The Galactic plane at faint X-ray fluxes – I. Properties and characteristics of the X-ray source population

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ABSTRACT
We investigate the serendipitous X-ray source population revealed in XMM–Newton observations targeted in the Galactic plane within the region 315° < l < 45° and |b| < 2.5. Our study focuses on a sample of 2204 X-ray sources at intermediate to faint fluxes, which were detected in a total of 116 XMM–Newton fields and are listed in the Second XMM–Newton Serendipitous Source Catalog. We characterize each source as spectrally soft or hard on the basis of whether the bulk of the recorded counts have energies below or above 2 keV and find that the sample divides roughly equally (56 per cent:44 per cent) into these soft and hard categories. The X-ray spectral form underlying the soft sources may be represented as either a power-law continuum with $\Gamma \sim 2.5$ or a thermal spectrum with $kT \sim 0.5$ keV, with $N_H$ ranging from $10^{20}$ to $10^{22}$ cm$^{-2}$. For the hard sources, a significantly harder continuum form is likely, that is, $\Gamma \sim 1$, with $N_H = 10^{22}–10^{24}$ cm$^{-2}$. For ~50 per cent of the hard sources, the inferred column density is commensurate with the total Galactic line-of-sight value; many of these sources will be located at significant distances across the Galaxy, implying a hard-band luminosity $L_X > 10^{32}$ erg s$^{-1}$, whereas some will be extragalactic interlopers. A high fraction (≥90 per cent) of the soft sources have potential near-infrared (NIR) (Two-Micron All-Sky Survey and/or United Kingdom Infrared Deep Sky Survey) counterparts inside their error circles, consistent with the dominant soft-X-ray-source population being relatively nearby coronally-active stars. These stellar counterparts are generally brighter than $J = 16$, a brightness cut-off which corresponds to the saturation of the X-ray coronal emission at $L_X = 10^{-3}L_{bol}$. In contrast, the success rate in finding likely IR counterparts to the hard X-ray sample is no more than ≳15 per cent down to $J = 16$ and ≳25 per cent down to $J = 20$, set against a rapidly rising chance coincidence rate. The make-up of the hard-X-ray-source population, in terms of the known classes of accreting and non-accreting systems, remains uncertain.

Key words: surveys – X-rays: binaries – X-rays: X-rays: general – X-rays: stars.

1 INTRODUCTION
The brightest sources discovered in the first all-sky surveys conducted at X-ray wavelengths (e.g. Uhuru, Forman et al. 1978; Ariel V, Warwick et al. 1981) were found to be X-ray luminous close binary systems powered by the accretion of matter on to a compact object. These sources, with intrinsic X-ray luminosities ($L_X$) typically in the range $10^{36}–10^{38}$ erg s$^{-1}$ in the 2–10 keV band, can be classed either as low-mass or high-mass X-ray binaries (LMXBs or HMXBs, respectively) depending on the nature of the non-degenerate star, the companion objects being either neutron stars or black holes. X-ray catalogues of the time also contained a few examples of other types of Galactic X-ray sources, including X-ray bright supernova remnants, cataclysmic variables (CVs) and coronally-active binaries, such as RSCVn systems, albeit with inferred X-ray luminosities typically much less than $10^{36}$ erg s$^{-1}$.

Later more sensitive X-ray surveys utilizing imaging instruments operating in a somewhat softer spectral regime (e.g. Einstein, Hertz & Grindlay 1984; ROSAT, Voges et al. 1999) showed that the X-ray sky at low Galactic latitude is crowded with nearby coronally-active stars and binaries dominating the source statistics in the soft (<2 keV) X-ray band (Motch et al. 1997). Subsequently, an imaging survey in the Galactic plane carried out by ASCA (Sugizaki et al. 2001) provided a first detailed view of the general population of faint Galactic X-ray sources in the 2–10 keV band. Since the impact of X-ray absorption by interstellar gas is greatly diminished above ~2 keV, the ASCA survey was able to detect hard-spectrum sources with X-ray luminosities markedly lower than those of the classical Galactic X-ray binaries across a significant fraction of the inner Galaxy.
More recently, the improved sensitivity, spatial resolution and energy range afforded by the Chandra and XMM–Newton observatories has provided the opportunity to revisit the issue of the faint Galactic source populations in both the soft and hard X-ray bands. For both missions, the fields of view (FoVs) of the onboard X-ray cameras are such that in a typical low-latitude pointing, in addition to the primary target, many tens of serendipitous sources are seen. Both missions have also invested observing time in studying specific regions of the Galactic plane, most notably the Galactic Centre, through both deep pencil-beam observations (Ebisawa et al. 2001; Muno et al. 2003, 2004; Ebisawa et al. 2005; Hong et al. 2009; Revnivtsev et al. 2009) and mini-surveys in which wider angle coverage is achieved by the mosaicking of multiple (relatively short) observations (Wang, Gotthelf & Lang 2002; Hands et al. 2004; Muno et al. 2006; Wijnands et al. 2006; Muno et al. 2009). The outcome is that 10 yr post-launch both the Chandra and XMM–Newton archives contain a wealth of data relevant to Galactic X-ray sources at intermediate to faint flux levels, spanning a wide range of intrinsic luminosity.

Recent results from Chandra and XMM–Newton demonstrate the potential of Galactic X-ray surveys, at readily accessible sensitivity limits, to detect a wide variety of source types. For instance, coronally-active binaries can be detected at distances up to 1 kpc or beyond (Hérent, Motch & Guillout 2006) and young stellar objects can be unveiled in regions of current star formation. In the case of the latter, evolved protostars and T Tauri stars with extreme coronal emission and hard X-ray spectra ($kT \sim 1–4\,\text{keV}$) can be detected in dense molecular clouds, despite the large line-of-sight column density (e.g. Feigelson & Montmerle 1999). Isolated neutron stars, such as those discovered in the ROSAT survey (Haberl & Pietsch 2001), are radio-quiet objects located at distances of no more than a few hundred parsecs that display soft thermal X-ray spectra. CVs constitute a source class that may, potentially, be found in large numbers in sensitive Galactic X-ray surveys. In particular, it has been proposed that intermediate polar may account for a large fraction of the low-$L_X$ sources which reside in the Galactic Centre region (Muno et al. 2006) and through their integrated emission may account for a significant fraction of the hard Galactic X-ray ridge emission (Revnivtsev et al. 2006; Sazonov et al. 2006). Relatively quiescent X-ray binaries with either low-mass (e.g. black hole transients) or high-mass (e.g. Be star) secondaries may also make a non-negligible contribution to the source statistics.

However, in truth, our knowledge of the makeup of the Galactic X-ray source population at relatively faint levels is quite limited. This is certainly the case in the 2–10 keV band where, in principle, the visible volume extends to the edge of the Galaxy. In order to better define the various populations in terms of their space density, scaleheight and luminosity function, we need to characterize and, where possible, identify much larger samples of sources than are currently available. More comprehensively characterized source samples might also reveal how X-ray sources map on to structures such as the Galactic spiral arms, the thin and thick disc, the Galactic bulge and the mass concentration within $\sim 100\,\text{pc}$ of the Galactic Centre. A range of astrophysical issues, for example, relating to the formation and evolution of close binary systems and accretion at low mass-transfer rates, might also be addressed.

In the above context, the Chandra Multiwavelength Plane (ChuMPlane) Survey is aiming at a systematic analysis of low-latitude fields with the objective of measuring or constraining the populations of low-luminosity ($L_X \lesssim 10^{31}\,\text{erg}\,\text{s}^{-1}$) accreting white dwarfs, neutron stars and stellar mass black holes in the Galactic plane and bulge (see Grindlay et al. 2005 for full details). The programme utilizes Chandra X-ray data in combination with follow-up optical and IR photometric and spectroscopic observations, so as to maximize the number of identified sources and explore the populations thereby revealed. Recent publications from the ChuMPlane programme include a study of Chandra fields in the Galactic anticentre (Hong et al. 2005), and the Galactic Centre and bulge (Laycock et al. 2005; Koenig et al. 2008; Hong et al. 2009; van den Berg, Hong & Grindlay 2009).

In the case of XMM–Newton, the XMM–Newton Galactic Plane Survey (hereinafter XGPS; Hands et al. 2004) has sampled a flux range which bridges the gap between the relatively shallow ASCA GPS (Sugizaki et al. 2001) and the sensitivity limits reached in deep Chandra pointings (e.g. Ebisawa et al. 2001). In a paper reporting the XGPS, Hands et al. (2004) discussed the results from a programme including 22 pointings which cover a region of approximately 3 deg$^2$ between $19^h–22^h$ in Galactic longitude and $\pm 0.6$ in Galactic latitude. Subsequent optical follow-up observations of a representative sample of the brightest identified low-latitude hard-band sources detected in the XGPS have recently been presented by Motch et al. (2010).

In this paper, we build on the XGPS studies of Hands et al. (2004) by carrying out a systematic investigation of the X-ray source population seen at intermediate to faint fluxes in XMM–Newton pointings targeted at the Galactic plane. More specifically, we consider observations encompassing a narrow strip of the plane towards the central quadrant of the Galaxy. In the next section of this paper, we give details of the set of XMM–Newton observations which provide the basis of the study. In Section 3, we describe the selection criteria we employ to extract a clean ‘serendipitous’ X-ray source sample from these fields, using the Second XMM–Newton Serendipitous Source Catalog (2XMMi catalogue) (Watson et al. 2009) as the input data base. Section 4 goes on to investigate various properties of the sample with a focus on the available X-ray spectral information. In Section 5, we present an investigation of the likely near-infrared (NIR) counterparts based on a cross-correlation of the X-ray sample with both the Two-Micron All-Sky Survey (2MASS) and the United Kingdom Infrared Deep Sky Survey (UKIDSS). This leads on to a discussion of the nature of the soft- and hard-source populations in Section 6, followed by a brief summary of our conclusions of this paper (Paper I). In subsequent papers (in preparation), we will explore the average X-ray spectral properties of a subset of relatively bright sources drawn from our source sample (Paper II), the log$N$–log$S$ curves for both the soft- and hard-source samples (Paper III) and the broad-band colours of likely counterparts to the X-ray sources (Paper IV).

### 2 THE XMM–NEWTON GALACTIC PLANE DATA BASE

In this paper, we utilize observations drawn from the XMM–Newton public data archive targeted at positions along the Galactic plane within the central quadrant of the Galaxy. More specifically, we use observations with pointings in the region bounded by $315^\circ < l < 45^\circ$ and $|b| < 2.5$. Our preliminary list of observations comprised of those used in constructing the 2XMMi catalogue (Watson et al. 2009) – see Fig. 1. However, given our focus on the serendipitous source content of the XMM–Newton fields, we excluded those fields dominated by a very bright source, which in most cases was the target source. We also excluded a number of observations otherwise dominated by the target, such as those containing nearby star...
A preliminary step involved dealing with the relatively small number of observations in which instrument filters other than the Medium filter were deployed. In these cases, the recorded count rates measured in each camera and in each energy band were scaled to equivalent values for the Medium filter, where the scalefactors applied were derived from the ratio of the appropriate energy conversion factors (ECF) quoted in Mateos et al. (2009).1

In our study of intermediate to faint Galactic plane sources, it has proven convenient to compress the available spectral information into two bands, a soft band representing the combination of Bands 2 and 3, encompassing the energy range 0.5–2 keV, and a hard band based on Bands 4 and 5, corresponding to the energy range 2–12 keV. The 2XMMi Band 1 information has not been used in this analysis. The count rates measured in each EPIC camera for the soft and hard bands were obtained as the straight sum of the rates recorded in the respective input bands. We also calculated an effective detection maximum likelihood (maxl) in the soft and hard bands by the prescription given in the SAS emldetect documentation (see also Mateos et al. 2008).

A further compression of the information for each detected source was achieved by combining the count rates measured in the different cameras for the soft band and, separately, for the hard band. For the count-rate measurements for a particular source in a given camera to be considered valid, a requirement was that the 2XMMi source parameter, frac, should be greater than 0.8 for that camera (i.e. at least 80 per cent of the source response was contained within the camera’s active FoV). Count-rate measurements passing this

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1 These ECFs are calculated assuming a broad-band source spectrum, characterized as a power-law continuum with photon index $\Gamma = 1.7$ absorbed by a line-of-sight column density $N_H = 3 \times 10^{20}$ cm$^{-2}$. 

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Figure 1. The spatial distribution of the $\textit{XMM–Newton}$ observations that fall within the Galactic plane region bounded by $|l| < 45^\circ$ and $|b| < 2.5^\circ$. Each colour dot corresponds to a field used in the construction of the 2XMMi catalogue (Watson et al. 2009), with the colour coding red-to-green-to-blue roughly scaling as the logarithm of the accumulated exposure. The 116 observations included in this study are circled in black.
Table 1. Details of the 116 XMM–Newton observations which comprise the current survey.

| Observation ID | Pointing | Exposure (ks) | Filter | FoV | Sources | Fraction | Total | Soft | Hard |
|----------------|----------|--------------|--------|-----|---------|----------|-------|------|------|
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.5 | 9.5 | 11.6 | 11.6 | Med | Med | Med | 13 | 12 | 1 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 1.7 | 12.4 | 16.6 | 16.3 | Med | Med | Med | 0.97 | 13 | 8 | 5 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 1.8 | 15.4 | 21.6 | 23.2 | Thinn | Thinn | Thinn | 0.88 | 27 | 19 | 8 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.1 | 7.1 | 8.7 | 8.7 | Med | Med | Thinn | 0.95 | 16 | 10 | 6 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.2 | 0.0 | 50.0 | 50.2 | Thick | Thick | Thick | 0.98 | 34 | 26 | 8 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.6 | 24.7 | 31.6 | 31.6 | Med | Med | Thinn | 61 | 47 | 14 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.9 | 6.0 | 7.6 | 7.6 | Med | Med | Med | 18 | 13 | 5 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.0 | 7.5 | 9.9 | 11.1 | Med | Med | Med | 0.82 | 23 | 16 | 7 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.4 | 18.1 | 21.0 | 21.3 | Thinn | Thinn | Thinn | 0.98 | 32 | 20 | 12 |
| lb             | pnn      | MOS1 | MOS2 | MOS1 | MOS2 | lb | 0.2 | 4.3 | 13.8 | 14.7 | Med | Med | Med | 0.97 | 8 | 5 | 3 |

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criterion were included irrespective of whether the source was classed as detected or not in the camera/band combination under consideration (see below). The actual compression process involved first averaging valid MOS-1 and MOS-2 count rates using a statistical weighting to give a combined-MOS count rate estimate and then scaling the latter measurement to pn equivalent units. Finally,

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the scaled-MOS and pn measurements were averaged, again using a statistical weighting, to give the final soft- and hard-band count rates. In following this process, the resultant source count rates may derive from one, two or three measurements depending on which combination of cameras were producing valid data for the source. Hereinafter, in this paper, we quote count rates in the soft, hard and total (soft+hard) bands for the combined EPIC cameras in units of pn count ks$^{-1}$.

The first step in excising relatively low-significance sources from the full 2XMMi source list involved the setting of a threshold value of maxl = 10 for the soft/hard-band detection. Sources were only retained in the source list if this threshold was exceeded in either the soft or hard bands (or both) and in one or more of the EPIC cameras. For a source detection to be classed as valid in a particular camera, we required frac $> 0.8$ in that camera. Further criteria for source removal included the 2XMMi parameter Extent $> 0$ (i.e. the exclusion of all non-point-like sources) and SUM-FLAG $> 3$ (i.e. a quality check to exclude sources described as ‘located in an area where spurious detections may occur and may possibly be spurious’ – see Watson et al. 2009).

After filtering the original 2XMMi source list using the above methodology, we visually inspected the soft- and hard-band images of each field (produced from the standard data products available from the XMM–Newton archive). As a result, a number of sources classified at this stage as ‘valid detections’ were flagged for removal. Frequently, such source exclusions stemmed from the confusion of one source with another, generally brighter, object. A few sources embedded in bright diffuse regions were also removed. At this point, we also excluded regions encompassing an obvious bright target source – essentially by spatially masking areas within the observation FoV. On occasion, regions affected by bright extended objects or by the scattering rings from very bright out-of-FoV sources were also excluded. Observations in which the target region or other specific regions have been excluded are flagged in Table 1.

Implementation of the above selection process left us with a catalogue of ~2700 sources. A source could be included in this list based on a nominal detection (above a maximum-likelihood threshold of 10) in just one band and one camera. Visual inspection suggested that at the limit, such sources were typically quite faint and in some cases potentially unreliable. Since a detailed analysis of the reliability of 2XMMi sources as a function of the detection maximum-likelihood threshold was beyond the scope of the investigation (but see Watson et al. 2009; Mateos et al. 2009), we instead employed an empirical approach to arrive at a robust final source catalogue based on a further signal-to-noise ratio (S/N) selection. More specifically, we calculated the ratio of the count rate to count-rate error for each source using the combined camera measurements. We then set a minimum requirement that this ratio should exceed a value of 4 in the soft and/or hard bands. This further selection resulted in the exclusion of 252 sources detected only in the pn camera and 101 (133) sources seen only in the MOS-1 (MOS-2) cameras, with just 10 sources removed for which there was a simultaneous detection in more than one camera.

After applying all the above, we were left with a catalogue of 2204 point sources drawn from the 116 survey fields. Table 2 summarizes the source-detection statistics in terms of the soft/hard bands and the pn/MOS-1/MOS-2 cameras.

Although the field selection described in Section 2 involved the exclusion of duplicate observations of the same target or pairs of observations with FoVs which significantly intersect, some modest degree of field overlap was permitted. As a consequence of this overlap, there are 44 source duplications in the total of 2204, that is, 2 per cent of the sample. Out of these 44 sources, 30 sources are soft detections and 14 hard; there are two instances of the same source being duplicated twice. In the following analysis, we have ignored this duplication and treated all 2204 entries as individual sources.

## 4 PROPERTIES OF THE SOURCE SAMPLE

### 4.1 Spatial distribution

The distribution in Galactic longitude and latitude of the sources which comprise our serendipitous source sample is illustrated in Fig. 3. These are the observed distributions without any correction applied for sky coverage or for the depth of the underlying observations.

It is evident from Figs 1 and 3 that the coverage of the Galactic plane by XMM–Newton is far from uniform. Near the Galactic Centre, within $|l| < 2^\circ$, there is an obvious concentration of pointings. Similarly, the regions near $l = 7^\circ$, $11^\circ$, $15^\circ$ and between $19^\circ$–$22^\circ$ have relative good coverage in narrow strips along the plane. The latter corresponds to the ‘XGPS region’ studied by Hands et al. (2004), whereas the other three directions have enhanced coverage as a result of later phases of the XGPS programme. The observations drawn from the XGPS programme are flagged as such in Table 1 – generally these consist of sequences of relatively short exposures with some overlapping of the FoVs so as to give extended, albeit shallow, sky coverage.
The Galactic plane at faint X-ray fluxes

Figure 3. (a) The source distribution in Galactic longitude. No corrections have been applied for the number or depth of the observations in the survey. (b) The same in Galactic latitude.

Figure 4. The distribution of the total (soft+hard) count rate for the source sample in units of pn count ks$^{-1}$ (0.5–12 keV).

4.2 Flux calibration and distribution

The distribution of measured total count rate for the source sample is illustrated in Fig. 4. Although the full distribution extends over three decades, 94 per cent of the sources have total count rates in the range 2–100 pn count ks$^{-1}$. Fig. 5 shows how the total count rate splits between the soft and hard bands. Roughly, 50 per cent of the sources are detected only in the soft band, with 36 per cent detected only in the hard band and just 14 per cent detected in both bands (see Table 2). With the objective of dividing the sample into non-overlapping soft and hard subsets, we calculate a broadband hardness ratio, HR = (H − S)/(H + S), where S and H refer to the soft-band and hard-band count rates, respectively. We then use HR = 0, corresponding to the diagonal line in Fig. 5 (i.e. equal soft and hard count rates), as the boundary between the two designations. This provides a close match to the soft-only and hard-only detections; on the other hand, for the sources detected in both bands, the division somewhat favours the hard category. Hereinafter, we refer to sources as soft or hard depending on their position relative to the HR = 0 fiducial. On this basis, there are 1227 soft sources and 977 hard sources in our sample.

Given the very different characteristics of the underlying source populations (see below), different spectral forms have been assumed for the soft and hard sources in deriving factors to convert the measured count rates to energy flux. In both bands, we apply a spectral model consisting of a power-law continuum of photon index $\Gamma$ subject to line-of-sight absorption in a column density, $N_H$. For the soft sources, the spectral parameters were set to $\Gamma = 2.5$ and $N_H = 10^{21}$ cm$^{-2}$, resulting in an ECF of $4.9 \times 10^{11}$ count cm$^{-2}$ erg$^{-1}$, where both the count rate and unabsorbed energy flux relate to the 0.5–2 keV band. For the hard sources, we use $\Gamma = 1.0$ and $N_H = 3 \times 10^{22}$ cm$^{-2}$ leading to an ECF of $7.9 \times 10^{10}$ count cm$^{-2}$ erg$^{-1}$, applicable to the 2–10 keV band. For a source with a nominal count rate of 2 pn count ks$^{-1}$ in the soft band, the equivalent unabsorbed flux is $4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ (0.5–2 keV). The same count rate in the hard band equates to an unabsorbed flux of $2.5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ (2–10 keV).

4.3 X-ray spectral properties

Fig. 6 shows the distribution of the broad-band HR for the source sample. The distribution has a saddle-like form, with a broad minimum centred around HR = 0 separating maxima at, or near, the two extremes. We note that our focus on source detections in either the soft or the hard bands (or both) might introduce a bias against sources of intermediate hardness in which the count rate is spread fairly evenly across the two spectral channels. However, when we plot the distribution in Fig. 6, including only relatively bright sources (e.g. sources with a total count rate greater than 20 count ks$^{-1}$), the saddle distribution remains broadly unchanged. We conclude that the underlying source population splits rather cleanly into the designated soft and hard categories.

We have also investigated the spectral distribution of the sources with respect to the four 2XMMi bands, namely Bands 2–5. In this context, a standard approach is to use X-ray two-colour diagrams,
Figure 6. Distribution of the sources with respect to the broad-band HR.

where each axis represents a different HR calculated for a pair of (adjacent) bands. However, for our sample which is strongly affected by absorption, the tendency was for such diagrams to be either dominated by errors (due to low intrinsic count rates in both selected bands) or, at least, very compressed along one axis. We have avoided this problem by calculating instead a set of Band Index (BI) values, where $BI_N$ is calculated simply as the count rate in Band $N$ normalized to the total source count rate (i.e. in this case the sum of the count rates in Bands 2–5). The comparison of BI values for adjacent bands (see Fig. 7) then provides very similar information to a set of two-colour HR diagrams. We note that ‘quantile’ analysis, as described by Hong, Schlegel & Grindlay (2004), represents an alternative strategy for investigating the spectral properties of source samples in the low count rate limit.

Each BI diagram in Fig. 7 shows a smoothly varying distribution representing the range of source characteristics from the hardest through to the softest spectral forms. A rough calibration of this spectral diversity is provided by the model curves in Fig. 7, which correspond to power-law spectra with $\Gamma$ ranging from 0.5 to 3, subject to absorption ranging from $N_H = 10^{20}$ to $10^{24}$ cm$^{-2}$. However, the sources with the softest spectra are not quite accommodated by the limits $\Gamma = 3$ and $N_H = 10^{20}$ cm$^{-2}$ in the BI 2 versus BI 3 diagram and are, in fact, better represented by a thermal (Mekal) spectrum with the same limiting $N_H$ and $kT \approx 0.5$ keV (the dashed curve in the top panel of Fig. 7). From the BI 3 versus BI 4 diagram, it is evident that transition from our soft to hard characterization occurs for $N_H = 3 \times 10^{21}$–$3 \times 10^{22}$ cm$^{-2}$ (depending on the slope of the continuum). In the hard spectral regime represented by the BI 4 versus BI 5 diagram, one finds that the bulk of the signal is contained in Bands 4 and 5 for $N_H > 3 \times 10^{22}$ cm$^{-2}$. Evidently, there are a significant number of sources with BI 5 $> 0.7$, implying $N_H$ in excess of $10^{23}$ cm$^{-2}$, provided the underlying continuum is not exceedingly flat ($\Gamma \lesssim 0.5$).

4.4 Column density constraints

We have used the measured BI values to set more specific constraints on the line-of-sight column density $N_H$ for each source. Assuming an absorbed power-law spectral model, we calculated a two-dimensional array of BI values (one such array for each of the four spectral Bands 2–5), with $\log N_H$ along the x-axis (in steps of 0.1) and the assumed $\Gamma$ along the y-axis (in steps of 0.5). For a given source, we identified the region in each array bounded by the measured BI value and its error bar (we actually used 1.65$\sigma$ errors corresponding roughly to 90 per cent confidence combined in quadrature with a 2 per cent systematic). The full constraint was then derived by taking the minimum

Figure 7. X-ray two-colour diagrams in the form of BI plots. Here BI $N$ is simply the count rate in Band $N$ divided by the total count rate summed across the 2XMMi Bands 2–5. Sources categorized as soft and hard are shown as red and blue, respectively. For clarity, only sources with a S/N threshold in excess of 6 are plotted. The solid curves represent the locus for a given photon index, $\Gamma$, as the column density $N_H$ varies from $10^{20}$ to $10^{24}$ cm$^{-2}$ (with the dots marking in an anticlockwise order: $10^{21}$; $3 \times 10^{21}$; $10^{22}$; $3 \times 10^{22}$; and $10^{23}$ cm$^{-2}$). The values of $\Gamma$ are as indicated (ordered such that the higher $\Gamma$ loci are at a farther distance from the origin). The top panel also shows the locus (dashed curve) for a thermal Mekal component with $kT = 0.5$ keV, with the same $N_H$ range as above. The dashed diagonal lines represent an upper bound at which the full count rate is accounted for by the two bands in question.
the Galactic Centre direction being $N_H = 10^{22.8} \text{ cm}^{-2}$. Similarly, sources located within $1^\circ$ of the Galactic plane typically have four times the column density of sources which are $1^\circ$--2.5 off the plane.

5 Near-infrared counterparts

The identification and characterization of longer wavelength counterparts represents a crucial step in determining the nature of Galactic X-ray sources. The ideal starting point for this would be a subarcsecond imaging survey in a set of wavebands not too strongly influenced by Galactic absorption, with commensurate high-precision astrometry. At present, a comprehensive dedicated image data base of this quality is not available for the XMM–Newton survey fields. However, we have conducted a systematic investigation based on cross-correlations with two NIR surveys which are available, namely, 2MASS and UKIDSS.

5.1 Cross-correlation with 2MASS

The 2MASS survey (Cutri et al. 2003; Skrutskie et al. 2006) provides uniform coverage of the entire sky in three NIR bands, namely, in $J$ (1.25 $\mu$m), $H$ (1.65 $\mu$m) and $K_s$ (2.17 $\mu$m) on a scale of 2.0 arcsec (this is the pixel size of 2MASS images; the full width at half-maximum of the point spread function was typically 2.5--3.0 arcsec). At high latitude, the nominal survey completeness is 15.8, 15.1 and 14.3, respectively. However, in the Galactic plane, the measured source counts turn down at limits 1 mag (or more) brighter because of the effects of source confusion on the detection thresholds. The astrometric uncertainty is generally less than 0.2 arcsec, although this may be compromised in very confused regions.

As a first step, we cross-correlated our X-ray-source sample with the 2MASS catalogue and, for each X-ray-source position, we extracted the set of 2MASS sources within a radius of 20 arcsec. A total of 27 485 2MASS sources were associated with the 2204 X-ray-source positions via this process. Here we use the X-ray source position and position error quoted in the 2XMmi catalogue for the individual source observations (parameters: RA, Dec., poserr), where the position error includes a systematic error added in quadrature with the statistical error (the former was set to 0.35 arcsec if the field astrometry was corrected by reference to the USNO B1.0 optical catalogue or 1 arcsec otherwise). Fig. 9 shows the distribution of X-ray position errors for the source sample; the range is from 0.37 to 3 arcsec, with an area-weighted average of 1.5 arcsec. In the event, we selected only those X-ray sources with X-ray position errors $<$2 arcsec for the cross-correlation study, resulting in a reduced sample size of 2016 X-ray sources.

A preliminary investigation of the incidence of 2MASS sources at or near the X-ray positions demonstrated that, at least for the soft-X-ray-source sample, there was a significant excess over the number expected by chance, presumably reflecting the presence of a real counterpart in a substantial number of cases. The distribution of this excess population with respect to the X-ray-source positions was studied by considering how the net number of sources contained within the soft-source error circles (over and above the background rate) varied as a function of the assumed X-ray error circle radius

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3 The procedure is, of course, only an approximation to detailed model fitting of the available X-ray spectral data. Nevertheless, it provides very useful indicative results.

4 In establishing the coincidence rate of 2MASS sources with the soft- and hard-X-ray-source samples, we did not employ any discrimination based on the 2MASS quality flags. However, the flags were used to select sources with good photometry in the later investigation of the impact of interstellar reddening on the stellar colours.
Figure 9. The distribution of X-ray (1σ) position errors for the source sample.

Figure 10. The cumulative probability of finding an associated 2MASS source in an X-ray error circle, plotted as a function of the error circle radius (in units of the 1σ X-ray position error). The analysis is restricted to 2MASS sources with J = 5–15 found in the fields of the soft X-ray sources. For this work, the radius of the X-ray error circle was taken to be 2.5 times the 1σ X-ray position error (as indicated by the vertical dotted line), thereby encompassing around 90 per cent of the likely NIR counterparts. 

(Fig. 10). On the basis of this empirical information, we set the X-ray error circle radius to be 2.5 times the X-ray position error quoted in the 2XMMi catalogue, at which point 90 per cent of potential real counterparts will be contained within the error circle.

For the soft X-ray sources, the number of error circles containing a 2MASS source was 987 out of 1120 (88 per cent), whereas for the spectrally hard sources, the statistics were 393 out of 896 (44 per cent). In most instances, there was only one 2MASS source within the X-ray error circle, but for the 85 X-ray sources for which this was not the case, we treated the brightest 2MASS source (in J band) as the potential counterpart. Fig. 11 shows how the incidence rate of 2MASS stars within the X-ray error circles accumulates as a function of the 2MASS J magnitude for both the soft- and hard-source categories. The chance coincidence rate for field stars is shown by the filled histogram.

Figure 11. The cumulative fraction of X-ray error circles containing a 2MASS star as a function of the J magnitude of the star. Separate curves are shown for the soft- and hard-X-ray-source samples. The chance coincidence rate for field stars is shown by the filled histogram.

20 arcsec of the X-ray source position, is also indicated. All three curves begin to flatten and eventually reach a plateau, around J ≈ 16, consistent with the fact that the spatial density of sources per unit magnitude in this set of Galactic fields peaks at J ≈ 15 (i.e. at a level roughly a magnitude brighter than the completeness limit of the 2MASS at high latitude, as noted earlier). The plateau level for soft and hard distributions is as quoted above, whereas for the chance distribution, it is ~30 per cent.

Fig. 12 shows the derived magnitude distribution for the brightest 2MASS stars found to be positionally coincident with the
X-ray-source positions. The predicted contamination due to chance coincidences is also shown, where a correction has been incorporated for the fact that an error circle may not be ‘available’ at faint magnitudes if a brighter star is already present. For the soft-X-ray-source sample, the magnitude distribution extends from \( J = 7 \) to 16. Down to \( J = 16 \), the underlying contamination due to field stars amounts to roughly 9 per cent out of the 88 per cent of error circles which contain 2MASS stars down to this magnitude limit. In contrast, the magnitude distribution for the hard sample shows a much more modest excess of coincidences with respect to the predicted chance rate; for \( J < 16 \), the coincidence rate is 38 per cent of which 24 per cent, that is, roughly two-thirds, can be attributed to contamination by field stars.

The probability of finding a positionally coincident 2MASS source is clearly very different for the soft- and hard-X-ray-source samples. We have investigated this in more detail by considering how this probability varies as a function of the broadband HR. Fig. 13 shows the result. The probability of finding a 2MASS star brighter than \( J = 16 \) in the X-ray error circle (inclusive of chance hits) exhibits a step function behaviour, remaining at close to 90 per cent for the spectrally soft sources with HR in the range \(-1\) to \(-0.1\), followed by a rapid transition to a level of about 50 per cent for HR values near 0 followed by further decline to a level very near to the chance rate for the sources with the hardest spectra.

5.2 Cross-correlation with UKIDSS

For our application, the 2MASS survey becomes incomplete below \( J \approx 15 \). In contrast, the UKIDSS survey (Lawrence et al. 2007) provides better spatial resolution (0.2 arcsec pixel-scale with typically \( \approx 1 \) arcsec seeing) and is significantly deeper. The nominal limiting magnitudes estimated for the UKIDSS catalogue are \( J = 19.77, H = 19.00 \) and \( K = 18.05 \), with uncertainties of up to \( \approx 0.2 \) mag. As with 2MASS, the appropriate limits for the Galactic plane will be considerably brighter, depending on the actual crowding within a given field (Lucas et al. 2008). The photometric data used in this analysis are taken from the UKIDSS GPS Data Release 4.

UKIDSS GPS \( J \)-band data were available for a total of 1117 X-ray sources drawn from our sample of X-ray sources with position errors less than 2 arcsec, with the coverage split roughly equally between the soft- and hard-source samples (i.e. 596 soft and 577 hard). For this analysis, we extracted a preliminary set of UKIDSS stars within a nominal 10 arcsec of each X-ray position, leading to a preliminary set of 36 974 stars down to \( J = 20 \). Using the same X-ray error circle radii as for the 2MASS study, we repeated the analysis of the coincidence rates of UKIDSS stars within the X-ray error circles. As before, we make the assumption that the brightest star in the circle (in \( J \) band) is the most likely counterpart.

As we push down to a \( J \) magnitude of 20, the incidence rate of IR stars in the X-ray error circles rises to 97 per cent for the soft sources and 92 per cent for the hard sources. Of course, at these faint levels, given the stellar density and size of the error circles, the chance rate is commensurately high, namely, 85 per cent. Fig. 14 shows the resulting magnitude distributions for the brightest UKIDSS star in the X-ray error circle.

For the soft sources, the magnitude distribution is truncated below \( J < 10 \) as a result of saturation effects in the UKIDSS images, with the apparent subpeak near \( J \approx 11 \) presumably attributable to the same effect. As was evident in the equivalent 2MASS distribution, there is a sharp cut-off between \( J = 15 \) and 16. Despite the fact that the UKIDSS survey goes between 3–4 mag deeper than 2MASS, the evidence is that very few real soft-source counterparts have \( J > 15.5 \). For the soft sources, the coincidence rate with bright UKIDSS stars (\( J < 16 \)) is 91 per cent inclusive of a chance rate of 9 per cent, values which are fully consistent with the equivalent 2MASS estimates.

For the hard sources, the coincidence rate with bright UKIDSS stars (\( J < 16 \)) is 45 per cent, which splits into a likely chance rate of 29 per cent and an excess rate (i.e. potential real counterparts) of 16 per cent. These percentages are again very comparable to those obtained from the 2MASS cross-correlation. There is also evidence that real counterparts are seen at fainter magnitudes, with the \( J = 16–20 \) coincidence rate of 47 per cent comprising a likely chance rate of 38 per cent and an excess rate of 9 per cent. It follows that \( \approx 25 \) per cent of the hard-source population may have counterparts visible, as the brightest star in the error circle, down to \( J = 20 \). Of course, for every error circle for which this is the case, there are roughly 2.7 instances where the brightest star is just a chance...
5.3 Reddening of potential stellar counterparts

In order to investigate the colours of the NIR stars found inside the X-ray error circles, we have carried out a further selection aimed at removing those objects affected by known issues in relation to their photometry. The 2MASS catalogue includes four quality flags. For our purpose, we utilize the so-called the photometric QUALITY flag and select only those stars flagged as AQA (i.e. valid measurements with S/N > 10 in the $J$, $H$ and $K_s$ bands). Similarly, for the UKIDSS stars, we required the error bit flag, $ppErrbits < 256$, for each of the three NIR bands and also $pstar \geq 0.99$ (i.e. the removal of sources with non-stellar profiles). A total of 840 2MASS stars, representing the brightest object in the X-ray error circle, passed this selection step, with the equivalent number for the UKIDSS stars being 444. A total of 130 stars were common to both lists and, in the event, we used only the 2MASS data for this subset of sources.

Fig. 15 shows the $H - K$ versus $J - H$ two-colour diagram for the combined 2MASS/UKIDSS sample of coincident stars, with the results for the soft and hard X-ray source samples shown separately. The locus of main-sequence dwarf stars from FOV to M0V (Pickles 1998) and the reddening vector for $A_V = 20$ are also defined. For the stars potentially associated with soft X-ray sources, there is a dense grouping in the region of the two-colour diagram encompassed by the locus of non-reddened main-sequence
dwarfs, with a spread along the reddening direction largely encompassed by an $A_V$ of up to 20. In the case of the hard X-ray sources, the implied reddening is much more substantial for many of the stellar candidates, although the bulk of the population are still bounded by $A_V < 20$. Particularly for the hard-band sample, there are a number of stars which lie off to the right-hand side of the main distribution (i.e. have very red $H - K$ colours); these may be pre-main-sequence (T Tauri) stars exhibiting an IR excess (cf. Koénig et al. 2008).

Fig. 15 also shows the variation of the $J$ magnitude versus the $J - K$ colour, with the impact of a visual absorption $A_V = 20$ again indicated. The absolute magnitude, $M_J$, for main-sequence stars of type FOV to M0V ranges from 2.43 to 5.72 (Covey et al. 2007), that is, a $\Delta J \approx 3.3$ for unreddened stars at a fixed distance. If we compare this with the spread of $\Delta J \approx 7$ apparent in the colour–magnitude diagram for the bulk of the stars associated with the soft X-ray sources, then the implied scatter in distance is roughly a factor of 5. Of course, the presence of significant numbers of dMe stars of spectral class later than M0 would compromise this argument. The stars found in the hard–X-ray-source error circles are significantly fainter and redder than the population associated with the soft X-ray sources. However, as noted earlier, a substantial fraction of the stars linked to the hard X-ray sources will be chance coincidences with field stars and to first order the scatter in the both the $H - K$ versus $J - H$ two-colour diagram and in the $J - K$ versus $J$ colour–magnitude diagram for the hard sources must reflect the underlying properties of the field star distribution.

For those stars linked to hard X-ray sources, we have estimated the visual absorption by projecting the star’s position in the two-colour diagram on to the reddening vector and determining the offset relative to an origin at $J - H = 0.61, H - K = 0.11$ (the colours of an unreddened GV star). In Fig. 16, the resulting estimate of $A_V$ is plotted versus the X-ray column density derived in Section 4.4. Compared to the standard conversion, $N_H = 1.79 \times 10^{21} A_V$ (Predehl & Schmitt 1995), most of the points in the diagram lie at $N_H$ values significantly greater than that implied by the $A_V$ determination. This is to be expected if many of the associated NIR objects are, in fact, foreground stars, albeit sufficiently distant to be subject

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**Figure 15.** Top panels: the $H - K$ versus $J - H$ colours of the brightest stars in the X-ray errors circles, shown separately for the soft- and hard-X-ray-source samples. The curved line is the locus of dwarf stars from FOV to M0V. The diagonal line shows the reddening vector for $A_V = 20$. Bottom panels: the $J - K$ colour versus $J$ magnitude of the brightest stars in the X-ray errors circles, shown separately for the soft- and hard-X-ray-source samples. The diagonal line shows the impact of $A_V = 20$ on the $J - K$ colour and $J$ magnitude of a given star.

**Figure 16.** A comparison of the visual absorption $A_V$ determined from the 2MASS/UKIDSS stellar colours with the estimated line-of-sight gas column density $N_H$ derived from the X-ray spectral characteristics. The curve shows the standard relationship $N_H = 1.79 \times 10^{21} A_V$ (Predehl & Schmitt 1995).
to significant reddening. One way of picking out potentially true counterparts might be to require the derived $A_V$ and $N_H$ estimates to be comparable; unfortunately, the large uncertainties implicit in the estimation of both parameters mitigate against this as a practical scheme.

6 DISCUSSION

6.1 Nature of the soft-X-ray-source population

In the soft band, the nominal sensitivity limit of our survey is around 2 pn count ks$^{-1}$ corresponding to an unabsorbed flux $F_X = 4 	imes 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (0.5–2 keV). This is roughly five times deeper than the ROSAT survey reported by Morley et al. (2001), which in turn was a factor of 5 deeper than the Einstein GPS (Hertz & Grindlay 1984, 1988) and the ROSAT GPS (Motch et al. 1991, 1997). By way of comparison, the stellar survey carried out recently under the auspices of the Extended Chandra Multiwavelength Project (Covey et al. 2008) reaches similar, or somewhat deeper, limits to those reported here. These surveys and many other studies have established that the Galactic source population in the soft X-ray band largely comprises late-type stars with active coronae. More specifically, the ROSAT all-sky survey clearly demonstrated that main-sequence stars from early-F to late-M dominate the source statistics and that stars younger than $\sim$2 Gyr are typically more luminous in X-rays than older populations; this is a consequence of the reducing efficiency with which the corona is heated by the dynamo mechanism as the rate of stellar rotation declines with age (see Güdel 2004, and references therein). At high Galactic latitude, as the flux limit is lowered, the surveyed volume will eventually extend beyond the scaleheight of the young star population, thereby altering the balance between relatively old and relatively young stars (e.g. Micela et al. 2007). Although this is not a consideration which applies directly to a narrow Galactic plane survey, line-of-sight absorption will suppress the surveyed volume most severely for higher $L_X$ sources, presumably giving rise to a similar bias.

From the cross-correlation of our soft-X-ray-source sample with the 2MASS catalogue, we concluded that 88 per cent of the error circles contain stars with $J < 16$, with only 9 per cent of this figure attributable to chance coincidences. Furthermore, since our error circles were scaled so as to contain $\sim$90 per cent of the true counterparts, it follows that active stellar coronae must account for almost our entire sample of soft X-ray sources. When the search for counterparts was extended some 4 mag fainter through the cross-counterparts, it follows that active stellar coronae must account for the 2MASS catalogue, we concluded that 88 per cent of the error circles were scaled so as to contain the 2MASS catalogue, we concluded that 88 per cent of the error circles contained stars with $J < 16$, with only 9 per cent of this figure attributable to chance coincidences. Furthermore, since our error circles were scaled so as to contain $\sim$90 per cent of the true counterparts, it follows that active stellar coronae must account for almost our entire sample of soft X-ray sources. When the search for counterparts was extended some 4 mag fainter through the cross-correlation with the UKIDSS catalogue, the evidence for a cut-off at $J \approx 16$ was quite stark. This prompts the question of why the stellar identifications are restricted to bright magnitudes?

In Fig. 17, we explore the distances out to which main-sequence stars of different spectral class may be detected in both the NIR and our XMM–Newton survey. In the NIR, the constraint $J \leq 16$ sets a distance limit which varies from 2.7 kpc for early-F stars down to $\sim$70 pc for late-M stars. In contrast, if we assume stellar X-ray luminosities typical of normal solar-type stars, as represented by the NEXXUS sample (Schmitt & Liefke 2004), then the X-ray-survey horizon is an order of magnitude closer. Of course, as the level of coronal activity increases, so does the surveyed volume in the X-ray band. As is clear from Fig. 17, if the X-ray horizon is to match the $J = 16$ boundary, then the X-ray luminosity will need to have increased to the point at which stellar-coronal emission is known to saturate, namely, at $L_X = 10^{-3} L_{bol}$ (Güdel 2004, and references therein). This, almost certainly, explains the origin of $J \sim 16$ cut-off alluded to earlier.

It is true that previous X-ray surveys have identified some coronal sources emitting above the nominal saturation limit, one explanation being that these are systems caught whilst flaring (e.g. Fleming et al. 1995; Morley et al. 2001). Fleming et al. (1995) estimate that $\sim$25 per cent of solar-like stars and $\sim$50 per cent of dMe stars were detected in the Einstein GPS, whilst flaring, so such sources could represent a non-insignificant fraction of the population in our current sample. However, on the basis of the above evidence, it would seem that even allowing for stellar flaring, the saturation limit is applicable to the vast majority of our soft-band detections. Similar arguments and constraints apply in the case of tidally interacting close binaries, such as RSCVn systems, which maintain fast rotation throughout their main-sequence lifetime possibly into their later evolution (Güdel 2004) and which are amongst the most-luminous sources correlating with stellar counterparts extracted from either the SIMBAD or Sloan data base also show a cut-off in their X-ray-to-IR flux ratio at or near this limit (Agúeros et al. 2009).

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$^{6}$ If we compare the corresponding X-ray and IR flux limits, $F_X = 4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ and $J = 16$, through the relation $\log(F_X/F_J) = \log(F_X)+0.4J+6.30$, we obtain $\log(F_X/F_J) = -1.7$. We note that ROSAT sources correlating with stellar counterparts extracted from either the SIMBAD or Sloan data base also show a cut-off in their X-ray-to-IR flux ratio at or near this limit (Agúeros et al. 2009).

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coronal emitters, with $L_X$ in some cases exceeding $10^{31}$ erg s$^{-1}$ (e.g. Makarov 2003).

Fig. 17 also shows an additional X-ray constraint at about 3 kpc, which is the distance at which the line-of-sight column density exceeds $N_{HI} \sim 1.2 \times 10^{22}$ cm$^{-2}$ (albeit based on a very simplistic absorption model as detailed in the figure caption). At this value of $N_{HI}$, the soft X-ray absorption is such as to move a source from the soft to the hard category (assuming a power-law spectrum with $\Gamma = 2.5$). The implication is that there is a 'spectral' horizon for the soft-X-ray-source sample at about 3 kpc, which corresponds to a soft-band X-ray luminosity of somewhat less than $10^{32}$ erg s$^{-1}$. On the basis of the saturation limit for coronal emission, it would seem that, at least amongst single stars, only F stars are likely to approach the $N_{HI}$ horizon. Conversely, one might conjecture that relatively distant F stars are likely to be predominant as one approaches the HR = 0 boundary.

Finally, we note that the soft-source population could also include some accretion-powered stellar systems, in particular, CVs containing only weakly magnetized white dwarfs. Such sources comprise $\sim 90$ per cent of the accreting white dwarf population (e.g. Warner 1995), have relatively soft thermal components in their spectra and have soft X-ray luminosities typically in the range $L_X \sim 10^{30}–10^{32}$ erg s$^{-1}$ (e.g. Verbunt et al. 1997). Presumably, non-magnetic CVs might be detected out to the $N_{HI}$ horizon and, given the low-mass nature of the secondaries, be rather faint in the NIR. However, given the above statistics, this class of object can, at best, represent only a small fraction of the soft-source population.

6.2 Nature of the hard-X-ray-source population

In the hard X-ray band, if we again take the nominal sensitivity limit to be 2 pm count ks$^{-1}$, then the corresponding unabsorbed flux limit is $F_X = 2.5 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV). This translates to a luminosity of $3 \times 10^{30} (d/1$ kpc)$^2$ erg s$^{-1}$ for a source at a distance $d$ in kpc. In the 2–10 keV band, our XMM–Newton survey is roughly an order of magnitude deeper than the ASCA GPS (Sugizaki et al. 2001), but shallower by about the same factor with respect to the Chandra deep pointing in the Galactic plane reported by Ebisawa et al. (2005).

The incidence of NIR counterparts brighter than $J = 16$ within the X-ray error circles shows a sharp downward step around HR = 0 (Fig. 13), indicative of the fact that the underlying source populations differ markedly between the hard and soft bands. On the basis of the 2MASS and UKIDSS cross-correlation analyses, it appears that true counterparts may be present, as the brightest star in the X-ray error circle, in roughly 25 per cent of cases, down to a limiting magnitude of $J = 20$, set against a chance rate which is 2.7 times this value. If the cut is set at a brighter limit, at, say, $J < 16$, then true counterparts may be present in roughly 15 per cent of cases, set against a chance rate of somewhat less than twice this value. This rather poor ‘success rate’ for an X-ray survey with source locations (or more specifically 90 per cent error circle radii) of better than 5 arcsec radius is, of course, evidence for the relative faintness in the NIR (and optical) of the bulk of the true counterparts. For the hard-band sample, the average $N_{HI}$ inferred from the X-ray spectral analysis is $\sim 3 \times 10^{22}$ cm$^{-2}$, implying $A_V \sim 17$ and $A_J \sim 5$, so it is not surprising that the NIR objects linked to the hard sources are typically very much fainter than the NIR counterparts of the soft sources, for which the impact of line-of-sight absorption is much less severe.

In broad terms, the various classes of hard X-ray-emitting source split into systems containing either a high-mass or a low-mass star (see below). For the stellar-light component, the difference in the absolute magnitude will be at least $\Delta M_J \sim 5$ (e.g. comparing $M_J$ for main-sequence stars earlier than B8 with that for dwarfs later than K0; Kraus & Hillenbrand 2007), implying a difference in log$(F_X/F_J)$ for high-mass and low-mass systems (at a given distance emitting at the same $L_X$) of at least a factor of 2. Even when the total systemic emission is considered, any additional contribution to the light from accretion discs, hotspots, etc., generally fails to bridge this gap (e.g. as in CVs; Ak et al. 2007). It follows that there will be a strong bias towards high-mass systems within the subset of sources with bright NIR counterparts. Of course, for relatively high luminosity systems ($L_X > 10^{32}$ erg s$^{-1}$) detectable in the hard band out to a few kpc and beyond, the impact of interstellar absorption at $J$ will also be a factor tending to suppress the ‘identification’ rate.$^7$

Although our knowledge of the hard-X-ray-source population of the Galaxy at intermediate to faint fluxes is very incomplete, due to the difficulty in identifying large samples of objects drawn from hard X-ray catalogues, we do know at least in qualitative terms which classes of source may be present in significant numbers. The largest single contribution is likely to come from CVs containing an accreting magnetic white dwarf (polars or intermediate polars) in which there is substantial hard emission characterized by thermal temperatures of $kT \gtrsim 10$ keV (e.g. Ezuka & Ishida 1999). This class of source which may account for the very high density of X-ray sources observed in the Galactic Centre (e.g. Muno et al. 2003) and also for a substantial fraction of the hard unresolved X-ray emission, known as the Galactic ridge, observed both near the Galactic Centre and also along the inner quadrant of the Galactic plane (e.g. Revnivtsev et al. 2006; Sazonov et al. 2006). LMXB and HMXB systems emitting at relatively low $L_X$ may also be present in the sample. For example, Pfaal, Rappaport & Podsiedlowski (2002) have suggested that neutron stars accreting from the winds of main-sequence stellar companions might be plentiful in the Galaxy. A similar idea was suggested by Willems & Kolb (2003), involving pre-LMXBs. However, on the basis of a population synthesis model, Liu & Li (2006) conclude that neutron-star LMXB transients in relative quiescence, LMXBs with white dwarf donors and rotation-powered pulsars may provide an alternative explanation for the high density of faint X-ray sources seen in the Galactic Centre. Our survey which encompasses star-forming regions both in the Galactic Centre region and in inner spiral arms of the Galaxy may also contain new examples of the highly embedded supergiant fast X-ray transients, recently discovered by INTEGRAL (e.g. Sguera et al. 2006), and of Be-star X-ray binaries, including $\gamma$ Cas analogues (e.g. Motch et al. 2007).

Relatively hard X-ray emission can also be produced in stellar sources without reliance on accretion power. Shocks produced in the unstable winds of massive Wolf–Rayet (WR) and O-supergiant stars can generate emission above 2 keV. This hard emission can be greatly enhanced in WR/OB binaries, systems which appear to be relatively common in the Galactic Centre (Mauerhan et al. 2009, 2010). Coronal emission in close, tidally interacting, $^7$Although the impact of interstellar absorption will be reduced at K, the commensurately higher stellar densities mitigate against any clear advantage in focusing on the longer wavelength band for the current application.
7 CONCLUSIONS

We have used the 2XMMi source lists pertaining to 116 XMM–Newton observations targeted at the inner quadrant of the Galactic plane to construct a sample of serendipitous Galactic X-ray sources. The main properties of the 2204 sources which comprise the sample are as follows:

(i) The bulk of the sources have total count rates in the range 2–100 pn count ks$^{-1}$(0.5–2 keV). In the soft (0.5–2 keV) band, 2 pn count ks$^{-1}$ corresponds to $F_X = 4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ (0.5–2 keV), assuming an absorbed power-law spectrum with $\Gamma = 2.5$ and $N_H = 10^{21}$ cm$^{-2}$. The same count rate in the hard (2–12 keV) band equates to $F_X = 2.5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ (2–10 keV), in this case assuming $\Gamma = 1.0$ and $N_H = 3 \times 10^{22}$ cm$^{-2}$.

(ii) Using a characterization based on whether the majority of the counts were recorded below or above 2 keV, the sample splits rather cleanly into 1227 soft sources and 977 hard sources.

(iii) Both the broad-band HR distribution and the BI plots reflect a widespread of underlying source spectra. For the soft sources, the X-ray spectra may be represented as either power-law continua with $\Gamma \sim 2.5$ or as thermal spectra with $kT \sim 0.5$ keV with $N_H$ ranging from $10^{20}$ to $10^{22}$ cm$^{-2}$. For the hard sources, a significantly harder continuum form is likely, that is, $\Gamma \sim 1$, with $N_H = 10^{22}$–$10^{24}$ cm$^{-2}$. The sources with HR $> 0.8$ have column densities commensurate with the total Galactic line-of-sight value.

(iv) A high fraction (90 per cent) of the soft sources have potential NIR (2MASS and/or UKIDSS) counterparts inside their error circles, consistent with the dominant soft-X-ray-source population being relatively nearby coronally-active stars. In contrast, the success rate in finding likely NIR counterparts to the hard-X-ray-source sample is no more than $\approx 25$ per cent down to $J = 20$, set against a much higher chance coincidence rate. The make-up of the hard-band population in terms of likely contributors such as CVs, active binaries, relatively quiescent LMXBs/ HMXBs and other classes of objects remains uncertain.

In future papers, we will explore the average X-ray spectral properties of a subset of relatively bright sources drawn from our source sample (Paper II), the $\log N$–$\log S$ curves for both the soft- and hard-source samples (Paper III) and the broad-band colours of likely counterparts to the X-ray sources (Paper IV).

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