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X-RAYS FROM THE GALACTIC CENTER AND ACTIVITY OF THE CENTRAL SUPERMASSIVE BLACK HOLE

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Abstract. Relics of intense past activity have been revealed by the X-ray observations covering the inner regions of our Galaxy provided by *XMM-Newton* and *Chandra* observatories. On the one hand, there is a non-thermal emission tracing the echoes of outbursts from the supermassive black hole, Sagittarius A*, that happened in the last centuries and whose light is currently propagating in the central molecular zone. On the other hand, and on even longer timescales, the activity of our Galactic nucleus shaped lobes and chimneys of hot gas extending on both sides of the Galactic plane. The exact origin of these structures is rather uncertain, but they could be the channel through which matter and energy is transported from the inner regions of our Galaxy into the large *Fermi* bubbles seen in γ-rays.

Keywords: Galaxy: center - X-rays: general.

1 Introduction

At about 8 kpc, the Galactic center is the closest galactic nucleus and it is therefore an excellent laboratory to study the complexity of these inner regions and, in particular, the interactions between a supermassive black hole and its environment. Since their respective launch about two decades ago, *XMM-Newton* and *Chandra* have been revealing an increasing number of X-ray features in the central degrees of our Galaxy, including numerous point and extended sources, such as X-ray binaries, stellar clusters or supernova remnants, but also more diffuse emission having thermal or non-thermal origins (see e.g. Ponti et al. 2015). Radio and sub-millimeter observations of this exact same region show that it also contains dense molecular gas and this is why it has been named the Central Molecular Zone (CMZ, Morris & Serabyn 1996).

At the very center, there is the supermassive black hole, Sagittarius A*, which is one of the very faint point sources seen in X-rays. Indeed, the $4 \times 10^6\,\mathrm{M}_\odot$ black hole Sgr A* is the least luminous known supermassive black hole. While its quiescent X-ray luminosity is around $L_X \sim 10^{33}\,\mathrm{erg\,s^{-1}}$, the X-ray counterpart of Sgr A* also experiences daily flares having a timescale of about an hour and during which the X-ray luminosity can increase by up to two orders of magnitude (e.g. Neilsen et al. 2013; Haggard et al. 2019, and references therein). This means that, since the advent of X-ray astronomy, the emission of Sgr A* has remained at least eight orders of magnitude lower than its Eddington luminosity: it is presently a dormant supermassive black hole.

Therefore, the current feedback from Sgr A* onto the Galactic center environment is expected to be extremely weak. Nevertheless, detailed studies of its surroundings have revealed signatures of important feedback, attesting to a higher level of activity from the Galactic nucleus in the past, with different tracers probing timescales from centuries to million years ago. We review the observations of the corresponding features detected in X-rays, namely: light echoes tracing the most recent past (Section 2) and bipolar outflows generated over much longer timescales (Section 3). The constraints obtained on the past activity of Sgr A* are then summarized in Section 4, along with relics seen at other wavelengths.

2 X-ray echoes tracing several short outbursts in the last centuries

The past X-ray emission from Sgr A* is propagating in the inner region of our Galaxy, where it is reflected by the dense molecular clouds of the CMZ, creating light echoes. The X-ray spectrum of the reflecting clouds is then

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characterized by a continuum component created by the Compton scattering of the incident signal, absorbed at low energy, and on top of which there are fluorescent emission lines, including a strong Fe Kα line at 6.4 keV (see e.g. Sunyaev & Churazov 1998). This fluorescent line is therefore a powerful tool to trace the echoes of Sgr A*'s past outbursts in the CMZ and the extent of this region combined with the sensitivity of the current instruments allows to probe the brightest events that occurred in the last thousand years.

The 6.4 keV emission correlated with molecular clouds has been detected across the whole CMZ and, in particular, towards the main molecular complexes: Sgr A, Sgr B and Sgr C (see Figure 1; Terrier et al. 2018, and references therein). Several attempts were made to constrain Sgr A*'s past light curve from the Fe Kα flux measured in individual molecular clouds but, due to the lack of constraints on the line-of-sight position of these clouds, this technique led to divergent results in terms of age and duration of the corresponding events (e.g. Ponti et al. 2010; Capelli et al. 2012; Ryu et al. 2013). The next step was then to use the variability of the echoes, also detected in an increasing number of molecular structures (e.g. Inui et al. 2009; Ponti et al. 2010; Clavel et al. 2013, 2014; Zhang et al. 2015; Chuard et al. 2018; Terrier et al. 2018), to better constrain Sgr A*'s past light curve. This alternative technique consists in studying the fine X-ray variations to spotlight the simultaneity in the illuminated cloud behaviors. Using *Chandra* high spatial resolution, two different time behaviors were identified among the brightest clouds of the Sgr A complex (Clavel et al. 2013). The constraints implied on both the density and the distribution of the clouds make these two behaviors no longer compatible with one single illuminating event. The conclusion of this work is that at least two distinct outbursts, having a luminosity of a few 10^{39} erg s^{-1} and a duration of about 2 and more than 10 years, are currently propagating in the inner region of our Galaxy (Clavel et al. 2013). To have more information about these events, a similar systematic analysis was performed making use of the light curves obtained across the whole CMZ with *XMM-Newton* from 2000 to 2012. This study concludes that all bright clouds are significantly varying over the 12-year period (see Figure 1), so the existence of a putative bright event lasting for several decades and currently propagating in this region is excluded. Moreover, all variations observed are compatible with the two time behaviors described previously and can therefore be explained by the same short events (Terrier et al. 2018).

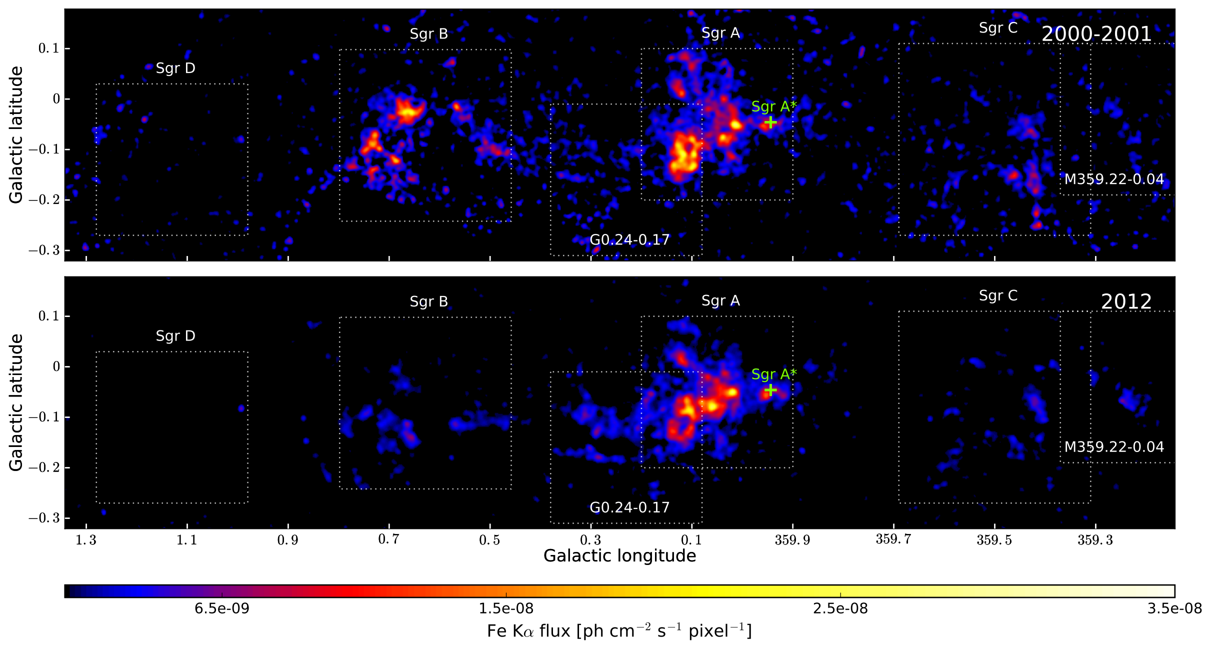

Fig. 1. Background- and continuum-subtracted intensity maps of the central molecular zone measured by *XMM-Newton* at 6.4 keV in 2000–2001 (**Top**) and 2012 (**Bottom**). The dotted square regions highlights areas where significant variations were detected. Figure published by Terrier et al. (2018).

Since the spectral shape of the reflected emission depends on the line-of-sight position of the reflecting clouds, dedicated spectral modeling can provide the age of the events identified through variability studies. The reflected spectra expected for different geometries were computed using Monte Carlo simulations and then used to fit the spectra observed in Sgr B and Sgr C (Walls et al. 2016; Chuard et al. 2018). This technique provided the line-of-sight position of several clumps. The 3D distribution obtained is only compatible with the presence of at least two different past events from Sgr A*, in full agreement with the results described in the previous paragraph. Furthermore, all slow varying features are compatible with being illuminated by the older event occurring about 240 years ago, while the ones seeing faster variations could be illuminated by a more recent, and probably shorter event, occurring about 140 years ago (Chuard et al. 2018). These results rule out the single-event scenario assumed to derive the line-of-sight position of the reflecting features from alternative techniques (see e.g. Churazov et al. 2017), but it does not exclude the existence of a putative third event that would be propagating in more distant portions of the CMZ than the ones investigated by Chuard et al. (2018).

As a summary, the X-ray signal reflected within the CMZ attests than the illuminating source experienced more than one order of magnitude variations over few years only, and several short events producing hard X-rays that are at least a million times brighter than Sgr A*'s quiescent state are needed to explain this variability. Possible alternatives to the supermassive black hole to produce such outbursts have been discussed and discarded based on the energetic involved and the spectral shape required for these events (see Terrier et al. 2010; Clavel et al. 2013; Mori et al. 2015; Zhang et al. 2015; Krivonos et al. 2017, for more details, including spectral constraints derived from *INTEGRAL* and *NuSTAR* hard X-ray observations). Therefore, there is strong evidence that Sgr A* has been brighter in the last centuries but the origin of these past outbursts remains uncertain. Several scenarios have been proposed (e.g. involving partial or full tidal disruptions of stars, planets, asteroids or gas clouds, Yu et al. 2011; Zubovas et al. 2012; Czerny et al. 2013), but a theoretical model matching all the constraints recently derived from the observations, in terms of recurrence, duration, luminosity and spectrum of Sgr A*'s past events has not yet been published.

3 X-ray lobes and chimneys carved by an enhanced level of activity in the last million years.

Periods of intense activity from the supermassive black hole are also expected to generate outflows that could possibly carve high-energy features in the Galactic nucleus environment, visible as an excess of thermal emission.

The first possible such signature has been detected close to Sgr A* and is known as the X-ray lobes (Baganoff et al. 2003; Morris et al. 2003; Markoff 2010; Heard & Warwick 2013; Ponti et al. 2015). They are 15-pc bipolar lobes extending from Sgr A* towards the Galactic north and south, with a plasma temperature $kT \sim 0.7{-}1$ keV, and are showing a strong pressure gradient (see Figure 2, left). Due to their apparent symmetry about the Galactic plane, these structures have been interpreted as outflowing gas originating from the central few parsecs of our Galaxy. This region contains the supermassive black hole and a young cluster of massive stars, as well as dense molecular gas forming the so-called circumnuclear disk (CND, see Genzel et al. 2010, for a review). The location and shape of the CND is such that it could have collimated an isotropic outflow emanating from Sgr A* itself or from its immediate vicinity, creating the bipolar lobes of hot plasma (see e.g. Morris et al. 2003). Assuming that the X-ray gas is filling the whole volume of the lobes, and considering an outflow velocity comparable to the speed of sound set by the gas temperature, the thermal energy of each lobe is $\sim 6 \times 10^{50}$ erg and they have a sound-crossing time $t_s \sim 3 \times 10^4$ yr (Ponti et al. 2019). The average power of the outflow is therefore allowing for several possible origins.

Over the time scale needed for the X-ray lobes to form, two continuous processes can be considered. First, winds from massive stars in the central parsec could be an important contribution in terms of energetic since their velocities are high enough to produce X-rays when they interact with the interstellar medium. However, the stellar cluster being several million years old and the lobes only $\sim 3 \times 10^4$ years old, this scenario does not allow to reproduce the morphology of the X-ray lobes and in particular their pressure gradient (e.g. Markoff 2010). The second possible continuous process is a putative outflow generated by the current level of accretion onto Sgr A*. Indeed, only a very small fraction of the material captured at the Bondi radius is expected to be effectively accreted onto Sgr A* (Wang et al. 2013), so the rest could be converted into outflows sculpting the environment of the black hole. If the energy budget could match the one needed to produce the lobes, again, the shape of the X-ray features is not in favor of this second continuous scenario but is rather pointing to explosive or outbursting events (e.g. Ponti et al. 2015).

Therefore, episodic scenarios have also been proposed. For instance, the X-ray lobes could be a supernova remnant (SNR). Indeed, the central cluster is expected to produce between one and ten supernova explosions every 10^5 years, so these events could contribute to power the lobes (e.g. Ponti et al. 2015). In this case, the compact object created during this event could be one of the known X-ray sources in the vicinity of Sgr A*. Several candidates have been proposed and a hydrodynamic simulation taking into account the complexity of

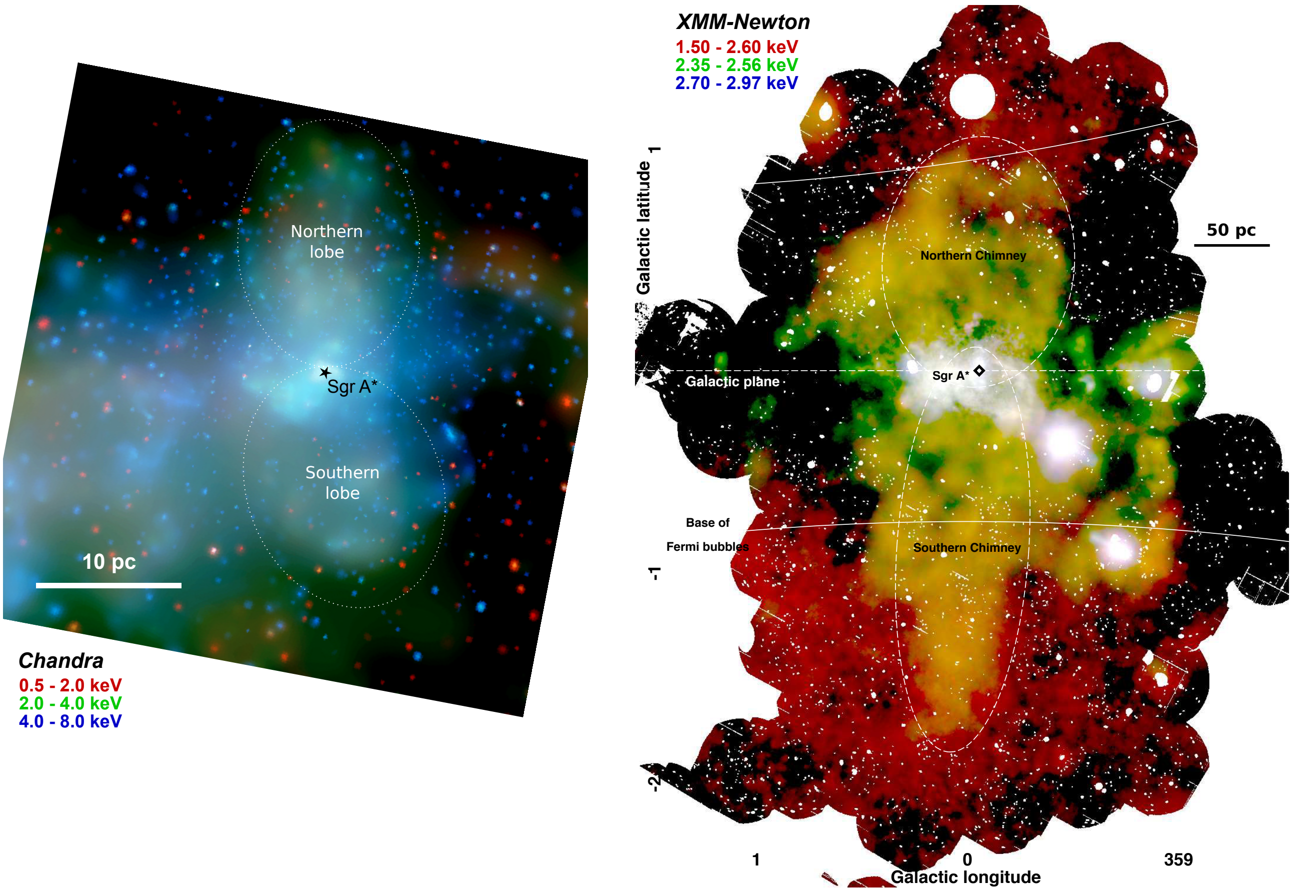

Fig. 2. Left: *Chandra* observation of the 15-pc X-ray lobes. Figure adapted from Muno et al. (2004). **Right:** *XMM-Newton* survey of the 160-pc X-ray chimneys. Figure published by Ponti et al. (2019). Both panels are displayed in Galactic coordinates. In each image, the three colors are tracing different X-ray energies soft (red) to hard (blue, see the corresponding inserts in each panel). These two bipolar structures are roughly symmetric about the Galactic plane, with the X-ray lobes nested at the base of the X-ray chimneys (in the right panel, the 15-pc lobes are the white tiny features surrounding Sgr A*). The slight asymmetry in the shape of the X-ray lobes can be explained by foreground absorption (Ponti et al. 2015), while the differences between the northern and southern chimneys could result from asymmetries in the dense interstellar medium distribution (Ponti et al. 2019).

the Galactic center environment has been able to reproduce the morphology of the X-ray lobes with a SNR that would be associated with the young magnetar SGR J1745–2900 (Yalinewich et al. 2017). From the X-ray point of view, this scenario is robust. However, no non-thermal radio counterpart of the lobes has been detected and this would be a major puzzle if the young supernova origin is confirmed (e.g. Ponti et al. 2015). This is why past outbursts from Sgr A* are also considered as a relevant hypothesis. The estimated age of the X-ray lobes is the same order of magnitude as the recurrence time computed for tidal disruptions of stars by the supermasssive black hole at the Galactic center ($1-2\times10^4$ yr, Alexander 2005), so one tidal disruption event, with a luminosity close to the Eddington one, could be responsible for the corresponding outflow. Nevertheless, less luminous but more frequent outbursts, such as the ones characterized from the X-ray echoes (see Section 2), can also be considered as a viable scenario. If we further assume that more prominent outbursts happened every 5000 years or so, such a collection of past events would also provide an explanation for the brighter knots observed within both lobes (Markoff 2010; Ponti et al. 2015). So the 15-pc X-ray lobes could be tracing Sgr A*'s past activity over the last $\sim 3\times10^4$ years.

Furthermore, all the energetic processes, either continuous or episodic, that have been described in the previous paragraphs are also expected to occur over much longer time scales, and could therefore have shaped even more extended structures. The first hint of such signatures has been an excess of soft X-ray emission detected by *Suzaku* to the south of the Galactic center. Its X-ray spectrum is consistent with a recombining plasma, its absorption indicates that it is located in the inner regions of our Galaxy and a past starburst activity or an episode of enhanced activity from Sgr A* have been proposed as most plausible origins (Nakashima et al. 2013). More recently, a similar excess interpreted as a magnetized hot gas outflow from the Galactic center was also detected by *Suzaku* towards the Galactic north (Nakashima et al. 2019). The high-latitude survey performed by *XMM-Newton* in 2016–2018 confirms the existence of these brighter regions and revealed that they are part of a 160-pc bipolar structure connected to the central region and extending on both sides of the Galactic plane (see Figure 2, right). These features, called the X-ray chimneys, have a plasma temperature $kT \sim 0.7$ keV and no pressure gradient is detected within them, which means that they are likely close to hydrostatic equilibrium. Their thermal energy is about 4×10^{52} erg and their sound crossing time $t_s \sim 3 \times 10^5$ yr, so the average power of the corresponding outflow is possibly only about a factor five greater than the one derived for the 15-pc lobes (Ponti et al. 2019). The energetic events shaping the X-ray chimneys could therefore be very similar to the ones discussed as possible origins of the X-ray lobes, and the lobes could even trace the most recent episode of energy injection into the chimneys.

However, the base of the chimneys is likely not limited to the X-ray lobes but could instead correspond to a $\sim$ 50-pc region surrounding Sgr A*. So, outflows from past energetic events, such as supernova explosions, occurring in this wider region could also be injected into the chimneys. Furthermore, Ponti et al. (2019) suggested that the X-ray chimneys could have transported powerful outflows from the Galactic center into the Halo, so the total energy conveyed by this channel could be greater than the one still radiating today. This scenario is supported by *ROSAT*, *Suzaku*, *Chandra* and *XMM-Newton* detections of X-ray emission at even higher latitudes, forming what could be the base of the *Fermi* bubbles (see Figure 2, right; Ponti et al. 2019, and references therein). If confirmed the power transported by the chimneys could be up to four orders of magnitude greater than the one computed from their X-ray emission (e.g. Su et al. 2010). Such powerful outflows could be associated with star formation processes at the Galactic center in the last few million years, and the contribution from Sgr A* could be limited. Nevertheless, scenarios involving the most extreme events such as tidal disruptions of stars by the supermassive black hole or periods of intense accretion transforming the Galactic center into an active galactic nucleus (AGN) cannot be excluded (see also Section 4).

4 Conclusions

By studying the X-ray features present in the inner regions of our Galaxy, it is possible to constrain the duty cycle of our dormant supermassive black hole.

The X-ray light emitted by Sgr A* in the last centuries is still propagating in the central molecular zone, generating X-ray echoes. The variability and the spectral properties of this reflected emission reveals the existence of several short outbursts from Sgr A* over the corresponding period. Despite an increasing precision in the description of these past events, their exact nature is still unknown.

The outflows generated by the past activity of our Galactic nucleus are also expanding away from the center, carving X-ray thermal features. The lobes and chimneys detected in the central degrees suggest periods of enhanced activity from the central region over the last million years. However, the link with Sgr A*'s past activity is uncertain as processes associated with stellar formation and supernova explosions have also been proposed. So, the energy levels derived from these X-ray structures can be considered as upper limits on the past luminosity of the supermassive black hole.

This review focused only on X-ray features and is therefore not exhaustive since relics of past activity from our Galactic nucleus have also been detected at other wavelengths. This is for instance the case of the *Fermi* bubbles already mentioned in Section 3. These large bubbles detected in γ-rays extend over $\sim$ 10 kpc towards the Galactic poles and were likely generated by an important injection of energy in the last ten million years, such as could have been produced by past accretion events onto Sgr A* or a nuclear starburst (Su et al. 2010). If these two scenarios are able to reproduce the γ-ray emission, it is not the case of the Hα emission detected along the Magellanic Stream. The latter is too bright to be the result of stellar formation and favors an AGN-like activity of the supermassive black hole, with an intense UV radiation emitted few million years ago (Bland-Hawthorn et al. 2013). Therefore, it is likely that the gaseous accretion disk that triggered the formation of the central stellar cluster about six million years ago also significantly increased the accretion rate onto Sgr A*, creating a period of intense past activity that likely contributes to the large X-ray and γ-ray relics detected in the Galactic environment.

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