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# UNVEILING THE PAST OF THE GALACTIC NUCLEUS WITH X-RAY ECHOES

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**Abstract.** Giant molecular clouds populating the central molecular zone have a high enough column density to reflect X-rays coming from strong compact sources in their neighbourhood, including possible powerful outbursts from the Galactic supermassive black hole Sgr A$^\star$. From observations of the molecular complex Sgr C made with the X-ray observatories *XMM-Newton* and *Chandra* between 2000 and 2014, we confirm this reflection scenario, even though the region hosts several objects (including two PWN candidates) that may be responsible for intense cosmic-ray production. By comparing data to Monte Carlo simulated reflection spectra, we are able to put the best constraints to date on the line-of-sight positions of the main bright clumps of the molecular complex. Ultimately, extending this approach by the inclusion of other molecular complexes allows us to partially reconstruct the past lightcurve of the Galactic supermassive black hole.

Keywords: Galaxy: center, ISM: clouds, X-rays: ISM

## 1 Introduction

Until the late 1990s, the presence of a supermassive black hole at the centre of the Milky Way (as in most nuclei of massive galaxies) was debated, mainly because the candidate radio source Sagittarius A$^\star$ (Sgr A$^\star$; Balick & Brown 1974) was not detected at other wavelengths (see e.g. Goldwurm et al. 1994, for hard X-ray observations). However, the detection of stellar proper motions in the immediate vicinity of the source, followed by the orbital analysis of the so-called "S-stars" (especially S2), led to the unambiguous identification of Sgr A$^\star$ as the electromagnetic counterpart of a supermassive black hole whose mass is about 4 million times that of the Sun (see Genzel et al. 2010, for a review). The source was resolved in X-rays (2–10 keV) with *Chandra* shortly afterwards, confirming that its absorption-corrected quiescent X-ray luminosity ($L_X \sim 10^{33}$ erg s$^{-1}$) is almost ten orders of magnitude below the Eddington limit (Baganoff et al. 2003). As a result, explaining the extreme faintness of the Galactic central black hole has become a challenge.

However, Sgr A$^\star$ might only be in a transient dormant phase. There are indeed several indications that the black hole may have been more active in the past (see Ponti et al. 2013, for a review). For instance, the discovery of two large gamma-ray bubbles extending up to 50° above and below the Galactic plane suggests, among other possibilities, that an intense AGN phase occurred a few $10^6$ yr ago (Su et al. 2010; Zubovas et al. 2011; Zubovas & Nayakshin 2012). Traces of potential more recent high-activity episodes can be found in the molecular material concentrated in the inner $\sim$ 600 pc of the Galaxy, known as the central molecular zone (CMZ; Morris & Serabyn 1996). While propagating through the CMZ, X-ray flares get reflected onto optically thick clouds (Sunyaev et al. 1993). This triggers echoes of the original flaring events than can be used to track the past activity of the Galactic nucleus.

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**Table 1.** Values of the spectral parameters for the two PWN candidates, obtained by fitting the *Chandra* data with an absorbed power law of photon index Γ. $N_H$ is the value of the gas column density responsible for interstellar absorption towards the Galactic centre. Errors are given at $1\sigma$ (68% confidence) level.

| Region | $N_H$ ($10^{22}$cm$^{-2}$) | Γ | $\chi^2$/d.o.f. |
|---|---|---|---|
| G359.40–0.08 | $11.1^{+2.6}_{-2.3}$ | $1.33^{+0.46}_{-0.42}$ | 17.0/14 |
| G359.39–0.08 | $8.2^{+5.0}_{-3.9}$ | $0.69^{+0.86}_{-0.73}$ | 7.5/11 |

These echoes can be identified by their spectrum, which exhibits a bright fluorescent line of neutral and low-ionised iron (Fe K$\alpha$) at 6.4 keV along with a continuum component produced by Compton scattering. Such reflected emission was first detected in the direction of Sgr B2, the most massive giant molecular cloud in the Milky Way (Koyama et al. 1996). It was interpreted as the echo of an outburst that took place at the Galactic center $\sim$ 300 yr ago. Since then, similar detections have been reported in the direction of all main molecular complexes, namely Sgr A, B, C and D, the most likely illuminating source being Sgr A$^\star$ itself (see e.g. Terrier et al. 2017). Yet, no proper reconstruction of the past lightcurve of Sgr A$^\star$ has been possible because the exact positions of the clouds, and hence the propagation delay of the echoes, are unknown. One way to tackle this issue is to correlate variations between multiple clumps all over the CMZ, assuming that they are illuminated by the same event (Clavel et al. 2013; Churazov et al. 2017; Terrier et al. 2017). Another is to use the properties of the reflected emission to constrain the line-of-sight positions of each cloud (Capelli et al. 2012; Ryu et al. 2013; Walls et al. 2016). Indeed, the flux and spectral shape of the reflected emission are very sensitive to the angle between the cloud, the illuminating source and the observer, referred to as the line-of-sight angle, as well as to the cloud column density (Walls et al. 2016), which makes possible the determination of these two parameters using spectral analysis. Here we focus on the reflected emission coming from the molecular complex Sgr C as it allows these two approaches to be applied together for the first time.

## 2 The molecular complex Sgr C

Sgr C is located approximately 0.5° away from Sgr A$^\star$, i.e. at a projected distance of $\sim$ 70 pc. It is an ideal position for studying correlations in the reflected emission from both sides of the Galactic plane, especially since Sgr B2 is located at a similar projected distance on the opposite side of Sgr A$^\star$. Sgr C is also a good candidate for line-of-sight position determination based on spectral analysis since its Fe K$\alpha$ emission is well resolved into a few distinct clumps (Nakajima et al. 2009). Moreover, it allows to verify if the 6.4 keV line is produced either by X-ray echoes or by an alternative mechanism based on cosmic-ray irradiation (e.g. Yusef-Zadeh et al. 2002; Dogiel et al. 2009; Tatischeff et al. 2012). Indeed, Sgr C hosts several objects that may be responsible for intense cosmic-ray production, including the supernova remnant (SNR) candidate G359.41−0.12 and an associated chimney-like outflow structure (Tsuru et al. 2009). It is indeed critical to disentangle the two possible Fe K$\alpha$ emission origins to avoid any misinterpretation.

Sgr C has been frequently observed with various X-ray observatories, during either dedicated pointings or CMZ scans. We consider here *XMM-Newton* and *Chandra* observations covering the period from September 2000 to August 2014. Exposure-corrected images and spectra are produced following the data reduction procedures detailed in Chuard et al. (2017a).

While studying the thermal diffuse emission from the Sgr C region (Chuard et al. 2017b), we report a new non-thermal cometary feature designated as G359.39−0.08 (Fig. 1). It is located within 30 arcsec of G359.40−0.08, another, brighter comet-like X-ray filament already identified by Johnson et al. (2009). This new object is revealed thanks both to *Chandra*'s unique high-resolution imaging capabilities and to the amount of cumulated exposure time ($\sim$ 200 ks). The spectra of these two structures are well fitted using a power-law model with interstellar absorption (Table 1). This, along with their morphology, suggests that they are likely pulsar wind nebulae (PWN). Their proximity to each other and to the SNR candidate is puzzling and suggests that the region might be more complex than previously thought (see also Ponti et al. 2015). Despite the possible interaction of all those structures with the $6 \times 10^5$ M$_\odot$ of molecular gas contained in Sgr C (Liszt & Spiker 1995), Terrier et al. (2017) and Chuard et al. (2017a) independently report that the Fe K$\alpha$ emission from Sgr C exhibits significant variability in both space and time, which confirms its reflection origin. Paradoxically, the Sgr C2 clump, which is located close to the possible interaction site of G359.41−0.12 with molecular gas, exhibits the strongest short-term variability. This strongly confirms the reflection scenario. However, cosmic-ray irradiation may still contribute to the much fainter diffuse background emission.

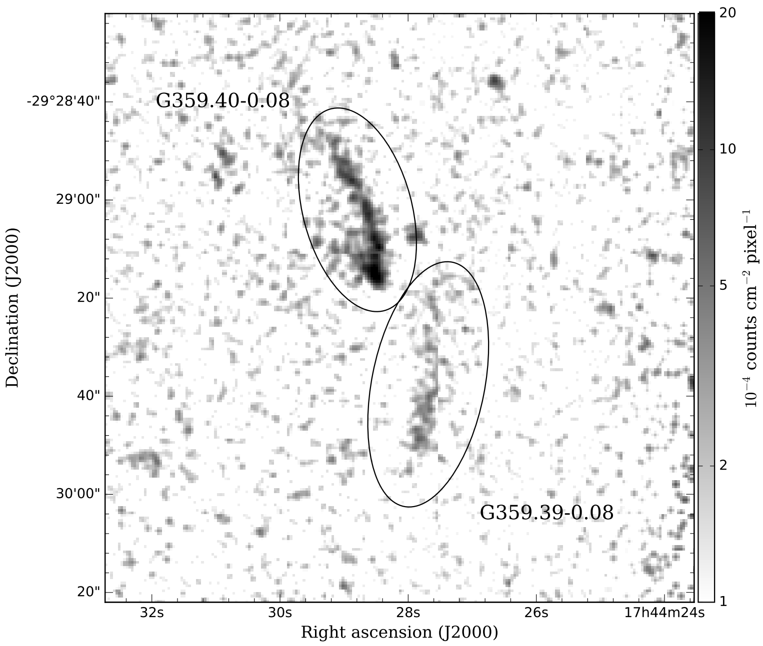


**Fig. 1.** Exposure-corrected image of the two non-thermal cometary features identified in Sgr C, obtained by compiling the 2005 and 2014 *Chandra* observations in the 2.0−8.0 keV band. The map is in units of counts $\mathrm{cm}^{-2}$ $\mathrm{pixel}^{-1}$ with pixel size of about $0.5''$, and smoothed using a Gaussian kernel of 1-pixel radius. It is given in logarithmic scaling with north defined as up and east as left.

## 3 Constraints on the past activity of Sgr A$^\star$

Walls et al. (2016) have developed a Monte Carlo model computing the spectrum produced by X-ray reflection onto a spherical molecular cloud. The geometry of the phenomenon is parametrised in the model by the line-of-sight angle. The total flux in the continuum notably increases with this angle at low energies since photons only penetrate shallowly into the cloud before being scattered towards the observer. The scattered photons are thus more likely to be absorbed in the low-angle case than in the high-angle case. The strength of the 6.4 keV line and the depth of the iron edge also depends on the line-of-sight angle, as well as on the cloud column density. Both are free parameters of the Monte Carlo model that can thus be constrained through a spectral fitting procedure. This allows us to precisely determine the line-of-sight positions of the Fe K$\alpha$ bright clumps, and hence to put constraints on the past lightcurve of Sgr A$^\star$.

For this purpose, we fit the data from the deepest available observations from both *XMM-Newton* and *Chandra* (taken in 2000, 2005, 2012 and 2014) with a spectral model composed of ($i$) two thermal plasmas whose temperatures are fixed at 1.0 and 6.5 keV respectively, ($ii$) the reflected emission as modelled by the Monte Carlo code and ($iii$) foreground interstellar absorption ($N_H = 7.5 \times 10^{22}$ cm$^{-2}$). The metallicity is set to solar values. For a given clump and a given period, the normalisation is left free to vary. The line-of-sight angle and the cloud column density (with a uniform density profile) are also left free but constant over all periods.

The best-fit values of the line-of-sight angles we obtain from the fits are used to derive the 3D positions of the clumps within the CMZ (Fig. 2). Among the three main subregions of Sgr C we study (indicated as Sgr C1, Sgr C2 and Sgr C4), two are found to be behind Sgr A$^\star$, at comparable line-of-sight distances, while the third one (Sgr C2) is in front of it. The error bars are rather small, but it should be kept in mind that some systematics affect our results (see Chuard et al. 2017a, for discussion). All clumps illuminated by the same event must be located on a parabola whose focus is Sgr A$^\star$. Given the positions we obtain, we test two hypotheses: ($i$) that all clumps (including Sgr B2; Walls et al. 2016) witness the same event and ($ii$) that the illumination in Sgr C2 is due to a second event. We fit the data with one-event and two-event models and compare the fit statistics using the $F$-test. The two-event scenario is found to be the best one ($p < 0.05$), with delay values (counted from the year 2000) of $\Delta t_1 = 138^{+27}_{-17}$ yr for Sgr C2 and $\Delta t_2 = 243^{+20}_{-25}$ yr for all other clouds (Sgr C1, C4 and B2). As the systematics mentioned above may affect these values, they should not be

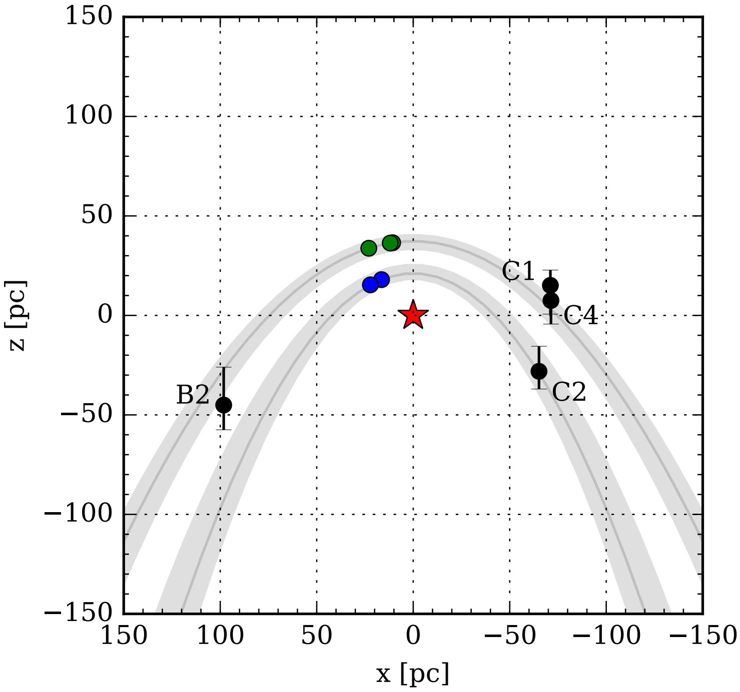


**Fig. 2.** Face-on view of the Galactic centre. The negative direction along the $z$-axis points towards the Earth. The red star marks the position of Sgr A$^{\star}$. The black dots show the best-fit positions for the bright clumps Sgr C1, C2, C4 (Chuard et al. 2017a) and Sgr B2 (Walls et al. 2016). The grey parabolas trace the best-fit associated wavefronts (as seen from Earth) for the two-event model. The width of the parabolas represents the uncertainty on the position, not the duration of the associated event. The green and blue dots are the predicted positions of the subregions of Sgr A (Clavel et al. 2013), assuming they witness the same two events.

considered definitive, but rather good estimates of the actual delays. Despite these limitations, our findings are confirmed by the two distinct patterns of variation seen in the lightcurves of the clumps (see Terrier et al. 2017; Chuard et al. 2017a). They are also consistent with the two-event scenario proposed by Clavel et al. (2013) for five clumps of the Sgr A complex. Indeed, their lightcurves exhibit the same two patterns of variation, which leads us to believe that they witness the same two events as the subregions of Sgr C. Based on this assumption, it is possible to predict their line-of-sight positions (Fig. 2). Testing this hypothesis by applying the Monte Carlo model to the Sgr A complex will be the subject of future work.

## 4 Conclusions

Sgr C is a complex region which notably hosts a SNR candidate possibly interacting with molecular material and two nearby non-thermal X-ray filaments whose spectrum and morphology suggest they are pulsar wind nebulae. These objects may be responsible for intense cosmic-ray production, which may lead to some Fe K$\alpha$ emission. However, the significant variability of the emission discards this hypothesis and strongly supports the reflection scenario.

Using a Monte Carlo spectral model to determine the three-dimensional positions of the 6.4 keV bright clumps, we propose that Sgr C1, C4 and B2 are all illuminated by the same event, while Sgr C2 is likely illuminated by a second flare that took place about 100 years later. These results are supported by imaging analysis and lightcurve extraction, and are consistent with previous works based on different approaches.

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