Mem. S.A.It. Vol. 79, 81
© SAIt 2008

Memorie della

Observing the Super-Massive Black Hole of the Galactic center with Simbol-X

A. Goldwurm

Laboratoire Astroparticule et Cosmologie (APC) - Paris and Service d'Astrophysique /DAPNIA/DSM/CEA - Saclay, 91191 Gif sur Yvette, France

Abstract. The Center of our Galaxy is one of the prime objective of the Simbol-X mission. This region of several square degrees around the dynamical center of the galaxy hosts a large variety of high energy sources and violent phenomena that involve different non-thermal processes contributing to the hard X-ray emission from the region. Here we present in detail the case for the observation of Sgr A*, the super-massive black hole of the galactic nucleus, with Simbol-X, stressing on the presently open questions and on the crucial measurements that will be performed in the hard X-ray domain with this formation-flying hard X-ray focussing telescope expected to flight in the next decade.

Key words. Simbol-X - Supermassive Black Hole - Galactic Center - Sgr A*

1. Introduction

The centre of our Galaxy is a complex region of about 450 pc × 150 pc (a sky area of 3°× 1° in projection) where a number of crucial high-energy phenomena take place. Located at about 8 kpc from the Sun, the galactic centre (GC) hosts the nearest super-massive black hole (SMBH) to the solar system, which is surrounded by a variety of objects including young stellar clusters, thermal HII regions, extremely dense molecular clouds, high magnetic and velocity fields, supernova remnants (SNR) and other non-thermal filamentary (NTF) structures and hot plasmas. All these objects interact with each other and generate peculiar astrophysical processes, the study of which allow us to explore the fundamental laws of physics.

The 3-4 million solar mass (M$_{\odot}$) BH at the GC is a unique link between the 10^9 M$_{\odot}$ black holes powering the Active Galactic Nuclei (AGN) and the stellar size (10-1000 M$_{\odot}$) BH acting in binary systems, microquasars and ultra-luminous X-ray sources. The typical timescales at the horizon of such a BH are of the order of minutes and hours compared to months-years for AGNs and seconds-milliseconds for stellar objects. These timescales are therefore more easily accessible to us and the observations of variable phenomena in the GC BH can bring information that cannot be provided by other systems. Totally obscured in the optical wavelengths by the dust and gas of the galactic plane, the GC is mainly observed in radio, infrared and in the X and gamma-ray energy bands (see Goldwurm 2007). In the 2-10 keV band this region is dominated by several bright X-ray binaries, mainly low mass X-ray binaries (LMXB) with stellar black holes or neutron stars as com-

---

Send offprint requests to: A. Goldwurm, e-mail: `andrea.goldwurm@cea.fr` pact object, and by a complex diffuse emission permeating the central 300 pc, including different components and in particular one attributed to a very hot plasma with temperature of about 8 keV and whose origin is still, today, a real mystery. Several supernova remnants and other non-thermal structures are also observed at these energies and, most important of all, the persistent as well as the flaring emission from the central SMBH of the Galaxy. The most recent, intriguing high energy results have been the detections by INTEGRAL and HESS of gamma-ray sources coincident with the GC. Their presence clearly indicate that non-thermal processes and particle accelerations at very high energies are taking place in the region, but the nature of these sources is still not understood.

The two main objectives of Simbol-X observations of the GC will be the study of the X-ray flaring activity of the central massive black hole at energies above 10 keV and of the hard X-ray diffuse emission. These investigations will lead to the identification of the INTEGRAL source and will shed light on the nature of the TeV source detected by HESS and in general on all the non-thermal processes acting in the core of our Galaxy. Here we present in detail the case for the observation of Sgr A* with Simbol-X stressing on the crucial measurements that will be performed in the hard X-ray domain for the first time by this new mission (Ferrando et al. 2007, these proceedings).

2. The supermassive black hole of the galactic nucleus

2.1. Flaring activity of Sgr A*

The study of the supermassive black hole at the centre of our Galaxy is certainly one of the primary objectives of the Simbol-X scientific program. The Chandra observations of the region revealed in 1999 for the first time the persistent, quiescent X-ray emission from Sgr A*, the compact radio source which is associated to the 3.5 10^6 $M_\odot$ black hole of the galactic nucleus. This emission is soft (power law photon index of ∼ 2.5), slightly extended (1″) and very weak, characterised by a 2-10 keV luminosity of only 2 10^{33} erg s^{-1}, showing that the SMBH at the GC seems accreting at a very low effective rate (Baganoff et al. 2003). Even though stellar winds from a close young stellar cluster seem to feed the BH at a reasonable rate, Sgr A* is indeed shining at less than one millionth times the available accretion luminosity. Such a low luminosity and the soft spectrum are not compatible with the thermal advective models which were developed to explain the low radiation efficiency of the accretion in Sgr A*. In 2000, however, Chandra detected a very bright X-ray flare from Sgr A*, which in few hours increased in luminosity by a factor of ∼50 (Baganoff et al. 2001). During this flare the spectrum hardened considerably to a slope of 1.4 and timing variations as short as few hundred seconds were detected showing that the emission is generated within 10-20 inner Schwarzschild radii. Other similar bright flares were detected with XMM-Newton in 2001 (Goldwurm et al. 2003) and again in 2002 (Porquet et al. 2003), in 2004 (Blanger et al. 2005) and more recently in 2007 (Porquet et al., 2007, in preparation) (Fig. 1). While the 2001 flare was rather similar to the one observed with Chandra, the 2002 one reached a luminosity increase factor of nearly 200 and the spectrum appeared softer, with a photon index of 2.5. The 2 flares in 2004 were also rather hard (indexes of 1.6 and 1.9) and the bright 2007 one had a intermediate slope. Following the first detections in X-rays, flaring events were also detected at near infrared (NIR) frequencies thanks to the adaptive optics large telescope of VLT and Keck (Genzel et al. 2003, Ghez et al. 2004). The NIR flares are more frequent (several per day) than the X-ray ones (∼ 1 per day) and their steep non-thermal spectra extending in the MIR domain Eisenhauer et al. (2005); Ghez et al. (2004) indicate a non-thermal radiation mechanism. Linear polarization during NIR events was also detected Eckart et al. (2006) which confirms that synchrotron emission is probably the main mechanism working in this energy range.

Several models, that consider either a hybrid thermal/non-thermal mechanism in a Keplerian flow (Liu et al. 2002, 2004, 2006) or a purely non-thermal mechanism in a jet

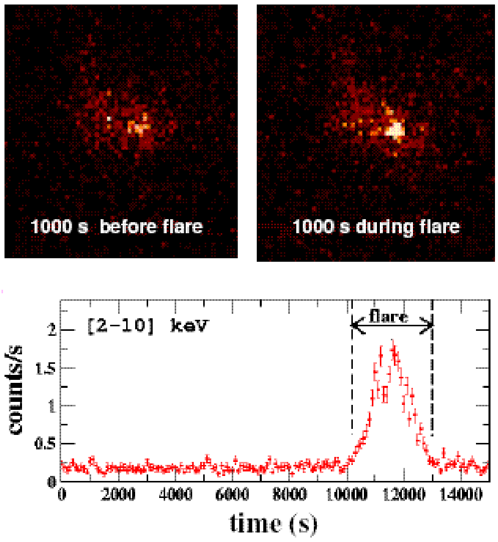

Fig. 1. XMM-Newton Sgr A* X-ray flare detections. Top: EPIC MOS 2-10 keV images (5′× 5′) before and during the 2001 Sep flare. Bottom: EPIC PN light curve of the brightest flare detetced in 2002.

(Markoff et al. 2001), have been proposed to explain the quiescent and flaring emission of Sgr A*. However it has not yet been possible to determine which model is the correct one because Chandra and XMM do not provide data at energies higher than 10 keV where the spectral models differentiate one from the other. The detection of Sgr A* flares with Simbol-X up to 40-60 keV or more should allow us to determine which is the dominant radiation mechanism (Bremsstrahlung, Inverse Compton or Synchrotron) and likely whether the emission comes from a Keplerian flow or a jet. Heating and cooling phases of Sgr A* flares have been modelled by Bittner et al. (2007) who have shown that spectral breaks and their variations during the flares are expected in hard X-rays.

Important constraints on the emission mechanism and characteristics of the accretion flow or jet can be provided also by simultaneous measurements of flares at different frenquencies. A bright event was observed simultaneously with XMM in the 2-10 keV range and the HST/NICMOS camera at frequencies between 1.6 and 1.9 μm on 31st August 2004 Yusef-Zadeh et al. (2006). The light curves of the simultaneous NIR and X-ray flares were very similar in shape and the lack of significant time lags indicate that the same population of particles must produce the two components. The synchrotron cooling time for producing X-rays in the typical 10 G magnetic field of the accretion flow is much shorter ($<$ 1 min) than the duration of flares, so the X-rays are most probably produced by inverse Compton of sub-mm photons off the transiently-accelerated electrons that generate the NIR emission via the synchrotron mechanism. The different spectral slopes of flares could be caused by a varying electron distribution or magnetic field Yusef-Zadeh et al. (2006); Liu et al. (2006). The main efforts are now directed to the simultaneous measurement of spectra from sub-mm to X-rays, which would provide constraints on the particle distribution, magnetic fields, and sizes of the emitting region. Indeed, as for X-rays, NIR flares have been observed with both blue and red spectral slopes and the presence of a flux-slope correlation (the more intense the harder) even within a single event was recently reported Gillessen et al. (2006) although this result has not been yet confirmed with the Keck Hornstein et al. (2007). The detection in 2004 of a sub-mm flare coincident with a NIR flare Yusef-Zadeh et al. (2006) could imply that emission decay is not due to synchrotron cooling (since for electrons emitting sub-mm photons the cooling time is longer than for NIR-emitting ones) but rather to adiabatic expansion and therefore plasma outflows. The inverse Compton emission responsible for the X-rays could also extend to the γ-ray regime depending on the electron distribution and magnetic field.

2.2. Flare quasi periodic modulation

Quasi-periodic structures in the light curves of flares from Sgr A* were first reported by Genzel et al. (2003) at NIR frequencies at a period around 17 min. A periodicity around 22 min was also detected with XMM-Newton in the longest (10 ks) of the 2004 X-ray flares by Bélanger et al. (2006b, 2006c). Using a

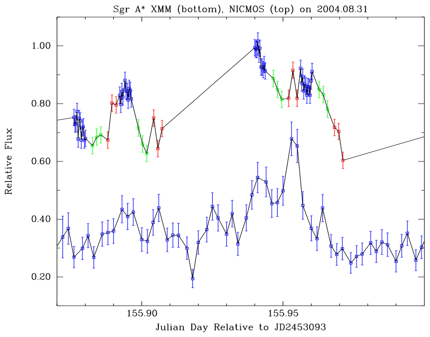

Fig. 2. HST NIR (top: blue 1.60 μm, green 1.87 μm, red 1.90 μm) and XMM X-ray (bottom) light curves of the 2004 Aug 31st Sgr A* flare. Units are flux density (mJy) for NIR and count rates for X-rays.

Z^2 test supported by a set of realistic simulations aimed to provide a reliable estimate of the chance probability of the Z^2 peaks for each tested frequency, they assigned a conservative probability of less than 7×10^{-5} to the observed peak at 1330 s present in the 2004 August 31st flare (Fig.3). This period is interestingly close to the Keplerian period of the last stable orbit (LSO) around a Schwarzschild BH of 3.5×10^6 $M_\odot$ ($\approx$ 27 min). Indeed 22 min correspond to the orbital period at the prograde LSO of such a BH with spin only 0.22 times the maximal allowed value. Other indications of ~20 min QPOs have been reported in NIR flares including evidence of variable linear polarization on similar timescales.

Such measures are extremely interesting and suggestives because can provide crucial diagnostic of the matter falling in the BH. Falanga et al. (2007) have modelled the X-ray modulation with emission from instability induced disk spiral waves distorted by relativistic effects of a non-rotating black hole. On the other hand such measures still need confirmation and could be established on solid bases with measures that extend at energies above 10 keV. The Simbol-X observations will allow the detailed study of the hard flares of Sgr A* in the broad 1-70 keV energy range and will in particular allow us to search for quasi periodic signals in hard X-rays. Since the high energy emission generally traces the inner region of the accretion flow (or of the jet) we will explore relativistic effect in the innermost regions close to the BH horizon and thus provide constraints on the geometry and on the inflow/outflow motion of the emitting material.

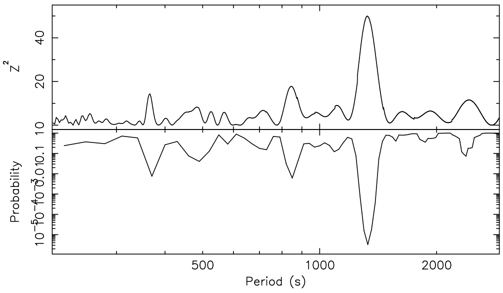

Fig. 3. Z^2-periodogram of the 2004 Aug 31st Sgr A* flare and associated probabilities. The searched period range was 100–3000 s and the Z^2 peak found at $P = 1330$ s with probability of $\sim 10^{-6}$.

3. The INTEGRAL view of the Galactic Center region

The most precise images of the GC ever collected in the 20-600 keV band are those obtained with the IBIS/ISGRI telescope during the 4.6 Ms effective time survey of the GC performed by the INTEGRAL γ-ray observatory in 2003-2004 Bélanger et al. (2006) (Fig. 4). In addition to few bright X-ray binaries INTEGRAL detected, for the first time, a faint and persistent high energy emission ($\sim 10^{35}$ erg s^{-1} in the 20-120 keV band) compatible, within the 1′ error radius, with Sgr A* position. The IBIS angular resolution ($\approx$ 13′ FWHM) does not allow to associate this source (IGR J17456–2901) to the SMBH or others objects of the dense nuclear region. The lack of variability and of a bright discrete X-ray counterpart suggest that it is rather a local (< 10-20 pc) and yet diffuse emission. The INTEGRAL spectrum was compared to the 1-10 keV one obtained from XMM-Newton, integrating X ray intensities over the region of the IBIS point spread function. The spectra combine well but the thermal plasma of kT $\approx$ 8 keV used to model the bulk of the X-ray diffuse emission cannot explain the data at > 20 keV (Fig.5). The weak transient sources seen by Chandra or XMM in the central arc-minute also cannot explain the observed emission. A non-thermal component extending up to 120-200 keV with spectral slope of photon index 3 is clearly present and its origin is still unexplained.

Simultaneous XMM-INTEGRAL observations performed during the 2004 multi-wavelength campaign dedicated to Sgr A* are not conclusive on the presence of γ-ray flares during Sgr A* X-ray flares Bélanger et al. (2006) since the two observed X-ray events occurred during the intervals when INTEGRAL was in the radiation belts and not collectig data. However, even if the Sgr A* X-ray flares extend at > 20 keV with their hard slope, they are too sparse to fully account for the central γ-ray source detected with INTEGRAL. The morphology of the latter seems to change with energy indicating that it may be the result of emission from different close objects. The IBIS angular resolution is not sufficient to establish the origin of this persistent non-thermal emission.

Simbol-X, with its imaging capabilities (better than 30″ angular resolution) and sensitivity 100 times better than INTEGRAL in the hard X-ray domain, is the only instrument that can disentangle the thermal and non-thermal components present in the GC and determine the nature of the INTEGRAL source. This hard X-ray emission could also be related to the TeV point source detected by the Cherenkov atmospheric detector HESS Aharonian et al. (2004), in the range 100 GeV - 4 TeV and which is also located at the Sgr A* position. The detection of very high energy gamma-rays indicate that particle accelerations is taking place in the inner 20 pc of the galaxy possibly originating in the SMBH or in a pulsar wind nebula close in projection to Sgr A*.

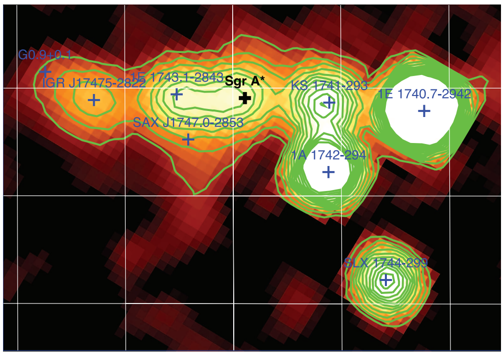

Fig. 4. INTEGRAL/IBIS 20-30 keV image of the Galactic Center from the 2003-2004 survey. Iso-significance contours are linearly-spaced from 9.5 to 75 σ, grids lines are separated by 0.5°.

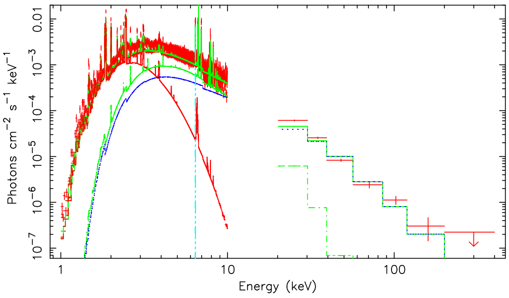

Fig. 5. XMM/INTEGRAL spectrum of IGR J17456–2901 with 1-10 keV XMM data integrated within 8′ from Sgr A*. The best fit model is an absorbed 2-temperature plasma (kT ≈ 1.0 (red) and 6.6 keV (green)) plus a broken power-law of indexes 1.5 and 3.2 with E$_{break}$ of 27 keV (blue).

4. Simbol-X observations of Sgr A*

Simbol-X will allow us to measure the spectra of Sgr A* flares in the energy band 1-80 keV in order to determine the spectral shape above 10 keV, the cut -off energy, if a cut-off is present, and the evolution of these parameters. These measurementsthe will provide constraints on the radiation mechanisms (IC vs. bremsstrahlung, maximal particle energy, cooling mechanism) and on models of matter dynamics in the inner part of the accretion flow or at the base of a compact jet around the SMBH.

To evaluate the capability of Simbol-X to observe the flares of Sgr A* we have simulated the spectrum obtained for a typical event using the expected spectral response and background of the telescope. The flare parameters that we used in the simulation were the following: duration of 10 ks, peak luminosity of a factor 50 compared to the quiescent one, power-law

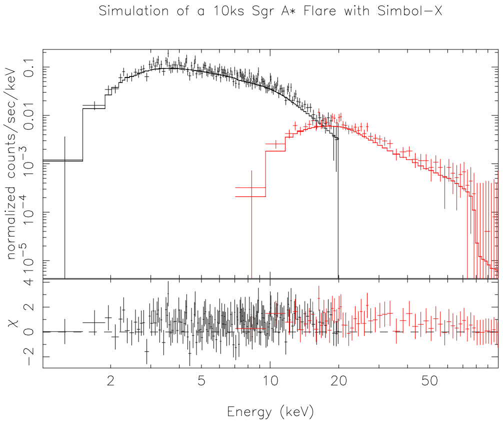

Fig. 6. Simulations of a Sgr A* flare count spectrum obtained with Simbol-X.

spectrum with photon spectral index 1.3 and column density of 10^{23} cm^{-2}. We simulated as well the contribution of the diffuse emission and of other point sources as were observed with Chandra in 1999 (Baganoff et al. 2003) within the extraction region (10″ radius around the source). To extract the spectrum of the flare we used another simulated spectrum of diffuse and point-sources emission including this time also the Sgr A* quiescent emission as background. Resulting flare spectrum is reported in Fig.6. The flare is detected up to 70 keV with the HED (red points) and the spectral index is determined with an uncertainties of ∼ 0.03 allowing both the search for a spectral break and the study of spectral evolution during the event. The estimated average source count rate provided by both the LED and the HED focal plane detectors of Simbol-X will allow to study the QPOs produced by particles at the maximum energy and the light curve profile dependence with energy to constraint the nature of the flares and of the modulation and explore the fate of the matter spiralling in towards the BH horizon. Simbol-X will also reveal the nature of the INTEGRAL hard X-ray central source, will establish its relation with Sgr A* and whether it is linked to the TeV source detected with HESS at the position of Sgr A*.

5. Conclusions

The study of Sgr A* goes well beyond explaining only this specific peculiar object. The observed correlation between radio and X-ray luminosity from a compilation of BH powered systems in the universe, from super massive AGN to stellar size BH binaries (e.g. Falcke et al. 2004) show that once the luminosity is properly scaled with the mass of the object all sources seem to follow the same correlation law which indicates that the same fundamental process is at work in these systems. Sgr A*, at mid-way between the most and the least massive objects, also follows the same trend and any significant progress in the understanding of this system will provide deep insights in the general domain of the accretion/ejection processes in the vicinity of black holes.

References

Aharonian, F., et al., 2004, A & A , 425, L13
Baganoff, F. K., et al., 2001, Nat, 413, 45
Baganoff, F. K., et al., 2003, ApJ, 591, 891
Bélanger, G., et al., 2005, ApJ, 635, 1095
Bélanger, G., et al., 2006, ApJ, 636, 275
Bélanger, G., et al., 2006b, ApJ, subm., (`astro-ph/0604337`)
Bélanger, G., et al., 2006c, JPhCS, 54, 420
Bittner, J. M., et al., 2007, ApJ, 661, 863
Eckart, A., et al., 2006b, A & A, 455, 1
Eisenhauer, F., et al., 2005, ApJ, 628, 246
Falanga, M., et al., 2007, ApJ, 662, L15
Falcke, H., et al., 2004, A & A 414, 895
Genzel, R., et al., 2003, Nat, 425, 934
Ghez, A. M., et al., 2004, ApJL, 601, L159
Gillessen, S., et al., 2006, ApJL, 640, L163
Goldwurm, A., et al., 2003, ApJ, 584, 751
Goldwurm, A., 2007, C.R.Phys, 8, 35
Hornstein, S. D., et al., 2007, ApJ, 667, 900
Liu, S. & Melia, F., 2002, ApJL, 566, L77
Liu, S., et al., 2004, ApJL, 611, L101
Liu, S., et al., 2006, ApJ, 636, 798
Markoff, S., et al., 2001, A & A, 379, L13
Porquet, D., et al., 2003, A & A, 407, L17
Yusef-Zadeh, F., et al., 2006, ApJ, 644, 198