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X-RAY HICCUPS FROM SGR A* OBSERVED ON APRIL 4, 2007

Porquet, D.[1]

Abstract. Our Galaxy hosts at its dynamical center Sgr A*, the closest supermassive black hole. Remarkably, its luminosity is several orders of magnitude lower than the Eddington luminosity. Thanks to *Chandra* and *XMM-Newton*, we are able to detect X-ray flares from Sgr A*, providing new exciting perspectives for the understanding of the processes at work in the Galactic nucleus. On April 4, 2007, we observed for the first time within a time interval of roughly half a day, an enhanced incidence rate of X-ray flaring, with a bright flare (peak amplitude of ∼100 above the quiescent luminosity) followed by three flares of more moderate amplitude (amplitudes ∼25–40). This is the first time that a such level of X-ray flaring activity from Sgr A*, both in amplitude and frequency, is reported. This bright flare represents the second brightest X-ray flare from Sgr A* on record. This new bright flare exhibits similar light-curve shape (nearly symmetrical), duration (∼3 ks) and spectral characteristics to the very bright flare observed in October 3, 2002 by *XMM-Newton*. Based on a fully self-consistent analysis approach, we established that the two brightest X-ray flares observed so far from Sgr A* exhibited similar (well constrained) soft spectra.

1 Introduction

Located at the center of our Galaxy, Sgr A* is the closest supermassive black hole to the solar system at a distance of about 8 kpc. Its mass of about $3–4\times10^6\,M_\odot$ has been determined thanks to the measurements of star motions (e.g., Schödel et al. 2002, Ghez et al. 2003). Amazingly, this source is much fainter than expected from accretion onto a supermassive black hole. Its bolometric luminosity is only about 3×10^{-9} $L_{\rm Edd}$. In particular, its 2–10 keV "quiescent" X-ray luminosity is only about 2.4×10^{33} erg s^{-1} within a radius of $1.5''$ (Baganoff et al. 2003). Hence, Sgr A* radiates in X-rays at about 11 orders of magnitude less than its corresponding Eddington luminosity. This has motivated the development of various radiatively inefficient accretion models to explain the dimness of the Galactic Center black hole, e.g., Advection-Dominated Accretion Flows, jet-disk models, Bondi-Hoyle with inner Keplerian flows (see Baganoff et al. 2003, and references therein). The recent discovery of X-ray flares from Sgr A* has provided new exciting perspectives for the understanding of the processes at work in the Galactic nucleus. The first detection of such events was found with *Chandra* in October 2000 (Baganoff et al. 2001). The bulk of X-ray flares detected (up to April 2007, see below) have weak to moderate peak flux amplitudes with factor of about 2–45 compared to the quiescent state (e.g., Bélanger et al. 2005, Eckart et al. 2006, Hornstein et al. 2007, Marrone et al. 2008). Only one very bright flare with a flux amplitude of about 160 was observed in October 2002 (Porquet et al. 2003). It is noteworthy that its peak luminosity of $\sim3.6\times10^{35}$ erg s^{-1} was comparable to the bolometric luminosity of Sgr A* during its quiescent state. The light curves of the X-ray flares can exhibit short (e.g., 600 s, Baganoff et al. 2001; 200 s, Porquet et al. 2003) but deep drops close to the flare maximum. This short-time scale could indicate that the X-ray emission is emitted from a region as small as $7R_{\rm S}$ ($\sim 13\,R_\odot$).

2 X-ray hiccups observed on April 4th 2007

We report here the main results of our Sgr A* observation campaign (PI: D. Porquet, ∼230 ks, splitted up into three observations) performed with *XMM-Newton* from March 30 to April 4, 2007. The detailed analysis and interpretation are reported in Porquet et al. (2008). On April 4th, 2007, for the first time, a high level of flaring activity were reported with four X-ray flares, one bright and three moderate, detected in half a day. The bright flare is the second brightest X-ray flare detected so far from Sgr A*.

[1] Observatoire astronomique de Strasbourg, Université de Strasbourg, CNRS, INSU, 11 rue de l'Université, 67000 Strasbourg, France

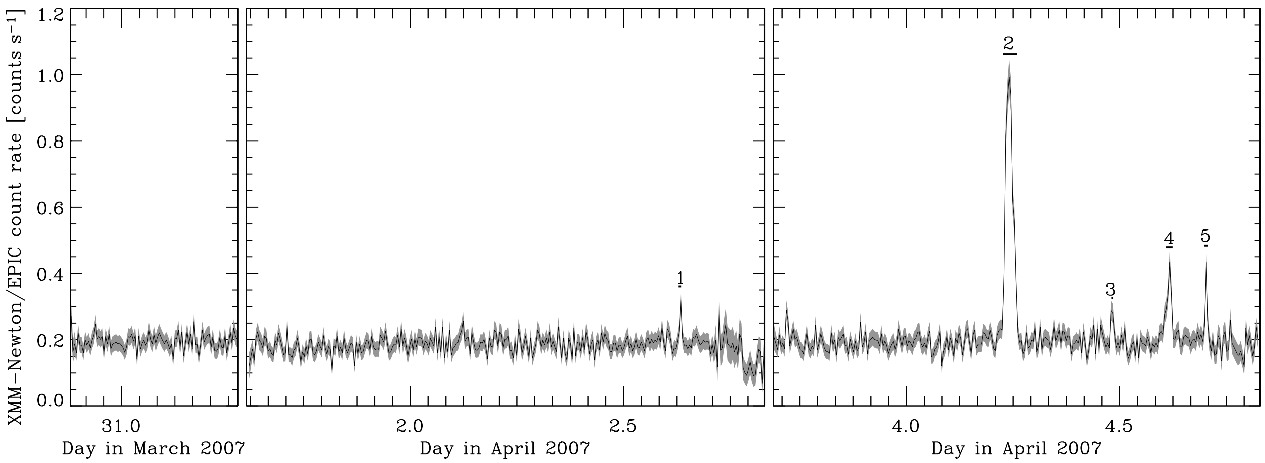

Fig. 1. *XMM-Newton*/EPIC (pn+MOS1+MOS2) light curves of Sgr A* in the 2–10 keV energy range obtained in Spring 2007. The light curves are corrected from soft-proton flaring background. The time interval used to bin the light curve is 350 s. The X-ray flares are labeled from 1 to 5. The horizontal lines below these labels indicate the flare durations. The quiescent level of Sgr A* corresponds to only 10% of the non-flaring level of these light curves.

2.1 X-ray light curves of Sgr A*

In Fig. 1 are reported the EPIC (pn+MOS1+MOS2) background subtracted light curves of Sgr A* in the 2–10 keV energy range, with a time bin interval of 350 s. During the first and second observations, the light curves are almost flat, with a non-flaring level of X-ray emission consistent with the level commonly observed (e.g., Porquet et al. 2003). Only 10% of this 2-10 keV non-flaring level comes from Sgr A* in its quiescent state. Indeed, inside the 10″-radius *XMM-Newton* extraction region centered on Sgr A* (excluding Sgr A* and any transient sources in outburst), 90% of the 2–10 keV non-flaring level comes mainly from one point source associated with the complex of stars IRS 13, the candidate pulsar wind nebula G359.95-0.04, and a diffuse component (Baganoff et al. 2003). We identify any significant deviation from the non-flaring level as possible flare. A flare (#1) was observed on April 2, 2007. On April 4, one bright flare (#2), with a peak amplitude of ∼100 (with a detection of $\sim 21\sigma$) above the quiescent luminosity was observed followed shortly by three moderate flares (#3: $\sim 6\sigma$; #4: $\sim 6\sigma$; and #5: $\sim 8\sigma$). The bright flare has a duration of ∼2.8 ks, similar to the duration that was observed for the (brightest) flare of October 2002 (∼2.9 ks; Porquet et al. 2003). Its light curve is almost symmetrical, but no significant deep drop (i.e., about 50% of flux decrease) is observed in contrast to the moderate flare of September 2000 (Baganoff et al. 2001) and the very bright flare of October 2002 (Porquet et al. 2003). The time gaps between two consecutive flares starting from flare #2 are 5.3, 3.0 and 1.8 hours. Therefore, four flares were observed in a time interval of only half a day. This is the first time that a such level of X-ray flaring activity from Sgr A*, both in amplitude and frequency, is reported. When the time coverage of the NIR observations allowed simultaneous observations with *XMM-Newton*, the NIR counterparts of these X-ray flares have been observed: flare #2 was observed with VLT/NACO (Dodds-Eden et al. 2008, in prep.), and flares #1, #4, and #5 were observed with HST/NICMOS (Yusef-Zadeh et al. 2008, in prep.). This strengthens the relationship observed up to now between X-ray and NIR flares when there is a simultaneous X-ray/NIR observation coverage: all X-ray flares have an NIR flare counterpart, while all NIR flares are not each time associated with an X-ray flare counterpart (e.g., Eckart et al. 06, Hornstein et al. 2007).

2.2 Spectral analysis of the X-ray flares

We report here the spectral analysis of the four flares observed on April 4th, 2007. We used as extraction region for each instrument, a 10″-radius region centered on the position of Sgr A* determined during the bright flare time interval. We would like to emphasize that the determination of the time interval of the X-ray flare is crucial to prevent from any bias in the spectral analysis, especially in cases of weak and moderate flares. To extract the background spectrum we used the same region, but limited to the non-flaring level time interval. We performed the spectral analysis of the bright flare #2, and of the sum of the three following moderate flares (i.e., #3+#4+#5) to increase the statistics. Instead of using the χ^2 statistic, which is not appropriate

Table 1. Best fit parameters (using W statistic) of the EPIC flare spectra for absorbed power-law continuum, taking into account dust scattering. $N_{\rm H}$ values are given in units of $10^{22}\,{\rm cm}^{-2}$. The mean unabsorbed fluxes for the flare period in the 2–10 keV energy range are in units of $10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$. The errors are given at the 90% confidence level.

Flare	$N_{\rm H}^{(a)}$	Γ	$F_{2-10\,{\rm keV}}^{\rm mean\ (b)}$	C/d.o.f.
April 2007				
#2	$12.3^{+2.1}_{-1.8}$	$2.3^{+0.3}_{-0.3}$	$16.1^{+3.1}_{-2.2}$	2560/2998
#3+#4+#5	$8.8^{+4.4}_{-3.2}$	$1.7^{+0.7}_{-0.6}$	$5.0^{+1.8}_{-1.0}$	2117/2998
October 3, 2002				
	$12.3^{+1.6}_{-1.5}$	$2.2^{+0.3}_{-0.3}$	$25.3^{+3.6}_{-2.7}$	2728/2998

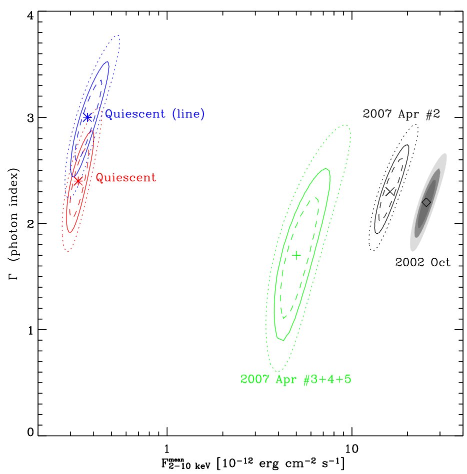

Fig. 2. Confidence regions of the photon index versus unabsorbed flux in the 2–10 keV energy range of the X-ray flares from Sgr A* for an absorbed power-law model taking into account the dust scattering. The dashed, continuous, and dotted contour levels correspond to confidence levels for two interesting parameters of 68%, 90%, 99%, respectively (i.e., to $\Delta C = 2.3$, 4.61, 9.21, respectively). The confidence regions corresponding to the quiescent state of Sgr A* are inferred from the spectral analysis of four archived Chandra observations, using the same spectral models (red contour levels) or including a Gaussian emission line (blue contour levels).

for the fitting of spectra with low counts (e.g., #3 + #4 + #5), we use a modified version of `cstat` statistic called the W statistic (Wachter et al. 1979) that must be used for *unbinned* background-subtracted spectra to prevent from information loose and hence bias of the fitting results. We fit the spectra in the 1–10 keV energy range. On Table 1, the parameter fits for both the bright flare and the sum of the moderates flares are reported, assuming an absorbed power law continuum including the effect of the dust scattering. The parameter fits for the bright flare are well constrained and show a well constrained soft photon index of 2.3±0.3. Though, the best fit parameters for the sum of the weak flares are much less constrained, they are consistent with those of the bright flare within the error bars.

We have made the first detailed comparison of X-ray flare properties observed with *XMM-Newton* (this April 2007 campaign and previous observations) based on a fully self-consistent analysis approach (for more details, see Porquet et al. 2008). We showed that only the *XMM-Newton* data of the brightest flare that occurred on October 2002 flares can be used for a safe comparison with the April 2007 data. In Fig. 2 are reported the confidence regions of the photon index versus the unabsorbed flux, at the confidence levels of 68%, 90%, and 99% (corresponding to ΔC=2.3, 4.61, and 9.21, respectively, for two interesting parameters). The fluxes of the flares span a large range, i.e., about a factor 5. The flare #2 has a flux lower than the October 2002 flare at the 90% confidence level, but has similar well constrained best fit values.

3 Summary and discussions

On April 4, 2007, with *XMM-Newton* we observed an unprecedented level of X-ray flaring activity from Sgr A*, both in amplitude and frequency, with four X-ray flares occurring within only half a day: one bright flare (peak amplitude of ∼100 above the quiescent luminosity) followed shortly by three moderate ones (peak amplitude ∼25–40). The flare #2 is the second brightest X-ray flare detected so far from Sgr A*. This new bright flare exhibits similar light-curve shape (nearly symmetrical), duration ($\sim$3 ks) and spectral characteristics to the very bright flare (peak amplitude of $\sim$160) observed in October 3, 2002 by *XMM-Newton* (Porquet et al. 2003). We have made the first detailed comparison of X-ray flare properties observed with *XMM-Newton* (this April 2007 campaign and previous observations) based on a fully self-consistent analysis approach (see Porquet et al. 2008 for more details), and showed that the two brightest X-ray flares observed so far from Sgr A* exhibited similar well constrained soft spectra (Γ=2.2–2.3$\pm$0.3). We show that such statement cannot be done for moderate flares. This result brings strong constraints on any model proposed to explain the flaring behavior of Sgr A*. Besides, such quick succession of several events separated by only a few hours, might argue against a disruption mechanism that relies on the temporary storage of mass and energy, if all the corresponding accretion energy is released during the flare. The accretion rate (e.g., Melia 2007) in this system might not produce a transient accumulation of mass between flares of sufficient magnitude. If instead the flares are due to a magneto-rotational instability, then the energy liberated during the flare must also be accumulated over the short inter-burst period. The low mass accretion rate, from which the energy is derived, might argue against this type of mechanism as well. On the other hand, if the flare arises from the infall of a clump of gas (e.g., Liu et al. 2006) then there would be less restriction on how often these could come in. Genzel et al. (2003) have shown that the total energy release $\geq 10^{39.5}$ erg during a flare requires a gas accreted mass of a few times 10^{19} g (assuming a radiation efficiency of $\sim$10%), i.e., comparable to that of a comet or a small asteroid. Recently, Cadez et al. (2006) have argued that the flares could be produced by tidal captures and disruptions of such small bodies. The comet/asteroid/planetesimal idea for depositing the additional mass and energy to initiate a flare is attractive. The distance from Sgr A* at which such a small body would get tidally disrupted is the Roche radius, which is for a rigid body:

$$\frac{R_{\mathcal{R}}}{R_{\rm S}} = 13.2 \times \left(\frac{M_{\rm BH}}{4\times10^6 M_\odot}\right)^{-2/3} \times \left(\frac{\rho_p}{1\,{\rm g\,cm^{-3}}}\right)^{-1/3},$$

where $M_{\rm BH}$ is the black hole mass and ρ_p is the density of the rigid body. Thus, for a black-hole mass of $4\times10^6\ M_\odot$ and a density of $1\,{\rm g\,cm^{-3}}$, this corresponds to $13.2\,R_{\rm S}$, in good agreement with the size of the region where the flares are thought to occur. The flaring rates would then depend on processes occurring much farther out, so the fact that so many flares are seen so close together on some days, and much less frequently at other times, would simply be due to stochastic events. However, it would still be difficult to distinguish between a compact emission region and emission within a jet, since these disruption events could still end up producing an ejection of plasma associated with the flare itself.

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