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Can we infer the past activity of M31* as we do for Sgr A*?

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Abstract. The history of supermassive black holes' activity can be partly constrained by monitoring the diffuse X-ray emission possibly created by the echoes of past events propagating through the molecular clouds of their respective environments. In particular, using this method we have demonstrated that our Galaxy's supermassive black hole, Sgr A*, has experienced multiple periods of higher activity in the last centuries, likely due to several short but very energetic events, and we now investigate the possibility of studying the past activity of other supermassive black holes by applying the same method to M31*. We set strong constraints on putative phase transitions of this more distant galactic nucleus but the existence of short events such as the ones observed in the Galactic center cannot be assessed with the upper limits we derived.

Keywords. Galaxy: center, galaxies: individual (M31), X-rays: ISM, reflection nebulae, radiation mechanisms: nonthermal.

1. Introduction

Sgr A* and M31* are the two nearest supermassive black holes, respectively at the Galactic center and in the Andromeda galaxy. Both are currently faint, with X-ray luminosities which are several orders of magnitude below their Eddington luminosities (e.g. Neilsen *et al.* 2015; Li *et al.* 2011), which leaves open the question of the duty cycle of such objects.

Any period of increased activity, from short catastrophic events to long AGN cycles, would generate a feedback on their surrounding environment, which would leave subsequent traces in the host galaxy. These relics, such as strong ionization, bubbles, fossil jets or reflection features, can be used to derive constraints on the past activity of these dormant supermassive black holes (e.g. Li *et al.* 2013; Ponti *et al.* 2014; Keel *et al.* 2015). We focus on one relic in particular: as the high-energy light propagates away from the central source, it interacts with the molecular gas present in the host galaxy and creates a reflection signal dominated by an Fe Kα fluorescent line at 6.4 keV. The properties of the incident event (age and luminosity) can then be derived using the intensity of this fluorescent line, the density of the reflecting gas and the 3D geometry of the system (e.g. Cramphorn & Sunyaev 2002; Walls *et al.* 2016).

This technique provides the strongest constraints we currently have on Sgr A*'s past activity (Section 2) and we investigate whether the same method could be applied to nearby supermassive black holes, starting with the closest one: M31* (Section 3).

2. Sgr A*: multiple short outbursts in the past centuries

Sgr A* is relatively close to the Earth (~ 8 kpc) and is surrounded by dense molecular gas forming the so-called Central Molecular Zone (CMZ), which occupies the inner 300 pc of the Galactic center. Therefore, any powerful event experienced by Sgr A* in the past 1000 years is expected to produce an observable reflection signal in this region (Sunyaev *et al.* 1993, Koyama *et al.* 1996).

Since the launch of *Chandra* and *XMM-Newton*, the Galactic center has been regularly observed in X-rays: a strong 6.4 keV emission associated with the main molecular complexes is detected, and the significant variability of this emission has been reported for an increasing number of molecular clouds (e.g. Ponti *et al.* 2010; Terrier *et al.* 2010; Clavel *et al.* 2013; 2014; Chuard *et al.* 2016). However, the uncertainties on the molecular 3D distribution have not allowed to use these detections to produce a unique coherent scenario for the past activity of Sgr A* (see Ponti *et al.* 2010; Capelli *et al.* 2012; Ryu *et al.* 2013, for different attempts). Based on this statement, we decided to extract as much information as possible from the X-ray data alone, by performing systematic studies of the 6.4 keV emission and its variability. This technique aims at studying the reflection signal on the smallest possible spatial and temporal scales in order to reveal fast variations and similarities among the cloud behaviors (see Clavel *et al.* 2013, for more details).

Complete survey of the CMZ. Taking advantage of the full *XMM-Newton* data set (2000–2012), and in particular of the two large surveys performed in 2000–2001 and in 2012, we apply our systematic analysis to the entire CMZ, using one-arcmin-squared subregions. On this scale, we confirm that the main molecular complexes are 6.4 keV emitters, and we report for the first time that all bright features have been significantly varying over the past decade (Terrier *et al.* 2016, in prep). This result confirms the reflection origin for a significant fraction of the 6.4 keV emission at the Galactic center and excludes any long period of increased activity ($L_X > 10^{39}\,\mathrm{erg\,s^{-1}}$) from Sgr A* in the recent past. Indeed, if a long-duration event (several decades) was currently propagating in the CMZ, we would expect to detect at least some bright features with a steady level of emission over the whole 2000–2012 period, which is not what we observe (Terrier *et al.* 2016, in prep). Therefore, Sgr A* is likely to have experienced only short outbursts in the past centuries.

High-resolution study of the Sgr A molecular complex. Using the full *Chandra* data set (1999–2011), we performed a dedicated study of the Sgr A complex. Going down to smaller scales ($15'' \times 15''$ subregions) and taking advantage of the yearly coverage available for this region, we were able to study the fine variations occurring within this molecular complex, and to highlight two distinct time behaviors (Clavel *et al.* 2013). These results provide additional constraints on the corresponding short events: there are at least two past events propagating in the Sgr A complex, they have similar luminosities ($L_X > 10^{39}\,\mathrm{erg\,s^{-1}}$) but different durations (about 2 and 10 years, respectively). The most recent *Chandra* observations (2015–2016) confirm the main predictions from this earlier study and reinforce its conclusion (Clavel *et al.* 2016a, in prep).

Inputs from hard X-ray observations. The *NuSTAR* survey of the Galactic center region (2012–2013) provides a description of the diffuse emission above 10 keV, permitting a better constraint on the non-thermal continuum component associated with the Fe Kα emission line. Therefore, using simultaneous *XMM-Newton* and *NuSTAR* observations, it is now possible to also infer the spectrum of Sgr A*'s past events. According to current constraints, they are compatible with a power-law of photon index $\Gamma \sim 2$ (see Mori *et al.* 2015; Zhang *et al.* 2015, for more details), in agreement with earlier *INTEGRAL* measurements (Terrier *et al.* 2010).

Monitoring the X-ray reflection features at the Galactic center, we were able to demonstrate that Sgr A* experienced several short outbursts in the recent past, and to give crucial constraints on the light curves and the spectra of these individual events. This information will be essential to identify the physical origin of the corresponding past outbursts, but additional high-energy observations as well as solid constraints on the molecular distribution in the CMZ are needed to fully reconstruct the recent history of Sgr A*. In particular, the recurrence of such bright events during the past thousand years is still to be assessed in order to understand their importance in the duty cycle of Sgr A*.

3. M31*: no long AGN cycle in the past millenniums?

M31* is significantly further away ($\sim$ 750 kpc) than Sgr A* and the Andromeda galaxy's dense molecular gas is mainly located in its outer rings, i.e. several kiloparsecs away from the central source (e.g. Nieten *et al.* 2006). Therefore, the chances of detecting a reflection signal from molecular clouds in this nearby Galaxy are *a priori* relatively low.

To investigate the 6.4 keV emission in M31, we use the full *XMM-Newton* data set covering this nearby galaxy (2000–2015), and we integrate all the observations into a single deep-exposure map. Then we select seven small regions corresponding to molecular clouds identified in the inner 1.5 kpc of M31 (Melchior & Combes 2011) and a larger region containing a fraction of its main outer ring (this second selection is based on the column density derived from H_I and CO maps of M31, on the exposure of our 6.4 keV map and on the isochrones we compute for putative past echoes propagating in this galaxy, Clavel *et al.* 2016b, in prep). In each one of these eight regions, the 6.4 keV emission is compatible with the background level, so we only report upper limits on the Fe Kα flux.

Taking into account the current description of M31's geometry (Melchior & Combes 2011), we derive the absolute 3D position of each of these regions, allowing us to compute the age of the events possibly reflecting off of them at the present time, but also to convert our non-detections into upper limits on the luminosity of the central supermassive black hole. These upper limits are all about four orders of magnitude lower than the Eddington luminosity of the $1.4 \times 10^8\,M_\odot$ black hole at the center of the Andromeda galaxy, constraining parts of its light curve between 1000 and 100,000 years ago (Clavel *et al.* 2016b, in prep). Therefore, we are able to rule out any long AGN state close to the Eddington luminosity in the corresponding period.

Nonetheless, the physical size of the regions we consider is such that the upper limits we derive from the clouds and the outer ring are averaged over more than 1000 and 10,000 years, respectively. Such averages could easily hide events of a few-year timescale at Eddington luminosities (e.g. tidal disruption events, Rees 1988). Moreover, due to the lack of known molecular structures in the inner part of M31, an important fraction of M31*'s past light curve is not constrained by the upper limits we derive, so putative bright events with longer durations (several centuries) could also be propagating in the non-sampled regions of M31.

Our preliminary study of the past activity of M31*, searching for reflection features that could be present in the Andromeda galaxy, is successful in excluding any long and bright AGN phase for this nearby supermassive black hole in the past 100,000 years. However, this investigation does not allow any constraint on the possible existence of either relatively short (<1000 years) or relatively faint ($<10^{-4}\,L_{\rm Edd}$) outbursts in its past light curve.

4. Conclusion

Using reflection features as a probe to study the past activity of our supermassive black hole, we demonstrated that Sgr A* is likely to have experienced several bright events in the past centuries. Our *Chandra* analysis better constrained two of these events, which are now known to have a duration of a few years only, while the strong variability quantified by our *XMM-Newton* analysis of the whole CMZ demonstrates than none of these bright events can be much longer than a decade or so. Yet, a regular monitoring of the corresponding X-ray echoes, along with further constraints on the 3D geometry, on the fine structure, and on the density of the molecular material present in the CMZ, are still needed to fully reconstruct Sgr A*'s past activity.

Using the same method, we investigated whether it is possible to draw similar conclusions for the nearby supermassive black hole M31*. However, due to the higher spatial resolution and sensitivity needed for this more distant galaxy, we conclude that outbursts of a few-year timescale cannot be investigated for M31*. Nonetheless, the upper limits we derived exclude any very long period of Eddington activity over the past 100,000 years, which is already an important constraint on the past activity of this second closest supermassive black hole. These first results could be significantly improved if additional dense molecular structures were identified within the Andromeda galaxy.

Despite the encouraging results obtained for the Andromeda galaxy, we conclude that the observation of Fe Kα reflection features produced by putative short outbursts from M31* is out of reach with the current instruments, and we can reasonably assume that similar conclusions could be drawn for even more distant galaxies. Therefore, the Galactic center is likely the only galactic nucleus where such reflection features can be investigated in great details, providing for the first time a direct measure of the importance of short outbursts in the duty cycle of a given quiescent supermassive black hole. It is therefore essential to pursue the on-going efforts towards the full characterization of the individual echoes currently propagating through the inner region of our Galaxy.

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