1 THE SKY BEHIND OUR GALAXY AS SEEN BY IBIS ON INTEGRAL

L. Bassani¹, A. Malizia¹, J.B. Stephen¹, F. Gianotti¹, F. Schiavone¹, A. Bazzano², A.J. Bird³, L. Bouchet⁴, T. Courvoisier⁵, A.J. Dean³, G. De Cesare², M. Del Santo², A. De Rosa², R. Hudec⁶, F. Mirabel⁷, P. Laurent⁷, L. Piro², S. Shaw³, A.A. Zdziarski⁸

¹ IASF-BO CNR/INAF, via Gobetti 101, 40129 Bologna, Italy
² IASF-Ro CNR/INAF, via Fosso del Cavaliere 100, 00133 Roma, Italy
³ School of Physics and Astronomy, Univeristy of Southampton, SO17 1BJ, UK
⁴ Centre d’Étude Spatiale des Rayonnements, CNRS/UPS, BP 4346, 31028 Toulouse France
⁵ INTEGRAL Science Data Center, Chemin d’Écogia 16, 1290 Versoix, Switzerland
⁶ Astronomical Institute, Academy of Sciences of Czech Republic, CZ-251 65 Ondrejov, Czech Republic
⁷ CEA Saclay, DSM/DAPNIA/SAp, 91191 Gif-sur-Yvette Cedex, France
⁸ Centrum Astronomiczne im M. Kopernika, Bartycka 18, 00-716 Warszawa, Poland

ABSTRACT

During the Core Programme, INTEGRAL has surveyed a large portion of the sky (around 9000 square degrees); although INTEGRAL is not optimized for extra-galactic studies its observations have nevertheless given us the opportunity to explore the sky behind our Galaxy, something which is impossible in some wavebands due to the presence of strong absorption. Preliminary results from this exploration are presented and compared with the pre-launch expectations. In particular, we detail all extragalactic detections obtained so far: 10 active galaxies and one cluster of galaxies. Of these sources, many have previously been studied at energies above 10-20 keV while a few are new hard X-ray discoveries. Since the number of detections is smaller than estimated on the basis of the IBIS/ISGRI sensitivity, it is likely that some of the new ISGRI sources found in this survey are extragalactic objects; a few of these are likely to be AGN and are described in detail.

Key words: hard X-ray sources; AGN .

1. INTRODUCTION

The so-called ”Zone of Avoidance” refers to the area contained within ± 10-15° of the disk plane of the Milky Way. Gas and dust obscure starlight within this region and screen nearly all background extragalactic objects from traditional optical-wavelength surveys; in the optical, as much as 20% of the extragalactic sky is obscured by the Galaxy. As a consequence, the Galactic plane historically has been neglected by extragalactic astronomers. Hard X-rays (≥ 10 keV) are able to penetrate this zone thereby providing a ”window” that is virtually free of obscuration not only relative to optical wavelengths but also partly in comparison to soft X-ray observations. Unfortunately the hard X-ray band is still poorly explored and the only truly all-sky survey conducted so far dates back to the 1980’s (Levine et al. 1984). This pioneering work, made with the HEAO1-A4 instrument yielded a catalogue of about 70 sources down to a flux level of typically 1/75 of the Crab (or 2-3 × 10⁻¹⁰ erg cm⁻² s⁻¹) in the 13-80 keV band. Only 7 extragalactic objects are reported in the A4 survey: none of these objects is within 10° of the galactic plane and only two (Centaurus A and the Perseus cluster ) are located below 20° in galactic latitude. Pointed observations by BeppoSAX/PDS have unveiled more sources but observations were sometimes limited by the lack of imaging capability of the instrument which is particularly crucial in the galactic plane region. A step forward in the study of the zone of avoidance is possible with the imager on board INTEGRAL, which allows detection with a sensitivity up to a few mCrab in the most exposed regions (i.e. the galactic center) and provides an angular resolution of 12” and a point source location accuracy of 2-3’.

Here we present a compendium of the extragalactic results obtained so far within the first year of the INTEGRAL Core Programme.
2. OBSERVATIONS AND DATA ANALYSIS

The IBIS coded mask instrument (Ubertini et al. 2003) on board INTEGRAL (Winkler et al. 2003) comprises two detection layers: ISGRI, an upper CdTe detector sensitive in the range 15 keV to 1 MeV and PICsIT, a bottom CsI detector sensitive in the range 200 keV to 8 MeV; herein we refer only to data collected by the first layer. The data analysed here belong to the Core Programme, i.e. were collected as part of the INTEGRAL Galactic Plane Survey and Galactic Centre Deep Exposure (Winkler et al. 2003) and are the just return to the instrument teams involved in the project. The data utilized for this work span from orbit 20 to orbit 145 inclusive. The total observation time varies from region to region in the sky and ranges from 0.8 Ms in the galactic center region which is the most exposed to typically 0.05 Ms in some parts of the galactic plane; some regions such as those of Cygnus, Crab and Vela are more exposed than a standard galactic plane region. During the 72 hours of the satellite’s orbital period (i.e. an INTEGRAL revolution) observations are performed as a series of fixed pointings that last about 37 minutes each and between which the satellite adjusts its position for the next pointing. The data collected during one such pointing are pre-processed and stored as one science window (scw); typically there are 110 scw in an orbit. Data reduction was performed with the OSA 3 INTEGRAL Science Data Center analysis software (Goldwurm et al. 2003), this version of the analysis procedures and calibration files is providing clean images although some systematic effects are still present. Briefly, image reconstruction is performed as follows: from the event list for one scw, a subset of events is selected according to given energy bands. This subset is then used to build a detector image or shadowgram from which a background map is subtracted. Convolution of the shadowgram with a decoding array provides the reconstructed sky image containing not only the main peak of all sources located within the field of view but also their secondary lobes (i.e. ghosts). The final reconstructed sky image is obtained after each source is identified and its secondary lobes subtracted. This procedure is repeated for each energy band and each scw; the data of many scw can then be mosaicked to obtain for each portion of the sky the total exposure available. For our search of active galactic nuclei (AGN) we choose to search the 20-100 keV band as this provides a good combination between sensitivity and overall background level over the entire image: above 20 keV, most AGN have power law spectra with $\Gamma=1.9$ and a break around 100 keV (Malizia et al. 2003) so that our choice of energy band perfectly matches these spectral characteristics. Using the data analysis procedure described above we sampled the whole sky by means of 40 (mosaicked) pointings which allow the full coverage of our galaxy; see figure 1 where circles have 10$^\circ$ radius to roughly match the half coded field of view of ISGRI; note that the top and bottom parts of the plane were also covered although not at the full instrument sensitivity. We then proceeded with the identification of all excesses (above 6 sigma confidence level) visible in the images in order to extract the detected extragalactic objects; identification of these excesses has been performed by cross checking the ISGRI error boxes (typically 2-3 arcmin) with the Simbad/NED and HEASARC data bases.
Figure 2. A typical 20-100 keV ISGRI image showing 2 Seyfert 2s (ESO103-G035 and NGC6300) just above the Galactic Plane.

Table 1. Sources detected so far

| Name              | z    | Type     | \(\sigma\) (scw) |
|-------------------|------|----------|------------------|
| GRS 1734-292      | 0.021| Sey1     | 27 (349)         |
| PKS 1830-21       | 2.57 | QSO      | 16.5 (166)       |
| Circinus Gal *    | 0.0015| Sey2    | 15 (23)          |
| Cygnus A          | 0.056| NLRG     | 12 (213)         |
| Oph Cluster       | 0.028| Cluster  | 10 (298)         |
| NGC 4945 *        | 0.00187| Sey2 | 9 (23)        |
| CEN A *           | 0.0018| NLRG/Sey2| 8 (23)          |
| NGC 6300 *        | 0.0037| Sey2     | 7.5 (43)         |
| ESO 103-G35 *     | 0.0133| Sey2     | 7 (43)           |
| MCG-5-23-16*      | 0.00828| Sey2 | 7 (161)         |
| NGC 6814 *        | 0.0052| Sey1     | 6.6 (80)         |

Note: * = objects observed by BATSE/OSSE on CGRO and PDS on BeppoSAX

Figure 3. The 20-100 keV ISGRI image of the Seyfert 1 GRS1734-292 (l=358.88\(^\circ\) and b=1.41\(^\circ\)). The field of view is 2\(^\circ\) x 1.8\(^\circ\).

3. RESULTS

On the basis of the number of AGN seen in the HEAO-A4 survey and the sensitivity in the energy band of interest here (typically around a few mCrab depending on the exposure available), we have estimated that the number of active galaxies which should be visible is around 20 when combining both the galactic plane survey (15) and the galactic center deep exposure (5). Some of these detections are expected to be known sources already observed by previous X-ray satellites but a number may be new hard X-ray objects. Analysis of the entire data set provides a list of 10 AGN plus one cluster of galaxies detected by IBIS/ISGRI in the 20-100 keV band: for each object Table 1 reports the source name, redshift, class, number of detected sigma and science windows.
used in the analysis. Here we present some highlights of this work, while a more detailed study of each individual source is postponed to dedicated papers. The first interesting result arising from table 1 is the ratio between type 2 (i.e. objects with the Broad Line Region (BRL) hidden behind gas and dust) versus type 1 objects (i.e. those with a visible BLR): we find a ratio of 7 to 2, which is interestingly close to the value found in optical spectroscopic surveys (Maiolino and Rieke (1995) and Ho et al. (1997)) if we assume that intermediate Seyfert of type 1.8-1.9 are grouped with Seyfert 2s. In figure 2 a particularly rich field containing 2 Seyfert 2s (ESO103-G035 and NGC6300) is shown, in all ISGRI images reported in this paper circles have no physical meaning, but are shown to better high-light the detected sources. Here too we assimilate narrow line radio galaxies like Cen A and Cygnus A with type 2 objects while the only QSO detected at high z is excluded from the present evaluation. That obscured AGN must be common is obvious from the fact that the 3 nearest (within 4 Mpc) active galaxies (NGC4945, Centaurus A and Circinus galaxy, all detected in the present survey) are all highly obscured with $N_H \geq 10^{23}$ cm$^{-2}$ (Matt et al. 2000). This situation has only recently been appreciated due to the fact that previous observations above 10 keV of two of the above objects were not available and also perhaps due to NGC4945 being a starburst at most wavebands and Circinus lying too close to the galactic plane. Just how common obscured AGN are is still uncertain but various arguments suggest that they are widespread, more than typically found in optical surveys which are generally insensitive to Compton thick sources with a high covering fraction. Hard X-rays are better suited to uncover absorbed AGN due to their more penetrating power; therefore our survey when completed can provide an estimate of the real ratio of type 2 to type 1 objects. On the other hand if we assume that AGN have randomly oriented viewing angles, the ratio of type 1 to 2 objects is related to $\Theta$ the half opening angle of the obscuring torus, via the relation $N1/N1+N2=(1-\cos \Theta)$, where N1 and N2 are the number of type 1 and 2 objects. From our ratio, we estimate $\Theta$ to be around 40°, in line with AGN unified model expectations. Many of the sources reported in table 1 (those marked by a star) are known hard X-ray sources and so have been previously studied in this band by OSSE and BATSE on CGRO and/or by the PDS on BeppoSAX (Zdziarski et al. 2000, Malizia et al. 1999, Westmore et al. 2000, Risaliti 2002, Matt et al. 2000). Rough flux estimates based on the detection level indicate an overall agreement with previous fluxes. In the particular case of NGC6814, the only previous detection of emission above 20 keV by OSSE is probably contaminated due to the presence of a nearby ($\sim 30'$) high energy emitter (the cataclysmic variable RXJ1940.2-1025, Bird et al. 2004), making this detection the first "real" measurement of this Seyfert 1 in the hard X-ray domain.

GRS1734-292 is another source poorly known above 10 keV: it was discovered by Granat/Art-P-Sigma in 1990 (Sunyaev et al. 1990) and subsequently detected over a broad energy band from soft X-rays (Barret and Grindlay 1996) to the hard X-ray band up to 400 keV (Pavlinski et al. 1994, Churazov et al. 1992). Afterwards it was found to be a radio jet like source and further identified with a Seyfert 1 galaxy (Martí et al. 1998). Further X-ray observations with ASCA (Sakano et al. 2002) indicate that the source is persistent and characterized by an absorbed power law spectrum ($\Gamma=1.3-1.7$ and $N_H=10^{22}$ cm$^{-2}$). The source is quite bright in the 20-100 keV band with a flux of $\sim 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (figure 3). The source lies within the 95% error box of the unidentified EGRET source 3EG J1736-2908; although it is a radio jet like source and so potentially a likely counterpart of the gamma-ray source, its radio flux and spectrum are not typical of EGRET blazars. Clearly analysis of the ISGRI spectrum and its extrapolation to the EGRET band can shed light on this issue. Also poorly studied at high energy is Cygnus A, the closest and best studied double radio galaxy belonging to the class of Fanaroff-Riley type II objects. It is interesting for a number of reasons including the presence of radio "hot spots", its location at the center of a cooling flow in a cluster of galaxies and the evidence for a "buried QSO" in the nucleus. This last aspect is particularly relevant for the ISGRI detection since gamma rays are able to penetrate heavily absorbing material. Cygnus A has recently been reported as a high energy emitting object by Young et al. (2002) after detection by RXTE-HEXTE: the overall nuclear spectrum combining high energy data with a Chandra measurement indicate a flat power law with $\Gamma=1.5$ and a column density of $2\times 10^{23}$ cm$^{-2}$. The source has also been observed by BeppoSAX-PDS but these data have never been published probably in view of possible contamination from nearby sources given its location in the galactic plane. Thanks to the imaging capability of IBIS/ISGRI we are now able to exclude such contamination and to analyse the PDS data which are well fitted with a power law with $\Gamma=1.8\pm0.3$ and provide a 20-100 keV flux of $7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ i.e. roughly the same brightness as seen by ISGRI (see figure 4). At these energies

Figure 4. 20-100 keV ISGRI image of the Seyfert 2 Cygnus A ($l=76.19°$ and $b=+5.76°$). The field of view is $1.5° \times 2°$.
PKS 1830-211 is a quasar at a redshift of $z=2.507$. Its radio image is gravitationally lensed by an intervening galaxy at $z = 0.89$ (Wiklind & Combes 1996) into two compact images (believed to arise from the core) separated by about $1^\circ$ and a ringlike extended structure (thought to arise from the jet) connecting the compact images (Promesh-Rao & Subrahmanyan 1988). The radio emission has a flat spectrum and shows a large time variability (Lovell et al. 1998). This source is also detected at infrared (Lidman et al. 1999), X-ray (Mathur and Nair 1997, Oshima et al. 2001), and gamma-ray (Mattox et al. 1997) wavelengths. These detections imply that PKS 1830-211 is a blazar. PKS 1830-211 has been reported as an ISGRI source in the galactic centre region both by Bird et al. (2004) and Revnivtsev et al. (2004): the 20-100 keV image is shown in figure 5 where this object is clearly detected with a flux of $\sim 6 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 20-100 keV band. At a redshift of 2.5 this is the farthest object so far detected by INTEGRAL. The broad band high energy spectrum of the source clearly confirms its blazar nature and further identifies it as a low frequency (i.e. MeV) peaked or red blazar (see figure 6).

### 3.2. Oph Cluster

The Oph cluster is a nearby ($z=0.028$) rich cluster (150 members) of galaxies with an angular extent of roughly 1 degree. With a 0.1-2.4 keV luminosity of $3.1 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ it is the second brightest cluster in the zone of avoidance after Perseus (Ebelling, Mullis and Tully 2002). The X-ray spectral data from ASCA indicate a temperature in the range 8-26 keV (depending on the cluster region) and an iron abundance of 0.2-0.5 relative to the cosmic value (Watanabe et al. 2001). This source too has been reported as a galactic centre source by Bird et al. (2004) and Revnivtsev et al. (2004). The source is close to RXJ1712.6-2414 (a LMXB), also detected by ISGRI, so that it is likely that a previous detection by BeppoSAX/PDS in the high energy part of the spectrum is contaminated. Our 20-100 keV image showing the two sources and the PDS field of view can be found in figure 7. The contaminating source is at the border of the PDS field of view so that its contamination is probably not significant (likely less than 10-20%). This is confirmed by the good agreement in flux between ISGRI and PDS both around $5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The PDS data provide an average $kT \sim 8$ keV.
4. MISSING SOURCES

A comparison between our findings and expectations indicate that we are still missing approximately half of the AGN. In this sense the list of ISGRI objects not yet firmly identified deserves special attention: around 30 objects detected in the first year of data have no obvious counterparts in optical or infrared (Bird et al. 2004). Most of these objects are believed to be X-ray binary systems, where one of the two members is either a black hole or a neutron star. There is however the possibility that some of them could be AGN similar to those reported here in Table 1. In fact, one of these new INTEGRAL objects, IGR J21247+5058 (Walter et al. 2004) shown in figure 8, has recently been associated with the radio source 4C50.55 by Ribó et al. (2004). These authors report that this source has a morphology typical of a radio galaxy at 1.4 GHz: a flat spectrum core with peak flux density of 237 mJy/beam and two large lobes with peak flux densities of 288 and 92 mJy/beam respectively; the lobes have spectra compatible with optically thin synchrotron radiation. It is also an infrared/optical source with R-K=3.73 indicating a red spectrum possibly due to strong extinction in the source direction. No bright or faint ROSAT source is reported at the position of this ISGRI object neither can we find a counterpart in the Uhuru or A1 all sky survey catalogues, possibly suggesting that strong absorption prevents X-rays below a few keV from escaping; otherwise we must assume that the source is extremely variable. Our data indicates a very bright and hard high energy source with a 20-100 keV flux of about $10^{-10}$ erg cm$^{-2}$ s$^{-1}$ and a 40-100 keV/20-40 keV ratio of 1.25 (Bird et al. 2004); although a blazar type object could fulfill some of the above characteristics still no catalogued EGRET source is found near IGR J21247+5058.

Another likely candidate is IGR J18027-1455 (see figure 9): inside the 2 arcmin error box of this source we have found an extended 2-MASS infrared source (2MASXi J1802473-145454) which is also a radio object with a flux of 10.5 mJy at 20 cm (NVSS180247-145451). The near-infrared source (see figure 10) is fairly bright (1.44 and 1.79 mJy in J and H respectively) while the optical counterpart is dim (B=19.3); here too we find a R-K colour index of 4 again indicating strong reddening in the source direction. This source is also an X-ray emitter being detected as a faint Rosat source (1RXS J180245.5-145432), which has a hardness ratio compatible with an AGN interpretation (Motch et al. 1998). The association with a possible extragalactic object derives from the fact that most objects found to be extended in the 2-MASS extended catalogue are galaxies although Galactic nebulae and HII regions as well as multiple stars (mostly double stars) and faint (mostly point-like) sources with uncertain classifications are also possible: of all these possibilities the AGN interpretation is more in agreement with the source being a hard X-ray emitter.

5. CONCLUSIONS

We have presented a compendium of the extragalactic results obtained so far within the first year of the INTEGRAL Core Programme. Observations of the galactic plane and center have revealed so far 11 extragalactic objects: 10 are active galaxies and one is a cluster of galaxies. Of the AGN sample, 2 objects are of type 1 and 7 are of type 2. This provides a type 2 over type 1 ratio which is in line with optical spectroscopic data and furthermore agrees with the expectations of the unified theory. Furthermore it implies a torus half opening angle of $\sim 40^\circ$. Many of the objects reported in this work are known to emit at high energies while a few are new hard X-ray discoveries. In particular we find PKS 1830-211 a low frequency (i.e. MeV) peaked or red blazar and Oph Cluster the first and only cluster so far reported by INTEGRAL. We also argue that a few of the new ISGRI sources discovered during the Core Programme could also be of extragalactic origin and describe two likely cases,
Figure 10. H-band of the field (1' × 1') containing IGR J18027-1455 showing the extended 2MASS object at the center nearby the radio source NVSS J180247-145451.

IGR J21247+5058 and IGR J18027-1455.

ACKNOWLEDGMENTS

We acknowledge financial support by ASI (Italian Space Agency) via contract I/R/041/02. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration; of the SIMBAD database, operated at CDS, Strasbourg, France; and of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Center.

REFERENCES

Barret D. and Grindlay J.E. 1996 A&A 311,239
Bird T., Barlow A.J., Bassani L. et al. 2004 ApJ submitted
Churazov E., Gilfanov M., Cordier B. and Schmitz-Frasse M.C. 1992 IAUC5623
Ebelling H., Mullis C.R. and Tully R.B. 2002 ApJ 580,774
Goldwurm A., David P., Foschini L. et al. 2003 A&A 411 L223
Ho L.C., Filippenko A.V. and Sargent W.L.W. 1997 ApJS 112,315
Lidman C., Courbin F., Meylan G. et al. 1999 ApJ 514,57
Levine A., Lang F.L., Lewin W.H.G. et al. 1984 ApJ 554, 581
Lovell J.E.J., Jauncey D.L. and Reynolds J.E. et al. 1998 ApJ 508, 51
Maiolino R. and Rieke G.H. 1995 ApJ 454, 95
Malizia A., Bassani L., Zhang S.N. et al. 1999 ApJ 519, 637
Malizia A., Bassani L., Stephen J.B. et al. 2003 ApJ 589, L17
Marti J., Mirabel I.F., Chaty S. and Rodriguez L.F. 1998, A&A 330, 72
Mathur S. and Nair S. 1997 ApJ 484, 140
Matt G., Fabian A.C., Guainazzi M. et al. 2000 MNRAS 318, 173
Mattot J.R., Schachter J. Mohlar. L. et al. 1997 ApJ 481, 95
Motch C., Guillout P., Haberl F. et al. A&A 132, 341
Oshima, T., Mitsuda, K., Ota, N., Yonehara, A., Hattori, M., Mihara, T., Sekimoto, Y. 2001, ApJ, 551, 929
Pavlinsky M.N., Grebenev S.A. and Sunyaev R.A. 1994, ApJ 425, 110
Promesh-Rao A. and Subrahmanyan R. 1988 MNRAS 231, 229
Revnitsev M., Sunyaev R.S., Varshalovich D. et al. 2004 Astronomy Letters in press
Ribo M., Combi J.A., Mirabel I.F. 2004 Atel 235
Risaliti G. 2002 A&A 386, 379
Sakano M., Kowama K., Murakami M., et al. 2002, ApJS, 138, 19
Sunyaev R.A. 1990 IAUC 5123
Ubertini P., Lebrun F., Di Cocco G., et al. 2003 A&A 411, L131
Walter R., Bodaghee A., Barlow E.J. et al. 2004 Atel 229
Watanabe M., Yamashita K., Furuzawa A. et al. 2001 Publ. Astron.Soc Japan 53, 605
Westmore M.J., Gurrian R., Dean A.J.D. et al. 2000 AIPC 510, 387
Wiklind, T., and Combes, F. 1996, A&A, 315, 86
Winkler C., Courvoisier T.J.L., Di Cocco G. et al. 2003 A&A 411 L1
Young A.J., Wilson A.S., Terashima Y. et al. 2002 ApJ 564, 176
Zdziarski A.A., Poutanen J. and Johnson W.N. 2000 ApJ 542, 703