GALACTIC ULTRACOMPACT X-RAY BINARIES: EMPIRICAL LUMINOSITIES

T. F. CARTWRIGHT1, 2, M. C. ENGEL1, C. O. HEINKE1, 3, G. R. SIVAKOFF1, J. J. BERGER1, J. C. GLADSTONE1, AND N. IVANOVA1

1 Physics Department, 4-183 CCIS, University of Alberta, Edmonton, AB T6G 2E1, Canada; heinke@ualberta.ca
2 International Space University, 1 rue Jean-Dominique Cassini, 67400 Illkirch-Graffenstaden, France
3 Ingenuity New Faculty.

ABSTRACT

Ultracompact X-ray binaries (UCXBs) are thought to have relatively simple binary evolution post-contact, leading to clear predictions of their luminosity function. We test these predictions by studying the long-term behavior of known UCXBs in our Galaxy, principally using data from the MAXI All-Sky Survey and the Galactic bulge scans with RXTE’s Proportional Counter Array instrument. Strong luminosity variations are common (and well documented) among persistent UCXBs, which requires an explanation other than the disk instability mechanism. We measure the luminosity function of known UCXBs in the Milky Way, which extends to lower luminosities than some proposed theoretical luminosity functions of UCXBs. The difference between field and globular cluster (GC) X-ray luminosity functions in other galaxies cannot be explained by an increased fraction of UCXBs in GCs. Instead, our measured luminosity function suggests that UCXBs only make up a small fraction of the X-ray binaries above a few \( \times 10^{36} \) erg s\(^{-1}\) in both old field populations and GCs.

Key words: accretion, accretion disks – globular clusters: general – white dwarfs – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

Ultracompact X-ray binaries (UCXBs) contain a compact accretor star (in all known cases, a neutron star, though black hole UCXBs are possible) and a compact donor star, with an orbital period \( P_{\text{orb}} < 80 \) minutes. Such short periods require the donors to be hydrogen-deficient, partially or fully degenerate stars (e.g., Rappaport et al. 1982; Deloye & Bildsten 2003). UCXB systems are more common in globular clusters (GCs), likely due to their formation thereby close dynamical interactions (Verbunt 1987; Deutsch et al. 2000; Ivanova et al. 2005).

UCXB systems can be roughly divided into persistent (over the decades we have been observing them) and transient systems. Transient UCXBs spend the majority of the time in a quiescent state with little or no accretion, punctuated by occasional outbursts (when they become quite luminous and are more easily detected). The outbursts of known transient UCXBs are rather short, which is expected given the small size of their accretion disks.

\textit{Chandra} X-ray observations of elliptical galaxies detect large numbers of X-ray binaries in GCs (e.g., Sarazin et al. 2001; Angelini et al. 2001; Kundu et al. 2002; Minniti et al. 2004; Jordán et al. 2004). The luminosity function of GC X-ray binaries differs from the non-cluster X-ray binary luminosity function, particularly below an X-ray luminosity \( L_X = 10^{37} \) erg s\(^{-1}\) where GCs have fewer X-ray binaries (Fabbiano et al. 2007; Kim et al. 2009; Voss et al. 2009; Zhang et al. 2011). UCXBs have been suggested to dominate bright GC X-ray sources (Bildsten & Deloye 2004), and their high frequency in GCs has been suggested to explain the different X-ray luminosity functions (XLFs) inside versus outside of clusters (Voss et al. 2009). This suggestion depends on the Fragos et al. (2008) model of the UCXB luminosity function, which cuts off below \( 5 \times 10^{36} \) erg s\(^{-1}\) (following current calculations of the He disk instability line), to explain the flat luminosity function of GCs at low \( L_X \). Ivanova et al. (2008) found that UCXBs are unlikely to constitute the majority of GC X-ray binaries due to the short lifetimes of persistent UCXBs; instead, main-sequence donors are preferred for that role. An empirical measurement of the UCXB luminosity function (along with re-consideration of the appropriate \( M_{\text{crit}} \)) can uncover the true role of UCXBs among the X-ray binaries in elliptical galaxy GCs, and is a target of this work.

In this paper, we compile histograms of the luminosities of galactic UCXBs from the most sensitive surveys available and calculate empirical UCXB luminosity functions. In Heinke et al. (2013), hereafter Paper II, we use the luminosities for individual sources found in this paper to discuss their disk stability and evolution.

2. DATA ANALYSIS

2.1. Sample Selection

As of 2013 January, 13 galactic UCXBs have reliable orbital period measurements (some tentative; see Table 1). Four other likely UCXBs show strong indications of their ultracompact nature, principally their X-ray/optical flux ratio (Bassa et al. 2006), lack of H lines in their spectra (Nelemans et al. 2004, 2006), and burst characteristics (Galloway et al. 2010). Eight objects have been suggested to be UCXBs based principally on their low (<2% of Eddington) persistent X-ray luminosity (in’t Zand et al. 2007). To study the UCXB XLF, we choose to omit the eight objects suggested on this basis alone, as this method of identification would clearly bias the derived luminosity function. We also note that a counterexample to the in’t Zand method—an apparently persistent system below 2% of its Eddington luminosity, not edge-on, and with a 2.15 hr orbital period (Engel et al. 2012)—is now known, H1825–331 in the globular cluster NGC 6652. Whether or not this system is a transient is debatable (Verbunt et al. 1995; Deutsch et al. 1998), but if it is a transient, it has been active as long as many systems thought to be persistent, so the discrepancy with the in’t Zand method remains.

We cannot be certain that other identification methods (which are not uniform) do not introduce luminosity biases, but at least they are not obviously biased. We list the remaining 17 systems...
in Table 1, separating them into transient and persistent systems. Of these 17, 5 accreting millisecond pulsars are known transients, while the rest are (so far) deemed persistent.

From the candidate ultracompacts listed by in’t Zand et al. (2007) and Nelemans & Jonker (2010), we exclude 4U 1822−00 (due to its optical modulation period of 191 minutes; Shahbaz et al. 2007), NGC 6652 A (due to its 2.15 hr optical period; Engel et al. 2012), NGC 6652 B (due to its apparently main-sequence donor; Heinke et al. 2001 and recent evidence against the proposed 45 minute period; Engel et al. 2012), and the ω Cen qLMXB (due to its strong H emission; Haggard et al. 2004). We also omit 4U 1905+000, due to a lack of high-cadence sensitive monitoring data (it has been quiescent ranges from indirect estimates; 15% errors on bursts (Kuulkers et al. 2003) and 5% errors on GC distances. Periods supported by only weak evidence have “?”s.

References: a Galloway et al. (2010); b Harris (2010); c Stella et al. (1987); d Sidoli et al. (2001); e Zurek et al. (2009); f in’t Zand et al. (2005a); g Zhong & Wang (2011); h Jütt & Chakrabarty (2003); i Wang & Chakrabarty (2004), distance estimate assumes M driven by gravitational radiation; j Homer et al. (1996); k Dieball et al. (2005); l White & Angelini (2001); m Chakrabarty (1998); n Krauss et al. (2007); o Yoshida (1993); p Walter et al. (1982); q Church et al. (1998); r Brandt et al. (1992); s Shahbaz et al. (2008); t Piraino et al. (1999); u in’t Zand et al. (2008); v Bassa et al. (2006); w Tarana et al. (2006); x Galloway (2006); y Markwardt et al. (2003); z Falanga et al. (2005); ? Papitto et al. (2008); 1 Markwardt et al. (2002); 2 Miller et al. (2003); 3 Galloway et al. (2002); 4 Jütt et al. (2003); 5 Krimm et al. (2007); 6 Altamirano et al. (2010).

2.2. Data Selection and Analysis

We took our data from all-sky monitoring surveys wherever feasible. The Monitor of All Sky X-ray Image (MAXI) detector (Matsuoka et al. 2009; Sugizaki et al. 2011) aboard the International Space Station (ISS) provides high-sensitivity light curves for bright X-ray binaries anywhere in the sky since 2009 August, while the Rossi X-ray Timing Explorer’s (RXTE) Proportional Counter Array (PCA; Jahoda et al. 1996) scans of the Galactic bulge (Swank & Markwardt 2001) permit higher-sensitivity light curves of X-ray binaries in the Galactic bulge from 1999 to 2012 (and expanded regions for shorter times).

We obtained daily binned MAXI Gas Slit Camera data, in units of counts s$^{-1}$ cm$^{-2}$ in the 2.0–4.0 keV and 4.0–10.0 keV energy ranges, from the MAXI Web site. We chose to omit the 10–20 keV energy range, due principally to its poorer signal-to-noise ratio, but also because we are focused on comparing to Chandra detections of extragalactic X-ray binaries below 10 keV. PCA bulge scan data were obtained from C. Markwardt’s Web site in the 2.5–10 keV band (C. Markwardt 2013, private communication). MAXI data collection began on MJD 55058 (2009 August 15), with our data spanning approximately 2 years and 8 months, while there is over 12 years worth of PCA bulge scan data for most sources (the bulge scans were extended to cover larger regions later).

We used MAXI data for persistent sources outside the bulge scan region, combining the 2–4 and 4–10 keV data and errors. We discarded roughly 30 data points per source corresponding to dates the shuttle was docked at the ISS, and high data points that were clearly attributable to Sun glints (identifiable as a bright, elongated source moving over the MAXI map around the source over a few days). We also identified data with large errors as noisy; the value of the error cutoff was determined on an individual basis for each source. This amounted to ∼0.5%–10% of the data from each source. Combined MAXI data points less than 3σ above zero were considered upper limits; we create 3σ upper limit points by replacing the data point with an upper limit three times the error above zero. For PCA data, we used a 4σ detection limit, since the PCA is more sensitive, and the

---

**Table 1**

UCXB Information

| Source            | Location | Distance (kpc) | Period (minutes) | $N_0$ $(10^{31}$ cm$^{-2}$) | MAXI Points | PCA Points |
|-------------------|----------|----------------|------------------|-----------------------------|-------------|------------|
| 4U 1728−34        | Field    | 5.2 ± 0.8$^a$ | 10.8$^b$         | 22.9$^a$                    | ...         | 803        |
| 4U 1820−303       | GC       | 7.9 ± 0.4$^b$ | 11$^c$           | 1.6$^d$                     | 600         | 0          |
| 4U 0513−40        | GC       | 12.1 ± 0.8$^b$| 17$^e$           | 0.26$^d$                    | 144         | 507        |
| 2S 0918−549       | Field    | 5.4 ± 0.8$^b$ | 17.4$^f$         | 3.0$^g$                     | 300         | 519        |
| 4U 1543−624       | Field    | 7.0$^h$        | 18.2$^i$         | 3.5$^b$                     | 667         | 50         |
| 4U 1850−087       | GC       | 6.9 ± 0.3$^b$ | 20.6$^j$         | 3.9$^b$                     | 106         | 645        |
| M15 X-2           | GC       | 10.4 ± 0.5$^b$| 22.6$^b$         | 0.67$^b$                    | ...         | ...        |
| 4U 1626−67        | Field    | 8.5$^k$, m | 42$^m$           | 1.4$^b$                     | 739         | 108        |
| 4U 1916−053       | Field    | 9.3 ± 1.4$^b$ | 50$^o$           | 3.2$^b$                     | 332         | 453        |
| 4U 0614+091       | Field    | 3.2 ± 0.5$^l$ | 51$^l$           | 3.0$^l$                     | 567         | 50         |
| 1A 1246−588       | Field    | 4.3 ± 0.6$^b$ | ?                | 2.5$^b$                     | 122         | 389        |
| 4U 1812−12        | Field    | 4.6 ± 0.7$^b$ | ?                | 15.0$^b$                    | ...         | 405        |

**Notes.** Known and suspected UCXBs in our sample, with best estimates of their distance, period, and $N_0$, plus the number of usable data points from MAXI and the PCA bulge scans. Location in the Galactic field, (direction of) the bulge, or in a globular cluster (GC) is also specified. Errors are ranges from indirect estimates; 15% errors on bursts (Kuulkers et al. 2003) and 5% errors on GC distances. Periods supported by only weak evidence have “?”s.

**References:**

- a Galloway et al. (2010);
- b Harris (2010);
- c Stella et al. (1987);
- d Sidoli et al. (2001);
- e Zurek et al. (2009);
- f in’t Zand et al. (2005a);
- g Zhong & Wang (2011);
- h Jütt & Chakrabarty (2003);
- i Wang & Chakrabarty (2004), distance estimate assumes M driven by gravitational radiation;
- j Homer et al. (1996);
- k Dieball et al. (2005);
- l White & Angelini (2001);
- m Chakrabarty (1998);
- n Krauss et al. (2007);
- o Yoshida (1993);
- p Walter et al. (1982);
- q Church et al. (1998);
- r Brandt et al. (1992);
- s Shahbaz et al. (2008);
- t Piraino et al. (1999);
- u in’t Zand et al. (2008);
- v Bassa et al. (2006);
- w Tarana et al. (2006);
- x Galloway (2006);
- y Markwardt et al. (2003);
- z Falanga et al. (2005);
- ? Papitto et al. (2008);
- 1 Markwardt et al. (2002);
- 2 Miller et al. (2003);
- 3 Galloway et al. (2002);
- 4 Jütt et al. (2003);
- 5 Krimm et al. (2007);
- 6 Altamirano et al. (2010).
crowded bulge leads to increased systematic errors. For systems known to be transients (e.g., observations with sensitive X-ray detectors found them in quiescence), upper limits were taken to indicate quiescence, and were simply replaced with a value of 0. Persistent sources were essentially always detected in PCA data.

Many of these UCXBs exhibit substantial variability. The light curves of 4U 1850–087, 4U 1728–34, and 2S 0918–549 (Figure 1) demonstrate variation of up to an order of magnitude, on timescales from days to months. Such variability was highlighted recently by Maccarone et al. (2010) for 4U 1543–40 (the UCXB in NGC 1851). Similar variability was noted from, e.g., the UCXBs 4U 1915–05 by Šimon (2005) and 1A 1246–588 by in’t Zand et al. (2008); see below.

We converted the MAXI data into 2.0–10.0 keV intrinsic luminosities using the Crab Nebula as a standard calibration source. In the 2–10 keV energy band, an average photon flux of 3.12 counts s$^{-1}$ cm$^{-2}$ was found for the Crab Nebula. Using the Crab’s flux in the 2.0–10.0 keV range ($2.16 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$), we find $6.9 \times 10^{-9}$ erg (2–10 keV)/count. We assume that our sources have roughly Crab-like spectra (power law of photon index 2.1) within this band. Altering the photon index by 1 in either direction, or increasing $N_{\text{H}}$ up to 10 times larger, alters the unabsorbed flux by at most 30%.

Figure 1. MAXI and PCA light curves of some persistent UCXB systems showing strong flaring; 2S 0918–549 (MAXI), 4U 1728–34 (PCA), and 4U 1850–087 (PCA).

(A color version of this figure is available in the online journal.)
For the PCA data, the Portable Interactive Multi-mission Simulator (PIMMS)\(^6\) was used to convert photon fluxes (counts per second per 5 PCU) into unabsorbed energy fluxes in the 2.0–10.0 keV range assuming a photon index of 2 for four faint transients (XTE J1751–305, NGC 6440 X-2, XTE J0929–314, and Swift J1756.9–2508) and M15 X-2, neither MAXI nor PCA bulge scan light curves provide a reliable history. For XTE J1751–305, we create daily 2–10 keV flux light curves of the 2002, 2005, 2007, and 2009 outbursts from the literature (Markwardt et al. 2002, 2007; Grebenev et al. 2005; Swank et al. 2005; Falanga et al. 2007; Riggio et al. 2011), and take other PCA bulge scan measurements as evidence of quiescence. For NGC 6440 X-2, we use the PCA bulge scan observations as for other sources (as it was detected in several; Heinke et al. 2010; Patruno et al. 2010b), but exclude the three major outbursts which were all produced by the other known transient in that cluster, SAX J1748.9–2021 (Patruno et al. 2010a; Altamirano et al. 2008). As it is a transient, we only use detections, and set upper limit observations to indicate quiescence. For XTE J0929–314, we use the outburst light curve data from Galloway et al. (2002). It was clearly observed

\(^6\) [http://asc.harvard.edu/toolkit/pimms.jsp](http://asc.harvard.edu/toolkit/pimms.jsp)

---

**Table 2**

| Bin Max \((\text{erg s}^{-1})\) | 4U 1728–34 | 4U 1812–12 | 4U 1820–303 | 4U 1850–087 | M15 X-2 |
|---|---|---|---|---|---|
| 3.16 × 10^{35} | ... | ... | ... | 0.005 | ... |
| 4.64 × 10^{35} | 0.001 | ... | ... | 0.015 | ... |
| 6.81 × 10^{35} | ... | ... | ... | 0.292 | ... |
| 1.00 × 10^{36} | 0.001 | 0.329 | ... | 0.426 | 0.931 |
| 1.47 × 10^{36} | 0.001 | 0.666 | ... | 0.149 | ... |
| 2.15 × 10^{36} | 0.003 | 0.003 | ... | 0.056 | ... |
| 3.16 × 10^{36} | 0.024 | 0.003 | ... | 0.036 | ... |
| 4.64 × 10^{36} | 0.070 | ... | ... | 0.021 | 0.025 |
| 6.81 × 10^{36} | 0.235 | ... | ... | ... | 0.025 |
| 1.00 × 10^{37} | 0.329 | ... | ... | 0.014 | ... |
| 1.47 × 10^{37} | 0.207 | ... | 0.004 | ... | 0.004 |
| 2.15 × 10^{37} | 0.107 | ... | 0.038 | ... | ... |
| 3.16 × 10^{37} | 0.021 | ... | 0.049 | ... | ... |
| 4.64 × 10^{37} | 0.001 | ... | 0.210 | ... | ... |
| 6.81 × 10^{37} | ... | ... | 0.425 | ... | ... |
| 1.00 × 10^{38} | ... | ... | 0.263 | ... | ... |
| 1.47 × 10^{38} | ... | ... | 0.011 | ... | ... |

**Note.** All data for these sources gave secure detections.

---

**Table 3**

| Bin Max \((\text{erg s}^{-1})\) | NCG 6440 X-2 | Swift J1756.9–2508 | XTE J1751–305 | XTE J1807–294 | XTE J0929–314 |
|---|---|---|---|---|---|
| 1.00 × 10^{35} | 0.985 | 0.972 | 0.996 | 0.964 | 0.987 |
| 1.47 × 10^{35} | ... | ... | ... | ... | 0.000 |
| 2.15 × 10^{35} | ... | 0.001 | ... | ... | ... |
| 3.16 × 10^{35} | ... | ... | ... | ... | ... |
| 4.64 × 10^{35} | ... | ... | ... | ... | 0.000 |
| 6.81 × 10^{35} | ... | ... | ... | 0.004 | 0.001 |
| 1.00 × 10^{36} | 0.003 | 0.004 | ... | 0.012 | 0.001 |
| 1.47 × 10^{36} | 0.003 | 0.003 | ... | 0.006 | 0.001 |
| 2.15 × 10^{36} | 0.004 | 0.004 | 0.001 | 0.007 | 0.004 |
| 3.16 × 10^{36} | 0.006 | 0.008 | 0.001 | 0.001 | 0.003 |
| 4.64 × 10^{36} | ... | 0.007 | 0.001 | ... | 0.003 |
| 6.81 × 10^{36} | ... | 0.001 | 0.001 | 0.004 | 0.001 |
| 1.00 × 10^{37} | ... | ... | 0.001 | 0.001 | ... |

**Notes.** All upper limits are taken to indicate quiescent observations. Data for sources except for XTE J0929–314 are from the RXTE PCA instrument; data for XTE J0929–314 are from Galloway et al. (2002).
by the RXTE All-Sky Monitor (ASM)\textsuperscript{7} in its 2002 outburst, but was not otherwise detected by RXTE ASM, so we consider the remaining ASM history since 1996 to be a record of quiescence. For Swift J1756.9\textminus2508, we use the 2007 outburst light curve data from Krimm et al. (2007) along with the PCA bulge scans, converting the Swift Burst Alert Telescope (BAT) 15–50 keV fluxes to 2–10 keV fluxes using a typical flux ratio of 3 (which aligns the BAT and PCA flux estimates when they are simultaneous). The 2007 outburst was missed by the RXTE PCA bulge scans due to Sun constraints, while other outbursts during the bulge scan era have been detected, so we take bulge scan upper limits as evidence of quiescence.

\textsuperscript{7} http://heasarc.gsfc.nasa.gov/docs/xte/asm_products.html

M15 X-2 cannot be separated from AC 211 (X 2127+12) with any X-ray instrument but Chandra. We use one archival and six reported Chandra observations of M15 to interpret its long-term light curves. White & Angelini’s (2001) Chandra HETGS spectral fit gives $L_X(2–10\text{ keV}) = 9 \times 10^{35}\text{ erg s}^{-1}$. Applying this spectral fit to three Chandra-High Resolution Camera (HRC) observations in 2001 (Hannikainen et al. 2005) and one in 2007 (Heinke et al. 2009) gives $L_X = 1.0 \pm 0.1 \times 10^{36}\text{ erg s}^{-1}$ in each case. We extract M15 X-2’s readout streak spectrum (using the standard analysis recipe\textsuperscript{8}) from archival Chandra ACIS-S ObsID 11029, finding $L_X = 7 \times 10^{35}\text{ erg s}^{-1}$. Finally, Sivakoff et al. (2011) report that M15 X-2 is responsible for a major X-ray

\textsuperscript{8} http://cxc.harvard.edu/ciao/threads/streakextract/
brightening of M15 in 2011, giving $L_X = 1.1 \times 10^{37} \text{ erg s}^{-1}$. We thus suggest that M15 X-2 is responsible for similar previous large flares in M15 seen by the RXTE ASM. M15 X-2 appears to be usually in the range of $7 \times 10^{35} < L_X < 1 \times 10^{36} \text{ erg s}^{-1}$, except for the bright flares seen by RXTE ASM and MAXI. AC 211 is typically fainter than M15 X-2, but more variable (Hannikainen et al. 2005). Thus, we take M15 X-2 to be between $7 \times 10^{35} < L_X < 1 \times 10^{36} \text{ erg s}^{-1}$ when the total flux from M15 is below $2 \times 10^{36} \text{ erg s}^{-1}$. We use RXTE ASM data to get better long-term statistics of the bright flares (as only one, very bright flare was detected with MAXI). We take a 5 day average of RXTE ASM data points, and select data with count rate $> 0.5 \text{ counts s}^{-1}$, and errors $< 0.5 \text{ counts s}^{-1}$, as “flaring,” finding 68 such data points and 915 “normal” data points. Although the resulting luminosity function is overly simplistic, it seems to represent the key elements of M15 X-2’s behavior reasonably well.

2.3. X-Ray Luminosity Functions

Calibrated data points were arranged into 32 luminosity bins between 0 and $1.47 \times 10^{38} \text{ erg s}^{-1}$, where all luminosity values less than $10^{35}$ were placed in the lowest bin. The errors for each bin were computed using Gehrels’ upper limit approximation, $1 + \sqrt{N} + 0.75$ (Gehrels 1986), and taken to be symmetric. XLFs for each source can be found in Figure 2, with upper limits also plotted for MAXI sources. For the five transient sources considered, the XLFs in Figure 2 represent periods of outburst only.

We create empirical XLFs for the UCXB population in two ways: taking one observation for each source creates a
“snapshot” luminosity function of the UCXB population (as from a single observation of our Galaxy) and compiling 100 observations of each source creates a combined luminosity function over time. Both require random sampling from their intrinsic luminosity functions, incorporating our detections and upper limits. For PCA-detected systems, we use the detections alone (Table 2). For known transients (Table 3), upper limits are assumed to indicate the source is in deep quiescence ($L_X \ll 10^{35}$ erg s$^{-1}$), as is typically found by deep Chandra or XMM observations. This assumption appears valid given both the rapid evolution of transient outbursts and recent results monitoring Galactic GCs for low-luminosity transients (D. Altamirano et al. 2013, in preparation).

For persistent sources with upper limit observations, we statistically estimate the true fluxes represented by upper limits using the maximum likelihood method of Avni et al. (1980). This method uses an analytic, recursive function to estimate the “true” shape represented by input data and upper limits, and was designed to be used with relatively sparse and binned astronomical data. Avni presents a formula appropriate for data with lower limits; since we deal with upper limits in our case, we delineate a brief derivation of our treatment, modified from Avni, in the Appendix (see also Feigelson & Nelson 1985). We compute maximum likelihood XLFs for the persistent sources for which we have upper limits (Figure 3 and Table 4).

We randomly selected 100 observations from each UCXB’s XLF. The 1700 data points were also combined to create a combined luminosity function of the population. Since the transients are rarely in outburst, they contribute little to the total UCXB luminosity function; most values drawn from their
distribution are “0.” Figure 4 displays the combined luminosity function with Gehrels (1986) errors plotted. The $y$-axis is in units of sources—including the quiescent points, the sum of all bins comes to 17. Repeated samples yielded similar histograms. Samples computed using only good detections (rather than the Avni-computed XLFs) for the MAXI sources showed only minor differences in bins greater than the peak, and the peak location did not change.

We fitted the slope of the 100 individual samplings of the XLF, and of the combined XLF, with a simple power law in Sherpa, using the $C$-statistic due to the low (or zero) numbers of counts in many bins. We computed Gehrels errors on the number of counts in each bin, and then put the XLF into a differential, $dN/dL$ format for fitting, by dividing the number of counts per bin by the bin width. We fit $7 \times 10^{35} < L_X < 10^{38}$ erg s$^{-1}$. Less luminous bins are significantly incomplete, due to the limitations of ASMs. (We suffer incompleteness in identification of UCXBs in all bins, but that incompleteness is not obviously luminosity-dependent and is difficult to quantify.)

The 100 individual samplings produced acceptable power-law fits, with indices of $\alpha$ (for $dN(L)/dL = k L^{\alpha}$) ranging from 0.91 to 2.51, with a mean of 1.63 and error of 0.28 (Figure 5). The combined XLF was poorly fit with a power law (Figure 6; index 1.57, probability 4e$^{-6}$, reduced statistic 3.9), likely due to the limited number of sources producing a “lumpy” XLF. However, we did obtain a similar power-law index (1.57) as the mean of the individual samples (1.63). The “lump” above $10^{37}$ erg s$^{-1}$, for instance, is...
produced by 4U 1820−30. Thus, a more complex fit would not be meaningful.

A relevant question is whether the XLF of GC UCXBs differs from that of field UCXBs. Unfortunately, our statistics are too small to significantly test this question, as we have only five GC UCXBs (one of them transient). Although the GC UCXBs include the highest luminosity system (4U 1820−30), the other globular UCXBs are not unusual compared to the field systems, or to other suspected ultracompact GC systems (e.g., in Terzan 2; in’t Zand et al. 2007).

2.4. Comparing to RXTE ASM Studies of Galactic UCXBs

We note that the recent work of van Haften et al. (2012) on the luminosity functions for galactic UCXBs, using individual RXTE ASM measurements, argues for rapid variations of all sources and finds luminosity estimates that differ from ours. Their analysis is an important contribution, but we have two concerns about the analysis procedures. First, systematic errors in the ASM data are not considered, which may affect both their individual dwell measurements (by increasing the number of spurious data points) and the count rates averaged over all dwells. Two of their sources show negative count rates averaged over all dwells, evidence for the existence of systematic errors.

Our other concern is that luminosities approaching 10^{38} erg s^{-1} for 10^{-4} of the observations suggest thermonuclear X-ray bursts, including normal short helium-burning bursts or, for lower mass accretion rates, intermediate-duration (up to half-hour) X-ray bursts (Galloway et al. 2008; in’t Zand et al. 2005b). We can roughly estimate the effect on 90 s dwells of short bursts if we know the recurrence time and α (the ratio of persistent to
burst fluence). 4U 1728−34, for instance, shows short bursts with decay timescales of 6.3 s, recurrence times of 2.5−5 hr, and $\alpha$ averaging 150 (from 90 to 300). Thus, each burst will affect one ASM data point, they will affect $5 \times 10^{-3}$−$10^{-2}$ of the dwells, and they will increase the flux typically by a factor of two. Fainter systems will typically show rarer bursts, with larger fractional increases. Intermediate-duration bursts and superbursts last longer than an ASM dwell, reach the Eddington limit, and are much rarer (e.g., intermediate-duration bursts appear once per 85 days for SLX 1737−282; Falanga et al. 2008). Bursts from UCXBs show a range of fluences between these extremes, which may substantially affect the observations of van Haften et al. (2012). Clearly more detailed analysis of the unique RXTE/ASM data set is suggested, and may provide deep insight into UCXB burst properties.

3. DISCUSSION

3.1. Prevalence of Strong Variability in Persistent UCXBs

The origin of substantial (up to a factor of 10) variability seen in a number of persistent UCXB sources is not understood. Maccarone et al. (2010) highlighted such variations in 4U 0513−40. Similar nonperiodic variations of up to a factor of 10 have been identified in several persistent UCXBs: 4U 1915−05 (Simon 2005), 1A 1246−58 (in’t Zand et al. 2008), 4U 1626−67 (Camero-Arranz et al. 2010), M15 X-2 (Sivakoff et al. 2011), and in’t Zand et al.’s (2007) (strong candidate) UCXBs SAX J1712.6−3739, SLX 1735−269, and 1RXS J170854.4−321857 (in’t Zand et al. 2005b). We now add 4U 1850−087, 2S 0918−549, and 4U 1728−34 to the list. Slightly smaller flaring (of up to a factor of five) is seen...
Figure 3. (Continued)

during times when the persistent flux is at particular values for 4U 0614+09 (Kuulkers et al. 2010) and in't Zand et al.’s (2007) strong UCXB candidate 4U 1722–30. in’t Zand et al. (2007) discusses an explanation of the rapid flaring behavior as a tidal instability due to a precessing accretion disk (Whitehurst 1988), with a possible dependence on mass transfer rate to explain its presence/absence in different epochs for, e.g., 4U 1722–30. Such variations may not exist for high-luminosity \( (L_X > 3 \times 10^{37} \text{ erg s}^{-1}) \) ultracompacts, with their presumably more massive donors in shorter orbits (Bildsten & Deloye2004), though 4U 1820–30’s well-known cycles illustrate the existence of strong variability in some such systems. The prevalence of strong variation reinforces Maccarone et al.’s (2010) point about the importance of considering variation among persistent systems when identifying extragalactic transients, and thus the importance of empirical observations of the luminosities of systems of known type for validating luminosity function modeling.

### 3.2. Luminosity Functions of UCXBs

We have produced an empirical XLF from known UCXBs in the Milky Way. The list of Galactic UCXBs is certainly incomplete and may suffer biases (for instance, we are probably missing persistent and transient sources below \( 10^{36} \text{ erg s}^{-1} \), so we advise readers to treat our luminosity function for bins below this simply as upper limits). However, it is important to test theoretical calculations against the best data available. We have few sources, and typically less than one above \( L_X = 10^{37} \text{ erg s}^{-1} \) (see Figure 4), which makes comparison of this UCXB luminosity function with those of LMXBs in distant galaxies difficult. However, a few nearby galaxies have been studied sufficiently to make a useful comparison.

First, we note that the slope of our XLF \((1.63 \pm 0.28\) for the samplings and \(1.57\) for the cumulative) down to \(~10^{36} \text{ erg s}^{-1}\) is in good agreement with the predicted slope for UCXBs
Figure 4. Results of extracting 100 data points at random from each of the 17 sources’ XLFs to make a combined luminosity function for UCXBs. Errors from Gehrels (1986). Counts in each bin were divided by 100 to produce the plot, whose ordinate is in units of sources (out of the 17 total used for sampling).

Figure 5. Histogram of power-law indices $\alpha$ fit to 100 differential XLF samplings ($dN(L)/dL = kL^{-\alpha}$). Typical index errors per fit are about 0.3.

Figure 6. Combined “population” differential XLF, compiled using 100 randomly drawn data points from each of the 17 sources’ XLFs. $dN/dL$ was computed for each bin by dividing the effective number of sources per bin by the bin width. A power law of index $\alpha = 1.57$ ($dN(L)/dL = kL^{-\alpha}$) fits the general slope, although the XLF has lumps due to individual sources.

Our result does not agree with simulations of the UCXB XLF presented in Fragos et al. (2008), which have similar slopes but cut off at $5 \times 10^{36}$ erg s$^{-1}$ for both persistent and transient UCXB systems. Our results indicate that the UCXB XLF continues down to at least $1 \times 10^{36}$ erg s$^{-1}$. The cutoff in Fragos et al. (2008) is physically motivated by the criterion for disk instability of irradiated pure helium disks, calculated in Lasota et al. (2008), and assumed to be appropriate for a population of UCXBs. Here, we show empirical evidence against this cutoff; in Paper II we identify the physical reasons behind the lowered disk instability limit.

The agreement of the theoretical UCXB slope with the XLF slope of several known elliptical galaxies suggested that ultracompact binaries dominate the XLF in GCs (Bildsten & Deloye 2004). However, deeper observations have shown that the XLFs of old populations break to shallower slopes at luminosities below $10^{37}$ erg s$^{-1}$, and that GCs have a significantly shallower slope at low luminosities. These results have been shown for the bulge and GC system of M31 (Kong et al. 2003; Trudolyubov & Priedhorsky 2004; Voss & Gilfanov 2007), Cen A (Voss et al. 2009), NGC 3379 (Fabbiano et al. 2007), and for combined studies of several nearby galaxies (Zhang et al. 2011). In particular, the similarity of the slope and $10^{37}$ erg s$^{-1}$ cutoff of the observed Cen A GC XLF to the theoretical UCXB XLF (cutoff at $5 \times 10^{36}$ erg s$^{-1}$ in Fragos et al. 2008) motivated Voss et al. (2009) to suggest that the Cen A GCs were dominated by UCXBs. Although this was an excellent idea (given the enhanced population of UCXBs in Milky Way GCs), our UCXB XLF indicates that this is not feasible. Other suggested explanations of the difference are significantly more complicated (Fragos et al. 2008; Kim et al. 2009; Zhang et al. 2011).

The steep XLF we find down to $L_X = 10^{36}$ erg s$^{-1}$, combined with the theoretical expectation that this XLF will continue to
higher $L_X$ and the relatively flat XLFs between $10^{36} < L_X < 10^{37}$ erg s$^{-1}$, indicate that UCXBs make up only a minor portion of bulge and GC XLFs above a few $\times 10^{36}$ erg s$^{-1}$.

4. CONCLUSIONS

We have constructed luminosity functions for clearly identified UCXBs from the best available long-term data, using, in order of priority, RXTE PCA bulge scans, MAXI light curves, RXTE ASM light curves supplemented with Chandra observations, and literature reports of the luminosities of systems during transient outbursts. Variability by up to a factor of 10 is quite common among persistent UCXBs, which is important to consider when identifying transient behavior in other galaxies (Maccarone et al. 2010). We have taken account of upper limits in constructing these luminosity functions, using the method of Avni et al. (1980) to calculate a best estimate of the true luminosity function. We combined this information to make “snapshot” luminosity functions (one sample from each source) and a combined luminosity function using 100 samples from each source. Both methods find consistency with a power law of slope $\alpha = 1.63 \pm 0.28$, extending down to $10^{36}$ erg s$^{-1}$ (below which we are incomplete).

Our empirical UCXB luminosity function extends down in luminosity without a break to $\sim 10^{36}$ erg s$^{-1}$, which disagrees with current theoretical luminosity functions that cut off at $5 \times 10^{36}$ erg s$^{-1}$. The slope, however, is in agreement with theoretical predictions from UCXB evolution. Comparing our UCXB luminosity function to current measurements of luminosity functions in old stellar populations and GCs in other galaxies suggests that UCXBs make up only a small fraction of the X-ray binary population in either case.

We thank M. Linares and C. Markwardt for helpful advice. This research has made use of MAXI data provided by RIKEN, JAXA, and the MAXI team, PCA bulge scan data provided by C. Markwardt and the RXTE team, RXTE ASM data products provided by the RXTE team, Chandra archival data, and the ADS. We acknowledge financial support from NSERC (Discovery Grants to C.O.H., N.I., and G.R.S., and an NSERC USRA, Julie Payette NSERC Research Scholarship, and André Hamer Postgraduate Prize supporting M.C.E.), an Alberta Ingenuity New Faculty award to C.O.H., a Canada Research Chair supporting N.I., and the Avadh Bhatia Fellowship supporting J.C.G.

APPENDIX

Consider $M$ luminosity bins indexed by $n$. If our data consisted only of valid detections, the value of the distribution function for the $n$th bin, $f_n$, would be straightforwardly given by

$$f_n = \frac{N(n)}{J}, \quad (A1)$$

where $N(n)$ is the number of valid detections in the $n$th bin, and $J$ is the total number of detections in all $M$ bins. Since we are dealing with upper limits as well as valid detections, we instead need to define for each of the $n$ bins an “effective” number of detections, which combines the valid detections and the most likely distribution of the upper limits,

$$f_n = \frac{N_{\text{eff}}(n)}{J}, \quad (A2)$$

where $N_{\text{eff}}(n)$ is an effective number of detections in the $n$th bin.

To calculate this effective number, the nature of the most likely distribution of upper limits needs to be considered.

An upper limit detection with luminosity value $L$ that falls into the $k$th bin could be random noise or a true detection with a luminosity value anywhere from 0 up to the value $L$. Thus, the true value could fall in any of $n \leq k$ bins, with $n \ll k$. If we consider an individual such bin $n$, it can contain a portion of the upper limits in all bins with $k \geq n$. To find the total number of upper limit counts that truly correspond to bin $n$, $T(n)$, then, we must perform the following sum:

$$T(n) = \sum_{k=n}^{M} U(k) f_n,$$  \hspace{1cm} (A3)

where $U(k)$ is the number of upper limit detections that fall into the $k$th bin. In the maximum likelihood scenario, the way that these $U(k)$ upper limit counts are distributed among all lower bins depends on the distribution function—that is, the probability bin $n$ would contain a count divided by the total probability for all bins lower than $k$. We must take the outer sum, over all bins with $k \geq n$, because upper limit counts from all of these bins contribute to “true” counts in bin $n$.

Once we know the way in which upper limits are likely to be distributed among the bins, it is a simple matter to derive $N_{\text{eff}}(n)$:

$$N_{\text{eff}}(n) = N(n) + \sum_{k=n}^{M} U(k) f_n,$$  \hspace{1cm} (A4)

where we have simply added the valid detections to the most likely number of upper limits that actually lie in bin $n$.

Now, returning to Equation (A2) and substituting Equation (A4) for $N_{\text{eff}}(n)$, we obtain

$$f_n = \frac{N(n) + \sum_{k=n}^{M} U(k) f_n}{J}, \quad (A5)$$

Isolating $f_n$,

$$f_n = \frac{N(n)}{J - \sum_{k=n}^{M} U(k) f_n}.$$ \hspace{1cm} (A6)

Finally, we note that we can rewrite the sum in the denominator as follows, using the fact that, by definition, all the probabilities in the distribution sum to 1:

$$\sum_{z=1}^{k} f_z = \sum_{z=1}^{M} f_z - \sum_{z=k+1}^{M} f_z = 1 - \sum_{z=k+1}^{M} f_z.$$ \hspace{1cm} (A7)

Making the above replacement, we thus obtain

$$f_n = \frac{N(n)}{J - \sum_{k=n}^{M} U(k) f_n - \sum_{z=k+1}^{M} f_z}.$$ \hspace{1cm} (A8)

This formula is clearly recursive, due to the presence of the distribution function values on the right-hand side. If we start with bin $M$, the sum in the denominator disappears (which makes sense, as there are no higher bins to potentially contribute their upper limits). Once we have $f_M$, we can use it to calculate $f_{M-1}$ and so on, proceeding from the highest to the lowest bin recursively.
