Discrete sources as the origin of the Galactic X-ray ridge emission

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An unresolved X-ray glow (at energies above a few kiloelectronvolts) was discovered about 25 years ago and found to be coincident with the Galactic disk the Galactic ridge X-ray emission\textsuperscript{1,2}. This emission\textsuperscript{3–10} has a spectrum characteristic of a $10^8\text{K}$ optically thin thermal plasma, with a prominent iron emission line at 6.7 keV. The gravitational well of the Galactic disk, however, is far too shallow to confine such a hot interstellar medium; instead, it would flow away at a velocity of a few thousand kilometres per second, exceeding the speed of sound in gas. To replenish the energy losses requires a source of $10^{43}\text{erg s}^{-1}$, exceeding by orders of magnitude all plausible energy sources in the Milky Way\textsuperscript{11}. An alternative is that the hot plasma is bound to a multitude of faint sources\textsuperscript{12}, which is supported by the recently observed similarities in the X-ray and near-infrared surface brightness distributions\textsuperscript{13,14} (the latter traces the Galactic stellar distribution). Here we report that at energies of 6-7 keV, more than 80 per cent of the seemingly diffuse X-ray emission is resolved into discrete sources, probably accreting white dwarfs and coronally active stars.
Observations clearly show that some fraction of the X-ray emission of the Galaxy is produced by hot truly diffuse interstellar plasma, heated by e.g. supernovae \(^{15}\), while the bulk of previously unresolved X-ray emission at energies above 1–2 keV remained unexplained. The strong similarity of the Galactic ridge X-ray emission (GRXE) large scale distribution and that of the NIR map of the Milky Way suggested a stellar origin of this emission. The stellar origin was further supported by the close agreement between the X-ray emissivity per unit stellar mass inferred for the GRXE and the collective X-ray emissivity of the stellar population within a few hundred parsecs of the Sun\(^{16}\).

These findings motivated us to perform in 2008 a decisive test with an ultra-deep, 1 Msec, observation of a small (\(\sim 16 \times 16\) arcmin) field near the Galactic Centre (\(l^\text{I I} = 0.08, b^\text{I I} = -1.42\)) with the Chandra X-ray Observatory. We selected this region of the Galactic plane because, here, a high GRXE intensity (essential for minimizing the contribution from extragalactic sources) combines with weak interstellar absorption (crucial for maximizing the 0.5–7 keV Chandra sensitivity for discrete sources). From what we know about the Solar neighbourhood, we can expect the sources producing the bulk of the GRXE to be as faint as \(\sim 10^{30}\) erg s\(^{-1}\) and to have a surface density of \(10^5\) per sq. deq or even higher in the Galactic plane. Only with the combination of an ultra-deep exposure and the excellent angular resolution of Chandra (\(\sim 0.5\) arcsec \(^{17}\)) has the task of resolving the GRXE become possible.

To place the most stringent limits on the fraction of the GRXE resolvable into discrete sources, we selected for our analysis a field where i) the telescope’s angular resolution is best...
and ii) spatial variations of the soft X-ray emission below 1.5 keV (which might be caused by supernova remnants) are minimal. We therefore restrict our present study to a small circle of 2.56 arcmin-radius near the telescope optical axis (see Fig. 1). Below we refer to this field ($l^H = 0.113, b^H = -1.424$) as ”HRES” (stands for ”High Resolution”).

The total measured X-ray surface brightness in HRES is $I_{3-7 \text{ keV}} = (4.6 \pm 0.4) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$ in the 3–7 keV band, or equivalently $I_{2-10 \text{ keV}} = (8.6 \pm 0.5) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$ in the more conventional 2–10 keV band, or, in scale-free units, $I_{2-10 \text{ keV}} = 3.8 \pm 0.2 \text{ mCrab deg}^{-2}$ (here and below the uncertainties are 68% confidence intervals which include both statistical and count rate to flux conversion uncertainties). The brightest source detected in our region has a 2–10 keV flux $\sim 1.8 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ and thus a luminosity $\sim 10^{32} \text{ erg s}^{-1}$ if it is located at approximately the Galactic Centre distance ($\sim 8 \text{ kpc}$). More luminous, rarer sources are found in our Chandra field, but outside HRES; we exclude such sources ($L_{2-10 \text{ keV}} > 10^{32} \text{ erg s}^{-1}$) from consideration when addressing the resolved fraction of the GRXE below.

The total measured X-ray surface brightness must include the contribution from the nearly isotropic extragalactic X-ray background (CXB$^{19}$). The mean CXB intensity over the sky measured by Chandra in the 2–10 keV energy band$^{20}$ $I_{\text{CXB}, 2-10 \text{ keV}} = 2.19 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$, of which 31% is provided$^{25}$ by sources (mostly active galactic nuclei and quasars) brighter than $2 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$. Given the absence of such bright sources in HRES, the total CXB contribution is $\sim 1.5 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$. After subtraction of this extragalactic emission, the GRXE intensity in HRES $I_{\text{GRXE}, 2-10 \text{ keV}} = (7.1 \pm 0.5) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$. 
Looking at the same field in the near-infrared band, which provides the best window on the Galactic stellar mass distribution, the $3.5\mu m$ intensity measured with the Spitzer IRAC instrument is $21 \pm 2$ MJy sr$^{-1}$ (the uncertainty being mainly due to the variance of the number of bright NIR point sources within the small area of the study). Given the interstellar extinction towards HRES $A_V \sim 3.5 - 4.5^{21}$ and adopting $A_{3.5\mu m}/A_V = 0.066^{21,22}$, the extinction corrected NIR surface brightness $I_{3.5\mu m} = 26-29$ MJy sr$^{-1}$. Therefore, the GRXE to NIR intensity ratio in HRES $I_{2-10 \text{ keV}} (10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2})/I_{3.5\mu m}$ (MJy sr$^{-1}$) = $0.25 \pm 0.04$, in perfect agreement with the value characterizing the entire Galaxy, $0.26 \pm 0.05$, deduced from large-scale mapping of the GRXE$^{13}$. This confirms that the findings of the present study of a tiny region of the Galaxy may be regarded as representative of the GRXE as a whole.

We have detected sources in the broad 0.5–7 keV energy band in the summed image of the HRES region (see Fig. 1). The sensitivity limit $f_{\text{lim}} \sim 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ (minimum detectable flux in the 0.5–7 keV band corrected for the interstellar absorption) corresponds to a minimum detectable luminosity $L_{0.5-7 \text{ keV}} \sim 10^{30} \text{ erg s}^{-1}$ at a source distance of 8 kpc, where most of the Galactic objects in this field are expected to reside. In total, 473 sources have been detected with statistical significance $> 4\sigma$ (minimum number of counts per source is about 10). In the upper panel of Fig. 2 we show the energy spectrum of the total emission from HRES, as well as the two components associated with the detected sources and with the remaining unresolved emission. Most importantly, the summed spectrum of detected sources exhibits a pronounced $\sim 6.7$ keV iron emission line, a distinctive feature of the GRXE which was often regarded as an important argument in favour of it being the emission of a truly diffuse hot plasma$^{3,11}$. Only now we clearly...
see that the bulk of the 6.7 keV line emission, as well as of the neighbouring continuum, is in fact produced by point sources. It is worth noting that apart from the dominant 6.7 keV line, the unresolved (partially due to finite energy resolution of the instrument and due to limited statistics of the observation) blend of lines at 6–7 keV may contain some contribution from 6.4 keV iron fluorescent emission, part of which may be unrelated to the GRXE and result from irradiation of the interstellar medium by discrete X-ray sources\textsuperscript{23,24}.

The derived fraction of the X-ray emission resolved into point sources is shown as a function of energy in the lower panel of Fig.\textsuperscript{2} In the narrow energy band 6.5–7.1 keV containing the iron emission line, $84 \pm 12\%$ of the total X-ray emission is resolved. Moreover, we should recall again that the remaining unresolved X-ray emission contains a non-negligible contribution from the CXB. Assuming that the intensity of this unresolved component in our 1 Msec Chandra observation is the same as in the Chandra extragalactic deep fields\textsuperscript{20} ($I_{\text{CXB, unresolved 1 Msec}} = (3.4 \pm 1.7) \times 10^{-12}$ erg s cm\textsuperscript{-2} deg\textsuperscript{-2} in the 2–8 keV energy band, or $(2.9 \pm 1.4) \times 10^{-13}$ erg s cm\textsuperscript{-2} deg\textsuperscript{-2} at 6.5–7.1 keV, assuming a power-law spectral shape with $\Gamma = 1.4$), we can estimate that $4 \pm 2\%$ of the total intensity in the 6.5–7.1 keV band is unresolved CXB emission. We conclude that we have resolved as much as $88 \pm 12\%$ of the GRXE emission into point sources at energies near the 6.7 keV line, the feature that was previously used as the strongest argument in favour of a diffuse origin for the GRXE.

Apart from a small contribution from extragalactic sources (about 40–50 sources out of 473), most of the sources detected by Chandra in HRES are by all likelihood accreting white dwarfs
(with luminosities $L_{2-10\,\text{keV}} \sim 10^{31}-10^{32}\,\text{erg s}^{-1}$) and binary stars with strong coronal activity (with $L_{2-10\,\text{keV}} < 10^{31}\,\text{erg s}^{-1}$). Indeed, if we plot the fraction of the total GRXE flux contained in sources with fluxes higher than a variable detection threshold (see Fig. 3), the resulting dependence proves to be in good agreement with the expectation based on the luminosity function of faint X-ray sources measured in the Solar vicinity\textsuperscript{16}. Furthermore, since this locally determined luminosity function continues to rise towards lower luminosities, we can expect the still unresolved $\sim 10-20\%$ of the GRXE flux also to be composed of coronally active and normal (Sun-like) stars with luminosities $L_{2-10\,\text{keV}} < 4 \times 10^{29}\,\text{erg s}^{-1}$, which are too weak to be detected at the Galactic Centre distance even in ultra-deep Chandra exposures. The contribution of such faint stellar sources should rise with the decrease of the photon energies because they typically have quite soft spectra. This might be one of the reasons why we resolve more flux at high energies than at lower energies.

The final resolution of the GRXE into discrete sources has far-reaching consequences for our understanding of a variety of astrophysical phenomena. Apart from the removal of a major energy problem for the Galaxy, the important immediate outcome is that we can now use the GRXE as a measure of the cumulative emission of faint Galactic X-ray sources in the sense that spatial variations of the GRXE properties over the Milky Way can indicate intrinsic variations in the stellar populations. It has also become clear that the apparently diffuse X-ray emission of external galaxies must contain, and in some cases be dominated by, unresolved emission from faint stellar-type sources, namely accreting white dwarfs and coronally active stars.
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**Figure 1** The deep *Chandra* image of the studied region in energy band 0.5-7 keV. Circles of 2-arcsec radius denote the positions of point sources detected after 1Msec exposure. The *Chandra* data were reduced following a standard procedure\(^\text{18}\). The detector background was modeled using the stowed dataset (http://cxc.harvard.edu/contrib/maxim/stowed) and adjusted to the conditions of the current observations using the count rate at energies 9–12 keV, where *Chandra* has virtually zero effective area. The total measured X-ray surface brightness in this area is \( I_{3–7\text{ keV}} = (4.6 \pm 0.4) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}\) in the 3–7 keV band, or equivalently \( I_{2–10\text{ keV}} = (8.6 \pm 0.5) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}\) in the 2–10 keV band. Throughout the field there are noticeable variations of the soft X-ray (< 2 keV) surface brightness due to what appears to be a previously unknown supernova remnant shell projected onto the Chandra field. It should be noted that if a 1 Msec *Chandra* observation were repeated in a nearby field, the measured X-ray surface brightness would slightly differ because the number of brightest point sources varies from field to field, an effect known as cosmic variance in extragalactic studies. For the same reason, there may be subtle field-to-field variations in the GRXE spectral shape, and in particular in emission lines ratios, and recent observations indicated that such variations to take place\(^\text{10}\). Additional variations of the spectrum of the unresolved Galactic X-ray emission can be caused by the presence of genuine diffuse X-ray emitters such as supernova remnants.

**Figure 2** GRXE spectrum and its resolved fraction. a): Spectra collected by *Chandra* within the HRES region. Black data points, error bars (68% confidence intervals) and histogram show the spectrum of the total emission from HRES; the collective spectrum of all
detected sources is presented in blue and the spectrum of the remaining unresolved emission in the current observations is in red. The integrated spectrum of detected sources exhibits a strong ~6.7 keV iron emission line, characteristic of hot (with temperatures 10–100 million K) plasma emission. This line has been the main support for the popular hypothesis that the GRXE has a truly diffuse, interstellar origin, even though such hot interstellar plasma cannot be confined within the Galaxy by its gravitational potential. Note that we took into account that a small fraction of photons, $X$ (10% at energies 4–6 keV, according to the Chandra Proposers' Observatory Guide$^{26}$) from a point source are scattered by the telescope outside the surrounding 2′′ radius circle. We therefore corrected the directly measured collective spectrum of detected sources $F_1(E)$ through the formula

$$\tilde{F}_1(E) = \frac{F_1(E) - F_2(E)A_1/A_2}{[1 - X - XA_1/A_2]}$$

where $F_2(E)$ is the spectrum of the unresolved X-ray emission, $A_1$ (∼2% of the total) is the area covered by the 2′′ radius circles used for collecting the source fluxes, and $A_2$ is the area outside these circles. 

b): Fraction of the X-ray emission resolved by Chandra into point sources as a function of X-ray photon energy.

**Figure 3** Fraction of resolved X-ray emission around the 6.7 keV iron emission line as a function of the limiting source flux/luminosity. The histogram shows the fraction of the total flux in the 6.5–7.1 keV energy band in the Chandra field provided by discrete sources with fluxes above a given detection threshold in the 2–10 keV energy band. The thick yellow curve shows the corresponding dependence expected for a combination of Galactic sources with luminosities below $10^{32}$ erg s$^{-1}$ (all located at the Galactic Centre distance...
of 8 kpc) and extragalactic sources with fluxes below $2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in this energy band. The blue curve shows the expected contribution of extragalactic sources (mostly active galactic nuclei)\textsuperscript{25}. The green and red curves show the expected contributions of accreting white dwarfs and coronally active stars correspondingly (X-ray spectra of these types of sources are described in e.g.\textsuperscript{27,28}), estimated using the luminosity functions of these classes of objects measured in the Solar vicinity\textsuperscript{16}. These Galactic curves were normalized so that the total resolved fraction given by the model is equal to the actual measured fraction of 84% at the detection limit of the 1 Msec \emph{Chandra} observation of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. Fluxes of sources detected in the total \emph{Chandra} band 0.5–7 keV were converted into the 2–10 keV energy band using a count rate dependent conversion factor that was estimated using stacked \emph{Chandra} spectra of bright, medium and faint sources ($> 100$, 10–100 and 5–10 net counts in the image, respectively). For Galactic sources, their fluxes in the 2–10 keV band were converted to the 6.5–7.1 keV band using a single conversion factor estimated from the stacked \emph{Chandra} spectrum of all detected sources. Comparison of the stacked spectra of bright, medium and faint sources indicates that this conversion factor does not vary by more than a factor of 1.3 around the adopted value. Conversion of fluxes of extragalactic sources from 2–10 keV to 6.5–7.1 keV was done assuming that they have power-law spectra with photon index $\Gamma = 1.4$. 