the Galactic

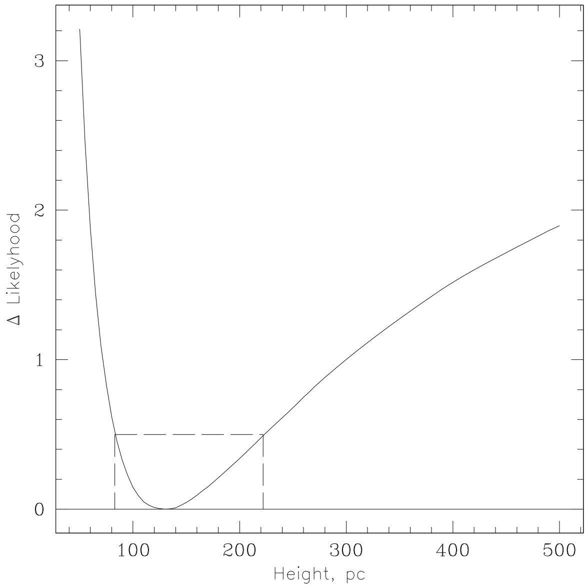

Fig. 2. Value of the maximum likelihood as a function of an assumed exponential scale height h of the CV spatial density distribution. The 68% confidence interval is indicated by the dashed lines.

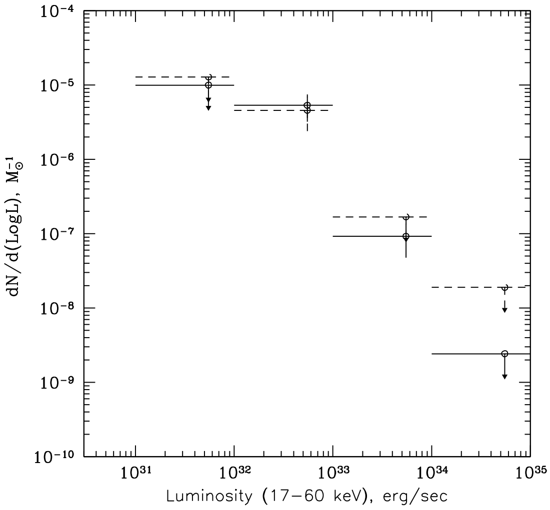

Fig. 3. Luminosity function of CVs detected by the INTEGRAL all-sky survey (solid crosses). Dashed crosses show the luminosity function constructed from those INTEGRAL CVs located at $|b| > 5°$, where the survey identification is almost complete. Arrows denote 95% upper limits to the space density.

disk population of long period CVs (more specifically in our case – mostly luminous intermediate polars). To this end, we constructed a maximum likelihood estimator of the scale height h. The probability for a source to be at a distance z from the Galactic plane depends on h and equals $P(z)\mathrm{d}z = (1/h)\exp(-z/h)\mathrm{d}z$. For each CV from the sample, we calculated the maximum distance $D(\mathbf{\Omega})$ in a given direction $\mathbf{\Omega}$ to which the source is detectable by the survey. The shape of the resulting volume V sampled by the survey over the entire sky was then taken into account in calculating the probability of source i to be at height z, i.e. $P_i^V(z)\mathrm{d}z$. The sum of the logarithms of these probabilities for all sources in the sample (except for IGR J17303−0601) defines our maximum likelihood estimator $ML = -\sum \ln P_i^V$.

The dependence of the ML value on h is shown in Fig. 2. The best-fit value of the scale height is 130 pc with a 68% confidence interval of 84–223 pc. This agrees with previous estimates of the scale height of luminous CVs (e.g. Patterson 1984; Ak et al. 2008), suggesting that most of our source distance estimates are reasonable.

Since the h value estimated above has a relatively large uncertainty, we adopt $h = 150$ pc for estimating the INTEGRAL hard X-ray luminosity function of CVs below.

4. Luminosity function

We employed the $1/V_{\max}$ method (Schmidt 1968) to construct the hard X-ray luminosity function of CVs detected by the INTEGRAL all-sky survey.

To take into account the inhomogeneous distribution of sources around the Sun, we weight the standard $\delta V_{\max}$ volume found for each small solid angle $\delta\Omega$ (at Galactic latitude b) of the survey by the space density of sources integrated over $\delta\Omega$ and over distance from 0 to $d_{\max}$, the maximum distance at which a given source can be detected. For an exponential distribution of sources with $\rho_{\rm CV} \propto \exp(-z/h)$, corresponds to a generic volume (Tinney et al. 1993; Schwope et al. 2002; Sazonov et al. 2006)

$$\delta V_{\rm gen} = \delta\Omega \frac{h^3}{\sin^3|b|}\left[2-(\xi^2+2\xi+2)\mathrm{e}^{-\xi}\right],$$

where $\xi = d_{\max}\sin|b|/h$. Each sampled source thus contributes $1/\sum\delta V_{\rm gen}$ to the estimated space density and $1/(\sum\delta V_{\rm gen})^2$ to the associated variance, where the sum is completed over the total solid angle of the survey. As noted above, we adopt the scale height $h = 150$ pc in our analysis.

The luminosity function of CVs detected by INTEGRAL is presented in Fig. 3. It was normalized to the local stellar density $\rho_* = 0.04\ M_\odot/\mathrm{pc}^3$ (Jahreiß & Wielen 1997). We present 95% ($\sim 2\sigma$) upper limits on the space density of CVs in the 10^{31}–10^{32} and 10^{34}–10^{35} erg s^{-1} luminosity intervals, where we have 0 and 1 sources, respectively. We do not consider the luminosity interval 10^{35}–10^{36} erg s^{-1}, which probably contains the source V2487 Oph, since this object is apparently very distant (Lynch et al. 2000; Hernanz & Sala 2002), making it impossible to apply the $1/V_{\max}$ method with the simple geometry of the Galactic disc adopted above.

The integrated space density of CVs with hard X-ray luminosity $L_{17-60\ \rm keV} > 10^{32}$ erg s^{-1} is $\rho_{\rm CV} = (3.8 \pm 1.5) \times 10^{-6}\ M_\odot^{-1}$.

It is important to note that at present the INTEGRAL all-sky survey catalog (Krivonos et al. 2007b) has significant incompleteness due to the unknown nature of a number of sources: 25 sources still do not have secure identifications. However, most of these sources reside very close to the Galactic plane and many are probably high-mass X-ray binaries, rather than CVs considered here.

If there was significant incompleteness in our CV sample, it would manifest itself in the observed distribution of CVs over the sky. We therefore calculated the expected numbers of CVs in 5-deg wide Galactic latitude bins assuming the exponential density distribution $\rho_{\rm CV} \propto \exp(-z/150\ \mathrm{pc})$ and luminosity function $N(>L) = 1.52 \times 10^{-7}(L_{17-60\ \rm keV}/10^{32}\mathrm{erg\ s^{-1}})^{-1.5}$ pc^{-3} (at $L_{17-60\ \rm keV} > 10^{32}$ erg s^{-1}), and taking into account the sensitivity map of the survey. Comparison of the observed and expected distributions (Fig. 4) suggests that our CV sample is not significantly incomplete.

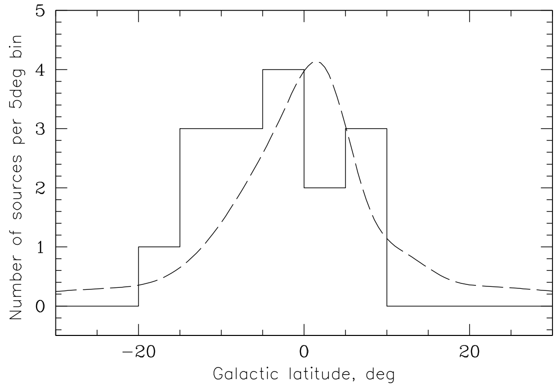

Fig. 4. Comparison of the Galactic latitude distribution of CVs observed by INTEGRAL (histogram) with that expected for an exponential distribution of CV space density, $\rho_{CV} \propto \exp(-z/150\,\mathrm{pc})$, taking into account the sensitivity map of the survey.

We can also assess more quantitatively the effect of possible sample incompleteness on our results. In Fig. 3, we show the luminosity function constructed from the CVs detected away from the Galactic plane ($|b| > 5°$), where the INTEGRAL all-sky survey catalog is highly complete (2 unidentified sources compared to 12 CVs). The good agreement of this luminosity function with the all-sky one indicates that our determination is robust.

However, we must bear in mind that the space density of hard X-ray emitting CVs measured for the entire sample of INTEGRAL CVs is in fact a lower limit to the true density in view of the remaining incompleteness in the source identification for the INTEGRAL all-sky survey.

Comparison of the derived space density of long period intermediate polars (constituting the majority of the INTEGRAL CV sample), $\rho = (3.8\pm1.5)\times10^{-6}\,M_\odot^{-1}$, or $\rho = (1.5\pm0.6)\times10^{-7}\,\mathrm{pc}^{-3}$ (assuming an average stellar density of 0.04 $M_\odot/\mathrm{pc}^3$ close to the Sun), with previous estimates, is complicated for several resons. In particular, our estimate of the space density of hard X-ray emitting CVs is very sensitive to the assumed limiting hard X-ray luminosity, and comparison with the results of e.g. optical surveys of magnetic CVs is not straightforward due to the uncertain X-ray-to-optical light conversion. This is important because CVs represent a diverse population of sources with different X-ray spectral shapes.

We attempt to compare our density estimate with the corresponding values for magnetic CVs of orbital periods above the period gap, which constitute the bulk of the INTEGRAL CVs sample (long-period magnetic CVs). For example, the space density of polars, which is the subclass of magnetic CVs in which the orbital rotation is synchronized with the rotation of the white dwarf, with orbital periods above the period gap was estimated in Thomas & Beuermann (1998) and can be estimated using results of Araujo-Betancor et al. (2005) $\rho \sim (1.5{-}1.7)\times 10^{-7}\,\mathrm{pc}^{-3}$. It should be noted that the total number of these sources in the abovementioned optical surveys is small, and, therefore there is large uncertainty in the density values.

4.1. Comparison with the luminosity function of CVs detected by the RXTE all-sky survey

The previous measurement of the spatial distribution and X-ray luminosity function of accreting white dwarfs was completed using the RXTE slew survey at $|b| > 10°$ in the energy band 3–20 keV (Sazonov et al. 2006). We might expect that the harder energy band of the INTEGRAL survey should select preferentially the hardest sources of all sub-classes of CVs. In our current INTEGRAL sample of sources, the vast majority are indeed intermediate polars, which are known to be the hardest of all CVs (see e.g. Sazonov et al. 2006 and Fig. 5).

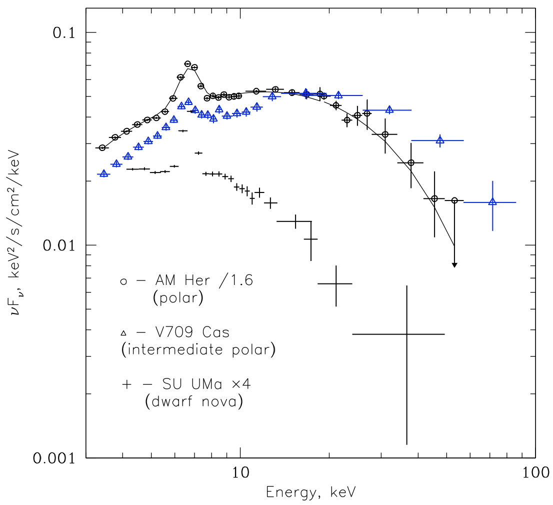

Fig. 5. Typical broad band spectra of different classes of CVs, indicating that INTEGRAL observations in the hard X-ray energy band (17–60 keV) are biased toward detecting the hardest CVs – intermediate polars.

The broad band (1–100 keV) spectra of IPs are typically so hard (see e.g. Suleimanov et al. 2005) that the luminosities measured for the 3–20 and 17–60 keV energy bands are similar. The ratio of luminosities in these bands does have some scatter but is typically $L_{17-60\,\mathrm{keV}}/L_{3-20\,\mathrm{keV}} \sim 0.6$–0.9. Therefore, by dividing the luminosities of IPs measured by INTEGRAL in the 17–60 keV band by this coefficient, we can compare the CV luminosity function derived in this work with that determined for RXTE data in the 3–20 keV energy band (Sazonov et al. 2006).

The result of this comparison is shown in Fig. 6. There is good agreement between the INTEGRAL and RXTE luminosity functions at luminosities $L_{3-20\,\mathrm{keV}} > 10^{32}$ erg s^{-1}, where most CVs are intermediate polars. At lower luminosities, other subclasses of CVs become numerous, but due to their relatively soft spectra, these sources are almost absent in the INTEGRAL (hard X-ray selected) sample.

5. Hard X-ray luminosity density of CVs

Using the same $1/V_{\max}$ method, we can also estimate the cumulative hard X-ray emissivity of CVs:

$$EM = \sum_i \frac{L_i}{\sum \delta V_{\max}(L_i)},$$

$$\delta EM = \sqrt{\sum_i \left(\frac{L_i}{\sum \delta V_{\max}(L_i)}\right)^2}.$$

We find that the cumulative 17–60 keV emissivity of CVs with $L_{17-60\,\mathrm{keV}} > 10^{32}$ erg s^{-1} per unit stellar mass is $L_{17-60\,\mathrm{keV}}/M_* = (1.3\pm0.3)\times10^{27}$ erg s^{-1} $M_\odot^{-1}$. Figure 7 shows the cumulative emissivity as a function of the threshold luminosity.

The obtained value of the CV cumulative emissivity is in remarkably good agreement with the emissivity of the unresolved hard X-ray emission observed by INTEGRAL from the Galactic plane region, which is given by $L_{17-60\,\mathrm{keV}}/M_* = (0.9{-}1.2)\times 10^{27}$ erg s^{-1} $M_\odot^{-1}$ (Krivonos et al. 2007a), suggesting that this emission is mostly the superposition of numerous CVs.

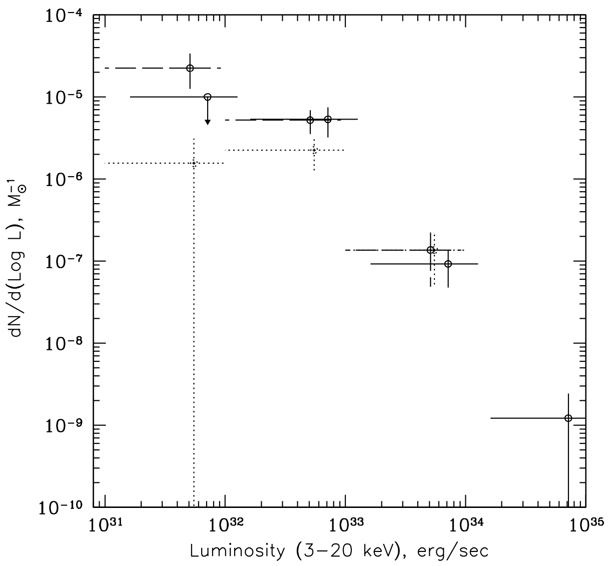

Fig. 6. Luminosity function of CVs (mostly intermediate polars) detected by the INTEGRAL all-sky survey (solid crosses), converted to the 3–20 keV energy band assuming the hardness ratio $L_{17-60\ \mathrm{keV}}/L_{3-20\ \mathrm{keV}} = 0.7$ for IPs. This luminosity function is compared with the luminosity function of faint Galactic sources detected by the RXTE slew survey at $|b| > 10°$ (dashed crosses), with dotted crosses showing the contribution of IPs to this luminosity function (Sazonov et al. 2006). Note that, in contrast to Fig. 3, we show an approximate estimate of the space density in the $L_{17-60\ \mathrm{keV}} = 10^{34}$–$10^{35}$ erg s^{-1} interval based on the single source detected by INTEGRAL in this range, rather than an upper limit.

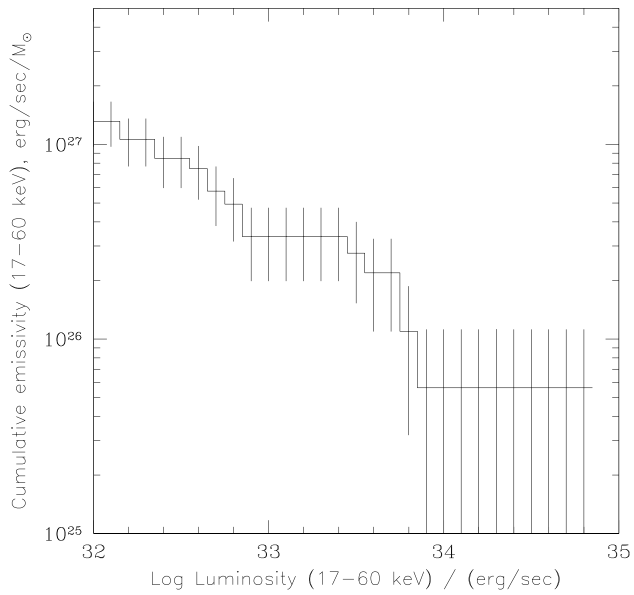

Fig. 7. Cumulative hard X-ray luminosity density of CVs determined from the INTEGRAL all-sky survey.

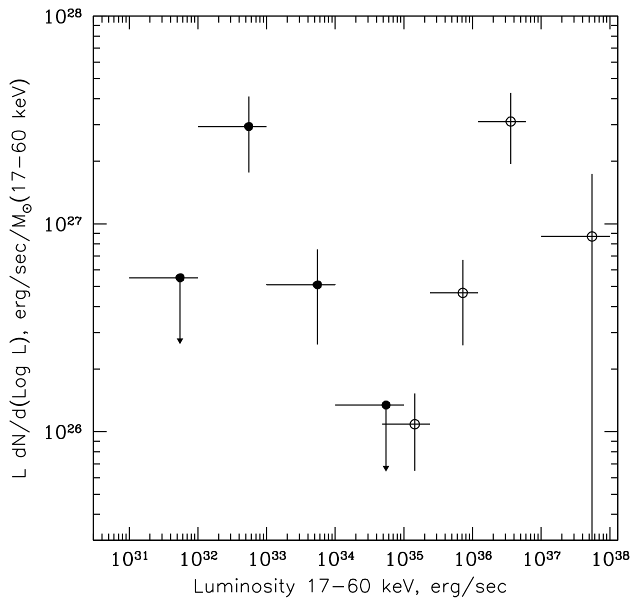

Fig. 8. Combined luminosity function of CVs ($L_{\mathrm{hx}} < 10^{34.5}$ erg s^{-1}, filled circles) and LMXBs ($L_{\mathrm{hx}} > 10^{34.5}$ erg s^{-1}, open circles).

6. Broad band hard X-ray luminosity function of the old stellar population in the Milky Way

Since early observations with focusing X-ray telescopes it has been known, that the cumulative emission of bright ($L_{\mathrm{x}} > 10^{37}$–10^{39} erg s^{-1}) discrete sources constitutes a significant fraction of the total X-ray emission of galaxies (Trinchieri & Fabbiano 1985). This is especially true for energies >2–3 keV, at which emission from hot interstellar gas cannot contribute significantly even in gas-rich galaxies because typical gas temperatures are $kT \lesssim 1$ keV. Therefore, it is often assumed that most of the hard X-ray emission of galaxies is produced by low- and high-mass X-ray binaries, while the contribution of weaker sources is usually neglected.

However, as we have shown in the previous section, CVs are expected to produce a hard X-ray emissivity comparable to that generated by brighter sources, i.e. low-mass X-ray binaries. This was previously suggested by Krivonos et al. (2007a) based on a study of the Galactic bulge with INTEGRAL in which the luminosity of the unresolved hard X-ray emission was found to be comparable to the cumulative luminosity of bright resolved sources. We therefore consider the combined hard X-ray luminosity function of CVs and LMXBs.

In Fig. 8 we present the luminosity function of CVs and LMXBs in the 17–60 keV energy band based on INTEGRAL data analysed in the present paper and in Revnivtsev et al. (2008). This plot demonstrates that the cumulative hard X-ray luminosity density of LMXBs is only marginally higher than that of CVs.

This ratio of the cumulative emissivities of LMXBs and CVs in the hard X-ray band is significantly smaller than in the standard X-ray band (2–10 keV) (see e.g. Sazonov et al. 2006). The major reason for this is that the brightest LMXBs ($L_{\mathrm{x}} \sim 10^{38}$ erg s^{-1} in the 2–10 keV band), which provide the majority of the cumulative emissivity of LMXBs, have very soft spectra and thus emit only a small fraction of their total emission in hard X-rays. At the same time, luminous CVs emit almost the same fraction of their bolometric luminosity in standard and hard X-rays.

7. Conclusions

We have studied a sample of CVs detected in the hard X-ray band (17–60 keV) by the INTEGRAL all-sky survey. This sample is one of the largest unbiased samples of luminous intermediate polars available to date.

Our findings are:

1. The scale height of the Galactic disc distribution of luminous hard X-ray emitting CVs is $h = 130^{+93}_{-46}$ pc.

2. We have measured the luminosity function of CVs in the 17–60 keV energy band. The space density of CVs with luminosities $L_{17-60\ \rm keV} > 10^{32}$ erg s^{-1} close to the Sun is $(3.8 \pm 1.5) \times 10^{-6}\ M_{\odot}^{-1}$.
3. The luminosity density of CVs with luminosities $L_{17-60\ \rm keV} > 10^{32}$ erg s^{-1} is $L_{17-60\ \rm keV}/M_{*} = (1.3 \pm 0.3) \times 10^{27}$ erg s^{-1} $M_{\odot}^{-1}$. This value is in remarkably good agreement with the emissivity of the unresolved (with INTEGRAL) hard X-ray emission in the Galactic plane region.

We emphasize that all of our estimates depend on the accuracy of the distance determination for our sources. Therefore, the current lack of accurate distances for a number of sources introduces additional uncertainties in the measured parameters of the Galactic population of cataclysmic variables which have not been included in the errors quoted above.

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