The 6.7-keV iron-line emission in the Galactic Centre

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Abstract. We use recent XMM-Newton observations to study the “diffuse” X-ray emission seen in the Galactic Centre Region. Spectrally, the emission can be separated into three major components, each characterised by a prominent spectral line. Using these lines as tracers, we investigate the underlying spatial distribution of the various components. Specifically, we find the 6.7-keV line of helium-like iron, has a relatively smooth, circularly symmetric distribution centred on Sgr A* and a surface brightness which falls off with radius as \(r^{-0.87\pm0.06}\) over the range \(r=3'-12'\). This mirrors the distribution of the underlying stellar population and adds strong support to the hypothesis that the 6.7-keV line and the associated hard thermal continuum (with \(kT\approx8\) keV) originates in the summed emission of faint point sources.

1. Introduction

Diffuse X-ray emission pervades both the Galactic Plane and the Galactic Centre Region. Prominent features of this emission are a hard continuum and an associated 6.7-keV emission line from helium-like iron, which, if thermal in origin, implies the presence of a plasma at a temperature of \(5-10\) keV [1]. This hard “Galactic Ridge X-ray Emission” (GRXE), has until recently, remained a major puzzle in the Galactic X-ray Astronomy [2]. However, since the 6.7-keV line is particularly bright in the Galactic Centre, one might hope that studies of this region would provide the best opportunity for identifying the processes giving rise to the phenomenon [3].

Taking account of its apparently diffuse nature, the most straightforward conjecture is that the GRXE is energised largely by supernova explosions. However, individual thermal supernova remnants are generally characterised by temperatures much lower than the \(5-10\) keV required to collisionally excite the observed 6.7 and 6.9-keV lines. A further difficulty is that if this hot emission is truly diffuse, the total amount of energy residing in the plasma is tremendous; for example, the Galactic Centre component alone requires an energy of \(\sim10^{54}\) erg, leading to a major problem of energetics. In fact, the temperature and pressure is so large that such a hot plasma cannot be confined by the Galaxy’s gravitational potential or bound by its magnetic field, implying a very high rate of energy loss (\(\sim10^{43}\) erg s\(^{-1}\) across the whole galaxy).

Chandra observations have recently led to important advances in this field. With its fine angular resolution, Chandra can resolve point sources down to an X-ray flux limit of \(\sim3\times10^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) (2–10 keV) in deep exposures. Even at this level, the bulk of the hard component remains unresolved both in the Galactic plane [4] and in the Galactic Centre [5]. Although this finding would appear to favour the diffuse hypothesis, recent studies of the large-scale distribution of the GRXE demonstrate that it closely follows the near-infrared background.
light of the Galaxy, which in turn is a good tracer of the stellar mass density [6]. This reinforces the alternative view [7], that we are in fact measuring the integrated emission of faint X-ray sources, most of which are likely to be cataclysmic variables (CVs) [6, 8]. It would appear that Chandra surveys reaching fluxes well below $\sim 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ (2–10 keV) will be required to resolve a significant fraction of the hard thermal emission into sources. Based on the Chandra source counts, the number of sources required in the Galactic Centre in order to fully account for the hard emission far exceeds the predicted number of CVs [6, 21]. However, since the nature of Galactic X-ray source population detected at faint fluxes is poorly understood, the uncertainties remain large. In fact, we have demonstrated with XMM-Newton that a population of weak point sources showing strong 6.7-keV line emission does exist in the Galactic Centre [9] and the ASCA and Chandra teams report similar findings [10, 21]. Judging from their strong 6.7-keV lines, these sources are most likely CVs, possibly intermediate polars, although some of them are unusually luminous and may represent the brightest members of a different class of object.

Historically the tracing of the GRXE into the Galactic Centre region has been complicated by both the confusion of luminous point sources and also the presence in the Galactic Centre of bright diffuse components of different origins. For example, much cooler ($kT$ typically $\sim 1$ keV) optically thin thermal emission is apparent throughout the region, presumably as a result of the material and energy released into the relatively dense interstellar environment by supernovae and the stellar winds of high-mass stars. A further diffuse X-ray component which, to date, has only been observed in the Galactic Centre Region, is fluorescent X-ray emission characterised by the 6.4-keV $K_\alpha$ line of neutral or near-neutral iron. This fluorescence has been observed from several dense molecular clouds, most notably the most massive cloud in the Galaxy, Sgr B2 [3, 11, 12, 13]. There remains some uncertainty as to the excitation process. One of the scenarios proposed involves the X-ray illumination of the clouds by external (or perhaps internal) sources, one possibility being that Sgr A$^*$ was much brighter in the past and hence provided the required illumination. An alternative model involves the excitation of the surfaces of the molecular clouds by an intense incident flux of low-energy cosmic-ray electrons (LECRE) [14, 15].

2. Observations and preliminary data reduction
In this paper we use recent XMM-Newton observations to explore the spectral and spatial distribution of the various components of the diffuse X-ray emission seen in the Galactic Centre Region. Specifically we use data accumulated from the series of XMM-Newton observations targeted at Sgr A*, which are available from the XMM public archive. For the present work we focus on images and spectra obtained from the EPIC pn camera, which has a 30$'$ diameter field of view. Both single and double pixel events (pattern 0–4) were selected and all the datasets were screened for periods of high background due to the incidence of soft protons. For each observation flat-fielded images in various wavebands were created by subtracting a constant (non-vignetted) background particle rate (estimated from the corners of the CCD detector not exposed to the sky) and dividing by the appropriate exposure map. The images from the different observations were then mosaiced and spatially smoothed prior to further analysis. For the present work, a composite Galactic Centre spectrum was accumulated from an annular region of inner radius 4$'$ and outer radius 10$'$ centred on Sgr A*. A background spectrum was similarly taken between 10$'$ and 12$'$. In both cases bright point sources and extended sources of particularly high surface brightness, such as the Arches cluster and the G0.1-0.1 molecular cloud, were excluded.

3. Results
3.1. The X-ray spectrum of the Galactic Centre Region
Fig. 1 shows the count-rate spectrum measured in the EPIC pn camera for the Galactic Centre Region. Between 2–4.5 keV the continuum plus prominent helium-like lines due to S, Ar and Ca imply thermal emission at a temperature of $\sim 1$ keV. Above 6 keV, the underlying hard
continuum and the prominent helium-like (6.7 keV) and hydrogen-like (6.96 keV) iron K lines are consistent with an 8-keV thermal component. The fluorescent iron K line at 6.4 keV identifies a third spectral component. Here we model the first two spectral components as thin thermal emission from a plasma in collisional equilibrium (via the Mekal code). We model the third component as the combination of fluorescent line emission and non-thermal bremsstrahlung produced at the surfaces of dense clouds by an incident flux of LECRe [14]. As is evident from Fig. 1, the helium-like sulphur line at 2.46 keV, the helium-like iron line at 6.7 keV and the fluorescent iron line at 6.4 keV can serve as tracers of these three distinct components.

**Figure 1.** XMM-Newton pn spectrum of the Galactic Centre Region. The full spectrum can be modelled (solid line) as the sum of three separate components. These comprise a 1-keV thermal component (dashed line), an 8-keV thermal component (dotted line) and fluorescent line emission plus an associated non-thermal continuum (dot-dashed line).

### 3.2. Imaging the Galactic Centre Region in the continuum and lines

Fig. 2 (top left panel) shows an image of the Galactic Centre Region produced in the 4.5–6 keV band, which is relatively clear of line emission. All three spectral components identified earlier will contribute to this band. The other panels in Fig. 2 show narrow-band continuum-subtracted images centred on each of the spectral lines identified earlier. Clearly the spatial distributions of the three emission lines are very different. The sulphur emission is concentrated in an extended region to the north-east of the Galactic Centre. The 6.4-keV fluorescent iron emission has a similarly asymmetric distribution with very bright clumps associated with known molecular complexes (*e.g.*, the G0.1-0.1 cloud). On the other hand the 6.7-keV iron line exhibits a much smoother distribution which, to a first approximation, is circularly symmetric about the
Galactic Centre.

Figure 2. *XMM-Newton* EPIC pn images of Galactic Centre Region in various wavebands: (a) the 4.5–6 keV X-ray continuum band; (b) a narrow band centred on the 2.46 keV sulphur line; (c) a narrow band centred on the 6.4-keV iron line; (d) a narrow band centred on 6.7-keV helium-like iron line. The three line images are all continuum subtracted. The grey scale is inverted such that the X-ray bright regions appear black. Bright point sources have been excluded, as has the region within 3′ of Sgr A* (the latter region is blanked out). These images have been spatially smoothed with a circular Gaussian mask with $\sigma = 20''$. Each image covers a square region of dimension 21.3′ on a side.

As a check of the hypothesis that the bulk of the diffuse emission seen in the Galactic Centre Region can be associated with one of the three spectral components identified earlier\(^1\), we have compared the observed 4.5–6 keV continuum image to one constructed by applying a scale factor to each of the line images and then simply summing together the scaled versions of the images. In this process, best-fit values for the three scale factors were determined by minimising a $\chi^2$ statistic calculated on the basis of the pixel-by-pixel differences between the constructed and observed images. Using the best-fitting scale factors, we obtained a very good match to the observed continuum image, as is illustrated by the correlation in Fig. 3. These best-fitting

\(^1\) Clearly this is only approximation, which excludes other known contributors to the Galactic Centre X-ray emission. Nevertheless, it does appear that the bulk of the emission resides in just three spectral components.
scale factors can be interpreted, in terms of the assumed spectral models, as measures of the abundance, \( Z \), relative to solar. We obtained \( Z = 0.5 - 1 \) for the sulphur line (in the 1-keV thermal plasma), \( Z \sim 1 \) for the 6.7-keV iron line (in the 8-keV thermal plasma) and \( Z \sim 2.5 \) for the 6.4 keV fluorescent iron line (in the LECRe model), all of which are consistent with the spectral modelling constraints.

Figure 3. Comparison of the fluxes in the 4.5–6 keV band image with those obtained by appropriately scaling and summing the sulphur, 6.4-keV iron and 6.7-keV iron line images. To reduce the size of the error bars, the original images were compressed to give a correlation based on pixels of dimension 72" × 72".

3.3. The radial distribution of the 6.7-keV component
As noted above, the 6.7-keV image shows a relatively smooth, circularly symmetric distribution. However, when we fit the observed surface brightness distribution with a simple \( r^{-\alpha} \) function, where \( r \) is the offset from Sgr A*, we find evidence in the residuals for excess brightness in the north-east of the image. This excess correlates reasonably well with the sulphur distribution and, in fact, we might expect some contamination of the 6.7-keV image by iron-line emission associated with the 1-keV thermal component (see Fig. 1). The approach we have adopted, therefore, is to fit the measured 6.7 keV distribution with a two-component spatial model consisting of a power-law radial dependence plus a scaled version of the sulphur image. The measured radial profile of the 6.7-keV emission (after subtracting the sulphur correction) is shown in Fig. 4. This profile follows a power-law form \( r^{-0.87 \pm 0.06} \) over the range \( r = 3' - 12' \).

The residuals to the two-component fit are shown in Fig. 5. Although regions around bright continuum sources were excluded when fitting the two-component model to the data, we have specifically not excluded these regions in Fig. 5, so as to illustrate the 6.7 keV emission in the Galactic Centre Region over and above the modelled distribution. Although a few bright 6.7
keV sources stand out in these plots, e.g., the Arches cluster ~ 11′ north of Sgr A* and the Sgr A East SNR within the central 3′ field, there is no evidence for any additional large-scale components. Furthermore the fitted radial profile appears to extrapolate reasonably well to within ∼1′ of Sgr A*.

4. Discussion
The measured fall-off in the surface brightness of the 6.7 keV emission in Fig. 4 is rather similar to the $r^{-1.0\pm0.1}$ decline in the surface density of the X-ray point sources resolved by Chandra within 9′ of Sgr A* [5]. Within this central region, resolved point sources with fluxes $\sim 3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ contribute about 10% of the hard diffuse flux [16], with a factor of 40-100 downward extrapolation of the measured source counts required to fully account for the bulk of the diffuse flux. The 6.7-keV surface brightness distribution also mirrors that of the underlying stellar distribution as deduced from infra-red observations of the Galactic Centre [17, 18, 19, 20]. This demonstrates that the correlation of the GRXE intensity with infrared-light observed in the Galactic plane and bulge/bar regions [6], also extends all the way into the central stellar cusp of the Galaxy. As there is no compelling reason to believe that a truly diffuse plasma would show the same spatial profile as that of the underlying stellar distribution, on scales ranging from arcmins to tens of degrees, this is strong evidence that the 6.7 keV represents the integrated emission of a population of discrete X-ray sources embedded within the general stellar population. Recent work suggests that the bulk of the GRXE is due to CVs and coronally active binaries and that the spectral characteristics of these classes of sources are fully consistent with the observed GRXE energy spectrum [6, 8]. In the context of the Galactic Centre a challenge for the future is to confirm that the $2 \times 10^5$ sources with X-ray luminosities in

Figure 4. The radial surface brightness distribution of the 6.7-keV iron line. The solid line has a power-law slope of $-0.87$. 
Figure 5. 6.7-keV band images of the Galactic Centre Region after subtracting the model radial distribution and a sulphur-related component. Left panel: The annular region between a radius of 3' and 12' centred on the position of Sgr A*. In producing this image the regions around bright point and extended sources were specifically included; as a consequence several bright 6.7 keV sources, e.g., the Arches cluster at the northern rim, are apparent. Right panel: The central 3'-radius region. The black contours delineate the Sgr A East SNR. The white contours trace low-level negative residuals, which peak on Sgr A*.

the range $2 \times 10^{29}$ – $2 \times 10^{31}$ erg s$^{-1}$, which are required within the central 40 pc diameter region [16], really do exist and to define the nature and properties of this extremely faint Galactic X-ray source population.

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