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HARD X-RAYS FROM THE GALACTIC NUCLEUS: PRESENT AND FUTURE OBSERVATIONS

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Abstract.
In spite of increasing evidences of the presence of a massive Black Hole at the Galactic Center, its radio counterpart, Sgr A*, shows little activity at high energies, and recent models involving energy advection (ADAF) have been proposed to explain this difficulty. We present results on the hard X-ray emission from the galactic central square degree obtained from the SIGMA/GRANAT 1990-1997 survey of this region. The best upper limits available today on the Sgr A* 30-300 keV emission are presented and compared to X-ray data and to the predictions of ADAF models. We also present simulations of Sgr A* observations with the future ESA γ-ray Observatory INTEGRAL, which show that the imager instrument (20 keV-10 MeV) will be able either to detect the expected ADAF emission from the accreting Galactic Nucleus black hole or set tight upper limits which will constrain the physical parameters of such system.

1. The Problem of the X/γ-Ray Low Luminosity of the Galactic Nucleus

Increasing evidences in support of the presence of a massive (2.5 10^6 $M_\odot$) Black Hole (BH) at the dynamical center of our Galaxy have been collected in the past years. Proper and radial motions of stars in the central parsec of the Galaxy, obtained with high resolution near-infrared observations [1], show indeed the presence of a dark mass with density $> 10^{12}$ $M_\odot$ pc^{-3} located within < 0.01 pc from Sgr A*, and governing the dynamics of the mass of the region.

The compact synchrotron radiosource Sgr A*, which coincides with the Galaxy dynamical center and shows very low proper motion, is therefore considered the visible counterpart of the Galactic Nucleus (GN) BH, and its spectrum has been studied at all wavelengths (for recent reviews on the Galactic Center see [2] [3]). However, unlike stellar-mass BHs in binary systems and super massive BHs in AGNs, the Galactic Nucleus is found in the infrared and X-ray domains extremely faint and underluminous. In particular the results of the Galactic Center SIGMA/GRANAT Survey [4] [5] [6] coupled to Rosat [7], ART-P [8] and ASCA [9] observations have shown that Sgr A* total X-ray luminosity is well below 10^{37} erg s^{-1}, i.e. $< 10^{-7}$ times the Eddington Luminosity for such a BH. This is rather intriguing since stellar winds of the close IRS 16 star cluster provide enough matter to power the accreting BH. Due to non uniformities in the winds the matter is accreted with substantial angular momentum and so the flow is certainly not in form of pure spherical free fall. In standard thin accretion disks around BH about 10% of the energy provided by the accreted matter ($\dot{M}c^2$) is expected to be radiated between infrared and X-ray frequencies. Estimates of accretion rate for Sgr A* are in the range $(6 - 200)\ 10^{-6}$ $M_{\odot}$ yr^{-1} [10] [11] and luminosities around $10^{40} - 10^{42}$ erg s^{-1} are therefore expected.

New models of accretion flow have been recently proposed, in which very low radiation efficiency is obtained, even for non-spherical infall, by assuming that most of the energy is advected into the BH rather then being radiated. These "advection dominated accretion flow" models (ADAF) seem to be able to interpret the whole Sgr A* spectrum from radio to γ-rays, and in particular to explain the observed low X-ray flux [12] [11] [13]. Sgr A* is in fact considered the test case for this set of models and observations in the X-ray domain of this object are crucial to establish the validity of the model assumptions and/or to constrain their parameters.

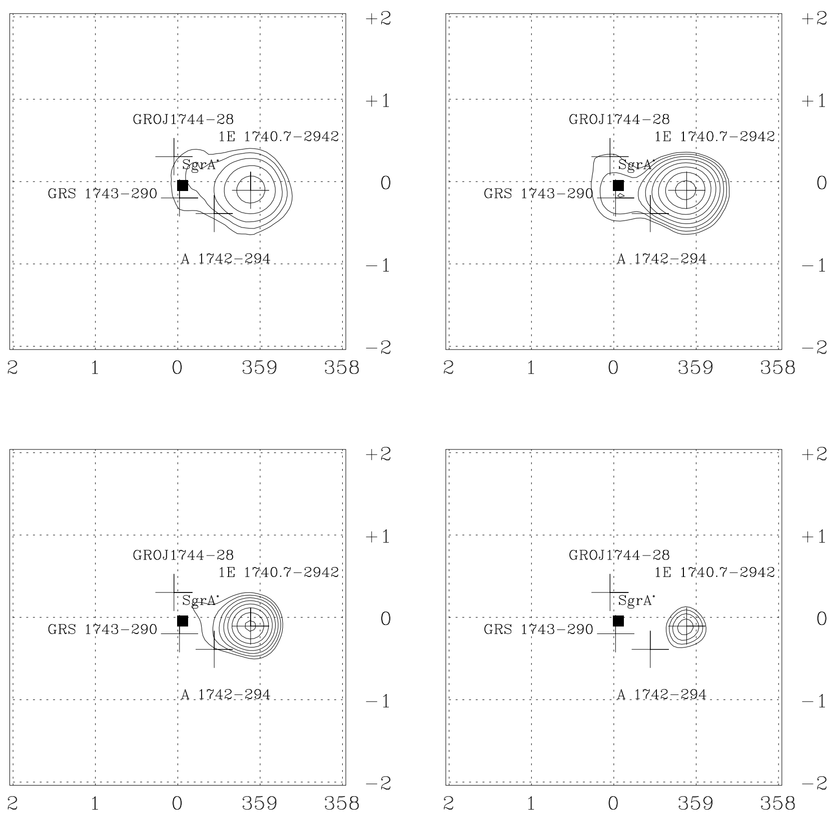

Figure 1. Images of the Galactic Center in galactic coordinates obtained from the 1990-1997 SIGMA Survey in 4 energy bands: 30-40 keV up-left, 40-75 keV up-right, 75-150 keV bottom-left, 150-300 keV bottom-right. Contours are in units of standard deviations, starting from 4.5 σ with logarithmic steps of 1.4. Crosses indicate positions of SIGMA point sources detected within the central degree in different periods [6] while the black square shows the position of Sgr A*.

2. The 1990-1997 SIGMA/GRANAT Survey of the Galactic Center: 30-300 keV Upper Limits on Sgr A*

The 30-1300 keV SIGMA telescope [14] on the GRANAT satellite, observed the Galactic Center between March 1990 and October 1997 about twice a year, for a total of 9.2 10^6 s effective time. The telescope provided an unprecedented angular resolution ($15'$) at these energies and, for the quoted observing time, a typical 1σ flux error of $<$ 2-3 mCrab (1 mCrab is about 8 $\times$ 10^{-12} erg cm^{-2} s^{-1} in the 40-80 keV band). Analysis of a subset of these data already provided the most precise hard X-ray images of the Galactic Nucleus [4] [5] and proved that the Sgr A* luminosity in the 40-150 keV band is lower then 10^{36} erg s^{-1}.

These results were important because, though it was known from the Einstein Observatory data [15], that the GN was not bright in soft X-rays, it was still possible that Sgr A* could have, as any respectable BH in low state, a bright hard tail extending to $>$ 100 keV and possibly also a component of 511 keV line emission. For example the close source 1E 1740.7-2942, weak at $<$ 4 keV was later observed, in particular by SIGMA, to be bright in soft γ-rays, was found associated to radio jets and even to display transient events of 500 keV emission (see references in [4]). Indeed 1E 1740.7-2942 is now recognized to be a good BH candidate at only $40'$ from the GN and to be responsible for most of the hard X-ray/γ-ray activity observed by early low-angular-resolution experiments from the direction of the Galactic Center and previously associated to the GN [16].

Recently Goldoni et al. (1999) [6], have re-analyzed the full set of SIGMA data to improve the upper limits estimation. In this analysis they included models with both point-source and diffuse emission to fit sky images. Reconstructed images of the central $4° \times 4°$ region in different energy bands are presented in Fig. 1. Four variable point-sources are contributing to the emission from the central 1° circle (1E 1740.7-2942, A 1742-294, GROJ 1744-28, GRS 1743-290). The last one is only $11'$ from Sgr A* and, if considered a single source, cannot be associated to Sgr A*. However the presence of some weak contribution from the Galactic Nucleus cannot be excluded and therefore 2 sets of limits were derived for the Sgr A* hard X-ray flux: one for which all GRS 1743-290 emission is attributed to one single source (case A) and another obtained by including a source at the Sgr A* position (fixed parameter) in the fitting procedure (case B). Results are reported in Table 1, for the four energy bands of Fig. 1. At high energy no emission at all is detected apart from 1E 1740.7-2942 and values in the two colums are identical.

The most stringent upper limits of Table 1 (A column) have been reported in Fig. 2 in units of E L_E for a distance of 8.5 kpc, and compared with the ADAF model predicted spectrum of Sgr A*. The reported model is the "best model" as defined in [11], and refers to a BH mass of 2.5 10^6 $M_\odot$, a mass accretion in Eddington units $\dot{m}$ = 1.3 10^{-4} (i.e. 7 10^{-6} $M_\odot$ yr^{-1}), a viscosity parameter $\alpha = 0.3$, an equipartition parameter $\beta = 0.5$ (exact equipartition between gas pressure and magnetic pressure), and a fraction of viscous heat converted in electron heat of $\delta = 0.001$.

Comparison with X-ray results, i.e. luminosities measured by Rosat (0.8-2.5 keV) and ASCA (2-10 keV), is also shown in Fig. 2. ASCA value is actually reported as upper limit, following Narayan et al. 1998 [11], because the observed flux was rather associated to the X-ray burster A 1742-289, located only at $1'$ from Sgr A* [9]. Note however that this interpretation is controversial and the ASCA measure may well contain some contribution from Sgr A* [17].

SIGMA/GRANAT Upper Limits on Sgr A*

Energy range keV	Integrated luminosity (A) erg s^{-1}	Integrated luminosity (B) erg s^{-1}
30 – 40 keV	2.6×10^{35}	4.5×10^{35}
40 – 75 keV	2.0×10^{35}	3.4×10^{35}
75 – 150 keV	2.0×10^{35}	2.4×10^{35}
150 – 300 keV	5.2×10^{35}	5.2×10^{35}

Table 1. SIGMA/GRANAT 2σ upper limits for Sgr A* luminosity

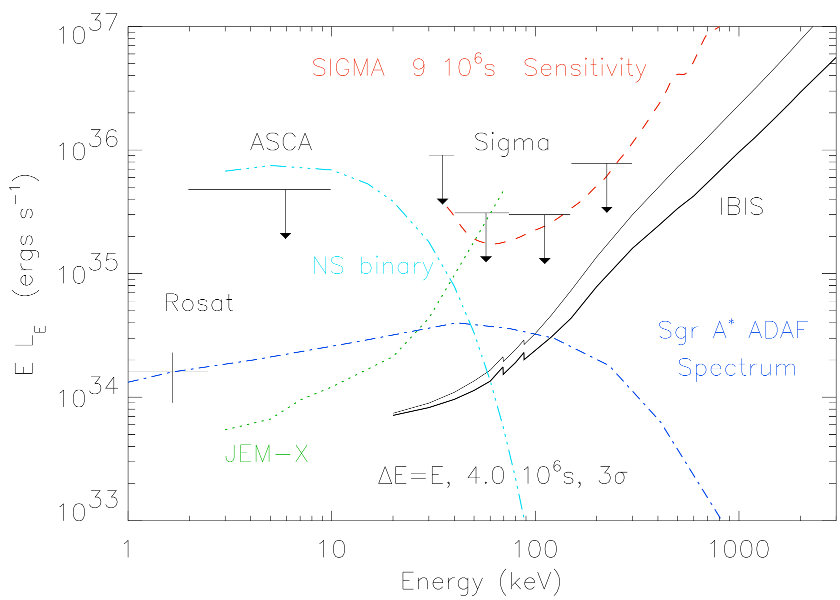

Figure 2. Sgr A* 30-300 keV upper limits in units of E L_E (d=8.5 kpc), obtained from the 1990-1997 SIGMA/GRANAT Galactic Center Survey, compared to the predicted ADAF spectrum (for M_{BH}=2.5 10^6 $M_\odot$ and $\dot{m}$=1.3 10^{-4}) [11] (blue dashed-dotted line), along with the SIGMA sensitivity (red dashed line) scaled to the survey time of 9 10^6 s. Rosat Sgr A* flux and the ASCA upper limit are also reported. IBIS (black full lines) and JEM-X (green dotted line) broad-band sensitivities for the Galactic Nucleus and the INTEGRAL Galactic Center Deep Exposure time of 4 10^6 s are also reported (JEM-X sensitivity at 20 keV is lower then IBIS one due to smaller FOV). A typical thermal spectrum (kT≈10 keV) of a neutron star LMXB (1E 1743.1-2864, [8]) (light-blue dashed-double-dotted line) is also shown for comparison.

3. The IBIS/INTEGRAL Galactic Center Deep Survey

The Imager on Board the Integral Satellite (IBIS) is one of the two main instruments of INTEGRAL, the ESA γ-ray mission to be launched in 2001. It provides, thanks to its coded-aperture imaging system composed by a tungsten mask and two pixellated detector layers, fine imaging ($12'$ FWHM resolution), good spectral resolution (< 8 % at 100 keV and ≈ 6 % at 1 MeV) and good sensitivity over a wide (20 keV-10 MeV) energy range and a very wide field of view ($29^\circ \times 29^\circ$ at 0 sensitivity) [18]. The INTEGRAL Core Program includes the so called Galactic Center Deep Exposure (GCDE) program, the deep observation of a central Milky Way region 60° wide in longitude and 20° in latitude. The GCDE will consist of a grid of 31×11 pointings separated by 2°. The net GCDE observing time is 4.8 10^6 s per year, of which about 84 % performed in pointing mode [19]. Considering the GCDE scan in pointing mode and the IBIS sensitivity over its FOV we estimated that the Galactic Nucleus will be actually observed by IBIS for an effective (on-axis equivalent) time of ≈ 4 10^6 s in 3 years (see Fig. 3 for the IBIS/Sensitivity of the INTEGRAL GCDE scan). Adding slew and Galactic Plane Survey times the total net 3-years IBIS Core Program exposure on the GN will increase to 5 10^6 s. IBIS broad-band sensitivity is shown in Fig. 2 for the pointing GCDE time on the E L_E vs. E plot to compare it with the ADAF model spectrum for Sgr A* [11]. Two curves for IBIS are represented for two extreme estimates of the in-flight background. In Fig. 2 is reported also the expected GCDE sensitivity for the INTEGRAL X-Ray monitor (JEM-X) which provides images in the range 3-60 keV but in a smaller field of view. This picture demonstrates that IBIS sensitivity estimated for the GCDE will allow either to detect the high energy emission predicted by ADAF from Sgr A* or to set tighter constraints on the model parameters.

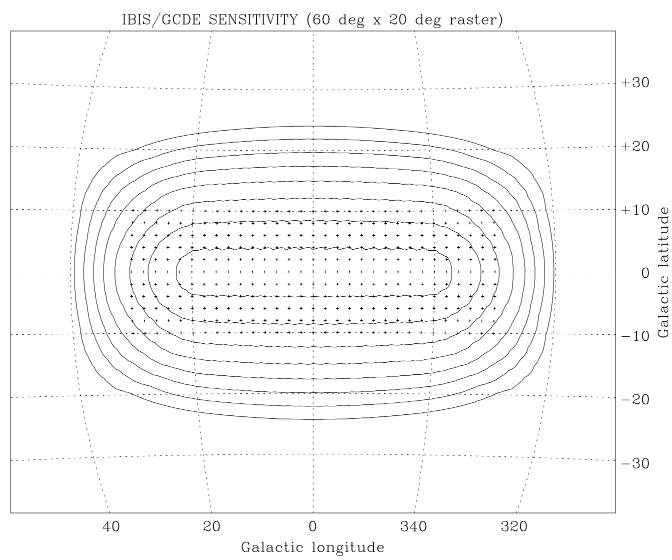

Figure 3. IBIS Sensitivity for the INTEGRAL CGDE Survey, as fraction of on-axis IBIS sensitivity for the same exposure time. Contours are between 0.06 and 0.48 with steps of 0.06. Crosses indicate pointing scan of the GCDE [19]. Maximum value (at $l=0^\circ$ $b=0^\circ$) is 0.51.

4. Simulations of the Galactic Nucleus IBIS/INTEGRAL Observations

ASCA, ART-P and Rosat results have shown that at low energies lots of point sources and also diffuse emission are present in the area and can make identifications difficult. In particular activity of the X-ray burster A1742-289, only $1'$ away from Sgr A*, would not be easily separated by the GN one even by X-ray instruments like JEM-X. On the other hands results at higher energies, i.e. around 80 keV, should be rather ideal to reveal emission from the GN, since at these energies, due to their softer spectra, most of the Neutron Star binaries will be significantly fainter than the expected emission from the GN BH (see NS binary typical spectrum in Fig. 2). Even at energies > 50 keV, however, imaging will be crucial since SIGMA showed the presence of several high-energy sources located within $2°$ from the Galactic Nucleus (see Fig. 1).

To prove the imaging capabilities of the IBIS telescope we performed simulations of a deep IBIS observation of the Galactic Center with the ISGRI low energy (20-700 keV) γ-ray detector layer of the telescope [20]. Basic simulation procedure was described in [21] [22], we used results of the SIGMA survey for source fluxes [4] and the predicted Sgr A* flux from ADAF spectrum. Sky image reconstruction procedures are based on standard cross-correlation techniques and iterative analysis and removal of sources as described e.g. in [23]. One simplified assumption was that the observation was performed as a single pointing rather then a sum of pointings along a grid as it is actually expected. This should not influence the results since the scanning will rather help to remove background unknown systematic effects, not presently included in the simulation. Work is in progress to include more realistic operational conditions.

Fig. 4 shows some of the results of the simulations. These are zooms of the central part of reconstructed sky images obtained by an iterative decoding and point-source cleaning algorithm applied to the simulated detector images. A cluster of 4 high energy sources in the central $2°$ circle appears in the images (Fig. 4, left). Fine image analysis allow to position them and to remove their contribution (Fig. 4, right). Sgr A* is then detected at the expected position and signal to noise ratio of $\approx 6\ \sigma$, corresponding to $L_{50-140\ \mathrm{keV}} \approx 3.5\ 10^{34}$ erg s^{-1}, the level predicted by the ADAF model. Including diffuse emission (possibly present at < 50 keV energies [9]) showed that its presence can make detection of faint sources more complicated and somemore refined procedures should be employed to model the composite diffuse plus point-sources emission. However diffuse emission will not influence the search for the GN emission at high energies.

5. Conclusions: XMM Core Program Observations of Sgr A*

We have presented here the best available hard X-ray upper limits on Sgr A*, obtained by the deep Galactic Center SIGMA/GRANAT survey. As shown above (Fig. 2), they do not constrain the present ADAF models, invoked to resolve the apparent contradiction between the presence of a massive black hole at the Galactic Center and its lack of activity in the X-ray domain. However we note that the ADAF model critically depends on mass accretion since $L \propto \dot{m}^2$. The assumed value of accretion rate in the model ($\dot{m}$=1.3 10^{-4} [11], actually determined by Rosat flux) is close to the lower limit of the estimated range of $\dot{m}$ (i.e. $(1-30)\ 10^{-4}$, [11] [10]). Even a factor 3 higher in $\dot{m}$ would make the model not consistent with our limits, and also not compatible with other spectral data of Sgr A*.

New generation of telescopes aboard the future X-ray (AXAF/Chandra, XMM)

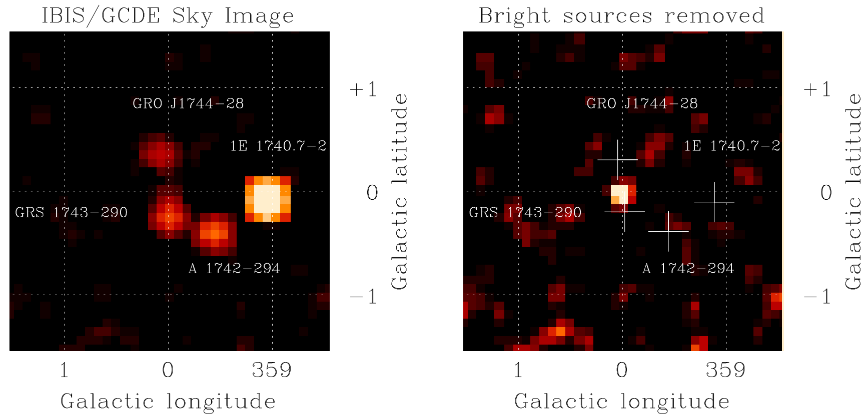

Figure 4. The central 3°×3° of the deconvolved and cleaned sky images in standard deviations (1 pixel ∼ 5′), from a simulation of the IBIS/ISGRI GCDE observation (4 10^6 s) in the 50-140 keV band (logarithm scale from 1 to 200 σ left, linear scale from 1 to 5 σ right). Simulation included 11 sources in the IBIS FOV with fluxes from 4 to 70 mCrabs [4], a background of 150 cts s^{-1} resulting in 1 σ imaging error of 0.11 mCrab and a 0.6 mCrab point-source in Sgr A* ($L_{50-140\ keV} \approx 3.5\ 10^{34}$ erg s^{-1}). After removal of the 4 brightest sources Sgr A* is detected at the simulated position and expected S/N level of ≈ 6 σ.

and gamma-ray (INTEGRAL) missions, will allow to deeply search and study the GN high energy emission and in this way to test present models for massive BH accretion.

We have shown with simulations that IBIS/INTEGRAL will be able to disentangle the hard X-ray emission of the Milky Way central square degree and to detect ADAF emission from Sgr A* or to set appropriate upper limits over the band 50-140 keV, by using 3 year data of the INTEGRAL/GCDE core program. In case of detection, the reconstructed flux will allow to test ADAF spectra and the radiation processes expected in such a massive BH. On the other hands the set of upper limits will imply an $\dot{M}$ at least a factor 1.4 lower then the present value of ADAF model, making the problem of low accretion rate even more difficult. The ADIOS models [24], in which advection is coupled to inflows/outflows of matter and which allow even lower emission then ADAF models for the same mass supply rate, may have then to be invoked. Alternatively different hypothesis on magnetic field will have to be included, e.g. allowing for lower values of the β equipartition parameter in order to steepen the spectrum and reduce contribution at high energies [11].

In this context hard X-ray results will be even more valuable if coupled to high resolution results at lower energies which could constrain the mass accretion rate and allow to study the spectral shape. XMM observations of the Galactic Center are planned in the Core Program of the first year of the mission operations. More than 5 10^4 s of the XMM Galactic Center scan will be devoted to observe the central half-degree of the Galaxy with the EPIC cameras. Such exposure time will provide sensitivities of the order of 10^{32} erg s^{-1} (5 σ for 8.5 kpc distance) in the energy range $2-10$ keV, with 6″ angular resolution (FWHM) and good spectral resolution. We expect that these observations will allow to resolve the confusion over the soft X-ray sources associated to Sgr A* [17] and to obtain spectral data to test radiative properties of the closest supermassive accreting black hole.

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