The Arches Cluster and G0.1−0.1 cloud
— A view with fluorescent lines

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Abstract. We present the X-ray results on the Arches Cluster and G0.1−0.1 cloud obtained with XMM-Newton. In particular we have found a big loop-like annular structure, adjacent to the Arches Cluster, with the diameter of ∼3 arcmin (∼7 pc) and width of ∼1 arcmin (∼2 pc). The structure is found to show a non-thermal X-ray spectrum with a best-fitting photon index of Γ = 1.4 ± 0.6, together with a strong fluorescent Kα line from neutral iron at 6.4-keV with an equivalent width of 1 keV. The G0.1−0.1 cloud shows a reasonable correlation among the 6.4-keV line, very hard continuum and 2.3-keV He-like sulphur line. We discuss the possible origin of these structures and further give a speculation to explain the origin of the fluorescent X-ray lines in the Galactic Centre Region.

1. Introduction
Since the hard X-ray imaging era began in the last decade, X-ray observations have given new insights into the Galactic Centre Region (GCR). Arguably the discovery of the diffuse fluorescent iron lines (Koyama et al. 1996) is the most exciting result among the diffuse structures there. It shows a very patchy distribution, which does not resemble any other distribution, and its origin is yet unsolved.

The fluorescent X-ray Kα-line from neutral or low-ionised iron at 6.4 keV (hereafter, simply a 6.4-keV line) is particularly characteristic of the GCR. The 6.4-keV line is a common feature in the X-ray spectrum of type-II active galactic nuclei (AGNs) and of some X-ray binaries. It is thought to come from neutral materials enveloping or surrounding a central strong X-ray emitter. When the continuum itself is blocked or absorbed by something, possibly the envelope itself, the continuum is suppressed, and as a result the 6.4-keV line appears prominent.

The GCR is full of dense molecular clouds, including the most massive cloud in the Galaxy, Sgr B2. Hence, there are a large number of potential emitters of a 6.4-keV line in principle. However, being different from AGNs or X-ray binaries, the GCR lacks an apparent central X-ray emitter bright enough to produce the observed line. One of the scenarios proposed is that Sgr A* used to be bright and that X-rays from Sgr A* at that time were reflected at the clouds and are now observed as a 6.4-keV line (Koyama et al. 1996; Murakami et al. 2000, 2001; Churazov et al. 2002). Another scenario explains it as the interaction between cosmic rays and molecular clouds (Valinia et al. 2000; Yusef-Zadeh et al. 2002; Bykov 2003).

The prototype of these fluorescent clouds in the GCR is Sgr B2. It is barely distinguishable in the continuum band, but is very distinctive in the 6.4-keV line (e.g., Koyama et al. 1996).
Interestingly the brightest spot in the 6.4-keV line in the GCR is not Sgr B2, but the G0.1−0.1 cloud (e.g., see the X-ray image in Koyama et al 1996). More interestingly, G0.1−0.1 apparently has more complex structure than Sgr B2, i.e., it shows thermal and/or continuum components (Koyama et al 1996; Wang et al 2002; Yusef-Zadeh et al 2002; Law & Yusef-Zadeh 2004).

In this paper we present the X-ray results from XMM-Newton observations of the Arches Cluster and G0.1−0.1. The former is one of the most massive star clusters in our Galaxy (e.g., Nagata et al 1995; Figer et al 2005). We have detected a strong iron 6.4-keV line from both the sources. Then we further discuss the possible origin of the 6.4-keV line in the GCR.

2. Observations
We have observed the Arches Cluster and G0.1−0.1 in six occasions with XMM-Newton (See Sakano et al (in prep) for the observation log). All the data with EPIC MOS and pn cameras on board XMM-Newton were analysed. In fitting the spectra, we fitted each spectrum from each camera simultaneously if it had enough statistics, or summed up the whole data set per camera for faint sources to increase the statistics before spectral fitting was carried out.

3. Results on the Arches Cluster
3.1. Images

Figure 1. XMM-Newton MOS1+2 mosaiced image of the Arches Cluster in the 2.0–9.0 keV band. White and black contours trace the 6.7 and 6.4 keV line emission, respectively, which are Kα-lines from He-like and neutral iron. The underlying continuum is subtracted for both the line emission (see text). The colour level and contours are linearly spaced. The Galactic north is up, where the galactic coordinates are given with dashed lines.

Figure 1 shows the X-ray image of the Arches Cluster taken with XMM-Newton/MOS1+2 in the 2–9 keV band, where the different exposures of MOS1 and 2 are summed. The surface brightnesses of two iron K-lines at 6.7 and 6.4 keV are displayed with overlaid contours, where the underlying continuum is subtracted, assuming the same spectral shape for the whole region (See Sakano et al 2004a for the detailed technique).

The peak of the whole energy band image coincides with the peak of the 6.7-keV line from helium-like iron. The peak position is also consistent with the Chandra one (Law & Yusef-Zadeh 2004), and so with the central area of the Arches Cluster.

The most striking result is the existence of the big loop-like annular structure, extending to the galactic north from the Arches Cluster, with the diameter of ~3 arcmin (~7 pc) and width of ~1 arcmin (~2 pc). It is brighter in the north and west sides. The south end is smoothly spread towards the diffuse emission surrounding the Arches Cluster; thus it is not clear whether
the loop structure is physically interacting with the Arches Cluster or not, within the current data and statistics.

The peak of the 6.4-keV line is found to be shifted by 0.8 arcmin to the galactic south of the peak of the full-energy band image and of the 6.7-keV line (or A3 component in Law & Yusef-Zadeh 2004). Interestingly a 6.4-keV line is emitted from the north end of the loop-like structure, as well as, though less significantly, from the west side.

3.2. Spectra
For both MOS1 and 2, we accumulated source spectra from regions of radii 28 arcsec centred on the positions of the peaks of the core and 6.4-keV emission. Note that pn spectra are not used because the area is located in the chip gap during most of the observations. A background spectrum was collected from the annular region that is centred on the averaged position of both the source regions, and has inner and outer radii of 60 and 88 arcsec. This was subtracted from the source spectra. We then simultaneously fitted the spectra from both detectors (i.e., for each detector for each exposure) for each of the core and 6.4-keV regions with trial models of either a thin thermal plasma or a power-law, modified with interstellar absorption.

We have found that the spectrum of the core region is well described with a thin-thermal plasma model with the best-fitting temperature of $2.7 \pm 0.4$ keV, absorption of $N_H = (9.2 \pm 0.9) \times 10^{22}$ H cm$^{-2}$ and respective abundances for silicon to calcium and for iron of $2 \pm 1$ and $0.85 \pm 0.15$ solar in 90% confidence. The equivalent width of the 6.4-keV line is $90 \pm 70$ eV.

![Figure 2. XMM-Newton MOS1+2 summed spectra of the core (red) and 6.4-keV peak (black) regions of the Arches Cluster, where all the exposures are summed, and the background is already subtracted appropriately (see text).](image)

![Figure 3. XMM-Newton MOS1+2 (red) and pn (black) spectra of the loop region, where the background spectra taken from the adjacent region are subtracted.](image)

On the other hand, the modelling of the spectra from the 6.4-keV-line peak region is more complicated. It must include some of the component seen in the core region due to the mirror response. Thus we fit the spectra with a power-law model, added to the best-fitting thermal model derived from the above with a fixed normalisation calculated from the response, and find that the best-fitting model gives the photon index of $\Gamma = 2.2 \pm 1.3$ and the absorption of $N_H = (14 \pm 6) \times 10^{22}$ H cm$^{-2}$. The equivalent width of the 6.4-keV line is $600 \pm 350$ eV, whereas the absolute best-fitting intensity of the line is two times higher than that of the core region.
Figure 2 shows the spectra of those two regions, summed up for MOS1 and 2 and for all the exposures for clarity, together with the best-fitting models. The figure clearly depicts in more quantitative way the strong and weak lines, which have been demonstrated in the image analysis. Moreover the above spectral analysis further shows that the 6.4-keV-peak region has 50% more absorption together with a flatter continuum than the core region.

Next, we accumulated the spectrum from the half-circular annular region that traces the brightest part of the loop region. The background spectra were collected from both the immediate inner and outer vicinities of the loop region, and were subtracted from the above source region. This time we also used the pn spectra. The resultant spectra are found to be even flatter than the 6.4-keV-peak region (Figure 3), with the best-fitting absorption and photon index of $N_H = (7.2 \pm 1.4) \times 10^{22} \text{ H cm}^{-2}$ and $\Gamma = 1.4 \pm 0.6$, respectively. The 6.4-keV line equivalent width is very large, 1000±250 eV.

4. Results on G0.1–0.1

Figure 4 shows the summed pn images of the Galactic Centre, where G0.1–0.1 is bright at the 6.4-keV line. The area is also bright in the very high energy band of 9–12 keV. Indeed an overall correlation between 9–12 keV band and 6.4-keV line images are seen. Above all one of the brightest spots at the 6.4-keV line in G0.1–0.1 is also the brightest spot in the 9–12 keV band apart from the Sgr A region, which is at the centre of the image.

Interestingly G0.1–0.1 is also bright at the 2.3-keV line, which is a Kα line from helium-like sulphur. In this case, the correlation between 2.3-keV and 6.4-keV lines are less clear. For example, the above mentioned brightest spot in the 9–12 keV is clearly dim at the 2.3-keV line. The spatial distribution of the 2.3-keV line is more extended than that of the 6.4-keV line, and possibly slightly shifted towards the galactic north. Nevertheless a rough correlation between them is seen; both of them are spread in the east side of the Galactic Centre in rather negative galactic-latitude and are peaked somewhere at G0.1–0.1. Comparing with the circular symmetric distribution of the 6.7-keV line image (see Warwick et al 2006 in this issue), there is certainly much resemblance between 2.3 and 6.4-keV line distributions.

5. Discussion

5.1. Origin of the X-ray emission from the Arches Cluster

The thermal emission is consistent with the scenario of heated plasma by the stellar wind collision within the cluster, as is previously suggested (Law & Yusef-Zadeh 2004), because the cluster is very massive and dense.

Both the X-ray emissions from the 6.4-keV-peak region and the loop region are, on the other hand, quite unusual. Being fitted with a power law, both of the regions are clearly non-thermal dominated. To produce the 6.4-keV photons through fluorescence, the existence of photons or particles with an energy higher than 7.1 keV is essential. Any thermal emission is unlikely to produce a large flux of those high energy photons. Hence, providing the strong 6.4-keV line is observed, it is natural that the continuum emission is non-thermal rather than thermal.

At the same time, the detection of a strong 6.4-keV line implies a heavy absorption. A heavy absorption is actually observed from the 6.4-keV-peak region, of which the absorption is 50% larger than the adjacent core region of the Arches Cluster. The absorption from the loop region is only a half of the 6.4-keV-peak one: $N_H \sim 7 \times 10^{22} \text{ H cm}^{-2}$. This is probably because the loop is located much farther away from the Galactic Plane, where the averaged absorption in the GCR is a steep function of the angular distance from the Galactic Plane (Sakano et al 1999).

Now, although the equivalent widths of the 6.4-keV line in these structures are large and unusual, being 600–1000 eV, they are not extreme. They could be reproduced by external primary sources or even internal sources, where the direct continuum from them can be observed.
Figure 4. *XMM-Newton* pn summed images in the 9–12 keV band (Left) and of a 2.3 keV line from He-like sulphur (Right), overlaid with the 6.4-keV line contour. The underlying continua for the line images are already subtracted (see Section 3.1 for the method). Apparent point sources are masked (white filled circles). The celestial north is up, whereas the galactic coordinates are displayed with dashed lines. The brightest spot in the 9–12 keV band at the centre is the Sgr A complex, including Sgr A East and West, the latter of which contains Sgr A*. A bright region in the upper-left side is G0.1−0.1.

Whichever the case is, the observed non-thermal continuum must be the remain of the original primary sources. Then, what and where are the primary sources that finally produce these observed non-thermal X-ray emission, associated with the 6.4-keV line? As is already discussed the above, the thermal emission from the Arches Cluster itself is too soft to be the candidate.

No obvious point source around the Arches Cluster is found. Because there are a couple of 6.4-keV structures near the Arches Cluster, if the primary source is a point source(s), it is likely to be more than one source and to be close enough to each 6.4-keV source. However, it is highly unlikely that ordinary point sources are distributed to form a loop-like structure as is seen, therefore the multiple point source synthesis must be rejected.

A more plausible scenario would be that on-site particle acceleration is occurring at each 6.4-keV cloud or in its close vicinity. Supernova remnants (SNRs) have been confirmed as a site for particle acceleration via their shocks, which would produce X-ray emission (*e.g.*, Koyama et al 1995; Hughes et al 2000; Bamba et al 2005).

Then, one possibility is that the loop structure adjacent to the Arches Cluster is just another shell-type SNR, which must be independent of the Arches Cluster. There is also a fairly smooth bridge-like structure in the 6.4 keV line between the loop-like structure and G0.1−0.1 from more global point of view (see Figure 4). Then this loop-like structure may just happen to be located adjacent to the Arches Cluster.

Alternatively, considering that a strong shock causes the particle acceleration, and that in this case low-energy electrons with an energy of a mere few tens of keV are all we need, even the starformation activity of the Arches Cluster may drive the shock. If this is the case, stellar winds or possibly a jet from the Arches Cluster are accelerating particles, following the loop-like shape, and then those high-energy particles produce the fluorescent lines as well as the continuum via the interaction with cold matter.
5.2. G0.1−0.1 and further: Origin of the fluorescent line clouds

We have found rough correlations in the spatial distribution of the 6.4-keV line and that of the very high energy-band continuum, as well as that of helium-like sulphur line. The former is a naturally expected one, taking into account the emitting process of the 6.4-keV line. However, the latter is not straightforward to explain, because the plasma and 6.4-keV lines have, generally speaking, no relationship in terms of the emission process.

The most simple solution may be just that the location coincides by chance, since we do not know the actual distance to each structure. However, if this is truly a result of some cause, the following speculation may work. First, a SNR is made. It produces a shock with ambient matter (possibly the molecular clouds), then the matter is heated to become a plasma, emitting soft X-rays characterised by a He-like sulphur line. At the same time, this shock also causes particle acceleration, possibly at the boundary with molecular clouds, since it will enhance the process in general as is suggested (Fukui et al. 2003). These accelerated particles interact with the ambient clouds, producing a 6.4-keV line as well as a non-thermal continuum.

If this speculation is the case, the sulphur line must be distributed close to the fluorescent clouds, but not exactly. And this indeed is the case for G0.1−0.1. The sulphur line distribution looks slightly shifted towards galactic north. Above all, the brightest spot in the very high energy band and at a 6.4-keV line is dim in the sulphur line. In fact, this situation is similar in the Arches Cluster. The peak position in the 6.4-keV line is shifted from the plasma peak. In addition, Sgr C cloud, the third brightest region with the 6.4-keV line in the GCR also shows a similar situation in a even clearer way (Sakano et al. 2004b).

Some counter-arguments against this speculation may be possible. Sgr B2 does not show this kind of situation. However, Sgr B2 has the largest column density, which is likely to make everything unobservable in the lower energy band, even if a low-temperature plasma exists, unless the plasma is located in front of the cloud.

Why then do star-forming galaxies do not show a 6.4-keV line, which may have to be seen in this scenario? The reason why we see the 6.4-keV line structures in the GCR is because we can spatially resolve the structure. If we take up all the spectra in the GCR, which would represent what could be seen from star-forming galaxies, the 6.4-keV line gets smeared heavily, and will be hardly observed any more. Moreover, star-forming galaxies show even much larger plasma emission, making it even harder to identify a 6.4-keV line.

Another argument is that galactic SNRs show hardly any 6.4-keV line as far as reported. Therefore in the GCR, there must be either an enhancement mechanism of the particle acceleration, e.g., the strong magnetic field, or exceedingly dense molecular clouds, or possibly both.

Finally we argue that whether this shock-origin speculation is true or not, the high-energy particles are the more likely sources for producing a 6.4-keV line than X-rays from discrete sources. The intensity of the (absorption-corrected) 6.4-keV line is simply proportional to the column density of the cloud and luminosity of the illuminating source(s) and is inversely-proportional to the distance of the source(s). Hence, the most influential factor to determine the intensity of the clouds is the distance from the primary source(s). A number of the 6.4-keV line structures have been reported in the GCR (e.g., Park et al. 2004), in addition to Sgr B2, G0.1−0.1 and Sgr C. The distribution is quite patchy; for example, most of them are concentrated in the east side of the Galactic Centre, excepting Sgr C. Added to that, some of them lack of molecular cloud counterparts. Although the brightest three have a molecular cloud counterpart, even these three do not have a perfect matching with molecular clouds in a finer scale less than 1 arcmin (\(< 2pc\)).

If the primary source is a single origin, such as Sgr A*, only the parameter left is the column density of the cloud, apart from the luminosity history of the primary source, once the coordinates of each cloud are determined. Thus, the 6.4-keV intensity should basically
follow the distribution of radio molecular clouds. However, observations tell it doesn’t.

Another possible hypothesis is that some of the X-ray transient sources, which happen to be located close to molecular clouds, may illuminate the clouds (probably by X-rays), producing a 6.4-keV line. It is well known that many transient sources exist in the GCR, which are on and off from time to time (e.g., Wijnands et al. 2006). If they are responsible for the 6.4-keV line, their spectra must be hard and they should have a fairly high duty ratio as a whole. However their nature is yet unclear. Moreover, no transient source has been identified as a candidate source for any 6.4-keV cloud. Therefore this hypothesis is not very likely, if not excluded.

Alternatively, if the primary source itself is a diffuse source, such as accelerated particles, they may also have a patchy distribution. In this case, wherever the diffuse structure closely meets a dense cloud, fluorescent lines are emitted. Hence the patchy distribution of fluorescent lines is relatively easily reproduced.

Acknowledgments
The authors would like to thank the referee Dr. M. Muno for his careful proof reading and valuable comments.

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