Dominance of magnetic cataclysmic variables in the resolved Galactic ridge X-ray emission of the limiting window

JaeSub Hong
Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Accepted 2012 September 7. Received 2012 September 6; in original form 2012 July 27

ABSTRACT
The diffuse appearance of the Galactic ridge X-ray emission has been puzzling since its discovery due to the lack of compelling theories for sustainable hot diffuse X-ray emission in the Galactic plane. Recently, Revnivtsev et al. claimed that \( \sim 90 \) per cent of the 6.5–7.1 keV X-ray flux from a small section of a low-extinction region at 1°4 south of the Galactic Centre has been resolved to discrete sources with \( L_X, 2–10 \) keV \( \gtrsim 4 \times 10^{-16} \) erg s\(^{-1}\) cm\(^{-2}\), using ultradeep (1 Ms) observations made by the Chandra X-ray Observatory. They also concluded that coronally active stars such as active binaries (ABs) contribute \( \sim 60 \) per cent of the resolved flux. However, our recent discovery of a large population of magnetic cataclysmic variables (MCVs) in the same region suggests their significant role in the resolved hard X-ray flux. In addition, deep X-ray surveys of other several Galactic bulge fields over the past decade have indicated that MCVs are likely the major contributor in the hard X-ray emission above 2–3 keV. To solve this mystery, we have conducted an independent in-depth analysis of discrete X-ray sources in the low-extinction region. The total fraction of the 6.5–7.1 keV flux we can confidently claim as resolved is \( \sim 70–80 \) per cent, which largely agrees with Revnivtsev et al., but leaves some room for diffuse components. However, despite the various attempts, we consistently find that the resolved hard X-ray flux above 3 keV is dominated by relatively bright, hard X-ray sources such as MCVs, whereas the contribution from relatively faint, soft sources such as ABs is below 20 per cent. We describe in detail our analysis procedure in order to elucidate possible origins of the discrepancy.

Key words: Galaxy: bulge – X-rays: binaries – X-rays: diffuse background.

1 INTRODUCTION
The X-ray glows along the Galactic plane, discovered almost 30 yr ago, form a narrow continuous X-ray bright ridge, known as the Galactic ridge X-ray emission (GRXE; Worrall et al. 1982; Warwick et al. 1985; Koyama et al. 1986). The origin of the GRXE, whether truly diffuse or from unresolved discrete sources, has been debated ever since. The GRXE resembles X-ray emission from an optically thin plasma of a high temperature (a few keV) with emission lines from highly ionized heavy elements such as Si and Fe (Koyama et al. 1986; Yamauchi & Koyama 1993). However, the shallow Galactic gravity and the lack of energy source to sustain such a plasma suggest discrete sources as the origin of the GRXE (Worrall & Marshall 1983; Yamauchi et al. 1996; Kaneda et al. 1997).

With subarcsec angular resolution and superb sensitivity, the Chandra X-ray Observatory launched a decade ago brought a new hope of revealing the nature of the GRXE. The early studies by Ebisawa et al. (2001, 2005) using deep Chandra observations (100 ks each) of two adjacent Galactic plane fields at \((l, b) = (28.5, -0.2)\) showed that the GRXE in the 2–10 keV band is largely unresolved with discrete sources of \( L_X, 2–10 \) keV \( \gtrsim 3 \times 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\). They claimed that the unresolved X-ray flux cannot be explained by the known types of undetected, fainter discrete X-ray sources, suggesting that a significant portion of the GRXE is truly diffuse. However, Revnivtsev & Sazonov (2007) claimed that the GRXE in the same region can be explained by discrete sources when taking into account a large number of unresolved, faint, coronally active X-ray sources such as active binaries (ABs). Motivated by the resemblance of the Galactic distribution of the GRXE and the near-infrared emission measured by Spitzer that closely follows stellar population (Revnivtsev et al. 2006), Revnivtsev et al. (2009, hereafter R09) conducted ultradeep observations (1 Ms) of a low-extinction region (limiting window; LW)\(^1\) at 1°4 south of the Galactic Centre. They claimed that 88 \( \pm 12 \) per cent of the highly

\(^1\) R09 call this region the 1°5 window.
Table 1. *Chandra* ACIS-I observations of the LW.

| Obs. ID | Start time (UT: y-m-d h:m) | RA (°) | Dec. (°) | Offset\(^a\) (arcmin) | Roll (°) | Exposure (ks) | GTI\(^b\) (ks) | Obs. mode | Chips |
|--------|---------------------------|--------|----------|-----------------------|---------|---------------|---------------|-----------|-------|
| 6362   | 2005-08-19 16:15          | 267.86694 | -29.59235 | 0.1                  | 273     | 38            | 37.7          | F         | 0123.67.. |
| 5934   | 2005-08-22 08:16          | 267.86692 | -29.59233 | 0.1                  | 273     | 41            | 30.8          | F         | 0123.67.. |
| 6365   | 2005-10-25 14:55          | 267.86630 | -29.59212 | 0.1                  | 265     | 21            | 20.7          | F         | 0123.67.. |
| 9505   | 2008-05-07 15:29          | 267.85740 | -29.57123 | 1.3                  | 82      | 11            | 10.7          | VF        | 0123.6..  |
| 9855   | 2008-05-08 05:00          | 267.85741 | -29.57124 | 1.3                  | 82      | 57            | 55.9          | VF        | 0123.6..  |
| 9502   | 2008-07-17 15:45          | 267.86685 | -29.59108 | –                    | 280     | 167           | 164.1         | VF        | 0123.6..  |
| 9500   | 2008-07-20 08:11          | 267.86148 | -29.58793 | 0.3                  | 280     | 165           | 162.6         | VF        | 0123.6..  |
| 9501   | 2008-07-23 08:13          | 267.86399 | -29.58953 | 0.2                  | 279     | 135           | 131.0         | VF        | 0123.6..  |
| 9854   | 2008-07-27 05:53          | 267.87404 | -29.59630 | 0.5                  | 278     | 25            | 22.8          | VF        | 0123.6..  |
| 9503   | 2008-07-28 17:37          | 267.86852 | -29.59311 | 0.2                  | 275     | 103           | 102.3         | VF        | 0123.6..  |
| 9892   | 2008-07-31 08:07          | 267.86853 | -29.59312 | 0.2                  | 275     | 65            | 65.8          | VF        | 0123.6..  |
| 9893   | 2008-08-01 02:44          | 267.87098 | -29.59490 | 0.3                  | 275     | 45            | 42.2          | VF        | 0123.6..  |
| 9504   | 2008-08-02 21:23          | 267.87097 | -29.59490 | 0.3                  | 275     | 127           | 125.4         | VF        | 0123.6..  |

Notes. \(^a\)The aim point offset relative to Obs. ID 9502. Table 1 in H12 shows the target coordinates of each pointing. \(^b\)The good time intervals (GTIs) are selected by the fluctuations (<3σ) of the background event rates in the 2.5–7 keV band, which is calculated after the discrete source contribution is removed. The GTIs shown here are based on the events processed through the EDSSR routine and the VF-mode cleaning (see Section 3.1). An additional manual inspection ensures the removal of the background flaring periods. As a result, the selected GTIs are slightly different from those in table 1 in H12 (see the text).

...analysis procedure (Section 3). We present our results in comparison with R09 (Section 4); the possible origins of the discrepancy are presented in the appendix. We also discuss the implications of our findings for future studies (Section 5).

2 OBSERVATIONS

The LW was observed for a total of 1 Ms exposure (100 ks in 2005 and 900 ks in 2008) with the *Chandra* ACIS-I instrument. Table 1 shows the basic observational parameters (see also R09 and table 1 in H12). The observations in 2005 were conducted in Faint mode (F mode) with six ACIS CCDs enabled, and the rest in Very Faint mode (VF mode) with five ACIS CCDs enabled. The VF mode allows an additional background reduction (see Section 3.1; Vikhlinin 2002). The CCD readout time and thus the correction factor for the readout background depend on the number of enabled CCDs (e.g. 41 ms readout time with 3.2 s frame time for six CCDs) (Markovich et al. 2000). The aim points of the observations varied about 0.1–1.3 arcmin from each other. The roll angles of two observations (~70 ks in 2008) were about 200° off from the rest. The roll angle and aim point variations made the CCD gaps less prominent in the merged data set.

3 DATA ANALYSIS

The analysis procedures for discrete sources can be grouped into four main steps: event processing and selection, stacking, source search and aperture photometry. Calculation of the total resolved X-ray flux requires modelling of the instrumental background in the analysis region. We have created a new analysis pipeline based on a custom analysis pipeline developed over the years for the *Chandra* multiwavelength plane survey (Grindlay et al. 2005).\(^2\) The latter is described in detail in Hong et al. (2005, H09b). The new analysis pipeline is built on version 4.3 CIAO analysis tools, and has many

\(^2\) For some of the more recent survey results, see also Servillat et al. (2012) and van den Berg et al. (2012a).
improvements over the previous pipeline. In particular, we have implemented various analysis approaches with multiple parameter choices including the one similar to what was employed by R09 for comparison. Table 2 summarizes key parameters of analysis approaches used in this paper.

### 3.1 Event process

The standard CXC\(^3\) pipeline provides Level 1 and 2 event files of each observation. Over the years, there are many subtle or significant improvements proposed and implemented for event processing. In order to identify the effects of these new implementations, we reprocessed the Level 1 event files with a few different options. Two main options considered for reprocessing are pixel repositioning and VF-mode cleaning. The pixel repositioning is introduced to reduce pixellation-induced artefacts. For instance, the energy-dependent subpixel event repositioning (EDSER) routine is shown to noticeably improve the point spread function (PSF) (Li et al. 2004). The VF-mode cleaning reduces instrumental background events by utilizing the 5×5 pixel readout of the VF mode (Vikhlinin 2002), but it may also remove some valid events. The Level 2 event files from the standard CXC procedure are generated with the random pixel repositioning under no VF-mode cleaning, which is equivalent to the F-mode data. We have implemented four approaches as shown in Table 2. Our default choice uses the EDSER routine and the VF-mode cleaning for the 2008 observations.

Another minor, but noticeable improvement from the earlier analysis (table 1 in H12) is in the good time interval (GTI) selection shown in Table 1. The GTIs are calculated to screen out events acquired during background flares. We consider an interval good if the background rate of the interval is <3σ from the mean rate. In this analysis, the background rates were calculated from events in the 2.5–7 keV band in 1 ks bins, which is known to be optimal for identifying background flares (Markevitch et al. 2003).\(^4\) In addition, they were generated after the point source contribution was removed, based on a preliminary source detection by the wavdetect algorithm (Freeman et al. 2002). The point source removal keeps the GTI selection algorithm from misrecognizing bright flares of discrete sources as instrumental background flares. For instance, we recovered an erroneously removed 20 min GTIs in Obs. ID 9502 (Hong et al., in preparation). Finally, we also manually verified all the GTIs for any anomaly. As a result, we have removed the full portion (~10 ks) of a background flare in Obs. ID 5934 from the GTIs, only a part of which was identified by the automatic procedure.

### 3.2 Event merge

We merge the selected events of multiple observations for the full benefit of the ultradepth exposure. We mainly consider two options in merging: boresight offset correction and the choice of reprojection tangential point. Since the aspect and pointing errors of the Chandra observations can be as large as 0.6 arcsec (90 per cent confidence),\(^5\) we use relatively bright X-ray sources detected in each observation for boresight correction (Hong et al. 2005; Zhao et al. 2005). Relative to Obs. ID 5934, the calculated boresight offsets of other observations range from 0.1 to 0.34 arcsec. We merged the data with and without the boresight offset correction for comparison.

For the default choice of the common reprojection tangential point, we use the aim point of Obs. ID 9502 with the longest exposure. Since the aim points varied as much as 1.3 arcmin from pointing to pointing (Table 1), we also used the exposure-weighted average aim point of the observations for the reprojection tangential point for comparison.

### 3.3 Source search

The wavdetect routine based on the wavelet algorithm (Freeman et al. 2002) is one of the popular source detection tools in X-ray astronomy. Its performance has been extensively studied and tested (e.g. M03, Kim et al. 2007). We have used the CIAO wavdetect routine for source detection for many applications in the past (e.g. Hong et al. 2005, H09b). The wavdetect routine delivers a list of sources with detection significance at a somewhat conservative level under

---

\(^3\) [http://cxc.harvard.edu](http://cxc.harvard.edu)

\(^4\) Markevitch et al. (2003) recommend using the events of S3 chip in the 2.5–7 keV band for flare identification, but S3 chip was not on for some observations, so we use the events of each CCD in the same energy band.

\(^5\) [http://cxc.cfa.harvard.edu/cal/ASPECT/celmon](http://cxc.cfa.harvard.edu/cal/ASPECT/celmon)
the standard parameter setting. Many researchers have developed new techniques or improved the algorithm to catch relatively faint sources missed by the standard wavdetect routine, some of which are visually identifiable even in the input images. These include the wvdecomp routine by A. Vikhlinin, a multistatistics-based approach by Wang (2004) and an enhanced wavdetect algorithm for multiple observations by Kashyap et al. (2011). In particular, the wvdecomp algorithm is well suited for detecting faint sources by implementing successive iterations that remove the contribution from bright sources in the image. A typical improvement acquired by these new tools is an \( \sim 10-30 \) per cent increase in source number under the recommended parameter settings. For instance, M09 found additional \( \sim 26 \) per cent of sources from the wvdecomp routine compared to the sources discovered by the wavdetect routine (see Section 4.1).

Since the final source number counting depends sensitively on some of the input parameters of each detection method, we employ three source detection lists along with the source list from R09 for subsequent aperture photometry. For the wavdetect routine, we employ a typical threshold of \( 10^{-6} \), which allows about one false source in each ACIS chip (1024 \( \times \) 1024 pixels, see also Section 4.1.2 and Appendix A). For the wvdecomp routine, we have tried two settings of the significance threshold (4.5\( \sigma \) or 4.0\( \sigma \)), which is the main driver of the final source number count. The original prescription of the routine recommends the threshold setting at 4.5\( \sigma \), but R09 lowered it to 4.0\( \sigma \) for their analysis under the following two justifications. First, sources only in the high-resolution (HRES) region (a central circular region of 2.56 arcmin radius), with the highest sensitivity and finest spatial resolution, were considered for analysis. Secondly, a similar detection run on the instrumental background data produces only one or two false sources. We will discuss the latter again in Section 4.1. The number of iterations were fixed at five since there is practically no change in source number after the fifth iteration.

3.4 Aperture photometry of discrete sources

Aperture photometry can also be applied in many different ways. For the aperture of a given source, we often use a circle around the source position enclosing 95 per cent of PSF for 1.5 keV X-rays, and for the background region, an annulus with the inner and outer radii of 2 and 5 times PSF, respectively. The background annulus region excludes the source regions of neighbours. This aperture choice allows aperture photometry over the entire field, even outside HRES. R09 used a fixed 2 arcsec radius circle around each source for the source aperture and the rest of the HRES region (excluding all the source regions) for the background region. The large, fixed background region provides higher statistics for background counts, but it may not properly reflect a local variation of the background around each source. We employ both approaches for comparison (Table 2).

For background subtraction, we need to know the aperture ratio of the source to background regions. There are a few ways to calculate this ratio; one is a simple geometric ratio of the regions, which is more appropriate for dealing with internal instrumental background, and another is an exposure-map (effective-area)-corrected geometric ratio of the regions, which is more appropriate for diffuse sky X-ray background. Since both ratios are consistent within less than a per cent of each other, here we use the ratio of the exposure-map-corrected areas, where the exposure map was generated for 1.5 keV X-rays. Note that although the effective area depends sensitively on energies, the ratio of the source to background regions for aperture photometry hardly does. We will discuss the ratio in more detail in Section 4.4 and Appendix B1.

The frequency of overlapping aperture regions increases, as the source number count increases. In order to avoid double counting of events due to the overlap we uniquely assign each event in the overlapping regions to a source, whose position is closest to the event.\(^{7}\) The aperture ratio of the source to background regions is adjusted accordingly.

3.5 Instrumental background

In aperture photometry of discrete sources, background subtraction handles both the instrumental and diffuse X-ray background simultaneously. In order to calculate the total resolved fraction, one also has to know the total incoming X-ray flux in the region, which requires an estimate of the total instrumental background in the region. As of this writing, two stowed data sets (Periods D and E) are available for modelling the instrumental background of the Chandra/ACIS instruments.\(^{8}\) Period E is from 2005 October 1 to the end of 2009, and Period D is from 2000 December 1 to 2005 August 31. Therefore, the stowed data in Period E are more appropriate for modelling the instrumental background of the observations of the LW. The instrumental background summed over the entire chip is shown to be consistent over the years (Hicox & Markevitch 2006). However, in HRES, both the count rate and the spectral shape of the instrumental background show a noticeable change between Periods D and E, which is significant enough to change the overall resolved fraction greatly (Appendix C1). For instance, if Period D stowed data set is used alone, the total resolved fraction of the iron line flux becomes more than 100 per cent, which is in part due to the low statistics of the stowed data set in HRES. We use the stowed data set of Period E alone and the combined set of Periods D and E for analysis.

4 RESULTS

Here, we summarize the results of our analysis in comparison with R09. As we explore several analysis approaches, the results are somewhat extensive. However, they are more or less consistent with a few noticeable exceptions, so we describe the main results based on the default choice of the analysis parameters and point out any significant variations resulted by other parameter choices. The default choice includes the EDSER procedure, the VF-mode cleaning for the 2008 observations, and the boresight offset correction as listed in Table 2.

4.1 Source detection

Table 3 summarizes the source search results under the default parameter choice. Two search routines with three parameter choices

\(^{7}\) This approach of handling the overlap is different from the equivalent procedure in H05. The latter tries to collect relatively pure events, free of contamination from neighbours, but in the process, it drops valid source events if it is highly ambiguous which source they belong to. The new, simple approach counts in all the events in the source regions, which is more appropriate for estimating the total resolved fraction later, although photometry results may suffer mild contamination from neighbours.

\(^{8}\) http://cxc.cfa.harvard.edu/contrib/maxim/acisbg
were applied to the 0.5–7 keV X-ray image of the field (column 2) with the exposure map generated at 1.5 keV. These results are compared with the source number from R09. We detected 251–274 sources from the wavdetect routine, depending on how we processed the event files (Table 2). Therefore, R09 detected 70–90 per cent more sources than what the wavdetect routine discovered. Compared to our search using the wvdetect routine under the presumably similar parameter settings (4.0σ) as in R09, R09 still found about 2–6 per cent more sources. Fig. 1 shows three of the four search results. In order to evaluate significance of these detections, we take both programmatic and analytic approaches.

4.1.1 Programmatic approaches

First, we applied the same search routines to the 0.5–7 keV image generated from the stowed data that were reprojected to the sky according to the aspect solution of the observations (column 10). For the analysis with the VF-mode cleaning, only the events with flag=0 were reprojected in simulating the portion of the 2008 observations. For no VF-mode cleaning, all the stowed data were reprojected (not shown in Table 3).

The reprojected stowed data can provide a good indicator of false detection rate since they are based on the actual events and the proper dithering motion is included through the reprojecton, but there are a few short comings. For instance, the equivalent exposure of the stowed data in Period E is 360 ks, which is a factor of 3 shorter than the LW data set to reflect the proper Poisson fluctuation for the 1 Ms observation. In addition, events in ACIS-I CCD 1 of the stowed data are artificially generated, based on events in CCD 0. We also note that the X-ray flux in the region below ~5 keV remained largely unresolved (Section 4.4, see also R09). Since the image used for source search is generated in the 0.5–7 keV band, the input image for source search routines contains a large diffuse (or unresolved) component besides the instrumental background, which can enhance false detection rate, but the effect of this diffuse sky component cannot be properly accounted for with the stowed data set. Therefore, the source number from the reprojected stowed data set [e.g. 25 in the 439 sources for wvdetect (4.0σ) in Table 3] represents only a lower limit of the false detections.

The legitimacy of the 473 sources in R09 is in part based on their claim that the same search routine found only one or two (false) sources on the stowed data set. The stowed data set they used is likely an earlier version of the ones we use and each reprojecton generates a different data set in the sky, so there can be some fluctuations from run to run. However according to our analysis, one or two false detections in the 473 sources of R09 appear to be a severe underestimate.

Secondly, we applied the search routines to the 9–12 keV image of the LW data (column 9), where no discrete sources are expected to be discovered due to the diminishing effective area (~10 cm^2) and the large PSF. This provides another estimate of the false detections [e.g. 24 in the 439 sources for wvdetect (4.0σ) in Table 3], but they are still lower limits since the 9–12 keV image also have the similar shortcomings as the stowed data set (e.g. the total number of events in the 9–12 keV band is much smaller than that in the 0.5–7 keV band).

Therefore, we took one more approach to address the false detection rate. We compared the four source lists to find out the objects that are not common to the lists as shown in Table 3.

---

Table 3. Source number counting in the HRES region (2.56 arcmin radius) of the LW.

| (1) Search routine | (2) Source number | (3) Sources with false det. prob. | (4) Sources with wavdetect (4.0σ) | (5) Comparison: sources not found in wavdetect wvdcomp (4.0σ) wvdcomp (4.0σ) (R09) | (6) Ref coord. change | (7) Source number 9–12 keV | (8) Source number 0.5–7 keV |
|--------------------|-------------------|-------------------------------|-----------------------------|---------------------------------|------------------|-------------------|------------------|
| wavdetect          | 274               | <0.005 per cent               | 0 (0 per cent)              | 13 (5 per cent)                  | N/A              | 29 (8 per cent)   | 24 (97 per cent)  |
| wvdcomp            | ≥4.0σ (R09)       |                               | 143 (30 per cent)           | N/A                             | N/A              | 25 (7 per cent)   | 25 (7 per cent)   |
| R09                |                   |                               |                             |                                 | N/A              |                   |                  |

Notes. (2) The number of sources detected. (3) The number of sources with false detection probability \( P_f < 0.005 \) per cent (or detection confidence \( C > 99.995 \) per cent; see Section 4.1.2). (5), (6) and (7) The number of unique sources not found by the other search methods in comparison. (8) The number of unique sources compared to the case where the reprojection tangential point was set at the exposure-averaged aim point of the 13 observations instead of the aim point of Obs. ID 9502. (9) The number of sources detected from the image of the LW in the 9–12 keV band. (10) The number of sources from the image of the reprojected Stowed data set (Period E) in the 0.5–7 keV band.

---

Figure 1. The image of the HRES region of the LW marked with sources. The (cyan) diamonds are from the wavdetect routine, the (yellow) squares from the wvdetect (4.0σ) and the (red) circles from R09. See Table 3.
Detection of faint sources near the detection limit is expectedly sensitive to small changes in the image. For instance, simply changing the image pixellation offset (e.g. 2901.5:5416.5:#2515 versus 2901.0:5416.0:#2515) or the reprojection tangential point (column 8) produces a different set of sources under the otherwise identical procedures (i.e. 42 different sources for wvdetect with 4.0σ from the tangential point change). Obviously one cannot rule out all of these list-unique sources as invalid, but it is clear that they are prone to small statistical fluctuations of the image and less reliable than the sources consistently detected through these variations. While our source number count (439) did not reach that by R09 (473) under a similar wvdetect run, the comparison of our source list with the list by R09 indicates that about 80–140 sources are in fact unique to each list.

We find a large number of the sources that are not common in our search and R09 in Table 3 puzzling. Are all of these sources, which now add up to ~550 objects, valid? To address this, we turn to analytic approaches.

4.1.2 Analytic approaches

In order to estimate detection significance (C) or false detection probability (P falsely = 1 − C) independently of the source search routines, we employ a Bayesian approach by Weisskopf et al. (2007) and Kashyap et al. (2010), which provide a more rigorous treatment of discrete Poisson distributions than simple-minded approaches using signal-to-noise ratio (SNR). In Appendix A, we describe a simplified version of the Bayesian approach used for calculating the detection significance and compare it with the SNR-based analysis.

Columns 3 and 4 in Table 3 show the number of sources with \( P_f < 1 \) and <0.005 per cent, respectively. The results in Column 3 give a false impression that the majority of these sources are significant. When dealing with a single source or a known source in a new observation, finding the source with a confidence level at 99 per cent (\( P_f = 1 \) per cent) can be considered sufficient to claim a true detection. However, in studying a population of sources newly discovered by a search algorithm, one has to consider the number of search trials explicitly, e.g. 99 per cent confidence means 1 out of 100 trials can be false.

The source search routines conduct searches in the entire input images using a small window or detection cell. The cell size is usually smaller than the source aperture region used in aperture photometry for efficient source detection. Following the description of Weisskopf et al. (2007), we assume that a 1 arcsec radius circle is appropriate for the cell size for Chandra images especially in the central regions like HRES. The number of independent search trials can be roughly estimated as the ratio of the search region to the cell size. In the HRES region, about 24k independent search trials can be performed. Under 2-Dim Nyquist sampling, these numbers quadruple (96k).

For simplicity, we assume that each search routine performed 20k trials in HRES, then having a detection with 99 per cent confidence means that there can be as many as 200 false detections arising from random Poisson fluctuations. Note that not all of these 200 sources will be in the source list since each search routine has its own selection criteria to remove false sources. What this means is that sources with 99 per cent confidence have the same significance of other 200 false sources that can be found in the search region. Therefore, in order to make sure that the source list contains 1 or less false sources, the required confidence level should be 99.995 per cent or higher (column 4).

Fig. 2 shows the distribution of source and background counts (see Appendix A) in detection cell (a 1 arcsec radius circle around each source), which is overplotted with various levels of \( P_f \). The figure also shows the cumulative distributions of the sources as a function of \( P_f \). The shaded region indicates the limit required to ensure one or less false source in the source list, corresponding to 24k–96k trials of source search. Fig. 2 indicates that ≤ 337 out of the 473 sources in R09 are detected with sufficiently high significance.

These analytic approaches also often provide only a lower limit of false detection rates due to missing implementation of (usually unknown) subtle features in real data that can give rise to false detections (e.g. source crowding, node boundaries of CCDs or dithering-motion-induced event scattering). Therefore, we believe the need for detection confidence level more stringent than 99 per cent for source selection remains valid.

In summary, the results in Table 3 indicate that the faintest ~100 sources in R09 may not be as significant as R09 claimed. We wonder whether the search parameters in R09 may have been pushed beyond the reasonable limit. On the other hand, our results directly conflict with the aperture photometry results of R09. Fig. 3 in R09 indicates that a large contribution in the resolved flux in the 6.5–7.1 keV band comes from the faintest sources, which is difficult to imagine if they are mostly false or insignificant detection. We will explore this through aperture photometry in the next section.

4.2 Aperture photometry

Table 4 summarizes the aperture photometry results of the resolved discrete sources in the HRES region. The table shows the summed total events in the source aperture regions and net photon counts after background subtraction in the 6.5–7.1 and 9–12 keV bands for the various analysis options. The default choice uses a fixed 2 arcsec radius aperture around each source for the source region and the rest of the HRES regions (excluding other source apertures) for the background region; the data were prepared and merged with the EDSER procedure, the VF-mode cleaning and the boresight offset correction. The table compares two aperture photometry methods.

This is a conservative estimate. Our main point, the need for high detection threshold, remains valid as long as the search trials ≥ 1. The precise trial number depends on each algorithm. For example, wvdetect employs iterations for finding faint sources, so the actual number can be much larger than the ratio of the search region to the cell size. The wavdetect routine internally considers each pixel as an independent trial, and the default threshold at \( 10^{-16} \) means allowing one false source in 1 Mipixels (one ACIS CCD). We believe that the detection cell size, which is proportional to the PSF size, should be accounted for in order to get the truly independent trial numbers. However, considering that the two closest sources in the 473 sources by R09 are about a pixel apart, the trial statistics counting scheme in wavdetect may be also appropriate for the wvdetect run by R09, in which case there are about 300k trials in HRES.
20 photons from the 274 sources by wavdetect versus 355

Figure 2. (a) Distribution of the source and background counts in detection cells (a 1 arcsec radius circle around each source), overplotted with false detection probability ($P_r$) calculated by the Bayesian analysis (Weisskopf et al. 2007; Kashyap et al. 2010). See also Appendix A. (b) Cumulative distributions of the source numbers as a function of $P_r$. The shaded region indicates the limit required to ensure one or less false source in the source list, assuming that 24k to 96k trials were performed.

The 6.5–7.1 keV band is chosen to represent the emission lines from highly ionized irons as in R09. The 9–12 keV band results are shown for sanity check: despite the large number of the total events in the source regions in the 9–12 keV band (1642–2818), which are roughly proportional to the number of sources, the summed net photon counts after background subtraction are essentially null, consistent with random Poisson fluctuations as expected.

The four analysis options in Table 4 produce essentially identical results, indicating the outcomes of the aperture photometry are very robust. Only the case with no boresight offset correction (option 4) produces consistently lower net photon counts for all the four source search routines. While the differences are still within the statistical fluctuations from the other results, the consistent deficit in the net photon counts with no boresight offset correction implies that the boresight offset correction was applied properly in the other options and does improve the aperture photometry.

Unlike the total event counts which are roughly proportional to the number of sources, the total 6.5–7.1 keV net photon counts after background subtraction do not vary significantly among the four source lists. The net photon counts are consistent within $\sim 3\sigma$, despite the large differences in the source numbers (e.g. in option 1, 295 ± 22 photons from the 274 sources by wavdetect versus 355 ± 27 photons from the 473 sources by R09). The source lists by the three wvdecomp routines produce the consistent results within $\sim 2\sigma$, indicating there is no significant contribution from additional $\sim 100$ sources found by R09 in comparison to the 356 sources found by the wvdecomp algorithm with 4.5$\sigma$. These aperture photometry results are consistent with the conclusion of the source search results in Section 4.1: the 50–100 faintest sources in R09 do not contribute significantly in the resolved flux in 6.5–7.1 keV band. This is very different from the conclusion in R09. In order to find the origins of the discrepancy, we explore the spectral and luminosity properties of these sources in more detail.

4.3 Spectral and luminosity distribution of the resolved X-ray sources

Fig. 3 shows the spectral and X-ray luminosity distributions of the 356 sources detected by the wvdecomp routine (4.5$\sigma$). These sources are chosen for illustration, and the conclusion remains unchanged for other source search results (see Fig. 4). Panels (a) and (b) plot the energy quantiles (Hong et al. 2004, 2009a) of the sources in the same phase space with two spectral model grids (power law and thermal Bremsstrahlung) for comparison. Panels (c) and (d) display the same sources in a phase space of the median energy ($E_{\text{med}}$, in the 0.3–8 keV band) and the 2–10 keV X-ray luminosity (see below) at a distance of 8 kpc (the Galactic Centre). The symbol sizes in (a) and (c) are semilogarithmically proportional to the absolute counts of net photons in the 6.5–7.1 keV band. The blue and red dots represent positive and negative net counts, respectively. Panels (b) and (d) mark a few dozen identified sources or sources with some clue about their nature (V09; H12; Hong et al., in preparation).

4.3.1 Diverse spectral types and flux calculation

Fig. 3 illustrates the diverse spectral types of X-ray sources in the region and the results are very intuitive: the bright, hard X-ray sources mostly contribute the hard X-ray flux. Table 5 also shows the spectral diversity by grouping similar sources. In order to estimate the flux and luminosity of each source in the 2–10 keV band, R09 rely solely on the net counts in the 0.5–7 keV net count rate (see Appendix B3). Both Fig. 3 and Table 5 do show a strong correlation between the spectral type and the net counts. However, the spectral diversity present in the same count range of the sources indicates that the count-to-flux conversion factor only based on the counts underestimates the spectral diversity and misassigns the flux values of the sources. Therefore, we group them by the median energy...
Figure 3. X-ray spectral and luminosity distributions of the 356 sources found by the wvdcomp (4.5σ) routine in HRES of the LW. (a) Quantile diagram (Hong, Schlegel & Grindlay 2004; Hong et al. 2009a) overlayed with the power-law model grids, and the symbol size is semilogarithmically proportional to the absolute net counts in the 6.5–7.1 keV band. The blue and red dots represent positive and negative net counts, respectively. The diamond and cross symbols represent the combined X-ray spectra of the groups selected by the median values (Q1, Q2 and Q3 in Table 5) and net counts (N1, N2 and N3), respectively. (b) The same as (a) with the thermal Bremsstrahlung model grids, and two dozen sources are marked according to their likely type. (c) and (d) The median energy versus the 2–10 keV X-ray luminosity at 8 kpc. In (c), the fractional contribution of source number (grey) and the 6.5–7.1 keV net photon counts (black) are noted in each quadrant of the diagram.

Table 4. Aperture photometry results of the resolved discrete sources in HRES in the 6.5–7.1 and 9–12 keV bands.

| Options/energy band | wavd | wvd (4.5σ) | wvd (4.0σ) | R09 |
|---------------------|------|------------|------------|-----|
| (1) Default         | 274 sources | 356 sources | 439 sources | 473 sources |
| Total events in 6.5–7.1 keV | 494 (22) | 569 (24) | 636 (25) | 690 (26) |
| 9.0–12. keV         | 1642 (41) | 2099 (46) | 2560 (51) | 2818 (53) |
| Net photons in 6.5–7.1 keV | 295 (22) | 316 (24) | 328 (26) | 355 (27) |
| 9.0–12. keV         | 23 (41) | 32 (47) | 34 (53) | 55 (55) |
| (2) 1.5 keV 95 per cent PSF with annulus bkg. | 274 sources | 356 sources | 439 sources | 473 sources |
| Net photons in 6.5–7.1 keV | 303 (23) | 322 (24) | 325 (25) | 355 (27) |
| 9.0–12. keV         | 17 (41) | 0 (47) | 2 (52) | 1 (54) |
| (3) F mode          | 264 sources | 354 sources | 458 sources | 473 sources |
| Net photons in 6.5–7.1 keV | 308 (25) | 322 (27) | 349 (30) | 366 (30) |
| 9.0–12. keV         | –3 (53) | 28 (61) | 19 (70) | 65 (72) |
| (4) No boresight    | 267 sources | 351 sources | 446 sources | 473 sources |
| Net photons in 6.5–7.1 keV | 293 (22) | 295 (24) | 315 (26) | 342 (27) |
| 9.0–12. keV         | 10 (41) | 33 (47) | 77 (53) | 31 (55) |
of the sources (only for the sources with less than 300 counts, where the spectral model fit for each source is not reliable). In this way, each group has more or less similar spectral types of sources, and the conversion factor from count rate to flux will reflect their spectral properties. Table 5 shows about a factor of 10 variation in the conversion factor between the softest (Q3) and hardest groups (Q1). It also shows that the combined spectrum of the brightest sources (B) is most consistent with the hardest sources (Q1). The 2–10 keV X-ray luminosity at 8 kpc in Fig. 3 are calculated using the conversion factors from the net photon counts in the 0.5–7 keV band of three median-energy-based groups under a simple power-law model. (10) The unabsorbed 2–10 keV flux in $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for sources with one net photon in the 0.5–7 keV band or conversion factor from the 0.5–7 keV counts to the 2–10 keV unabsorbed X-ray flux in $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ ph$^{-1}$.

Table 5. Count to flux conversion factor and X-ray luminosity by source group.

| ID  | Net counts | QDx | Source number | 6.5–7.1  | 0.5–7 keV E$_{50}$ (keV) | N$_{HI2}$ | $\Gamma$ | flux ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 8 kpc L$_{X}$ ($10^{29}$ erg s$^{-1}$) |
|-----|------------|-----|---------------|----------|--------------------------|----------|-------|----------------------------------|----------------------------------|
| Q3  | $\leq$300  | $<$0.5 | 123           | 19 (10)  | 4181 (89)                | 1.27 (1) | 0.31 (5) | 3.4 (2)                              | 0.29 (2)                           |
| Q2  | $\leq$300  | 0.5..0.6 | 121           | 37 (11)  | 4098 (88)                | 1.81 (2) | 1.11 (8) | 2.8 (1)                              | 1.20 (0.91)                        |
| Q1  | $\leq$300  | $\geq$0.6 | 102           | 171 (16) | 5628 (94)                | 2.98 (4) | 1.5 (1) | 1.6 (1)                              | 2.87 (2.19)                        |
| B   | $>300$     | 0.5..0.6 | 102           | 95 (10)  | 4364 (68)                | 2.65 (4) | 0.24 (7) | 0.86 (6)                             | 2.59 (1.97)                        |
| N1  | $>100$     | 0.5..0.6 | 35            | 203 (15) | 8583 (98)                | 2.61 (3) | 0.40 (5) | 1.04 (6)                             | 2.50 (1.91)                        |
| N2  | 10..100    | 0.5..0.6 | 293           | 125 (19) | 9529 (137)               | 1.73 (1) | 0.37 (6) | 1.94 (8)                             | 1.23 (0.94)                        |
| N3  | 5..10      | 0.5..0.6 | 19            | 0 (5)    | 142 (26)                 | 1.4 (1)  | 0.3 (7)  | 3 (2)                                | 0.49 (0.37)                        |

Notes. Based on the 356 sources detected by wvdecomp (4.5σ). (1) Group IDs. (3) QDx = log ($E_{50}$/0.3)/log (8/0.3). It is a normalized logarithmic value of the median energies, x-axis values of the quantile diagram (Hong et al. 2009a). (5) and (6) Summed net photon counts of the sources in the group. (7) The median energy of the combined X-ray spectrum of the group. (8) and (9) Interstellar absorption and power-law index of the combined X-ray spectrum of the group under a simple power-law model. (10) The unabsorbed 2–10 keV flux in $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for sources with one net photon in the 0.5–7 keV band or conversion factor from the 0.5–7 keV counts to the 2–10 keV unabsorbed X-ray flux in $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ ph$^{-1}$.

4.3.2 Sources with clues

Two best candidate cataclysmic variables (CVs) are classified as such based on the blue colour, $H_{\alpha}$ excess of the optical counterpart and high $F_{X}$/F$_{R}$ ratio. Accreting binaries or more marginal candidate CVs are based on the blue colour and high $F_{X}$/F$_{R}$ ratio. Coronal sources are the OGLE-III variables or have bright UCAC2$^{12}$ counterparts (see V09 and references therein). Three (candidate) active galactic nuclei (AGN) are based on their hard X-ray spectrum and high absorption: one with an extended optical counterpart, another with a very red counterpart and the other with a blue counterpart (i.e. it can also be an accreting binary). These sources are based on the initial 100 ks Chandra ACIS-I observations of the LW (V09), and a similar study

$^{11}$ http://ogle.astrouw.edu.pl
$^{12}$ http://ad.usno.navy.mil/ucac/a2_readme.html
using the sources from the full 1 Ms exposure is underway (van den Berg et al., in preparation). Two periodic sources found in the region are likely MCVs (H12), one of which is recognized as a candidate accreting binary in (V09). Two of four non-periodic variable sources (flaring or transient) found in the region (Hong et al., in preparation) are also the two best candidate CVs in V09. Periodic or variable X-ray sources are identified from the 1 Ms exposure data.

In the LW outside of the HRES region, a few dozen more sources are either identified or show some clues about their nature (V09; H12). Their distribution shows a similar pattern in the quantile diagram, namely MCVs and AGN are dominantly located at median energy $E_{\text{50}} \gtrsim 2.2$ keV, whereas non-magnetic CVs and coronal sources such as ABs are at $E_{\text{50}} \lesssim 2.2$ keV as illustrated by the vertical grey line in the diagram (see V09; H12). For instance, fig. 9 in H12 shows that all 10 MCVs identified in the LW through their periodic X-ray modulation are at $E_{\text{50}} \gtrsim 2.2$ keV. The symbol size and colour clearly show the large contribution to the 6.5–7.1 keV flux from the sources located at $E_{\text{50}} \gtrsim 2.2$ keV despite their relative paucity in the diagram (see also Fig. 4). In the case of the luminosity distribution, the dominant contribution to the 6.5–7.1 keV flux comes from the relatively bright sources ($\gtrsim 10^{31}$ erg s$^{-1}$). Panel (c) in Fig. 3 shows the source fraction and the 6.5–7.1 keV net count contribution of each quadrant in the diagram. The bright, hard sources contribute about 70 per cent of the 6.5–7.1 keV net counts, although they are only about 10 per cent of the total source number.

4.3.3 Sources resolving iron line flux

Fig. 4 shows the spectral and luminosity distributions of the sources found in HRES. Panel (a) contrasts the source number distribution (black lines), which is dominated by the soft sources, with the resolved 6.5–7.1 keV net counts (red lines), which are dominated by the hard sources. The same trends are visible in different source lists by wvdetect (dashed lines), wvdcomp (4.5σ, solid) and R09 (dotted). Panel (b) shows the cumulative source number and 6.5–7.1 keV net counts as a function of the 2–10 keV X-ray luminosity for three source lists. The source number distribution (black lines) are again distinct from the resolved 6.5–7.1 keV net count distribution (red lines). Although comprising a relatively small fraction of the total source number, the relatively bright and hard X-ray sources contribute most of the resolved iron line flux. The small increase in the resolved fraction as the source number counts increases from 274 by wvdetect to 473 by R09 can be in part due to a small addition of real sources as expected from the lowered detection threshold (false negatives; see Kashyap et al. 2010). We will address the unresolved spectra in the next section (e.g. Fig. 6).

4.4 Resolved fraction of the iron emission lines

Table 6 summarizes the total events and net photon counts in the HRES region in the 3–7, 6.5–7.1 and 9–12 keV bands. The total net photons in the HRES region are calculated by subtracting the instrumental background from the total event counts in the region. The instrumental background counts are acquired from the reprojected stowed events in the same region. For subtraction, we matched counts in the 9–12 keV band. The total measured X-ray surface brightness in HRES is $I_{\text{3–7 keV}} = (4.9 \pm 0.2) \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$, which is consistent with the result in R09 [(4.6 ± 0.4) × 10$^{-11}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$]. Table 7 shows the total resolved fraction based on Tables 4 and 6. For instance, with the VF-mode cleaning using the stowed data of Period E, the total net photons ($N_{\text{E}}$) in the 6.5–7.1 keV band in the HRES region are estimated to be 523 ± 119 (Table 6). The resolved 356 sources by wvdcomp (4.5σ) contain 316 ± 24 net photons ($N_{\text{E}}$) (Table 4). This would mean the total resolved fraction of 61 ± 15 per cent (versus 65 ± 17 per cent in Table 7), but aperture correction for missing photon counts (loss fraction $X$) due to the finite aperture size needs to be taken into account.

For the fixed 2 arcsec radius PSF, R09 assumed X to be 10 per cent. However, there are caveats in this assumption when calculating the total resolved fraction, and our simulation shows that the proper value is about 7 per cent (Appendix B2). After the aperture correction, we get the total resolved fraction of 65 ± 17 per cent from the 356 sources by wvdcomp (4.5σ) under the VF-mode cleaning, using the stowed data of Period E (Table 7). For the 473 sources by R09, we get 73 ± 19 per cent. With the combined stowed data set of Periods D and E (see Appendix C1), we get 83 ± 22 per cent, which is essentially identical to 84 ± 12 per cent reported by R09 (before accounting for the unresolved CXB, which is about 4 per cent according to R09; see Section 5). However, there is a, perhaps critical, difference in the procedure, which is the estimation of ratio of source to background aperture regions ($r$). Table 7 lists $r$ for each case (8.7 versus 2 per cent in R09). We will address this issue in Appendix B1 and here we review the results in Table 7.

Various event repositioning methods or aperture choices made little differences. The only major difference comes from the VF-mode cleaning, which increases the resolved fraction by about 10–12 per cent. The increase mainly comes from the significant reduction in the total net photons of HRES. For the 473 sources by R09, the VF-mode cleaning results in 355 net photons in the source regions, which is similar to 366 net photons by the F mode (Table 4). On the

| Band options | Data | Stow E | Stow DE |
|--------------|------|--------|---------|
| 3–7 keV      | All the events | 38412 (196) | |
| VF clean     | Reproj. stowed | 10 196 (91) | 14 650 (109) |
| Net photon counts | 11 787 (397) | 12 257 (352) |
| Surface brightness | 492 (17) | 514 (15) |
| 6.5–7.1 keV  | All the events | 4520 (67) | |
| VF clean     | Reproj. stowed | 13 183 (102) | 19 282 (123) |
| Net photon counts | 11 948 (459) | 10 169 (406) |
| Surface brightness | 77 (18) | 68 (16) |
| 9–12 keV     | All the events | 34 424 (186) | |
| VF clean     | Reproj. stowed | 12 663 (113) | 18 206 (135) |
| Net photon counts | 643 (159) | 520 (142) |
| Surface brightness | 95 (23) | 77 (21) |

Table 6. Photon count in HRES in 3–7, 6.5–7.1 and 9–12 keV.

$^a$Surface brightness: 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$.

---

13 This is identical to the procedure in R09, although in R09 the count rate in the 9–12 keV band is matched instead of the counts. It is because their subtraction is done in count rate space and ours in count.
other hand, in the HRES region as a whole, the VF-mode cleaning produces 523 net photons as opposed to 643 photons by the F mode. The two results are consistent within 1σ due to the large errors, and these large statistical errors dominate the uncertainty of the total resolved fraction. Projecting from the count decrease by 11 in the source region by the VF-mode cleaning, we estimate that the total real photons removed by the cleaning in HRES is about 19. In other words, at least about 80 per cent of 100 events removed by the VF-mode cleaning are indeed background events.

Note that the total resolved fraction has a relatively larger error compared to net photon counts in the source regions due to the additional uncertainty of the instrumental background subtraction. The uncertainty of the instrumental background is dominated by the relatively poor statistics of the stowed data in comparison to the 1 Ms observation (the count ratio in the 9–12 keV band between the two is 2.6, as shown in Table 6). The dominance of the stowed data in the error budget becomes clear when the Period D data set is used; more than 100 per cent is resolved (not shown), which is improbable (see Fig. 8 and Appendix C1 for more about large variations between the two stowed data sets).

Fig. 5 shows the total net spectrum of HRES, the resolved spectrum and the resolved fraction as a function of energy, and compares their results with three source search routines. Both Table 7 and Fig. 5 show that the additional ~100 sources added by R09 (or by the wvdecomp routine at 4.5σ) relative to the 356 sources from the wvdecomp routine at 4.5σ do not contribute significantly to the resolved X-ray flux in the iron emission lines and the 2–9 keV band in general.

Fig. 6 shows the resolved spectrum and fraction for soft ($E_{\text{iso}} < 2.2$ keV) and hard (>2.2 keV) sources. There is a clear disparity in the combined spectrum between the hard (blue) and soft (red) sources, which is consistent with the large variations in count-to-flux ratio conversion factors between the different spectral groups in Table 5. The large majority of the resolved fraction above 3 keV comes from the hard sources, which are likely MCVs and AGN, whereas the soft sources such as ABs and non-magnetic CVs contribute about 15 per cent or less. See also Appendix C2. Among the additional 117 sources in R09 relative to the 356 sources from wvdecomp (4.5σ), the increase in the resolved fraction above 5 keV is mainly from the 22 hard sources rather than the 95 soft sources, although the increase is within the statistical uncertainty. This implies that if indeed some real sources are added by lowering the detection threshold between these two source lists, they are mainly in the hard X-ray sources, and the trend of the dominance of the hard X-ray sources in the 6.5–7.1 keV band continues at low fluxes.

Fig. 7 shows the X-ray luminosity distribution of the resolved fraction in comparison with the results of R09. Our analysis show that the faint sources do not contribute significantly to the resolved fraction (See also Appendix C3).

### 5 DISCUSSION

Our estimate of the total resolved fraction (73 ± 19 per cent under Period E or 83 ± 19 per cent under Period D+E) in the 6.5–7.1 keV band in HRES from the 473 sources found by R09 is consistent with the estimate by R09 (84 ± 12 per cent under Period D+E) within the large uncertainties. However, our results regarding source search, aperture photometry and the resolved fraction, all consistently indicate that the relatively bright, hard X-ray sources such as MCVs and AGN contribute ~80 per cent of the resolved flux, more dominantly than the faint, soft X-ray sources such as ABs and non-magnetic CVs, which contribute ≤20 per cent. Subsequently our results indicate that the faintest ~100 sources found by R09 are insignificant. Therefore, we consider that the results from the 356 sources by wvdecomp (4.5σ) is more reliable, and we can confidently claim that the resolved fraction in HRES is 65 ± 17 per cent (Period E) or 73 ± 19 per cent (Period D+E). Assuming the unresolved CXB in the 6.5–7.1 keV flux to be $2.9 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$ (R09), which is about 3–4 per cent of the total intensity (Table 6), the total resolved fraction of the 6.5–7.1 keV flux in HRES is 69 ± 17 per cent (Period E) or 77 ± 19 per cent (Period D+E). This result is also roughly consistent with 88 ± 12 per cent by R09, but unlike R09, our finding of the dominance of relatively bright, hard X-ray sources in the resolved fraction draws a drastically different picture in the source composition and strongly motivate the analysis beyond HRES and the LW.

First, our finding is consistent with the previous studies indicating that MCVs are likely major candidates for the low-luminosity bulge hard X-ray sources (e.g. M03, M09, H09b). These studies also found a hint of an excess of hard X-ray sources in the central bulge relative to stellar population models. On the other hand, Revnivtsev et al. (2006), Revnivtsev & Sazonov (2007) and R09 argue the similarity of the Galactic distribution of the GRXE and the IR flux, which follows the stellar population. This apparent inconsistency is in part due to the relative shallow survey of the previous studies.
Figure 5. GRXE spectrum and resolved fraction. (a) The X-ray spectrum before background subtraction, (b) the X-ray spectrum after background spectrum and (c) the resolved fraction as a function of energies. The total spectrum in HRES and the results for three source lists are shown. In (a), the estimated instrumental background is shown in grey (scaled by 0.8 for clarity) and the spectra for the source regions are not corrected for event loss due to the finite PSF size. In (b) and (c), the event loss is corrected (see the text). The results are based on the default parameter choice (the EDSER routine, the VF-mode cleaning, the Period E stowed data set and fixed 2 arcsec radius source apertures).

The excess of the hard X-ray sources is only observed in the very central bulge within a few arcmin of Sgr A*.

We do not consider the possibility of inaccurate modelling of stellar population or the disparity between the stellar population and the IR flux, both of which are outside of this analysis.

Figure 6. The same as Fig. 5 for two source lists by wvdecomp (4.5σ, thick lines) and R09 (thin lines). The contribution from the resolved discrete sources are broken up by the soft (red, $E_{50} < 2.2$ keV) and hard (blue, $E_{50} > 2.2$ keV) sources. The residual unresolved X-ray spectrum and its twin scaled by 0.2 are shown in green for comparison with the X-ray spectra from the hard and soft sources. Among the additional 117 sources in R09 relative to the 356 sources from wvdecomp (4.5σ), the increase in the resolved fraction above 5 keV is mainly from the 22 hard sources rather than the 95 soft sources.

Shallow exposure of the large survey (e.g. H09b; M09). The overall X-ray flux used to match with the IR flux is still dominated by the soft X-ray contribution, which is largely unresolved and may not trace the hard X-ray sources. Therefore, the hard X-ray emission of the GRXE can be mainly from a relatively small number of hard X-ray sources, and the above apparent inconsistency can be explained by the fact that these previous studies were tracing a different population of X-ray sources. Secondly, if indeed relatively bright, hard X-ray sources dominate the iron emission line flux of the GRXE, we should be able to resolve a large fraction of the same emission line in the region beyond HRES despite some sensitivity loss due to the large offset. This argument also applies to the Galactic plane fields with relatively high extinction if a similarly ultradeep exposure is available. Then with the majority of the hard X-ray emission in the GRXE being resolved, we are positioned to investigate the possible variation of X-ray source composition between the fields and bulge, which can provide a hint in the unique formation and evolutionary history of the bulge. Extending the analysis beyond HRES also allows a significant reduction of the uncertainty in the resolved fraction by improving the instrumental background statistics of the stowed data.
Dominant MCVs in GRXE

Figure 7. The resolved 6.5–7.1 keV flux as a function of the 2–10 keV luminosity at 8 kpc. (a) The total resolved fractions by three source lists are compared with the result by R09. (b) The contribution from the hard and soft sources are separated out for the 356 sources by wvdecomp (4.5σ). Note that the hard sources reaching the plateau at higher luminosity are due to the higher sensitivity limit for the hard X-ray sources (see Fig. 3).

set, which is the dominant source of the uncertainties (Appendix C1).

In the following, we extend our analysis beyond HRES in light of our new results and discuss future observations and analysis plan to improve our understanding of the spatial variance of the source composition and the GRXE (see also Morihana et al. 2012). Finally, we summarize our thoughts on the origin of the discrepancy between our results and R09 and some of the analysis caveats in the appendices (B and C).

5.1 Beyond HRES

Fig. 8 shows the source number density, net photon counts and the resolved fraction of the 6.5–7.1 keV flux as a function of the radius from the centre of HRES using the resolved sources from the wvdecomp routine (4.5σ). The figure also shows the hard (blue) and soft (red) sources separately, and the results with (solid) and without (dotted) the VF-mode cleaning. For a given source, we use the 1.5 keV 95 per cent PSF for the source region and the surrounding annulus for the background region for aperture photometry since the fixed 2 arcsec radius aperture is no longer applicable at large offset angles and using the rest of HRES (excluding the source regions) for the background region does not reflect the local variation of background. The use of variable apertures is justified since in HRES both cases of the aperture choices (variable and fixed sizes) produce the consistent results (Table 4 options 1 versus 2).

Figure 8. Radial distribution of (a) the source surface density, (b) the net photons in the 6.5–7.1 keV band within the given radius and (c) the resolved fraction using the sources detected by wvdecomp (4.5σ). Source apertures are 1.5 keV 95 per cent PSF and the background apertures are the surrounding annulus (2 and 5 times of the PSF radius for inner and outer radii, respectively). The solid lines are for VF-mode cleaning and the dotted lines for F mode. The soft (red) and hard (blue) sources are separated based on the median energies.

As expected, the surface density of the soft sources (red in Fig. 8a) shows a more significant change with the radius of the analysis region than that of the hard sources (blue in Fig. 8a). The former drops noticeably beyond 2.5 arcmin from the centre, whereas the latter are more or less uniform out to 5 arcmin. The similar trend can be seen in the total net photons in the 6.5–7.1 keV band from the hard X-ray sources (blue in Fig. 8b) and the analysis region altogether (grey in Fig. 8b), which peaks at around 5 arcmin. On the
other hand, the 6.5–7.1 keV photons from the soft X-ray sources (red in Fig. 8b) rise up and peak at 3.5 arcmin and drop afterwards, which can be partially explained by a patch of seemingly diffuse soft emission region at around 3–4 arcmin.

The contribution to the resolved fraction from the soft sources are insignificant throughout the field. In fact, their contribution in the very central region is non-existent despite the relatively large number of sources found in the region. This again supports our finding of the dominance of the relatively bright, hard X-ray sources in the resolved GRXE. It is also consistent with a recent independent analysis of the region by Morihana et al. (2012). In the case of the resolved fraction, the radial variation is not significant, but its uncertainty drops noticeably as extending to the larger region. If we limit our analysis to 5 arcmin where the total net photon density in the 6.5–7.1 keV band of the analysis region is highest, the resolved fraction is 64 ± 6 per cent (Period E) or 69 ± 7 per cent (Period D+E) for wvdecomp (4.5σ); after including the 3.7 per cent CXB contribution, the total resolved fraction is 68 ± 6 per cent (Period E) or 73 ± 7 per cent (Period D+E).17

5.2 Unresolved GRXE

Fig. 9 shows the GRXE and its resolved spectra in the 5 arcmin radius region. The result is consistent with that in HRES (Fig. 6). Now with higher statistics, one can see a few more features in the spectra. First, there appears to be a lack of the 6.4 keV emission line in the region (e.g. see the black lines in the 6–6.5 keV band in Fig. 9a). Although the ACIS CCD spectral resolution in HRES may not be suitable for clear separation of the 6.4 and 6.7 keV lines under the given relatively poor statistics (cf. Ebisawa et al. 2008), other bulge fields such as the Galactic centre strip surveyed by Wang, Gotthelf & Lang (2002) show a prominent emission line feature at 6.4 keV, a large fraction of which may be of diffuse origin. Secondly, the spectra from the resolved sources, in particular, the soft sources, shows an absorption feature in the 5–5.5 keV band. In turn, the unresolved spectrum (green) shows an emission feature in the same energy band.

Given high stellar density in the LW, where often more than a few stars with $V < 24$ within the error circle of X-ray positions are observed in the HST image (V09), it is still possible that the unresolved 20–30 per cent can be from the X-ray emission of the unresolved discrete sources. The relatively soft X-ray spectrum of the unresolved residual GRXE (green in Figs 6 and 9) suggests a possibility that the unresolved discrete sources are mainly soft coronally active stars such as ABs. In fact, the unresolved spectrum is clearly softer than the combined spectrum of the soft sources, so there may be more contribution from ABs than non-magnetic CVs in the unresolved spectrum, whereas the resolved spectrum of the soft sources may have relatively larger contribution from non-magnetic CVs. This interpretation is consistent with ABs and other coronally active sources being fainter ($\sim 10^{-30} - 10^{-31} \text{ erg s}^{-1}$) than accreting sources such as non-magnetic CVs ($\sim 10^{-29} - 10^{-30} \text{ erg s}^{-1}$), but it also implies that the contribution from ABs is not resolved at this luminosity limit.

Alternatively it is also possible that the hard X-ray flux ($> 4$ keV) of the unresolved GRXE is mainly from the faint hard X-ray sources such as MCVs and the soft flux from the coronally active stars like ABs. For instance, the X-ray spectrum of the unresolved CXB (~4 per cent of the total flux in the 6.5–7.1 keV band) can be described by a power-law spectrum with photon index of 1.4. In other words, the combined unresolved spectrum (green) in Figs 6 and 9 contains a contribution from the sources whose spectra are much harder than the combined unresolved spectrum itself or the combined spectrum of the soft sources. If the 8 per cent increase in the resolved fraction of the 6.5–7.1 keV band from the 356 sources by wvdecomp (4.5σ) to the 473 sources by R09 is credible (thick to thin lines in Fig. 6), the latter scenario is supported by the fact that most of the 8 per cent increase is from the faint hard X-ray sources but not from the faint soft X-ray sources. Then, the paucity of the hard X-ray sources implies that a truly diffuse hard X-ray component may be present in the GRXE.

5.3 Future studies

It is now possible to draw a rather complete picture of the Galactic X-ray source composition and their Galactic distribution, through

---

17 The total resolved fraction does not change significantly even out to 10 arcmin. This is because the X-ray flux at large off-axis angles does not contribute significantly due to the reduction in the effective area. Subsequently, there is no improvement in the uncertainty of the total resolved fraction.
resolving the majority of the GRXE by ultradeep Chandra exposures. This calls for more observations and analysis of the other fields. The LW field, while perhaps ideal for resolving the GRXE due to the proximity to the Galactic Centre (GC) and the low extinction, may not represent a typical bulge region in the Galactic plane. First, the total X-ray spectrum of the LW field lacks the neutral Fe 6.4 keV emission line, which is often outstanding in the plane fields and suspected to be mainly from the diffuse emission (e.g. Wang et al. 2002). Therefore, an ultradeep exposure of the plane fields (apart from the Sgr A* field, which contains many complex diffuse features) is required. Secondly, unlike the Fe 6.7 keV line, the 2–6 keV medium-hard flux remains largely unresolved. As seen in the previous section, a comparison of the unresolved GRXE spectrum with the combined spectra of the soft and hard X-ray sources may indicate spectral transitions from hard MCVs, to soft non-magnetic CVs, and to even softer, unresolved ABs (or diffuse components). Therefore, the medium band GRXE and its spatial variation will allow modelling of the relative composition of the three major source types. For this, another low-extinction field such as Baade’s Window (BW) at 4′ south of the GC might be ideal. For instance, unlike the LW, in BW the apparent diffuse X-ray emission is remarkably absent. The lower extinction and the lack of the apparent diffuse emission in BW improve a chance of resolving the GRXE in a broader band than in the LW. In addition, unlike the hard X-ray sources whose density falls radially from the GC, there is an excess of the soft X-ray sources in BW relative to the LW at the same 100 ks exposure (H09b), despite the larger offset of BW from the GC (4′ versus 1.4′ for the LW). Therefore, when the spatial variance of the GRXE between BW and the LW is compared to the variance of the hard and soft X-ray source numbers, the unambiguous contribution of each source type to the GRXE can be calculated.

The wide-band coverage (5–200 keV) and large effective area (700 cm² at 7–12 keV) of the nuclear spectroscopic telescope array (NuSTAR) (Harrison et al. 2005) bring a new promise of constraining the GRXE. A mildly deep observation (e.g. 200 ks) of the LW with NuSTAR will enable the absolute intensity measurement of the GRXE in the region above 6 keV. Such a measurement will allow a precise calculation of the resolved fraction of the GRXE by the Chandra sources without relying on the somewhat uncertain Chandra/ACIS instrumental background.

6 SUMMARY

Through an independent analysis of the X-ray sources in the LW, we resolved the iron emission line of the GRXE in the 6.5–7.1 keV band up to (69–77) ± 19 per cent in the central circular region of 2.56 arcmin radius and (65–73) ± 7 per cent for the 5 arcmin radius. The dominating uncertainty is from the instrumental background in both statistical and systematic nature (e.g. VF-mode cleaning, Period D+E versus E). We find that the resolved GRXE is dominated by the relatively bright (≥ 10^{31} erg s^{-1}), hard X-ray sources (E_0 ≥ 2.2 keV), which are likely MCVs and AGN. The relatively faint, soft X-ray sources such as ABs and non-magnetic CVs do not contribute more than 20 per cent of the resolved flux.

The refined resolved fraction in the 5 arcmin radius region leaves room for truly diffuse components in the GRXE, but the undetected large population of the relatively faint (≤ 10^{31} erg s^{-1}), hard X-ray sources can make up for the unresolved fraction. We also believe that we have identified a few analysis caveats in R09, which led to the disagreement with our results regarding the source composition of the resolved GRXE.

ACKNOWLEDGMENTS

We thank M. van den Berg and M. Servillat for the manuscript and useful comments. We thank V. Kashyap for his help on calculation of detection confidence. We also thank M. Revnivtsev for providing his source list and the extensive discussion on the topic and analysis despite some disagreement in the results. We also thank J. Grindlay for his support and useful suggestions in the analysis.

REFERENCES

Brandt W. N. et al., 2001, AJ, 122, 2810
Ebisawa K., Maeda Y., Kaneda H., Yamauchi S., 2001, Sci, 293, 1633
Ebisawa K. et al., 2005, ApJ, 635, 214
Ebisawa K. et al., 2008, PASJ, 60, 223
Freeman P. E., Kashyap, V., Rosner R., Lamb D. Q., 2002, ApJS, 138, 185
Gehrels N., 1986, ApJ, 303, 336
Grindlay J. et al., 2005, ApJ, 635, 920
Harrison F. et al., 2005, Exp. Astron., 20, 131
Hiccox R. C., Markovich M., 2006, ApJ, 645, 95
Hong J., Schlegel E. M., Grindlay J. E., 2004, ApJ, 614, 508 (H04)
Hong J., van den Berg M., Schlegel E. M., Grindlay J. E., Koenig X., Laycock S., Zhao P., 2005, ApJ, 635, 907 (H05)
Hong J., van den Berg M., Laycock S., Grindlay J. E., Zhao P., 2009a, ApJ, 699, 1053 (H09a)
Hong J., van den Berg M., Grindlay J. E., Laycock S., Zhao P., 2009b, ApJ, 706, 223 (H09b)
Hong J., van den Berg M., Grindlay J. E., Servillat M., Zhao P., 2012, ApJ, 746, 165 (H12)
Kaneda H., Makishima K., Yamauchi S., Koyama K., Masatsuki K., Yamasaki N. Y., 1997, ApJ, 491, 638
Kashyap V., van Dyk D. A., Connors A., Freeman P. E., Siemiginowska A., Xu J., Zezas A., 2010, ApJ, 719, 900
Kashyap V., Drake J., Wright N., Aldcroft T., 2011, AAS, 218, 228.27
Kim M., Wilkes B. J., Kim D.-W., Green P. J., Barkhouse W. A., Lee M. G., Silverman J.D., Tananbaum H. D., 2007, ApJ, 659, 29
Kim D.-W. et al., 2004, ApJS, 150, 19 (K04)
Koyama K., Makishima K., Tanaka Y., Tsunemi H., 1986, PASJ, 38, 121
Laycock S., Grindlay J. E., van den Berg M., Zhao P., Hong J., Koenig X., Schlegel E. M., Persson S. E., 2005, ApJ, 634, L53 (L05)
Li J., Kastner J. H., Prigozhin G. Y., Schultz N. S., Feigelson E. D., Getman K. V., 2004, ApJ, 610, 1204
Markovich M. et al., 2000, ApJ, 541, 542 (see also http://ccx.harvard.edu/contrib/maxim/make_readout_bg)
Markovich M. et al., 2003, ApJ, 583, 70
Morihana K., Tsujimoto M., Yoshida T., Ebisawa K., 2012, ApJ, submitted
Muno M. P. et al., 2003, ApJ, 589, 225 (M03)
Muno M. P. et al., 2009, ApJS, 181, 110 (M09)
Revnivtsev M., Sazonov S., 2007, A&A, 471, 159
Revnivtsev M., Sazonov S., Gilfanov M., Churazov E., Sunyaev R., 2006, A&A, 452, 169
Revnivtsev M., Sazonov S., Churazov E., Forman W., Vikhlinin A., Sunyaev R., 2009, Nat, 458, 1142 (R09)
Servillat M., Grindlay J., van den Berg M., Hong J., Zhao P., Allen B., 2012, ApJ, 748, 32
van den Berg M. et al., 2006, ApJ, 647, L135
van den Berg M., Hong J., Grindlay J. E., 2009, ApJ, 700, 1702 (V09)

© 2014 The Author, MNRAS 427, 1633–1650

Monthly Notices of the Royal Astronomical Society, 2012 RAS

Dominant MCVs in GRXE 1647
APPENDIX A: DETECTION SIGNIFICANCE

Detection significance is often estimated based on SNR. If the background count \( B_c \) in the detection cell \( \Omega_2 \) is known, the SNR to describe detection significance\(^{20} \) is given as \( \text{SNR} = \sqrt{S/C} \), where \( S \) are the photon counts from the source and \( C \) is the fluctuation of the background counts. For Poisson distribution, \( \text{SNR} \) is simply \( \sqrt{S} = \gamma \), or \( 1 + \sqrt{S} = \gamma \beta \), at low counts (\( \gamma \ll 1 \)).\(^{15} \) Gehrels (1986). The SNR-based approaches involve a number of approximations: for a given confidence (C) or a false detection probability \( P_f = 0 \) for \( B_c = 1 \), it is often assumed that the SNR follows a Gaussian distribution. For instance, for 90\% confidence \( P_f < 0.1 \) with \( B_c = 1 \), \( S > 1.8 \) (SNR > 1.8) or \( S > 2.97 \) for Gehrels’ approximation, see red and blue lines in Fig. A1.

A more rigorous approach based on discrete Poisson distributions and a Bayesian treatment of false detection probability can be found in the literature: equation A11 in Weisskopf et al. (2007) (see also equation A8) and footnote 13 in Kashyap et al. (2010). Their formulae are identical\(^{21} \) to each other except for their interest of unmarginalized parameters: the cell size \( \Omega \) and the exposure \( T \) in the latter. If we assume that \( B_c \) is measured, the false detection probability is simplified as \( P_f = 1 - C \)

\[
P_f(S > S | S = 0, B_c = 1) = 1 - C = \frac{1}{\sqrt{2\pi}} \sum_{m=0}^{S} \frac{B_c^m m!}{m!} e^{-B_c} = \frac{\gamma(S^2 + 1, B_c)}{\Gamma(S + 1)},
\]

where \( \gamma \) and \( \Gamma \) are incomplete and regular gamma functions, respectively. Under this approach, for >90\% confidence \( P_f < 0.1 \) with \( B_c = 1 \), \( S > 0.8 \) (see black lines in Fig. A1).

\(^{20} \) Note the difference from the SNR often used to describe the confidence range of the source count, where the noise term includes the error contribution of the source count as well. For example, when the error of the background count is estimated independently, \( \text{SNR} = \sqrt{S/C} \), where \( \epsilon \) is the error of the total counts in the source region.

\(^{21} \) Note that there is an error in the formula in footnote 13 of Kashyap et al. (2010): \( \gamma(S^2 + 1, r e^{\epsilon^2}) = 2/\pi r e^{\epsilon^2} \).

\(^{22} \) Note that this is not entirely a correct statement since \( P_r \) is defined for \( S \), the total counts in the source region, but for not \( S_c \), the source count. The correct statement is \( S > 1.8 \).

---

Figure A1. Detection threshold \( (S - B_c) \) for source count under a given false detection probability \( (P_r = 1 - C) \), where \( C \) is the detection confidence. The simple minded approaches using SNRs (red dash for Gaussian statistics and blue dot-dashed for Gehrels’ approximation for Poisson statistics) are compared with the Bayesian approach (black solid) by Weisskopf et al. (2007) and Kashyap et al. (2010). The detection threshold for source counts \( (S_c) \), but for easy illustration of how bright the source needs to be for detection, the detection threshold is expressed for \( S_c \) under the assumption that \( B_c \) is known (Subsequently the plot ignores the discrete nature of the counts as well). A more rigorous approach based on discrete Poisson distributions and a Bayesian approach to account for trial statistics can underestimate the false detection probability for high background cases.

We use a circular region of 1 arcsec radius around each source for detection cell, following Weisskopf et al. (2007), and calculate the source counts \( (S_c) \) by subtracting the background counts \( (B_c) \) from the total counts \( (S) \) in the cell. For the background counts \( (B_c) \), we take the counts in an annulus around the source with 4 and 10 arcsec radii (excluding the 3 arcsec radius circles of neighbouring sources), and scale them by the ratio of the detection cell size to the background region. Here, we assume that \( B_c \) represents the true mean value of the background counts in the detection cell for simplicity. The range of \( B_c \) for the sources in HRES is 3.1 to 21. Note that the detection cell is chosen to be smaller than the source aperture regions in aperture photometry (Section 3.4), since the former is designed for efficient source detection and the latter is designed for accurate flux estimation.

Fig. A1 compares the two approaches under the assumption that \( B_c \) is known. Gehrels’ approximation is often used to account for the asymmetric deviation of Poisson distributions from Gaussian distributions at low counts (\( \gamma \ll 1 \)). However, Fig. A1 shows in fact using simple Gaussian errors is more accurate than using Gehrels’ approximation, indicating the latter may result in detection loss of faint sources. On the other hand, the real data can often deviate from a pure Poisson distribution or contain features that are not easy to account for, and thus it is usually a safe approach to have a higher threshold by using Gehrels’ approximation.

For detection confidence of a population of sources discovered by a search routine, one has to take into account the number of search trials explicitly. Without accounting for trials statistics, both simple Gaussian errors and Gehrels’ approximation of Poisson errors result in a wrong estimate of false detections. Interestingly using...
Gehrels’ approximation without accounting for trial statistics may accidentally produce a proper estimate of false detections at low background count cases but it will underestimate false detections at high background count cases. For example, in Fig. A1, the detection threshold for \( P = 1 \) per cent using Gehrels’ approximation (the blue line) matches the threshold for \( P = 0.01 \) per cent from the Bayesian approach (the black line) when \( B_C \sim 1 \), but the threshold for the former is lower than the latter when \( B_C \gtrsim 2 \).

APPENDIX B: ORIGIN OF DISCREPANCY IN APERTURE PHOTOMETRY

In our opinion inaccurate estimations of the following three quantities in R09 are the major origins of the discrepancy between R09 and ours in the aperture photometry results.

B1 Source to background region ratio

Table 7 shows the exposure-map-corrected geometric sky ratio \( (r) \) of the source to background aperture regions after overlap correction. The ratios gradually increase from \( \sim 5 \) to 9 per cent as the source numbers increase from the 274 to 473 sources. For comparison, the 473 fixed 2 arcsec radius circles in a 2.56 arcmin radius circle means \( r = 8 \) per cent without considering source aperture overlap (about 100 sources) and the gaps between the CCDs. We validate our calculation of the ratios by the fact that the same aperture photometry produces the essentially null net photons in the 9–12 keV band in the combined source regions (Table 4).

Interestingly R09 quote 2 per cent for this ratio for their 473 sources, which is a factor of 4 smaller than our estimate. R09 justify their ratio based on a claim that their aperture photometry is done using the pixellated image rather than event files (Revnivtsev, private communication). However, as shown in Li et al. (2004), we believe aperture photometry benefits substantially from the sub-pixel information by using event files instead of pixellated images. In addition, a few techniques have been developed and proven to reduce pixellation-induced uncertainties for aperture photometry using event files. 23

Given the dominance of the background in the region, the underestimated ratios \( (r) \) by a large factor has significant consequences. First, it mistakenly increases the resolved flux. Secondly, it smears the spectral diversity of sources by adding a constant term of the background spectra. Now the effect gets amplified proportionally to the number of sources since each source adds a constant background contribution into its spectrum. This generates an illusion in the resolved flux as one approaches the faint side of flux where an increasingly large number of sources are added to the source list. Therefore, we believe the underestimation of the ratios \( (r) \) contributes to the discrepancy in the X-ray luminosity distribution of the resolved GRXE. It also explains the apparent large contribution of the soft (relatively faint) sources to the resolved fraction of the 6.5–7.1 keV band in R09.

23 For instance, the exposure-corrected aperture area of a source region is calculated by multiplying the mean value of the exposure map in the source region with the geometric aperture size instead of adding up the exposure map values of the pixels inside the source region. The latter is subject to pixellation-induced errors when the aperture size is small, whereas the former is accurate even if the aperture radius is similar to a pixel size. See Kim et al. (2004) and H05.

Figure B1. Photon loss due to finite aperture size. (a) An example of MARX (Model of AXAF (Advanced X-ray Astrophysics Facility) Response to X-rays) simulations using 6.7 keV photons for a source near the boundary of the HRES region. Some photons outside the 2 arcsec radius aperture of the source still fall inside of other source regions (small red circles) or outside of the HRES region altogether, which is outlined by a part of the large (blue) circle. (b) Effective photon loss fraction of the 473 sources by R09 in HRES as a function of X-ray energies, which is smaller than 10 per cent expected for a single source in the full ACIS-I field of view (see the text). The larger variable aperture using 1.5 keV 95 per cent PSF captures slightly more photons at high energies than the fixed 2 arcsec radius apertures.

B2 Aperture correction for missing photons

When the ratio of source to background regions is \( r \), the true net photons \( (N_C) \) from the source is given as \( N_C = (N_S - rN_B)/(1 - X - rX) = N_S/(1 - X - rX) \), where \( N_S \) and \( N_B \) are the total events in the source and background regions, respectively, and \( X \) is the missing photon fraction due to the finite aperture size. For the fixed 2 arcsec radius PSF, R09 assumed \( X \) to be 10 per cent. This is alright in estimating the true net flux of a single point source in the field, but for calculation of the total resolved fraction in a small section of the field, there are two caveats as illustrated in Fig. B1. First, the multiple source regions capture more photons than the 90 per cent of photons enclosed by the single source aperture. Secondly, the large tail of the PSF (partially due to CCD readout intervals) makes the source photons scatter even outside of the HRES region, i.e. some fraction of the missing 10 per cent photons are outside of the HRES region altogether, which should not be counted for calculating the total resolved fraction in the HRES region. The latter is prominent for sources that fall near the edge of the HRES region. For the proper aperture correction, we have conducted a set of MARX simulations using various source and background
regions. Fig. B1(b) summarizes the effective photon loss fraction as a function of energies for two different aperture choices using the positions of the 473 sources detected by R09. For example, the proper correction factor X is 7.1 per cent for the fixed 2 arcsec radius apertures of the 473 sources in the HRES region at 6.7 keV and 6.9 per cent for 1.5 keV 95 per cent PSF variable apertures. This correction factor approaches to the expected 10 per cent as we expand the analysis region beyond HRES. Since the subsequent correction factor for the total resolved fraction is proportional to the resolved flux before the correction, so the error in the missing photon fraction can also get amplified accordingly.

### B3 Count rate to flux conversion factor

R09 use $(a + bS_C^{1/2})S_C$ for the count-to-flux conversion factor, where $S_C$ is the net source counts in 0.5–7 keV and $a$ & $b$ are constant (Revnivtsev, private communication). This conversion solely relies on the net counts, disregarding the spectral variation of sources in the same count range, and the resulting $S_C^{1/2}$ term artificially stretches the luminosity range. For instance, for two bright sources with $S_C \sim 300$ and $800$ in HRES that show similar spectral type under a simple power-law fit, it is reasonable to estimate that their flux would also differ by a factor of 2.7 ($= 800/300$), but under the above conversion scheme by R09, their flux turns out to differ by a factor of 5. In our opinion, the conversion scheme by R09 likely misassigns the flux values of many sources, and in the resulting X-ray luminosity distribution the contribution of the faint sources appears larger than what it should be.

### APPENDIX C: ANALYSIS CAVEATS

#### C1 Statistical uncertainty of stowed data in HRES

The dominant contribution to the uncertainty of the total resolved fraction of the 6.5–7.1 keV flux is from the statistical uncertainty of the reprojected stowed data. In addition, there appears to be an even larger systematic uncertainty between the Period E and D data sets. How can this be since Hicox & Markevitch (2006) demonstrated that the stowed data do not exhibit any significant variation in the flux and spectrum over the years? Fig. C1 illustrates the origin, which plots the relative count ratio of the 6.5–7.1 to 9–12 keV bands as a function of the radii from the centre of HRES. When most of the data in the ACIS-I chips from CCD 0 to 3 are used, which correspond the right-hand side of the plot (radius $\gtrsim 8$ arcmin), the relative count ratio of 6.5–7.1 to 9–12 keV does not show any significant variation between the two periods, which is consistent with Hicox & Markevitch (2006). But the same ratio shows large fluctuations at small radii.

In addition, for instrumental background subtraction, the stowed data are reprojected to sky according to the aspect solution of the observations as aforementioned in order to properly account for the spatial variation. Each reprojection produces different results originating from random assignment of events to the aspect solution, and each reprojected stow data shows a similar scale of fluctuation as the error bars of statistical origin in Fig. C1. Note that the curves for the stow data in Fig. C1 are based on the average values of 100 separate reprojections for each data set. Therefore, using a particular reprojection result may lead to a significant different outcome in the resolved fraction.

In summary, the instrumental background is sensitive to the choice of the stowed data set (D+E versus E), VF-mode cleaning, and the analysis region size (unless it is larger than 7–8 arcmin.

#### C2 Soft versus hard X-ray sources

One may argue the distinction of hard and soft X-ray sources by median energy of 2.2 keV and the subsequent association with source types like MCVs and ABs are too crude. In fact, coronally active stars exhibit spectral hardening during flares. However, a few dozen sources with some clues about their source type (e.g. Fig. 3) are consistent with our division scheme, and the median energy of typical flares from coronally active stars are below 2.2 keV (e.g. $E_{50}$ keV means $kT > 10$ keV for thermal plasma models with $N_{H2} \sim 0.7$). Therefore, despite its arbitrary aspect, our distinction of source types with the median energy is statistically justified.

#### C3 Faint versus bright X-ray sources

One may claim that the dominance of the relatively bright ($\gtrsim 10^{31}$ erg s$^{-1}$), hard ($E_{50} \gtrsim 2.2$ keV) X-ray sources in the resolved GRXE is because we have not resolved the flux from the faint sources although we resolved the flux of the bright sources properly. If we simply add the resolved fraction of the faint sources by R09 to the resolved fraction of our bright sources, the total resolved fraction exceeds 100 per cent. This means that there should be an error in the aperture photometry. However, it is difficult to imagine that any mistake in aperture photometry would channel the X-ray flux into a smaller number of sources. Errors in the analysis usually influence the results in an opposite way, smearing the outcome rather than sharpening the results. For instance, the incorrect boresight correction or lack thereof would smear the image, resulting more evenly spread events among the sources and background region. In summary, the total resolved fraction from our analysis and their dependence of the source type and luminosity strengthen the earlier conclusion that the majority of the resolved flux are from relatively bright, hard sources such as MCVs and bright AGNs.

This paper has been typeset from a \TeX\ file prepared by the author.