THE INTEGRAL VIEW OF THE GALACTIC NUCLEUS

A. Goldwurm\textsuperscript{1,2}, G. Bélangér\textsuperscript{1,2}, P. Goldoni\textsuperscript{1,2}, J. Paul\textsuperscript{1,2}, R. Terrier\textsuperscript{1,2}, M. Falanga\textsuperscript{1}, P. Ubertini\textsuperscript{3}, A. Bazzano\textsuperscript{3}, M. Del Santo\textsuperscript{3}, C. Winkler\textsuperscript{5}, A.N. Parmar\textsuperscript{4}, E. Kuulkers\textsuperscript{5}, K. Ebisawa\textsuperscript{5}, J.P. Roques\textsuperscript{6}, G. Skinner\textsuperscript{6}, N. Lund\textsuperscript{7}, F. Melia\textsuperscript{8}, and F. Yusef-Zadeh\textsuperscript{9}

\textsuperscript{1}Service d’Astrophysique, DAPNIA/DSM/CEA - Saclay, 91191 Gif-sur-Yvette, France
\textsuperscript{2}Fédération de Recherche Astroparticule et Cosmologie, 11 Pl. Berthelot, 75005 Paris, France
\textsuperscript{3}IASF-CNR, via del Fosso del Cavaliere 100, 00133 Roma, Italy
\textsuperscript{4}Research and Scientific Support Department, ESA ESTEC, PB 299, NL-2200 AG Noordwijk, Netherlands
\textsuperscript{5}Integral Science Data Center, Chemin d’Ecogia, 16, CH-1290 Versoix, Switzerland
\textsuperscript{6}Centre d’Etude Spatiale des Rayonnements, CNRS, 9, avenue du Colonel Roche, Toulouse Cedex 4, France
\textsuperscript{7}Danish Space Research Institute, DK-2100 Copenhagen 0, Denmark
\textsuperscript{8}Physics Dept. and Stewart Obs., University of Arizona, 1118 E. 4th St., POB 210081, Tucson, AZ 85721, US
\textsuperscript{9}Dept. of Physics and Astronomy, Northwestern University, Evanston, IL 60208, US

ABSTRACT

We present the preliminary results of the observational campaign performed in 2003 to study the Galactic Nucleus with INTEGRAL. The mosaicked images obtained with the IBIS/ISGRI coded aperture instrument in the energy range above 20 keV, give a yet unseen view of the high-energy sources of this region in hard X- and gamma-rays, with an angular resolution of 12′. We report on the discovery of a source, IGR J17456-2901, compatible with the instrument’s point spread function and coincident with the Galactic Nucleus Sgr A∗to within 0.9′. The source is visible up to 60-80 keV with a 20-100 keV luminosity at 8 kpc of 3 × 10\textsuperscript{35} erg s\textsuperscript{-1}. Although we cannot unequivocally associate the new INTEGRAL source to the Galactic Nucleus, this is the first report of significant hard X-ray emission from within the inner 10′ of the Galaxy and a contribution from the galactic center supermassive black hole itself cannot be excluded. Here we discuss the results obtained and the perspectives for future observations of the Galactic Nucleus with INTEGRAL and other observatories.

Key words: Black hole physics; Accretion; Galaxy: center; Galaxy: nucleus; Gamma-rays: observations; X-Rays: individuals: Sgr A∗.

1. INTRODUCTION

The Galactic Nucleus (GN) is among the most interesting objects in the high-energy sky, as it links our own galaxy with active galactic nuclei and quasars. At a distance of 8 kpc (Eisenauer et al. 2003), it hosts the closest massive black hole (BH) to us, as shown in particular by near-infrared (NIR) observations of star proper motions near the galactic center (GC) (Schoedel et al. 2002, Genzel et al. 2003, Ghez et al. 2003). The detailed NIR observations of the central cluster of young and luminous stars have now constrained the enclosed mass within 0.001 pc (≈ 120 AU) to a value which implies a core density > 10\textsuperscript{17} M\textsubscript{⊙} pc\textsuperscript{-3}. This density is most naturally explained by the presence of a massive black hole of (4.0 ± 0.8) 10\textsuperscript{6} M\textsubscript{⊙}. Such a BH would have a Schwarzschild radius (R\textsubscript{S}) of about 1.2 × 10\textsuperscript{12} cm or 0.08 AU and is supposed to accrete the environmental matter producing detectable emission in a broad frequency range (Melia & Falcke 2001).

The bright (∼ 1 Jy), compact, non-thermal radio source Sgr A∗, discovered exactly 30 years ago by Balick and Brown (1974) and located at less than 0.01″ (83 AU) from the dynamical center of the central star cluster is believed to be the radio counterpart of this extreme object. Its radio spectrum is described by an inverted or flat power law with high and low frequency cut-offs, and a peculiar sub-mm bump at frequencies > 100 GHz. Only recently detected in NIR both in quiescent, and flaring states (Genzel et al. 2003, Ghez et al. 2004), this source is undetectable in the visible and UV bands due to the large absorption and is also very weak in X-rays. The Chandra Observatory measured in 1999 a quiescent luminosity of only L\textsubscript{X}[2 – 10 keV] ≈ 2 × 10\textsuperscript{33} erg s\textsuperscript{-1} from Sgr A∗and the emission appeared partly extended. However, in October 2000, Chandra detected a bright 3 hr flare, characterized by rapid intrinsic variability (Baganoff et al. 2001, Baganoff et al. 2003). During this flare the luminosity increased to L\textsubscript{X}[2 – 10 keV] ≈ 10\textsuperscript{35} erg s\textsuperscript{-1} in 4 ks, the power law spectrum hardened, with a change of the photon index from 2.7 in quies-
Two other bright X-ray flares from Sgr A* were detected with XMM-Newton on September 4, 2001 and on October 3, 2002 (Goldwurm et al. 2003a; Porquet et al. 2003a). In 2001 XMM-Newton detected the beginning of a flare in the last 900 s of an observation pointed towards the GN (Goldwurm et al. 2003a). In this interval the Sgr A* flux increased by up to a factor 30 and the spectrum hardened to a slope of index 1. In October 2002 the most powerful flare from this source was discovered with XMM-Newton. It lasted only 2.7 ks but the source luminosity reached \( \approx 3.6 \times 10^{35} \text{ erg s}^{-1} \) with an increase factor of nearly 200 in luminosity and a rather soft spectrum (\( \alpha \approx 2.5 \)) (Porquet et al. 2003a).

These last observations have opened challenging new questions regarding the accretion process, activity and emission mechanisms at work in Sgr A* and have also re-opened the possibility of observing the source in the hard X-ray and gamma-ray bands (>10-30 keV). At energies between 10 and 20 keV a number of detections of Sgr A* were claimed in the past, the most significant were those based on Spacelab 2 observations in 1985 (Skinner et al. 1987) and those of ART-P on GRANAT in 1990-1991 (Pavlinsky et al. 1994). Skinner et al. (1987) re-opened the possibility of observing hard X-rays from the GN, a measure of which may particularly shed light on the relative role of accretion and ejection in the Sgr A* system.

We have recently analyzed the large set of data collected with INTEGRAL during the galactic center survey performed in the first part of 2003, and found some excess emission at energies > 20 keV from the region including the Sgr A complex (Belanger et al. 2004). We review these first INTEGRAL results on the GN and present a more recent analysis performed on the entire 2003 INTEGRAL data set.

### 2. OBSERVATIONS AND DATA ANALYSIS

INTEGRAL (INTernational Gamma-Ray Astrophysics Laboratory), the ESA gamma-ray observa-

---

Table 1. List of the 2003 INTEGRAL observations of the Galactic Nucleus (GN)

| Observation Type | Target | Mode | Dates (2003) | Exposure (ks) | GN Eff. Exp. (ks) |
|------------------|--------|------|--------------|--------------|------------------|
| ToO              | XTE J1720–318 | 5 × 5 D | 28/02 - 02/03 | 176          | 128              |
| GCDE             | Survey | Survey | 02/03 - 01/05 | 675          | 369              |
| ToO              | H 1743–31 | 5 × 5 D | 06/04 - 22/04 | 280          | 256              |
| GO               | Sgr A*  | 5 × 5 D | 30/08 - 24/09 | 1000         | 938              |
| GCDE             | Survey | Survey | 02/08 - 14/10 | 675          | 374              |

Notes:

a) GO = Guest Observer Observation, GCDE = Galactic Center Deep Exposure (Core Program), ToO = Target of Opportunity Observation

b) 5 × 5 D = 5 × 5 Dithering Pattern, 7 HEX = 7 Hexagonal Dithering Pattern
tory (Winkler et al. 2003) launched on 2002 October 17, carries two main instruments, the gamma-ray imager IBIS and and the gamma-ray spectrometer SPI, and two monitors, JEM-X, the Joint European X-ray Monitor, and OMC, the Optical Monitoring Camera. The results reported here were obtained with the IBIS coded mask imaging instrument (Ubertini et al. 2003), sensitive over the energy range between 15 keV and 10 MeV and characterised by a wide field of view (FOV) of $29^\circ \times 29^\circ$, an angular resolution (FWHM) of 12$''$ and a sensitivity of about 1 mCrab at 100 keV for 1 Ms exposure. The IBIS performance in the low energy range (15–1000 keV) is achieved thanks to the ISGRI camera (Lebrun et al. 2003) made up of more than 16000 CdTe detectors.

The Galactic Center is a priority target for the INTEGRAL mission. A specific survey of the central regions of the galaxy, the Galactic Center Deep Exposure (GCDE) program, is performed each year during the INTEGRAL mission. A specific survey of the central region of the Galactic Center was achieved thanks to the ISGRI camera (Lebrun et al. 2003) made up of more than 16000 CdTe detectors.

The Galactic Center is a priority target for the INTEGRAL mission. A specific survey of the central regions of the galaxy, the Galactic Center Deep Exposure (GCDE) program, is performed each year during the INTEGRAL mission.

The results reported here were obtained with the IBIS coded mask imaging instrument (Ubertini et al. 2003), sensitive over the energy range between 15 keV and 10 MeV and characterised by a wide field of view (FOV) of $29^\circ \times 29^\circ$, an angular resolution (FWHM) of 12$''$ and a sensitivity of about 1 mCrab at 100 keV for 1 Ms exposure. The IBIS performance in the low energy range (15–1000 keV) is achieved thanks to the ISGRI camera (Lebrun et al. 2003) made up of more than 16000 CdTe detectors.

The Galactic Center is a priority target for the INTEGRAL mission. A specific survey of the central regions of the galaxy, the Galactic Center Deep Exposure (GCDE) program, is performed each year during the INTEGRAL mission.

The total effective exposure on Sgr A$^*$, accounting for partial coding and performed data selections, was $\sim 2.1$ Ms.

INTEGRAL observations are generally made of several exposures, performed at fixed pointing directions with a specific pattern on the plane of the sky and each having durations ranging from 1800 s to 4000 s (Courvoisier et al. 2003). The reduction and analysis of the IBIS/ISGRI data were performed with the INTEGRAL Offline Scientific Analysis (OSA) package provided by the INTEGRAL Science Data Center (ISDC). The algorithms relative to the IBIS data analysis are described in Goldwurm et al. (2003b).

In a preliminary study we treated only the set of data collected between 2003 February 28 and May 1, using the OSA 2.0 version of the analysis software and without correction for background structures. To account for the residual systematic noise we measured the distribution of the residuals in the images and applied a correction factor to reduce the significance accordingly. The results published by Bélanger et al. (2004) are summarized in section 3. In a more recent analysis (section 4) we have used the new version (v. 3.0) of the OSA and of the calibration files performing the background subtraction with the latest available background maps to process the whole data set of Table 1.

3. PRELIMINARY RESULTS

The maps of the Galactic Center shown in Fig. 1 were constructed by summing the reconstructed images of the 571 individual exposures of the first part of the data set of Table 1, those taken between 2003 Feb 28 and May 1, for a total effective exposure time of about $8.5 \times 10^5$ s at the position of Sgr A$^*$. In these signal-significance maps of the central two degrees of the Galaxy where ten contour levels mark iso-significance linearly from about $4\sigma$ up to $15\sigma$, we can see what appear to be six distinct sources: 1E 1740.9–2942.7, KS 1741–293, A 1742–294, 1E 1743.1–2843, SLX 1744–299/300, whose nominal positions are marked by crosses, and a source coincident with the radio position of Sgr A$^*$. Of these sources, 1E 1740.7–2942 is a black hole candidate and microquasar, KS 1741–293 and A 1742–294 are neutron star Low-Mass X-Ray Binary (LMXB) burster systems, SLX 1744–299/300 are in fact two LMXBs separated by only 2.7$''$ and 1E 1743.1–2843 is an X-ray source whose nature is still uncertain (Porquet et al. 2003b). The 20–40 keV band contours of the central source clearly peak, with a maximum of 8.7$\sigma$, at the Sgr A$^*$ position but are elongated towards GRS 1741.9–2853. This suggests some contribution to the emission from this transient neutron star LMXB burster system observed to have returned to an active state in 2000 (Muno et al. 2003), but the elongation could also be due to an uncorrected background structure. The central source is also marginally visible in the 40–100 keV band at a level of 4$\sigma$.

The position and flux of the central excess in the 20–40 keV map were determined by fitting the peaks with a function approximating the instrument’s Point Spread Function (Gros et al. 2003) in two different ways: (1) all the emission is attributed to one source and is fitted as such to determine its peak height and position, (2) the emission is attributed to two sources: a new source and GRS 1741.9–2853, whose position is then fixed. Both of these involve a simultaneous fit of all the other sources listed above. In the first case, we obtain a source position of R.A.(J2000.0)=17h45m22.s5, decl.(J2000.0)=–28°58’17’’ and a flux of about 5.4 mcrab or $3.21 \pm 0.36 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. In the second, the position is 17h45m38s5, –29°01’15’’ and the flux is about 3.2 mcrab or $1.92 \pm 0.36 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. The central source’s 40–100 keV peak position is in very good agreement with the one determined using the second method outlined above, and since there is clearly no visible contribution from a neighboring source, the 40–100 keV flux was extracted at that position giving an estimated flux of $(1.86 \pm 0.40) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ ($\sim 3.4$ mCrabs). The fluxes were determined using a standard spectral shape for the Crab (Bartlett 1992) and the derived 20–100 keV luminosity at 8 kpc is $(3.0 \pm 0.4) \times 10^{35}$ erg s$^{-1}$. The estimated uncertainty on the position is of about 4$'$ for a detection at the significance level of 8.7$\sigma$ in images still dominated by systematic noise. These positions are respectively 4.6$'$ and 0.9$'$ from the radio position of Sgr A$^*$, within...
the uncertainties. The hardness ratio (HR) — ratio of the count rate in the high-energy band over that in the low-energy band — for the detected excess is 0.90 ± 0.20. As a possible indication of the nature of the detected excess, we can compare the values of the HR to the two brightest sources in the field. The BH candidate 1E 1740.7–2942 has a HR of 1.20 ± 0.03, and the neutron star LMXB KS 1741–293 has a HR of 0.89 ± 0.08. We also found that the source presented some level of variability, although this result was somehow hampered by the presence of residual noise due to uncorrected background structures. In particular a peak at 5σ over the average was detected in the source light curve on April 6. This last result has not been confirmed by the most recent analysis of the data. As discussed by Bélanger et al. (2004) the central excess is not compatible with a simple extrapolation at high energies of the total X-ray diffuse and point-source flux as observed by X-ray instruments within 10′ from the center. We concluded that it is due to a hard source, not identified with the well known high energy sources of the region, and which was therefore named IGR J1745.6–2901.

4. RECENT RESULTS

The whole set of IBIS/ISGRI data collected in the first part of the 2003 were re-analyzed using the new version of the INTEGRAL OSA, with updated calibration files and lookup tables, and including the background correction. In addition we performed a preliminary analysis of the new data collected from August 2003 (see Table 1). The derived images were much cleaner and the residual noise greatly reduced. We combined the data in 2 sets of equivalent effective exposure on the Galactic Nucleus. An image of the Galactic Center region in the 20-40 keV band was obtained from all the GCDE and ToO data (Fig. 2). Using the data of the observation specifically performed to study the Galactic Center (marked as GO in Table 1) we produced an equivalent image reported in Fig. 3. Both independent sets of data clearly show the presence of a relevant excess at the Sgr A* position thus confirming the results reported by Bélanger et al. (2004). IGR J1745.6–2901 was detected at a level of 20σ in Fig. 2 and at 27σ in Fig. 3. The combined data provide a signal at the GN of about 35σ. Some of the other sources were seen to vary significantly. For example the other closest source to the center (KS 1741-293) disappeared during the GO observation (Fig. 3), but IGR J1745.6–2901 was still clearly present. A fit of the reconstructed images with the PSF of the IBIS/ISGRI telescope for the six sources detected provided a position of IGR J1745.6–2901 which is offset from the Sgr A* radio position by only 52″ for the data of Fig. 2 and 48″ for the data of Fig. 3. These offsets are smaller than the expected uncertainty in source location.

From the whole data set of Table 1 we obtained the 20-40 keV light curve reported in Fig. 4.
Figure 2. Reconstructed IBIS/ISGRI images of the Galactic Center region in the 20-40 keV obtained using all data of the 2003 GCDE and ToO observations and more recent versions of the analysis tools. Height contours indicate significance levels from 10 to 35σ. Five well known high energy sources are indicated along with the position of Sgr A*.

Figure 3. Reconstructed IBIS/ISGRI images of the Galactic Center region in the 20-40 keV obtained using data of the dedicate observation of September 2003. Height contours indicate significance levels from 10 to 35σ. Five well known high energy sources are indicated along with the position of Sgr A*.

Figure 4. IBIS/ISGRI 20-40 keV light curve of IGR J1745.6–2901 from all data collected by INTEGRAL where the source was coded at > 40%. Data points were binned in time intervals of 1 day. The universal time is in units of IJD = MJD-51544 days.

source flux cumulated in time bins of 1 day is represented as a function of the universal time. The source flux appears rather stable over the year with no apparent large flares. The average flux was $(4.5 \pm 0.12)$ mCrabs in the 20–40 keV band and $(2.5 \pm 0.23)$ mCrabs in the 40–60 keV one. More detailed variability studies will be reported elsewhere. However, we do not confirm the detection of a flare during the observations of April 6 and the 5σ excess we reported previously (Bélanger et al. 2004) is probably due to an uncorrected background feature. The source GRS 1741.9–2853 also does not appear significant in the combined images and is not needed to fit the data of Fig. 2 and Fig. 3. As a consequence, the low energy band flux is more important than estimated previously, which indicates a softer spectrum for IGR J1745.6–2901 than estimated before.

5. DISCUSSION

The new analysis of the 2003 INTEGRAL data on the galactic nucleus confirms the preliminary result of a detection of a hard source at the position of the Sgr A complex (Bélanger et al. 2004). The position of this source is offset from the position of Sgr A* by less than 1′ compatible with a 90% confidence level error radius of 1.3′ for a source at 20σ (Gros et al. 2003). At the moment we cannot associate this excess unambiguously to Sgr A* or other sources of the region and it is designated as a new INTEGRAL source, IGR J1745.6–2901. As discussed in Bélanger et al. (2004), IGR J1745.6–2901 cannot be explained by the simple extrapolation at high energy of the average total diffuse and point-source flux observed by the X-ray instruments within 10′ from the center. On the other hand a few X-ray sources have been detected in the past within a few arcmin from Sgr A* and they could contribute to the emission if they were in high/hard state during the INTEGRAL observations. In particular, the ASCA tran-
sient AX J1745.6–2901, compatible in position with IGR J1745.6–2901, was observed to be bright with Chandra in June 2003 (F. K. Baganoff, private communication) and could provide an important contribution to the excess seen at energies above 20 keV. Some contribution to the observed high energy emission could also come from non-thermal X-ray filaments observed in the nuclear region with Chandra and XMM-Newton (Sakano et al. 2003) or other non-thermal sources like Sgr A East. This option is particularly relevant considering the presence in the region of an unidentified (GeV) gamma-ray EGRET source, 3EG J1746–2851, Mayer-Hasselwander et al. 1998 (Markoff et al. 1999) and the recent detections of significant TeV emission from the galactic center with Whipple (Kosack et al. 2004) and Cangaroo-II (Tsuchiya et al. 2004). All these very high energy sources appear compatible with a non-variable, point-like source at the GC and could be related to IGR J 1745.6–2901.

A detailed analysis of all INTEGRAL data available on the Galactic Nucleus is in progress and will provide better constraints on the position, spectral shape, variability properties and on the possible multiple nature of IGR J1745.6–2901. We also expect to further constrain these results by the simultaneous observations of Sgr A* in gamma-rays, X-rays, and at infrared and radio wavelengths. Such observations have been planned, by a large collaboration of astronomical laboratories, for 2004, driven by an approved XMM-Newton large project dedicated to the study of the X-ray flares of Sgr A*. The program includes simultaneous observations of the GN with HESS, INTEGRAL, VLT, HST, VLA and other radio, mm and sub-mm ground based observatories during part of the 550 ks observing program of XMM-Newton. Such a program will allow to search for correlated variability of the Sgr A* emission in different energy domains. The measure of the broad band spectrum of the flares and its evolution will allow to constrain the models of the physical processes and emission mechanisms taking place around the supermassive black hole at the center of our galaxy.

ACKNOWLEDGEMENTS

Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA. GB and MF acknowledge financial support from the French Space Agency (CNES). The authors thank the INTEGRAL project team at ESA for the support during the phases of the programme.

REFERENCES

Bartlett, L. M., 1994, Ph.D. Thesis, NASA Goddard Space Flight Center
Balick, B. & Brown, R. L. 1974, ApJ, 194, 265
Baganoff, F. K., 2001, Nat, 413, 45
Baganoff, F. K., 2003, ApJ, 591, 891
Béleranger, G., et al., 2004, ApJ, 601, L163
Cadolle Bel, M. et al., 2004, these Proceedings
Courvoisier, T.J.-L., et al. 2003, A&A, 411, L53
Eisenhauer, F. et al., 2003, ApJ, 597, L121
Falcke, H. & Markoff, S., 2000, A & A, 362, 113
Genzel, R., et al., 2003, Nat, 425, 934
Ghez, A., et al., 2003, ApJ, 586, L127
Ghez, A., et al., 2004, ApJ, 601, L159
Goldoni, P., et al., 1999, ApL, 38, 305
Goldwurm, A., et al., 1994, Nat, 371, 589
Goldwurm, A., 2001, ESA SP, 459, 455
Goldwurm, A., et al., 2003a, ApJ, 584, 751
Goldwurm, A., et al., 2003b, A&A, 411, L223
Gros A., et al., 2003, A&A, 411, L179
Hartman, R.C., et al., 1999, ApJ Supp., 123, 79
Jensen, P.L., et al., 2003, A&A, 411, L7
Kosack, K., et al., 2004, ApJ, 608, L97
Lebrun, F., et al., 2003, A&A, 411, L141
Liu, S. & Melia, F., 2002, ApJ, 566, L77
Liu, S., et al., 2004, ApJ, submitted, astro-ph/0403487
Maeda, Y., et al., 1996, PASJ, 48, 417
Markoff, S., et al., 2001, A&A, 379, L13
Mayer-Hasselwander, H. A., et al., 1998, A&A, 335, 161
Melia, F. & Falcke, H., 2001, ARAA, 39, 309
Muno, M., et al., 2003, ApJ, 598, 47
Narayan, R., et al., 1998, ApJ, 492, 554
Parmar, A.N., et al. 2003, A&A, 411, L421
Pavlinsky, M., et al., 1994, ApJ, 425, 110
Porquet, D., et al., 2003a, A&A, 407, 17
Porquet, D., et al., 2003b, A&A, 406, 299
Sakano, M., et al., 2002, ApJ Supp., 138, 19
Sakano, M., et al., 2003, MNRAS, 340, 747
Schödel, R., et al., Nat, 419, 694
Skinner, G., et al., 1987, Nat, 330, 544
Ubertini, P., et al., 2003, A&A, 411, L131
Tsuchiya, K. et al., 2004, ApJ, 606, L115
Winkler, C., 2001, ESA SP, 459, 471
Winkler, C., et al., 2003, A&A, 411, L1
Yuan, F., et al., 2002, A&A, 383, 854
Yuan, F., et al., 2003, ApJ, 589, 301