XMM-Newton observations of Sagittarius A East

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ABSTRACT
We present an analysis of a recent XMM-Newton observation of Sgr A East, a supernova remnant located close to the Galactic Centre. Very high quality X-ray spectra reveal many emission lines from highly ionized atoms consistent with a multi-temperature thin thermal plasma in ionization equilibrium. We use a two-temperature model to fit the spectra and derive temperatures of 1 keV and 4 keV. There is significant concentration of iron towards the centre of the X-ray source such that the iron abundance varies from \( \sim 4 \) times solar in the core down to \( \sim 0.5 \) solar in the outer regions, which contrasts with the rather uniform distribution of other metals such as sulfur, argon and calcium, which have abundances in the range 1–3. The derived total energy, mass, and the abundance pattern are consistent with a single supernova event, either of type-Ia or type-II origin, involving a relatively low-mass progenitor star. A weak 6.4-keV neutral iron fluorescence line is also detected, the illumination source most likely being Sgr A East itself. The morphology and spectral characteristics of Sgr A East show no clear linkage to putative past activity in Sgr A∗.

Key words: Galaxy: centre – ISM: supernova remnants – X-rays: individual: Sgr A East.

1 INTRODUCTION
Sagittarius A (Sgr A) is an extremely bright radio source situated at the Galactic Centre. At its core is Sgr A∗, a region which harbours a supermassive black hole with a mass of \( 2\times 10^6 \, M_\odot \) (e.g. Genzel et al. 2000). Many reviews have addressed the variety of structures, which are apparent on a wide range of spatial scales, and the complex web of interactions which characterise this region (e.g. Yusef-Zadeh et al. 2000; Falcke et al. 1999; Mezger, Duschl & Zylka 1996).

The Sgr A complex consists of Sgr A West and Sgr A East. Sgr A West includes Sgr A∗, a three-arm spiral-like structure (the mini-spiral) in orbit around Sgr A∗, and the central star cluster (IRS 16). On the plane of the sky, the Sgr A East radio source encompasses Sgr A West and has a non-thermal shell-like structure (Ekers et al. 1975). This morphology has been explained in terms of a supernova remnant (SNR) (i.e. SNR G0.0+0.0; Jones 1974; Ekers et al. 1983; Green 2001). However, alternative and more exotic interpretations have also been proposed, e.g. this is the remnant of an outflow triggered by an explosion in Sgr A∗. It is certainly the case that if Sgr A East has a direct physical link to Sgr A West and Sgr A∗, then its study is particularly interesting in the context of past activity of the central supermassive black hole. But equally well, if Sgr A East is simply an SNR, then its study should lead us to a better understanding of the special interstellar environment of the Galactic Centre region.

The non-thermal shell of Sgr A East is elongated nearly parallel to the Galactic plane with an overall size scale of \( 3.5\times 2.5 \, \text{pc}^2 \) (8.0 kpc distance). It is surrounded by a dust ring (Mezger et al. 1989) and, in projection, overlaps with the giant molecular clouds M−0.02−0.07 (the 50 km s\(^{-1}\) molecular cloud; e.g. Serabyn, Lacy & Achtermann 1992) and M−0.13−0.08 (the ‘20 km s\(^{-1}\)’ cloud; e.g. Mezger et al. 1986). The morphology of the dust ring and the cloud M−0.02−0.07, as well as the detection of coincident OH maser emission (Yusef-Zadeh et al. 1996, 1999), strongly suggests that the non-thermal shell physically interacts with the dust ring and cloud. Based on this observational result, Yusef-Zadeh & Morris (1987) proposed a model in which a supernova occurred inside the molecular cloud and created the Sgr A East shell. More recently Yusef-Zadeh et al. (2000) have outlined a picture in which Sgr A West is embedded in the frontmost region of Sgr A East and both lying within an ionized gas halo of dimension \( \sim 4 \) arcmin \( \sim 9 \) pc (Anantharamaiah, Pedlar & Goss 1999).

Optical, ultraviolet, and soft X-ray observations of Sgr A East are curtailed due to heavy interstellar absorption

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in the line of sight, whereas hard X-ray to γ-ray observations have provided only limited information due to the lack of instruments affording sufficient spatial resolution. Mayer-Hasselwander et al. (1998) detected a significant GeV γ-ray source towards the Galactic Centre with EGRET with a spatial accuracy of 0.2 deg (2EG J1746–2852 = 3EG J1746–2852, re-designated in Hartman et al. 1999). Melia et al. (1998a, b) and Fatuzzo & Melia (2003) suggest that the γ-rays may originate in Sgr A East, although other possibilities, for example the candidate source may be Sgr A∗ or other point/diffuse sources, cannot be excluded. In the soft X-ray band below 3 keV, although major part of the emission is absorbed, Einstein (Watson et al. 1981) and ROSAT (Predehl & Trümper 1994) have detected a diffuse emission extending for ∼20 arcmin. The detailed structure in the close vicinity of Sgr A was left unknown. In the harder X-ray band of Sgr A complex measured, respectively, in the hard (2–10 keV) and soft (0.5–1.4 keV) X-ray bands. When we exclude the 20 arcsec-radius region around Sgr A∗, the central massive black hole. We find that the emission around Sgr A∗ is not point-like and that Sgr A∗ itself is not resolved. Goldwurm et al. (2002) have reported the occurrence of an X-ray flare from Sgr A∗ at the very end of this observation, but here we have specifically excluded data taken during this time interval from our analysis. According to recent Chandra results (Baganoff et al. 2003), Sgr A∗ is the brightest individual source in the central 10 arcsec region, however, its contribution to the total emission from the region is only about 10 per cent. Since the spatial resolution of XMM-Newton is ∼5 arcsec (for the MOS cameras; Jansen et al. 2001), our present result is fully consistent with the Chandra picture.

There is a further extended X-ray emission to the east from Sgr A∗, which is distinct in both the soft and hard bands. When we exclude the 20 arcsec-radius region around Sgr A∗, the centre of the diffuse emission is found to be located at (17h 45m 44s, −29° 0′.3) in the J2000 coordinates. The e-folding radius is 28 arcsec in the core in the 2–10 keV band, although the enhancement in the surface brightness (with respect to the surrounding region) has a full extent closer to ∼200 arcsec across. This diffuse feature

2 THE OBSERVATIONS

We focus on the XMM-Newton observation of the Sgr A region carried out on 2001 September 4 as part of a survey of the whole Galactic Centre region (see Warwick 2002 and Sakano et al. 2003c) and specifically concentrate on the results from the European Photon Imaging Camera (EPIC). The EPIC instrument comprises of two MOS CCD cameras (MOS1 and 2; Turner et al. 2001) and one pn CCD camera (Strüder et al. 2001), which work simultaneously. The MOS and pn CCDs were operated in Full Frame and Extended Full Frame mode, respectively, with the medium filter selected.

We have carried out the data reduction and filtering with the Standard Analysis Software (sas) Ver.5.4. A preliminary screening of the data was applied to exclude intervals of high instrumental background (based on the full-field light curve above 10 keV, which is dominated by particle background events). The effective exposure times for MOS1, 2 and pn after filtering are 23.0 ks, 23.1 ks, and 19.7 ks, respectively.

For each event, we accepted the pixel patterns of 0–12 (single to quadruple events) for MOS. For pn, we only accepted the single event (pattern of 0) because of the calibration uncertainties for other pixel patterns in the pn Extended Full Frame mode.

3 RESULTS

3.1 Image Analysis

Fig. 1a and b shows images of the region encompassing the Sgr A complex measured, respectively, in the hard (2–10 keV) and soft (0.5–1.4 keV) X-ray bands with the MOS1+2 cameras. The highest surface brightness feature in the hard band coincides with the location of Sgr A∗, the central massive black hole. We find that the emission around Sgr A∗ is not point-like and that Sgr A∗ itself is not resolved. Goldwurm et al. (2002) have reported the occurrence of an X-ray flare from Sgr A∗ at the very end of this observation, but here we have specifically excluded data taken during this time interval from our analysis. According to recent Chandra results (Baganoff et al. 2003), Sgr A∗ is the brightest individual source in the central 10 arcsec region, however, its contribution to the total emission from the region is only about 10 per cent. Since the spatial resolution of XMM-Newton is ∼5 arcsec (for the MOS cameras; Jansen et al. 2001), our present result is fully consistent with the Chandra picture.

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Figure 1. Greyscale images of Sgr A East and its surroundings measured with the MOS 1+2 cameras in various energy ranges as follows: (a) 2–10 keV band; (b) 0.5–1.4 keV; (c) a narrow bandpass centred on the 6.7 keV He-like iron line; (d) a narrow bandpass centred on the 2.4 keV He-like sulphur line. Each image is overlaid with the J2000 coordinates (thin dotted lines), the Galactic Plane ($b_{II} = 0^\circ$) (thick dotted line) and the position of the oval radio shell (thin dashed line). The contours trace the 2–10 keV band surface brightness. The data have been smoothed with a Gaussian filter with $\sigma = 4$ arcsec. In the line images (c, d), the underlying continuum has been estimated from an adjacent energy band image (assuming an averaged spectral shape – see text) and subtracted. The two large circles (thick solid lines) with radii of 100 arcsec show the regions used to accumulate the primary source and background spectra, but excluding the contribution of two discrete sources, namely Sgr A$^*$ and XMM J174545.5–285830 identified by name (and by the two small circles drawn with thick dotted lines) in panels (a) & (b). The two circles (thin solid lines) with radii of 28 arcsec and 60 arcsec (a, c) correspond to sub-regions of Sgr A East discussed in the text. The positions of a hard X-ray filament (XMM J174540–2904.5; Sakano et al. 2003a) and a soft X-ray source RX J1745.7–2904 (identified as a star GSC 06840–00590) are also marked.

is clearly elongated along an axis roughly parallel to the Galactic plane.

As shown in Fig. 1, the X-ray emitting region is mostly confined within the radio shell of Sgr A East, in full agreement with earlier Chandra observations (Maeda et al. 2002). On the basis of this strong correlation between the extended X-ray emission and the radio shell structure, hereafter we refer to this bright diffuse X-ray source as Sgr A East.

Since the X-ray spectrum of Sgr A East shows distinct emission lines (see Section 3.2), we have made line intensity images at 6.7-keV and 2.4-keV; the former represents the Kα line from helium-like iron (Fe) whereas the latter is from helium-like sulfur (S). We made three images corresponding to energy bands 2.2 keV–2.6 keV (2.4-keV-band), 4.0 keV–6.0 keV (continuum), and 6.55 keV–6.85 keV (6.7-keV-band). From the measured continuum image, we estimated continuum images appropriate to the 6.7-keV and 2.4-keV bands, taking into account the detector energy re-
sponse and the continuum shape averaged over the whole region. These narrow-band continuum images were then subtracted to reasonable approximations to pure line images at 6.7-keV and 2.4-keV (Fig. 1c, d). The 6.7-keV line is clearly more concentrated in the core of Sgr A East than the continuum (Fig. 1c). This implies that the core of Sgr A East is more abundant in iron, or possibly higher in temperature, or a combination of these two effects. In contrast, the 2.4-keV line peak is located on Sgr A* (Fig. 1d). These effects are investigated quantitatively via the spatially-resolved spectral analysis described in the later sections (Section 3.2.4).

We note that three further bright sources are visible in Fig. 1(a, b). The hard source XMM J174540−2904.5 appears to be a non-thermal X-ray filament (see Sakano et al. 2003a for details). The two soft sources, XMM J174545.5−285830 and RX J1745.7−2904, have previously been detected by ROSAT (Predehl & Trümper 1994; Sidoli, Belloni & Mereghetti 2001). XMM J174545.5−285830 is presumably identical with a Chandra source CXOGC J1745.2−285828 (Muno et al. 2003). We identify RX J1745.7−2904 as a foreground star, GSC 06840−00590†.

3.2 Spectrum

3.2.1 Spectrum accumulation and background subtraction

As illustrated in Fig. 1(a,b), we accumulated the source spectrum from a circular cell of 100 arcsec-radius but excluding the regions within 24 and 16 arcsec-radii of Sgr A* and XMM J174545.5−285830, respectively. The choice of an appropriate background field is not a trivial task due to the clumpy nature of hot plasma, which pervades the whole region. Variations in absorption also add to the complexity of the situation. Here, we chose a nearby background region at nearly the same galactic latitude as the source region (see Fig. 1), so as to minimize systematic effects. In fact, the X-ray hardness does not vary strongly along this axis (Sakano et al. 2003b), and the difference of the X-ray absorption between the source and background regions is also minimized. Since Sgr A East is a very bright source, the spectrum is not strongly affected by selection of the background, except for the outer region defined in Section 3.2.4, as long as we choose the background from a relatively nearby region. For example, the use of a different background dataset gave rise to an overall flux increase in Sgr A East of 5 per cent, whereas the derived temperature changed by ∼10 per cent or less. Although the best-fitting values change slightly depending on the background selection, the spectral structure never changes. We conclude that the spectral results presented below which are derived on the basis of the background field identified in Fig. 1(a) are reasonably robust.

Fig. 2 shows the resultant pn spectra. Several emission lines can be seen, implying that a significant fraction of the spectrum originates from hot thermal plasma.

3.2.2 Fitting with a phenomenological model

Using the xspec package we initially experimented with the simultaneous fitting of the MOS1 and MOS2 spectra with a “phenomenological model” consisting of a multi-temperature continuum plus many Gaussian lines. The continuum comprised three thermal bremsstrahlung components with temperatures initially set at 0.5, 1.0 and 4 keV, each absorbed by a separate column density component. However, in the event it proved necessary to reduce the number of free parameters describing the continuum; this was achieved by fixing the temperature and column for the softest component at 0.5 keV and $7 \times 10^{22}$ cm$^{-2}$ respectively and absorbing the two higher temperature components with the same column density. With continuum so defined, we were able to determine the equivalent widths and centre energies for the set of lines, although for most of the weak lines we fixed the centre energies at the theoretical values expected for a thin-thermal plasma emission (Mewe et al. 1985). In this fitting process, in addition to Ko lines from highly ionized atoms, we also included some Kβ lines, but in this case fixed the line energy and the ratio of the normalisation between Ko and Kβ lines at the values predicted by thin-thermal plasma models (Mewe et al. 1985). Similarly the fluorescent lines from neutral iron (Ko, Kβ) were fitted at fixed line energies. As for the line width, we only allowed that of the 6.7-keV line, which has by far the best statistics, to be free. The other line widths were fixed at the values expected for a thin-thermal plasma (Mewe et al. 1985), taking the energy resolution of the detector into account; e.g., we fixed the width of the 3.13-keV line, which is presumably a Ko-line from helium-like argon, to be 9 eV because this line is actually a combination of resonance, forbidden, intercombination, and satellite lines.

With the best-fit to the MOS spectra determined, we then fitted the pn spectrum with the same model. The MOS and pn results were found to be consistent with each other except for slight differences in the normalisation and energy scale (the latter plausibly attributable to a detector gain error). The pn and MOS spectra were aligned when we applied a gain correction of ∼0.1 per cent to the former. Since the calibration uncertainty is ∼0.3 per cent (Kirsch 2002), this

† http://www-gssss.stsci.edu/gsc/gsc.html

Figure 2. The measured background-subtracted EPIC/pn spectrum of Sgr A East. The best-fitting “phenomenological model” corresponds to a multi-temperature bremsstrahlung continuum plus multiple Gaussian lines. The bottom panel illustrates the spectral fitting residuals.
difference is within the probable uncertainty. In the analysis described below the pn gain was fixed at 1.001.

Table 1 summarises the best-fitting results for the separate MOS and pn fits including probable line identifications, while Fig. 2 displays the pn spectrum with the best-fitting model. The quoted uncertainties in Table 1 and henceforth are at the 90 per cent confidence level for one interesting parameter, unless otherwise mentioned. In particular, the most distinct four lines are identified with $K_{\alpha}$ lines from He-like sulfur, argon (Ar), calcium (Ca), and iron.

Table 1 also gives the results of a simultaneous fit to all three detectors (but with all the line energies fixed as indicated). The global normalisation factor between the pn and MOS spectra was found to be 0.87 (which may be accounted for at least in part by photons in the spectrum-accumulating region in the pn falling on a chip gap). We apply an appropriate correction for “the lost pn photons” in the analysis which follows.

Next we estimated the ionization temperature of the plasma from the ratio of He-like and H-like $K$-lines for each atomic species, using the theoretical results of Mewe et al. (1985). Fig. 3 summarises the derived temperatures. The plasma temperature is found to vary significantly from atom to atom; for example, the ionization temperatures of sulfur and iron are 1 keV and 4 keV, respectively. This implies that the spectrum consists of multiple temperature components. In fact, when we tried to apply a single-temperature thermal model to the spectrum, it is clearly rejected. We note that at the energy of the silicon (Si) line the continuum is strongly affected by absorption, hence the estimate of the ionization temperature of silicon may be subject to some additional systematic uncertainty.

### 3.2.3 Fitting with a thermal plasma model

On the basis of the results presented above, we have applied a two-temperature thin-thermal plasma model (MEKAL) both subject to the same absorption component to the EPIC spectra observed from Sgr A East. We initially adopt the solar abundance ratio (Anders & Grevesse 1989) and, for the absorption, assume the cross sections tabulated by Morrison & McCammon (1983). The ratio of the normalisation between pn and MOS detector was fixed at the value obtained previously. Fig. 4 (upper panel) shows the pn, and MOS1 and 2 spectra with the best-fitting model, whereas the third column in Table 2 gives the fitting results. Notice that the residuals to the fit are most prominent below 4 keV (Fig. 4).

As the next step in the fitting process, we allowed the relative abundances of silicon, sulfur, argon, calcium, and iron in the plasma to be free (but tied across the two different temperature components). The abundance of nickel was linked to that of iron. The result was found to give a reasonably good fit (see the fourth column in Table 2 and the lower panel in Fig. 4). In particular the model reproduces the data above 2 keV very well.

The origin of the residuals apparent below 2 keV is not clear. The current best-fitting model gives a silicon abundance of $\sim 5$ solar, which is 2.5 times higher than that of sulfur and, hence, may not be realistic. On the other hand...
Table 1. Best-fitting parameter values for the phenomenological model discussed in the text

| Param. | Best-fit\(^a\) MOS1+2 | Best-fit\(^a\) pn | Best-fit\(^a\) pn+MOS1+MOS2 | Identification\(^b\) |
|--------|------------------------|-------------------|----------------------------|---------------------|
| Norm.(1) | 44.6 (0.0–79.0) | 43.9 (7.6–94.0) | 15.3 (0.0–21.5) | Si XIII Kα (1.86) |
| Norm.(2) | 31.2 (15.2–47.2) | 29.4 (16.6–50.4) | 22.3 (10.1–62.1) | Si XIV Kα (2.01) |
| Centre(3) | 2.46 (2.44–2.46) | 2.44 (2.44–2.45) | 2.44 (fixed) | S XV Kα (2.44) |
| Norm.(3) | 21.7 (20.1–24.5) | 15.6 (11.8–17.1) | 17.5 (13.1–23.7) | Si XIV Kβ (2.38) |
| Norm.(4) | 2.48 (1.12–3.18) | 1.74 (0.61–2.85) | 1.69 (0.79–2.91) | Si XVI Kα (2.62) |
| Centre(5) | 3.11 (3.09–3.12) | 3.15 (3.10–3.15) | 3.13 (fixed) | Ar XVII Kα (3.13) |
| Norm.(5) | 1.57 (1.30–2.05) | 1.18 (0.77–1.57) | 1.36 (1.03–1.75) | Si XVI Kβ (3.11) |
| Norm.(6) | 0.70 (0.46–0.95) | 0.66 (0.31–0.91) | 0.67 (0.46–0.89) | Ar XVIII Kα (3.32) |
| Centre(7) | 3.89 (3.87–3.91) | 3.91 (3.89–3.94) | 3.89 (fixed) | Ca XIX Kα (3.89) |
| Norm.(7) | 0.84 (0.69–0.98) | 0.64 (0.48–0.82) | 0.78 (0.65–0.89) | Ca XX Kα (4.10) |
| Norm.(8) | 0.06 (0.00–0.17) | 0.09 (0.00–0.22) | 0.08 (0.00–0.17) | Ca XXI Kα (4.10) |
| Centre(10) | 6.67 (6.66–6.67) | 6.68 (6.67–6.68) | 6.68 (fixed) | Fe XXV Kα (6.68) |
| σ(eV)(10) | 37 (15–45) | 44 (34–54) | 40 (31–48) | (17 eV is expected) |
| Norm.(10) | 2.11 (1.99–2.25) | 1.79 (1.70–1.93) | 2.07 (1.97–2.18) | |
| Norm.(11) | 0.16 (0.09–0.25) | 0.13 (0.06–0.19) | 0.15 (0.09–0.20) | Fe XXVI Kα (6.96) |
| Norm.(12) | 0.05 (0.00–0.15) | 0.00 (0.00–0.04) | 0.00 (0.00–0.05) | Ni XXVI Kα (7.76) |
| Norm.(13) | 0.06 (0.00–0.16) | 0.00 (0.00–0.05) | 0.00 (0.00–0.07) | Ni XXVII Kα (8.03) |
| N\(_H\) | 15.2 (14.9–15.4) | 15.2 (14.8–15.5) | 14.7 (13.5–15.7) | (10\(^{22}\)H cm\(^{-2}\)) |
| kT\(_e\) | 3.97 (3.75–4.13) | 4.17 (3.96–4.39) | 4.07 (fixed) | (keV) |
| Norm.\(^c\) | 8.48 (8.01–8.74) | 7.35 (6.97–7.65) | 8.52 (8.09–8.89) | (see below\(^c\)) |
| kT\(_e\) | 1.01 (0.98–1.04) | 1.00 (0.97–1.03) | 1.01 (fixed) | (keV) |
| Norm.\(^c\) | 106 (100–113) | 93.3 (85.9–101) | 94.8 (74.6–118) | (see below\(^c\)) |
| N\(_H\) | 7.00 (fixed) | 7.00 (fixed) | 7.00 (fixed) | (10\(^{22}\)H cm\(^{-2}\)) |
| kT\(_e\) | 0.50 (fixed) | 0.50 (fixed) | 0.50 (fixed) | (keV) |
| Norm.\(^c\) | 58.9 (50.9–72.1) | 61.6 (54.4–77.5) | 70.8 (50.1–88.9) | (see below\(^c\)) |
| Factor | — | — | 0.87 (0.85–0.89) | (pn/MOS) |
| \(\chi^2/\text{dof}\) | 234.0/204 | 123.34/81 | 389.27/314 | |
| \(F_X\)(pn)\(^d\) | — | 1.10 | 1.09 | (10\(^{-11}\)erg s\(^{-1}\) cm\(^{-2}\)) |
| \(F_X\)(MOS)\(^d\) | 1.25 | — | 1.25 | (10\(^{-11}\)erg s\(^{-1}\) cm\(^{-2}\)) |

Adding to these lines, we also included, in the fitting, the Kβ-lines of Si XIII, S XV, Fe I, Fe XXV, and Fe XXVI at the respective energies of 2.18, 2.88, 7.06, 7.90, and 8.21 keV, fixing the centre energy and the ratio of the normalisation to the corresponding Kα line at the theoretical value.

\(a\) The derived line energy and normalisation in units of keV and 10\(^{-4}\) photons cm\(^{-2}\) s\(^{-1}\), respectively. For most of the Gaussian lines, the centre energy is fixed to the theoretically expected value, which is indicated in the last column, in the fitting.

\(b\) The value in the parentheses is the theoretical line-centre energy (in keV), assuming a temperature of 1 keV, 2.2 keV, and 4 keV for He-like lines below calcium, for H-like lines below calcium, or for other lines (nickel, iron and calcium lines), respectively. Most of the lines are combinations of unresolved narrow lines. Thus, we define the centre energy as the weighted mean for these unresolved lines.

\(c\) The unit of \(10^{-12} \int n_e n_H dV/(4\pi D^2)\), where \(n_e\) and \(n_H\) are the electron and proton number densities (cm\(^{-3}\)) and \(D\) is the distance of the source (cm).

\(d\) Observed X-ray flux in the 2–10 keV band.
the addition of a third (lower) temperature component to the spectral model does not give a significant improvement in the fit for reasonable ranges of temperature. The description of the absorption in terms of partial covering does improved the fit ($\chi^2$/dof=359.3/320) significantly but the model parameters are rather poorly constrained and, in any event, the applicability of such a model is questionable.

In summary, the spectral results for the whole of Sgr A East are: (1) the temperatures derived for the two plasma components are $\sim$1 keV and $\sim$4 keV, which are fully consistent with that estimated from the line-ratios (see Fig. 3); (2) the lower-temperature component has a much higher emission measure than the higher-temperature one; (3) the derived metal abundances are, on average, slightly higher than solar values with calcium showing the highest apparent abundance ($\sim$ 2.5 solar).

3.2.4 Spectral variation within Sgr A East

Fig. 1 (c) shows that the He-like iron K-line emission shows a greater concentration in the core region of Sgr A East than is apparent in the 2–10 keV image (Fig. 1a). To investigate spectral variations within Sgr A East, we have extracted spectra from three sub-regions of the source (see Fig. 1c), namely the core (a circle region with $r < 28$ arcsec centred on the peak of the 6.7-keV line), the central annulus (with $r = 28$–60 arcsec again centred on 6.7-keV line peak) and the outer region (i.e. the whole source region except for the core and central annulus). We fitted the spectra of these sub-regions with the same model described in the previous subsection, allowing the relative normalisations for pn and MOS detectors to vary.

Fig. 5 shows the measured spectra together with the best-fitting models, and the last three columns of Table 2 lists the corresponding best-fitting parameter values. Consistent with the image analysis, we find that the iron abundance is highest in the core region ($Z_{Fe} \approx 3.3$), dropping to about half this value in the central annulus to only $Z_{Fe} \approx 0.5$ in the outer region. In contrast the abundances of the other metals (S, Ar, and Ca) do not show large spatial variation across Sgr A East. The derived plasma temperatures are slightly lower in the core region but the ratio of the emission measures of the lower- and higher-temperature components does not change. The 6.4-keV iron fluorescent line is highly significant particularly in the outer region of Sgr A East, where the equivalent width is $\sim$85 eV.

3.2.5 Plasma parameters

The line-of-sight column density measured for Sgr A East is $\sim 1.5 \times 10^{23}$ H cm$^{-2}$. The column density measured for X-ray point sources in the Galactic Centre region is found, in general, to be inversely correlated with the angular distance from the Galactic plane (Sakano et al. 1999; Sakano 2000) and for the position of Sgr A East, the measured column would typically be in excess $10^{23}$ H cm$^{-2}$. In fact, the foreground column density is probably only $3 \times 10^{22}$ H cm$^{-2}$ (Sakano 2000), hence based on column density arguments alone one would place Sgr A East truly in the Galactic Centre region. We therefore assume the distance of Sgr A East to be that of the Galactic Centre, namely 8.0 kpc (Reid

Figure 5. The fitting of the two-temperature thin thermal plasma model with patchy absorption to the spectra measured from three separate regions of Sgr A East. The notation is the same as that of Fig. 4. Top Panel: the core region. Middle Panel: the central annulus. Bottom Panel: the outer region of the source.
Table 2. Spectral fitting results for Sgr A East and its sub-regions

| Params.        | Unit       | Whole | Whole | — Data —  |
|----------------|------------|-------|-------|-----------|
|                |            |       |       | $r < 28''$ | $r = 28''–60''$ | $r > 60''$ |
| Norm(pn/MOS)   |            | 0.87 (fixed) | 0.87 (fixed) | 1.03 (1.00–1.08) | 0.78 (0.75–0.81) | 0.86 (0.82–0.90) |
| $N_H$          | (H cm$^{-2}$) | 11.8 (11.3–12.3) | 13.5 (12.8–14.2) | 15.7 (15.3–16.0) | 14.4 (14.1–14.7) | 11.1 (10.8–11.3) |
| $kT_e(1)$      | (keV)      | 3.81 (3.52–4.06) | 4.23 (3.82–4.71) | 3.05 (2.85–3.17) | 5.5 (5.1–6.1) | 4.41 (4.20–4.89) |
| $I_{\alpha}$   |            | 2.29 (2.15–2.59) | 1.66 (1.33–1.93) | 0.41 (0.36–0.43) | 0.37 (0.35–0.39) | 0.80 (0.74–0.84) |
| $kT_e(2)$      | (keV)      | 0.88 (0.81–0.95) | 0.94 (0.85–1.00) | 0.91 (0.88–0.95) | 1.03 (0.98–1.08) | 0.92 (0.84–0.97) |
| Norm(2)$^a$    |            | 12.1 (9.96–17.3) | 11.6 (9.5–12.7) | 2.7 (2.5–2.9) | 4.2 (4.0–4.4) | 3.8 (3.2–4.0) |
| $Z_{\text{Si}}$|            | 1 (fixed) | 5.1 (3.5–7.3) | 8.9 (7.5–11.9) | 5.6 (4.4–6.9) | 2.7 (2.2–3.3) |
| $Z_{\text{Fe}}$|            | 1 (fixed) | 1.94 (1.56–2.47) | 2.7 (2.3–3.3) | 2.0 (1.7–2.3) | 1.6 (1.3–1.8) |
| $Z_{\text{Ar}}$|            | 1 (fixed) | 1.25 (0.84–1.67) | 1.8 (1.1–2.5) | 1.4 (0.89–1.8) | 1.0 (0.58–1.5) |
| $Z_{\text{Ca}}$|            | 1 (fixed) | 2.54 (2.04–3.07) | 2.5 (1.7–3.3) | 2.6 (1.9–3.2) | 2.9 (2.1–3.5) |
| $Z_{\text{Ne,H}_2}$| 1 (fixed) | 1.33 (1.18–1.51) | 3.8 (3.5–4.0) | 1.50 (1.37–1.65) | 0.47 (0.39–0.54) |
| $\text{Fe-K}\alpha$| $(10^{-5}\text{ph s}^{-1}\text{cm}^{-2})$ | 1.8 (1.0–2.1) | 1.4 (1.1–2.2) | 0.3 (0.1–0.5) | 0.3 (0.1–0.7) | 1.0 (0.6–1.3) |

$\chi^2$/dof

\begin{align*}
\chi^2/\text{dof} & = 459.9/326 \quad 374.5/321 \quad 203.5/182 \quad 241.8/232 \quad 207.7/198 \\
F_X^d & = (10^{-12}\text{erg s}^{-1}\text{cm}^{-2}) \quad 12.6 \quad 12.6 \quad 3.2 \quad 4.2 \quad 5.0
\end{align*}

\begin{align*}
\eta_H & = \frac{\eta_{\text{tot}}}{1 + \frac{\eta_{\text{tot}}}{EM_{\text{H}}}(\frac{T_H}{T_e})^2} \approx 0.63 \eta_{\text{tot}} \quad (6) \\
n_{e,L} & = \sqrt{EM_L + EM_{\text{H}}}(\frac{T_e}{T_L})^2 \approx \frac{19}{\sqrt{\eta_{\text{tot}}}} \quad (cm^{-3}) \quad (7) \\
n_{e,H} & = \sqrt{EM_{\text{H}} + EM_{\text{L}}}(\frac{T_H}{T_e})^2 \approx \frac{5.6}{\sqrt{\eta_{\text{tot}}}} \quad (cm^{-3}) \quad (8)
\end{align*}

Using the above values, the pressure ($P$), energy of the plasmas ($E_L$, $E_H$), and mass ($M_L$, $M_H$) are calculated as follows,

\begin{align*}
P & = n_{e,L}T_L \quad (= n_{e,H}T_H) \quad (9) \\
& \approx 2 \times 10^8 \sqrt{\eta_{\text{tot}}} \quad (K \text{ cm}^{-3}) \quad (10) \\
E_L & = 3n_{e,L}kT_L\eta_LV \approx 5 \times 10^{39} \sqrt{\eta_{\text{tot}}} \quad (erg) \quad (11) \\
E_H & = 3n_{e,H}kT_H\eta_HV \approx 8 \times 10^{38} \sqrt{\eta_{\text{tot}}} \quad (erg) \quad (12) \\
M_L & = n_{e,L}\eta_LV \approx 0.9 \sqrt{\eta_{\text{tot}}} \quad (M_\odot) \quad (13) \\
M_H & = n_{e,H}\eta_HV \approx 0.5 \sqrt{\eta_{\text{tot}}} \quad (M_\odot) \quad (14)
\end{align*}

The inferred total thermal energy $E_{\text{tot}}$ and total mass in the hot plasma is, accordingly, $\sim 1.3 \times 10^{49} \text{ erg}$ and 1.4 $M_\odot$, respectively. Note that we assume solar abundance ratios in the calculation of the mass.

The above estimates related to the core region of Sgr A East. If we use the best-fitting parameters for the whole source (the fourth column in Table 2) and assume $\eta_{\text{tot}}$ to be 0.02 ($\approx (28''/100'')^2$), the derived values are not appreciably changed; for example, the derived total thermal energy and total mass are $\sim 3.0 \times 10^{49} \text{ erg}$ and 2.4 $M_\odot$, respectively. We note that these values may be larger, depending on the filling factor $\eta_{\text{tot}}$ (eq. 11–14).
4 DISCUSSION

4.1 The Sgr A East X-ray source

The X-ray spectrum of Sgr A East shows many emission lines from highly ionized atoms. The line-ratio analysis and the spectral fitting give a consistent view, namely that there are (at least) two temperature components present at $kT \sim 1$ keV and 4 keV. We explain a modest soft spectral excess in terms of patchy absorption. Averaged over the whole source, the derived abundances for different elements are in the range 1–3 times solar. However, there is a significant concentration of iron in the core of the source, amounting to a factor $\sim 4$ overabundance with respect to solar norm.

Koyama et al. (1996), Sidoli & Mereghetti (1999), and Maeda et al. (2002) have presented the ASCA, SAX, and Chandra results of Sgr A East, respectively. Our results are in general consistent with the published findings but also give further constraints on the nature of the source.

On the basis of ASCA data, Koyama et al. (1996) claimed that the X-ray spectral characteristics of Sgr A East are very similar to that of the hot plasma which extends over the whole of the Galactic Centre region (i.e. over a $\pm 1$ deg scale). Our XMM results confirm the presence of a multi-temperature hot plasma in Sgr A East which, at least in qualitative terms, matches the spectral form seen elsewhere in the region. However, Tanaka et al. (2000) report that the helium-like and hydrogen-like iron lines in the integrated spectrum of the whole Galactic Centre hot plasma are broadened by $73\pm14$ eV, whereas we find little evidence for broadening of these lines in the spectrum of Sgr A East.

The higher spatial resolution afforded by Chandra is an advantage for Galactic Centre studies in that much fainter point sources can be identified and their contribution excluded in spectral accumulation. In fact, in the case of Sgr A East the total contribution of discrete sources is less than 1 per cent of the diffuse emission (Y. Maeda; private communication), hence such sources represent a negligible contamination of the XMM-Newton data. Using Chandra, Maeda et al. (2002) find that the spectrum of Sgr A East can be approximated as a thin-thermal plasma model with a temperature of 2 keV, whereas we require temperatures of 1 and 4 keV. We regard these results as consistent, given that the XMM spectra have much better statistics$^\dagger$. Maeda et al. (2002) also find that the iron line is significantly stronger in the inner region of Sgr A East. We confirmed this result and are able to track a decline in iron abundance from the core to the outer region of the source.

Further investigation shows that the X-ray spectrum of the outer region of Sgr A East is, in fact, remarkably similar to that measured for the region immediately around Sgr A* (which we have specifically excluded in the present analysis – but see Sakano et al. 2003b). In particular, the inferred iron abundances are very consistent (i.e. at least a factor three below that measured for the core region of Sgr A East). Given this spectral similarity could these two structures have the same origin? Koyama et al. (1996) have suggested that the high-temperature plasma which pervades the whole Galactic Centre region might in fact be linked in some way to past activity in Sgr A*. However, the only realistic mechanism for heating and ionizing the surrounding media would seem to be episodic outbursts of the central black hole and it is far from clear how the observed X-ray morphology of the Galactic Centre region could arise in such a scenario. In what follows, we interpreted the whole of Sgr A East as one coherent object.

The present XMM-Newton observations demonstrate very clearly that Sgr A East (and particularly its core region) is not bright in the 6.4 keV iron fluorescence line, which characterises regions such as Sgr B2 (Murakami et al. 2000; Murakami, Koyama & Maeda 2001b), where the density of cold molecular material is particularly high (see below). Murakami et al. (2000, 2001a, b) argue that the 6.4-keV line is produced as fluorescent emission on the surface of dense molecular clouds which are illuminated by some external source (or possibly one or more intense embedded sources). An alternative scenario is that the X-ray fluorescence is excited by cosmic rays (e.g. Valinia et al. 2000).

Our measurements show that the 6.4-keV line in Sgr A East is significant with the overall equivalent of $\sim 30$ eV. In the outer region the equivalent width of the 6.4-keV line ($85_{-26}^{+40}$ eV) is significantly stronger than the inner region (<25 eV in the core region) (see Section 3.2.4). This outer region is nearly coincident with the observed dust ring/shell (Mezger et al. 1986, 1989), suggesting the possibility that the dust ring is the source of the line. Mezger et al. (1989) reported that the dust shell has a density of $10^4$ cm$^{-3}$ on average. Then, for a thickness of 1 pc, the column density of the shell is $3\times10^{22}$ H cm$^{-2}$. On the other hand, to account for the equivalent width of (50–110) eV in the highly simplified setting of a central illuminating X-ray source emitting a bremsstrahlung with a temperature of 4 keV and surrounded by an isotropic absorbing medium, a column density of $(4 - 9) \times 10^{22}$ H cm$^{-2}$ is required. Clearly these two estimates of the column are sufficiently close for the dust shell model to be considered a very viable explanation of the observed iron fluorescence emission. Presumably in this scenario the illuminating source is Sgr A East itself.

4.2 Is Sgr A East a SNR?

The observed radio-shell and X-ray centre-filled morphology suggest that Sgr A East may be a so-called mixed-morphology SNR (Rho & Petre 1998). Since the X-ray morphology is not shell-like, estimating the age of the SNR from the X-ray data is not a trivial task. For the 1 and 4 keV plasma components, the velocities of sound are roughly 490 and 900 km s$^{-1}$, respectively. It follows that the sound-crossing times within the radio shell (a radius of $\sim 4$ pc) for the two temperature components are 7700 and 4200 yr, respectively, which are at least zeroth order estimates of the SNR age.

The centre energy of each line (Table 1) suggests that the plasma has already reached a state of ionization equilibrium. The ionization parameters $n_e \xi$ for both

$^\dagger$ We have tested whether our results are dependent on the choice of background region. If we use the same background region as employed by Maeda et al. (2002) we still have incontrovertible evidence for a two-temperature plasma, although the inferred flux in the outer region drops by 50%. The latter is a consequence of the background region being much smaller and closer to Sgr A*. However, the result for the core region is much less affected (<10% change in flux).
the temperature components are calculated to be \( \sim 6 \times 10^{43} t_4 \eta_{\mathrm{hot}} \frac{\text{erg cm}^{-3}}{\text{s}} \) and \( \sim 2 \times 10^{43} t_4 \eta_{\mathrm{hot}} \frac{\text{erg cm}^{-3}}{\text{s}} \), where \( t_4 \) is the time since the explosion in units of 10\(^4\) yr, and \( \eta_{\mathrm{hot}} \) is the total filling factor defined in Section 3.2.5. This means that \( t \gtrsim 5000 \) yr is required for the establishment of ionization equilibrium using the estimated densities. Thus, the larger of the two age estimates quoted above is consistent with the spectral constraints. Mezger et al. (1989) and Uchida et al. (1998) independently estimated the age of Sgr A East, basically from the radio data, to be 7500 and 10000 yr leading to a consistent overall picture.

Sgr A East was found to comprise a two-temperatures component. Most likely, this is only a rough approximation of a reality in which there are many plasma blobs present with temperatures in the range 1–4 keV (or even lower). Since there is little temperature variation across Sgr A East (see Sakano et al. 2003b), the size of each blob is probably relatively small, \(<0.5 \) pc. Adopting this blob model, the filling factor (\( \eta_{\mathrm{hot}} \)) can be smaller than unity.

The total energy of \( \sim 1.3 \times 10^{49} \eta_{\mathrm{hot}} \text{ erg} \) derived from the core region is smaller than the nominal energy for a SNR (\( \sim 10^{51} \text{ erg} \)). Even if we take into account the full extent of the SNR, the total energy is less than \( 10^{49} \text{ erg} \). Since we believe that the plasma has already reached ionization equilibrium, the estimated energy should represent the whole observed thermal energy in the hard X-ray band. Part of the emission in Sgr A East might have already cooled, possibly due to localised, very high-density clouds. Alternatively a significant portion of the energy might have been used for particle acceleration, which has as its signature GeV \( \gamma \)-rays (Mayer-Hasselwander et al. 1998). In any event, there is no requirement for multiple supernova explosions in interpreting Sgr A East as a SNR. The total energy we derive here is consistent with the Chandra measurements (Maeda et al. 2002), but is smaller by 3 orders of magnitude than the estimates quoted by Mezger et al. (1989).

The estimated mass of \( 1.4 \eta_{\mathrm{hot}} \times 10^4 \text{ M}_\odot \) in the hot plasma in the core region is consistent with the SNR hypothesis. For an age of 8000 yr, this mass of the core region could be largely that of the ejecta or could be largely swept-up interstellar matter. In the latter case the concentration of iron in the central 2 pc region of Sgr A East is problematic. If the overabundance is the result of past supernova activity over a timescale of say several million of years, then the extent of the enriched region would be larger than 50 pc. However, the effect of Galactic shear induced by differential Galactic rotation is also critical on such a timescale (see Lugten et al. 1986). We note that the total X-ray emitting mass from the full extent of this SNR could be \( \sim 10 \text{ M}_\odot \), when we use the parameters from the whole region for the estimates, and this mass should be mostly swept-up mass.

A remarkable feature in the spectrum of the core region is the over-abundance of iron, \( Z_{\text{Fe}} \sim 4 \) solar, whereas the abundances of the lighter elements stay at 1–3 solar. The current fitting is based on the emission integrated along the line of sight. However, we estimated the true iron abundance of the core region inside a radius of 1.1 pc to be \( Z_{\text{Fe}} \sim 5 \) solar, once its contribution of the annular regions, i.e. in front of and behind the core region, are subtracted. On the other hand, the abundances of other lighter elements (sulfur, argon, and calcium) show the rather uniform distribution.

Therefore, the abundance of iron in the actual core region of a radius of 1.1 pc relative to the lighter elements can be 2–3 times solar.

The progenitor of type-Ia supernovae is, theoretically, more abundant in iron than lighter elements (e.g. Tsujimoto et al. 1995; Nomoto et al. 1997b). On the other hand, the iron abundance in type-II supernovae is known to be a strong function of the mass of the progenitor star; i.e. as the mass increases, the iron abundance reduces, with iron becoming less abundant than lighter elements if the mass is \( > 20 \text{ M}_\odot \) (e.g. Thielemann, Nomoto & Hashimoto 1996; Nomoto et al. 1997a). Taking into account the uncertainty of both the observation and models, we conclude that Sgr A East is a remnant of either a type-Ia supernova or a type-II event with the mass of the progenitor star of \( \lesssim 20 \text{ M}_\odot \) in the latter case. Our estimated mass (see Section 3.2.5) is consistent with both of these scenarios because a significant part of the X-ray emitting material can be a swept-up mass.

Our findings of a fairly uniform temperature distribution and of a sharp density increase towards the core of the source, as well as the indication from radio observations of an interaction between the shell and the nearby molecular cloud, are in good agreement with the observed properties of other mixed-morphology SNRs (Rho & Petre 1998), as already discussed by Maeda et al. (2002). One major difference in Sgr A East from other mixed-morphology SNRs is that the X-ray emission (of the core region) is associated mostly with the ejecta. Another difference is the unusually high temperature of 4 keV. In fact, this temperature is comparable with, or even higher than, the temperatures of young ‘historical’ SNRs such as Cas A (Holt et al. 1994; Hughes et al. 2000), Kepler (Kimigasa & Tsuemi 1999) and Tycho (Hwang, Hughes & Petre 1998; Decourchelle et al. 2001). Although the cause of this unusually high temperature is unknown, the special environment in the Galactic Centre region may be responsible.

5 SUMMARY

From a recent XMM-Newton observation of Sgr A East, we obtain the following results;

(i) The measured X-ray spectrum probably implies the presence of a multi-temperature thin-thermal plasma but this can be approximated as a two temperature system with \( kT \approx 1 \) keV and 4 keV.

(ii) The abundance averaged over a 100 arcsec radius (~4 pc) region is somewhat higher than solar for atoms from sulfur to iron.

(iii) The iron abundance is high in the core region of the source (where \( Z_{\text{Fe}} \sim 4 \) but less than the solar value in the outer region.

(iv) The volume density is estimated to be 19 electrons cm\(^{-3}\) for the 1-keV plasma and 6 electrons cm\(^{-3}\) for the 4 keV component. The total energy and X-ray emitting mass of the core region are estimated to be \( \sim 1.3 \times 10^{49} \text{ erg} \) and \( 1.4 \text{ M}_\odot \), respectively. Here we have assumed the pressure balance between the different temperature components and the total filling factor of 1 within a spherical volume of radius 1.1 pc.

(v) The abundance pattern of the plasma from sulfur to iron suggests that the X-ray emission originated in a Type-Ia
supernova explosion or Type-II one in a relatively low-mass progenitor star.

(vi) Fluorescent 6.4 keV iron line emission is observed. Plausibly the illumination source is Sgr A East itself.

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