THE FOURTH IBIS/ISGRI SOFT GAMMA-RAY SURVEY CATALOG*

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ABSTRACT

In this paper, we report on the fourth soft gamma-ray source catalog obtained with the IBIS gamma-ray imager on board the INTEGRAL satellite. The scientific data set is based on more than 70 Ms of high-quality observations performed during the first five and a half years of the Core Program and public observations. Compared to previous IBIS surveys, this catalog includes a substantially increased coverage of extragalactic fields, and comprises more than 700 high-energy sources detected in the energy range 17–100 keV, including both transients and faint persistent objects that can only be revealed with longer exposure times. A comparison is provided with the latest Swift/BAT survey results.

Key words: Galaxy: general – gamma rays: observations – surveys

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Since its launch in 2002, the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) observatory has carried out more than seven years of observations in the energy range from 5 keV to 10 MeV. INTEGRAL is an observatory-type mission, and most of the total observing time (65% in the nominal phase, 75% during the mission extension) is awarded as the General Program to the scientific community at large. Typical observations last from 100 ks up to 2 weeks. As a return to the international scientific collaborations and individual scientists who contributed to the development, design and procurement of INTEGRAL, a part of the observing time (from 35% to 25%) was allocated to the Core Program. During the nominal lifetime (five years), this program consisted of three elements: a deep exposure of the Galactic central region, regular scans of the Galactic Plane, pointed observations of the Velab region, and Target of Opportunity follow up. In order to exploit INTEGRAL’s unique capabilities, Key Programs were introduced in 2006 (AO5). These are deep observations requesting a few Ms observing time that allow the observatory to accommodate various different requests of the community at large by amalgamating many individual scientific targets present in the selected sky fields as well as ultra-long nucleosynthesis and diffuse emission studies.

The IBIS (Imager on Board INTEGRAL Spacecraft) imaging instrument is optimized for survey work with a large (30°) field of view (FOV) with excellent imaging and spectroscopy capability. Instrumental details and sensitivity can be found in Ubertini et al. (2003). The data are collected with the low-energy array, ISGRI (INTEGRAL Soft Gamma-Ray Imager; Lebrun et al. 2003), consisting of a pixellated 128 × 128 CdTe solid-state detector that views the sky through a coded aperture mask. IBIS/ISGRI generates images of the sky with a 12’ (FWHM) resolution and typical source location of better than 1’ over a ∼19° (FWHM) FOV in the energy range 17–1000 keV.

A sequence of IBIS survey catalogs has been published at regular intervals as more data have become available (Table 1). The frequent Galactic Plane Scans (GPS) within the Core Program, performed in the first year of operations, were successfully exploited to yield a first survey of the Galactic plane to a depth of ∼1 mCrab in the central radian (Bird et al. 2004). This gave evidence of a soft gamma-ray sky populated with more than 120 sources, including a substantial fraction of previously unseen sources. The second IBIS/ISGRI catalog (Bird et al. 2006) used a greatly increased data set (of ∼10 Ms) to unveil a soft gamma-ray sky comprising 209 sources, again with a substantial component (∼25%) of new and unidentified sources. The third IBIS/ISGRI catalog (Bird et al. 2007) further increased the data set, with a substantial improvement in extragalactic coverage, resulting in the detection of a total of 421 sources.

In this paper, we provide the fourth IBIS/ISGRI soft gamma-ray survey catalog that now comprises more than 700 high-energy sources. This fourth catalog continues to build on the source data provided by previous catalogs by incorporating an additional two years of data, and using the latest software and source detection techniques. Particular care has been taken to optimize the detection of the transient sources that are common

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in the hard X-ray sky but are only visible for a small fraction of the total exposure now available.

2. DATA ANALYSIS AND CATALOG CONSTRUCTION

2.1. Input Data Set and Pipeline Processing

The survey input data set consists of all available pointings at the end of 2008 April. This consists of the first five years of Core Program observations, including the GPS, Galactic Center Deep Exposure (GCDE), and all available pointed observations. Data coverage from revolution 12 (first light, 2002 November) to revolution 530 (2007 April) is almost complete, while data between 2007 April and 2008 April constitute only Core Program and public pointings. INTEGRAL/IBIS data are organized in short pointings (science windows, scw) of \( \sim 2000 \) s. In total, 41,588 scw were input into the pipeline processing. After removal of pointings flagged as Bad Time Intervals (BTI) by the Science Data Centre (Courvoisier et al. 2003), this number is reduced to 39,548 scw of good-quality data.

Pipeline processing was carried out using the standard OSA 7.0 software (Goldwurm et al. 2003) up to and including the production of sky images for individual scw with 4\,pixel resolution. Five primary energy bands (20–40, 30–60, 20–100, 17–30, and 18–60 keV) were used to maximize the detection sensitivity for sources with various energy spectra. The input catalog used for image processing was those sources marked as detected by ISGRI in the ISDC Reference Catalog version 28, which had been updated to include all sources previously detected by the surveys and in guest observer pointings.

The overall sky exposure is summarized in Figure 1. When discussing exposure, we use the accumulated instrument live-time, corrected for off-axis coding fraction, but not corrected for energy-dependent on-axis absorption. It can be seen that near the Galactic plane, half the sky is covered with more than 1 Ms of exposure, while for the whole sky, that fraction drops to \( \sim 15\% \). 90\% of the sky is exposed at the 100 ks or greater level. The exposure does not result from any specific pointing or operational constraints, but is merely the summation of all science observations performed during the accumulation of the data set. The overall exposure uniformity is improving as the mission continues, and as the science program includes a greater number and diversity of targets.

2.2. Mosaic Construction

Each scw image was tagged with its rms (after removal of sources) to act as an indicator of the overall image quality. As in previous survey construction, the primary aim of this step is to remove data taken during periods of enhanced background (during solar activity or soon after perigee passage). Filtering was applied based on the rms value of the image, such that the rms should not exceed a limit of 2\( \sigma \) above the mean image rms for the whole data set). This function now somewhat overlaps with the BTI flagging provided by the ISDC, but we still remove around 5\% of the scw that exceed this rms limit. Although they are still processed, data taken in the staring mode are not used in the construction of the final sky mosaic images as they contribute a far higher level of systematic noise than the standard dithered observations. Some 1230 scw in the input data set were flagged as consisting of staring data.

After the removal of high-rms and staring data, approximately 36,000 scw remained in the data set, with a total exposure of \( \sim 70 \) Ms. The selected scw were mosaicked using a proprietary tool optimized to create all-sky galactic maps based on large numbers of input scw. Mosaics were constructed for five energy bands (see Section 2.1), four map projections, and four timescales, all with 2\,pixel resolution, significantly oversampling the intrinsic system point-spread function (PSF).

We constructed mosaics over the same three timescales used for the third catalog, and a newly introduced one for identifying transients as explained in Section 2.4. Maps were created for each revolution (a satellite orbit; approximately 3 days) that contained valid data. This is optimized to detect sources active on timescales of the order of a day. We also identified 32 sequences of consecutive revolutions that had similar pointings. Thus, these revolution sequences could best be analyzed as a single observation, and sensitivity for sources on longer timescales than revolutions (i.e., order of weeks) could be optimized. Ultimately, persistent sources can best be detected in an all-archive accumulation of all available high-quality data. The problem of higher exposure and long timespaned by this latest data set has further worsened the problem noted in the third catalog—namely, the source search methods we employ are optimized for the detection of persistent flux from a source; a highly variable source may be clearly detectable during outburst, while having an undetectably low mean flux over the full data set. In addition, we searched for the optimum detection timescale (from 0.5 days to the length of the data set) for known or suspected sources (see Section 2.4) and created one additional mosaic for each source on the optimum timescale for that source.

For each energy band and time period, all-sky mosaics were made in four projections: centered on the Galactic Center, centered on the Galactic anti-center, north galactic polar, and south galactic polar. The purpose of these multiple projections is to present the automatic source detection algorithms with source PSFs with the minimum possible distortions.
2.3. Source Searching and Candidate List Production

In total over 11,500 maps were created at this stage of processing. Each of the mosaics was searched using two methods.

1. The SExtractor 2.5 software (Bertin & Arnouts 1996). The source positions measured by SExtractor represent the centroid of the source calculated by taking the first-order moments of the source profile (referred to by SExtractor as the barycenter method). Source detectability is limited at the faintest levels by background noise and can be improved by the application of a linear filtering of the data. In addition, source confusion in crowded fields can be minimized by the application of a bandpass filter. To this end, the mexhat bandpass filter is used in the SExtractor software. The convolution of the filter with the mosaic alters the source significances, hence SExtractor uses the source positions identified from the filtered mosaic to extract the source significances from the original mosaic.

2. A proprietary “peakfind” tool which employs a basic iterative removal of sources technique, combined with an assessment of the local background rms to reduce the false detection of sources in areas of the map with high systematic noise structures—mainly in crowded regions and around the brightest sources.

A list of candidate sources was constructed by merging the >4σ excess lists from each mosaic, using a merge radius of 0.1 degrees. A source had to be detected by both search methods in order to be included in the candidate list. Manual inspection was performed on each map to check for the (rare) occasions where SExtractor fails due to the close proximity of two sources, and any additional sources found were added to the excess list. We also added all previous declared INTEGRAL detections which were not detected in any of our maps, in order to be able to search for them on different timescales and around the brightest sources.

This resulted in a list of 1266 excesses which were passed to the next stage of analysis.

2.4. Light Curve Generation and Search on all Timescales

The main change initiated in this catalog compared to previous ones is intended to address the detection of variable sources. The hard X-ray sky is extremely variable, and this leads to problems in detecting sources when the search is only performed on a limited number of timescales. As an example, a source in outburst in the early mission becomes of lower and lower significance as more and more data are acquired when the source is in quiescence.

These variability issues have led to a number of unfortunate effects.

1. Sources detected in earlier catalogs may drop below the detection threshold after long periods of quiescence.

2. A number of sources known to be detectable in IBIS have not been included because the source search was not optimized for the particular timescale on which the source was active.

In this catalog, we have performed a systematic search for any source detected in a previous IBIS catalog or declared as a new IBIS detection in the literature prior to 2008 April when the data set was frozen. This was performed by creating a light curve for each source in the 18–60 keV band on scw timescales, and then scanning a variable-sized time window along each light curve. The window length is varied from 0.5 days (∼10 scw) to the full length of the light curve, and all data points within the time window are included in the analysis. The duration and time interval over which the source significance is maximized is recorded.

We define the bursticity of a source as the ratio of the maximum significance on any timescale, compared to the significance defined for the whole data set. Thus, a bursticity of 1 defines a persistent source, where the inclusion of any data maintains or increases the detection significance. Conversely, a bursticity of greater than 1 implies that the significance of a source can be increased by the omission of some observations from the analysis, presumably when the source was in quiescence. Note that we only use the single time interval when the significance is maximized, we do not combine multiple non-consecutive outbursts which, for some sources, could yield an even higher significance.

The impact of this bursticity analysis is significant. Around 100 sources are recovered that would not have been without this analysis. Furthermore, by defining the time interval over which the significance is maximized for every source, we gain an insight into the variability behavior of the sources. Finally, by building a mosaic map only for the timescale of maximum significance, we can optimize the chance of source detection and determination of some source parameters—notably the best possible source position (since error radius is inversely proportional to significance).

A few examples can serve to illustrate the effect of the bursticity analysis. The first is IGR J00245+6251, a GRB reported in the third IBIS/ISGRI catalog as an 11.5σ detection in revolution 266. The bursticity analysis instead identifies that the source was active on a 0.5 day timescale (this is actually the minimum search time, and is still much longer than the burst itself). By mapping on a more appropriate timescale, the significance is increased to 28.6σ and the position error reduced from 2.3 to 1.1. It should be noted that the majority of GRB and a number of other fast (duration < 0.5 days) transient objects with lower fluxes are still not recovered with sufficient significance to be included in this catalog. The second is IGR J17191−2821, a transient discovered during the Galactic Bulge monitoring (Kuulkers et al. 2007). This source was therefore added to the checklist as a previously declared INTEGRAL detection, despite the fact that it was totally undetectable (below 4σ) in any of the long-term maps. It would not have been detected using the methods employed for the third catalog. Bursticity analysis, however, confirms its detection at the 8σ level during a 1.2 day outburst. These two examples show the efficiency of finding short outbursts. However, there is another class of detection—non-persistent sources of long duration that are too faint to appear at either revolution or whole-archive timescales. Illustrating this is IGR J13400−6428, a source put forward for further analysis due to a marginal detection (4.0 < σ < 4.5) in the whole-data-set maps. Mapping over the optimum 500 day period identified by bursticity analysis provides a clear 7.5σ detection, but again this source would not have been found by the methods used for the third catalog.

At the end of this process, the significance of each source in each energy band, and for both whole data set and “outburst” are known, and these significances are used in a final decision on the acceptance of each source. An indication of the bursticity level, the significance obtained, and a peak flux during the detected outburst are included in the source list.
Table 2
Sources Required in Galactic Center and North Blend Fitting

| ID   | Name                   | R.A.  | Decl. | New |
|------|------------------------|-------|-------|-----|
| NB1  | XTE J1739−285          | 264.989 | −28.487 | N   |
| NB2  | SLX 1373−282           | 265.179 | −28.291 | N   |
| GC1  | GRS 1741.9−2853        | 265.249 | −28.919 | N   |
| GC2  | IGR J17456−2901        | 266.410 | −29.021 | N   |
| GC3  | IGR J17457−2858        | 266.428 | −28.982 | Y   |
| GC4  | IGR J17459−2902        | 266.485 | −29.043 | Y   |
| GC5  | 1E 1743.1−2843         | 266.580 | −28.735 | N   |
| GC6  | IGR J17463−2854        | 266.587 | −28.907 | Y   |
| GC7  | IGR J17467−2848        | 266.683 | −28.805 | Y   |
| GC8  | IGR J17468−2902        | 266.690 | −29.045 | Y   |
| GC9  | SAX J1747.0−2853       | 266.761 | −28.883 | N   |

2.5. Source List Final Filtering

We have performed a number of steps to minimize the possibility of false catalog entries. These methods are designed to counter both statistical fluctuations in the maps (which we can to some extent assess) and systematic effects present in the maps, which are much harder to quantify.

First and foremost, each source is manually inspected by a number of people experienced with working with IBIS/ISGRI maps. The inspection covers aspects such as PSF shape, consistency across multiple energy bands, and the significance of the source relative to the local noise levels in the map. We require a unanimous agreement among many viewers that the excess is a true source, a very conservative approach, but one designed to minimize the false detection rate.

A flux-exposure analysis has been carried out in which each detected flux has been compared to the predicted minimum detectable flux for the exposure in which the detection was made. Sources for which the mean flux is much lower than that which could reasonably be detected in a corresponding timescale may have been boosted by systematic effects, or may just be an outlier in the statistical fluctuations of the maps—in either case, the excess is rejected.

2.6. Detection Significance Thresholds

In order to identify an excess in one of the mosaicked images, it is necessary to determine the significance level at which the source population dominates over the noise distribution. To this end, we produce a histogram of the individual pixel significance values in each of the mosaics where a source was found. A Gaussian, with mean ~0 and standard deviation ~1, is found to be a good representation of the noise distribution. This is shown in Figure 2 for the 18–60 keV all-sky mosaic; at high significances it is clear that the data deviate from the noise distribution model.

Looking at the pixel significance distribution across all mosaics, we can confidently conclude that ~1% of the pixels found at significances above 4.8σ are produced by the statistical noise distribution. Furthermore, in the 18–60 keV all-sky mosaic, of the pixels found between 4.5σ and 4.8σ, ~6% are from the statistical noise distribution. However, these limits are not reliable.

Table 3
Fourth IBIS/ISGRI Catalog

| Namea                                      | R.A.    | Decl.   | Errorb | F20–40c | F40–100c | Typed | Vari†     | Peak Fluxf | Signifg | Exposurebh | MapCodei |
|-------------------------------------------|---------|---------|--------|---------|----------|-------|----------|------------|---------|-----------|----------|
| IGR J00040+7020                           | 0.960   | 70.305  | 3.2    | 0.7 ± 0.1| 1.0 ± 0.2| AGN, Sy2 | Y         | 1.7 ± 1.1 | 5.1     | 3030.8    | B1       |
| IGR J001582+5605                          | 3.961   | 56.092  | 4.0    | 0.5 ± 0.1| <0.3     | AGN?   | Y         | 1.9 ± 1.1 | 9.2     | 3767.5    | B4       |
| IGR J002344+6141                          | 5.738   | 61.677  | 2.9    | 0.7 ± 0.1| <0.3     | CV, IP | Y         | 1.9 ± 1.1 | 9.2     | 3767.5    | B4       |
| IGR J002452+6251                          | 6.115   | 62.835  | 1.1    | <0.2    | <0.3     | GRB    | YY        | 23.1 ± 0.9| 28.6    | 3797.7    | burst    |
| 4U 0022+63                              | 6.313   | 64.133  | 2.5    | 0.7 ± 0.1| 0.6 ± 0.1| SNR    |           | 10.5     | 3729.3    | burst    |
| IGR J002568+6281                          | 6.329   | 68.357  | 2.6    | 0.7 ± 0.1| 1.0 ± 0.2| AGN, Sy2|           | 9.6      | 3174.2    | B3       |
| V709 Cas                                 | 7.198   | 59.284  | 0.6    | 4.5 ± 0.1| 2.7 ± 0.1| CV, IP |           | 56.9     | 3562.7    | B5       |
| IGR J00291+5934                          | 7.255   | 59.564  | 0.4    | 2.4 ± 0.1| 2.8 ± 0.1| LMXB, XPT| Y         | 29.8 ± 0.3| 113.3    | 3580.2    | burst    |
| IGR J00333+6122                          | 8.326   | 61.458  | 2.6    | 0.7 ± 0.1| 0.9 ± 0.1| AGN, Sy1.5 |           | 9.8      | 3700.7    | B3       |
| 1ES 0033+595                             | 8.964   | 59.830  | 1.6    | 1.3 ± 0.1| 0.9 ± 0.1| AGN, BL Lac |           | 18.2     | 3562.7    | B4       |

Notes.

a Name in boldface indicate new detections since third catalog.

b Position errors expressed as radius of 90% confidence circle in arcminutes.

c Time-averaged flux expressed in units of mCrab; appropriate conversion factors are: (20–40 keV) 10 mCrab = 7.57 × 10−11 erg cm−2 s−1 = 1.71 × 10−3 ph cm−2 s−1; (40–100 keV) 10 mCrab = 9.42 × 10−11 erg cm−2 s−1 = 9.67 × 10−4 ph cm−2 s−1.

d Source-type classifications: A = Atoll source (neutron star); AGN = active galactic nuclei; AXB = anomalous X-ray pulsar; B = Bursting (neutron star); Be = B-type emission-line star; BH = black hole (confirmed mass estimation); BHC = black hole candidate; BL = broad line; Cluster = cluster of galaxies; CV = cataclysmic variable; D = dipping source; DN = dwarf nova; G = globular cluster X-ray source; GRB = gamma-ray burst; HMXB = high-mass X-ray binary; IP = intermediate polar; LMXB = low-mass X-ray binary; M = microquasar; Mol Cloud = molecular cloud; NL = narrow line; NS = neutron star; P = polar; PSR = radio pulsar; PWN = pulsar wind nebula; QSO = quasar; RG = radio galaxy; SXFT = supergiant fast X-ray transient; SG = supergiant; SGR = soft gamma-ray repeater; SNR = supernova remnant; Sy = Seyfert galaxy; Symb = symbiotic star; T = transient source; XB = galactic X-ray binary; XBONG = X-ray bright, optically normal galaxy; XP = X-ray pulsar; Z = Z-type source (neutron star)

† Variability indicator, see Section 4 for details.

‡ Maximum significance in a single map; see mapcode column to identify map with maximum significance.

b Corrected on-source exposure (ks).

f Peak flux in 20–40 keV band, measured during largest detected outburst, see Section 4 for details.

h Maximum significance in a single map; see mapcode column to identify map with maximum significance.

i Blended source. Position determined by simultaneous fitting is reliable, but other measured values (flux, significance) may be contaminated by nearby source(s) and are unreliable.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
based upon the global properties of the mosaics and the maps contain systematic errors which are localized to specific regions. The majority of the systematic noise is produced from the very brightest sources and from very crowded regions. This is dealt with through the visual inspection of each candidate excess in the context of the region of sky in which it has been detected.

3. GALACTIC CENTER LOCALIZATIONS

The Galactic Center region poses a number of specific problems for the determination of the source population which gives rise to the emission seen by IBIS/ISGRI. A number of sources there are not fully spatially resolved and are highly variable, and the region is subject to some systematic structures that make the identification of faint sources difficult.

A 50.4 × 52.8 image in the 20–40 keV band centered at \( l = 0\,\text{h}\), \( b = 0\,\text{deg}\) was extracted from each revolution during which the Galactic Center was observed (∼140 in total). The region was optimized to minimize the impact of nearby known bright sources but to allow good assessment of the local background statistics. A core set of three sources, 1E 1743.1–2843, SAX J1747.0–2853, and IGR J17456–2901, was used as a starting point, the evidence of their presence being determined from simultaneous, spatially well-separated detection with JEM-X during observations of the Galactic Center and Bulge region performed in revolutions 407–429 (2007 February–April).

For each revolution, these three sources were fit as two-dimensional Gaussians with their positions fixed to those in Kuulkers et al. (2007), FWHM fixed to 5 pixels (the PSF of the mosaics described above), and normalizations free to vary. The Gaussian can be taken as an adequate approximation of the true PSF (Gros et al. 2003) given that the images are typically constructed from ∼50 dithered scw. If \( \chi^2 \gg 1 \), and a significant (>3\( \sigma \)) excess was present in the residuals, a new Gaussian was added with both position and normalization free to vary. The presence of bright sources centered outside of the fitting region, but still influencing it, was taken into account when necessary. The procedure was repeated for the “North Blend,” a region centered at \( l = −0\,\text{h}\), \( b = 1\,\text{deg}\). The two fitting regions are shown in Figure 3.

The fit results from all revolutions were merged and a consistent set of nine sources in the Galactic Center and two in the North Blend was generated. All sources resulting from these fits are identified as B1GCF in the mapcode column of the source list and shown in Table 2. Apart from the three core sources listed above, we confirm the detection of GRS 1741.9–2853 and detect five new variable sources. The limited angular resolution of IBIS prevents these from being unambiguously associated with previous X-ray sources. The time variability and nature of these sources will be discussed in more detail in a future publication.

4. THE TABLE DATA

The 723 sources of the catalog are presented in Table 3. The name of the source is given following the convention to quote wherever possible the name declared at the time of the first X-ray detection. The names are given in bold for the ∼300 sources added to the catalog since the third catalog.

The astrometric coordinates of the source positions were extracted from the mosaics by the barycentring routines built into SExtractor 2.5. In almost all cases, the position for a source was extracted from the map yielding the highest source significance. In a few cases, primarily for blended sources, other maps were chosen in order to minimize the interference of other sources. Simultaneous fitting of multiple Gaussian PSFs was used in the most difficult cases—these sources are indicated as blended in the notes accompanying the table. The point source location error of IBIS is highly dependent upon the significance of the source detected (Gros et al. 2003). We use this formulation, combined with the significance of the detection used to locate the source, in order to define an error on the source position. The source localization errors quoted are for the 90% confidence limit.

The mean fluxes quoted in the table as F20–40 and F40–100 are the time-averaged fluxes over the whole data set derived in two energy bands (20–40 and 40–100 keV). These are provided for compatibility with past catalogs, but we note that their relevance as an average measure diminishes as the data set increases and becomes longer than the average time of activity for many of the sources. Therefore, in addition for variable sources, we provide a variability indicator and indicative peak flux in the 20–40 keV band. A flag of Y indicates a bursticity >1.1 (i.e., a 10% increase in significance can be obtained by selecting a subset of the data). A flag of YY indicates a bursticity of >4, indicating a strongly variable source. In both cases, the peak flux is defined as the mean flux during the single period of time for which the significance is maximized.

The type of the source is encoded into up to four flags, which are explained in the table footnotes. We have followed the convention of Liu et al. (2007) wherever possible. Identifications, and hence source types, are provided only if considered robust. The exposure quoted is the total effective exposure on the source after all filtering of the data has been carried out.

The significances quoted are the highest significance in any single map (the map from which the significance is derived is also identified in the table), since this gives the best indication of the robustness of source detection. However, it should be noted therefore that the flux and significance values may derive from different energy bands and/or subsets of the data, and may initially appear contradictory.

5. DISCUSSION

We have derived an “unbiased” catalog of 723 sources observed in a systematic analysis of the IBIS/ISGRI Core
Figure 3. Fitting regions and resulting sources for the analysis of Galactic Center and North Blend.

Program and public data spanning nearly five years of operation. Of these, 684 are secure detections of greater than $4.8\sigma$, the remainder are detected with between $4.5\sigma$ and $4.8\sigma$ but still with a good statistical significance.

We can estimate the minimum detectable flux as a function of the sky position (Figure 4) based on the accumulated exposure. The sensitivity of the survey is still strongly biased by the non-uniform exposure. Within the region of the Galactic Plane, $\sim 70\%$ of the sky is covered to better than 1 mCrab sensitivity, while 90% of the extragalactic sky is now covered at the 5 mCrab level.

The evolution of the number of sources through the four IBIS/ISGRI catalogs is shown in Figures 5 and 6. Starting with the first IBIS survey release, we note a continuous increase in the number of extragalactic sources accounting initially for only 4% of the detected sources in 2005 and now 35% in the latest source list (see Figure 6). Experience from previous studies shows that this number will increase further once follow up of the currently unidentified sources can be initiated. It is clear that the changes in the sources dominating the catalogs are strongly linked to the sky coverage. INTEGRAL spent the first four years more on the plane and in particular in the region of the Galactic Bulge, while more recently the high latitude sky has been exposed more thoroughly.

There are 331 new sources when compared to the third catalog. Of these, $\sim 120$ are associated with extragalactic sources, while only $\sim 25$ are associated with known Galactic sources, and the remainder are so far unidentified. This could lead us to conclude that INTEGRAL is now primarily detecting extragalactic objects and that the survey of the Galactic Plane has reached its limits. However, the sky distribution of new sources (Figure 7) shows a rather different picture. When superimposed on the delta exposure (i.e., the increase in exposure since the third catalog), the new sources can be seen to be following the exposure, and still comprises a very significant Galactic component. We are forced to conclude, therefore, that while the extragalactic observations are at a sensitivity limit where IBIS is still re-detecting known objects, the observations near the Galactic Plane have reached a level of depth where previous

Figure 4. Sky fraction as a function of minimum detectable flux.
(A color version of this figure is available in the online journal.)
X-ray observations are no longer always able to provide associations for the new sources. Combined with the variability of the Galactic sources, this is a clear indication that further observations of the Galaxy will continue to uncover new sources, and follow up of these new sources is of critical importance. However, we should also point out that many of the new sources found in the Galactic Plane by INTEGRAL have been identified as active galactic nuclei (AGNs), so this separation of Galactic and extragalactic sources is not a straightforward one.

With regards to the “unknown” sources that now constitute nearly 30% of the source list, one of the main values of this catalog will be to provide hard X-ray sources that will need follow up at X-ray wavelengths in order to reach a firm identification. To this end, we expect a large fraction of them to be identified in the coming year, as part of an ongoing multi-wavelength campaign. In the third IBIS catalog, 113 sources were not firmly classified. Many of these sources have been followed up at other wavelength starting with an X-ray observation to provide more precise location, allowing for more diagnostic optical or infrared observations. As a result of these observations, 24 previously unidentified sources now have a firm identification and 16 have a tentative but unconfirmed identification. The firm classifications comprise 10 AGNs, five CVs, five HMXB, three LMXB, and an XB, while tentative...
results. But now both no other imaging instruments were able to improve on the most recent results from these missions is informative. The imaging surveys of the hard X-ray sky, and a comparison between their long recurrence times between outbursts, together with by IBIS (so far) of these 13 transient systems can be attributed GRO 1744 X-ray novae (Revnivtsev et al. 2004). The IBIS catalog includes a region. A total of 37 objects were detected above 35 keV , of about 100 mCrab reaching 8–10 mCrab for the Galactic Center region. A total of 37 objects were detected above 35 keV , of which 9 Ms were devoted to the Galactic Center region. It is clear that the sources not detected by IBIS have in general a much shorter exposure time which will account for their not being seen. In the overlap region around $10^5–10^6$ s, the lack of detection in IBIS can be ascribed to source strength and variability reasons.

We also note the reappearance of one source, IGR J07506–1547, detected in the second IBIS/ISGRI catalog, but not the third. As a result of the burstiticity analysis, we are able to confirm the detection of this source that was clearly more active during the early mission phase.

In this catalog, we can state that the detections about 4.8$\sigma$ are drawn from an ensemble of maps, all of which show statistical quality that indicates much less than 1% of the excesses above that level will be false detections. Of the 40 sources below 4.8$\sigma$, half are associated with known X-ray emitters, and the estimated ~6% false detection rate should result in a total number of false detections in this catalog of no more 10, with the vast majority drawn from the sources detected below 4.8$\sigma$.

5.1. Comparison with Other Hard X-ray Catalogs

It is informative to compare our source list with those coming from other surveys performed in a similar energy range with imaging instruments.

The main difference between the sky as surveyed by the two instruments resides in the ratio of the Galactic and extragalactic source populations. The IBIS sky in the range 20–100 keV is almost equally shared by Galactic (36%), extragalactic (35%), and unidentified sources (29%). Conversely, the extragalactic sources account for 69% of the BAT list, which contains only 27% Galactic objects and 4% of the sources known to be X- or gamma-ray emitters not yet identified. Within the two lists, the most evident difference is the very high number of blazars from BAT of which IBIS detected only 30%. This could be explained by both the different exposure/sensitivity, larger FOV, and by the flaring activity characterizing these objects. Once parts of the sky recently exposed with INTEGRAL via the Key Programs are added to the existing public database, we will be in a better position to fully investigate this difference.

Cross-correlation of the IBIS and BAT source lists results in 333 correlations within $\sim$400”, the number of false correlations at this level should be around 0. Figure 8, on the other hand, shows the histogram of the exposure for all BAT sources seen above 4.8$\sigma$ in at least one of the three energy bands (14–150, 14–30, 14–70 keV). This is based on 72.7 Ms exposure that is very similar to the IBIS one reached with this fourth catalog. The main difference between the sky as surveyed by the two instruments resides in the ratio of the Galactic and extragalactic source populations. The IBIS sky in the range 20–100 keV is almost equally shared by Galactic (36%), extragalactic (35%), and unidentified sources (29%). Conversely, the extragalactic sources account for 69% of the BAT list, which contains only 27% Galactic objects and 4% of the sources known to be X- or gamma-ray emitters not yet identified. Within the two lists, the most evident difference is the very high number of blazars from BAT of which IBIS detected only 30%. This could be explained by both the different exposure/sensitivity, larger FOV, and by the flaring activity characterizing these objects. Once parts of the sky recently exposed with INTEGRAL via the Key Programs are added to the existing public database, we will be in a better position to fully investigate this difference.

Cross-correlation of the IBIS and BAT source lists results in 333 correlations within $\sim$400”, the number of false correlations at this level should be around 0. Figure 8, on the other hand, shows the histogram of the exposure for all BAT sources seen in this IBIS catalog (solid line) and the same for all sources not seen in this IBIS catalog (dotted line). Clearly, the great majority of those not seen have a low exposure in IBIS (around 100 below 50 ks and another 200 below 200 ks). Thus, we can conclude that the majority of the differences between the two source lists can be explained by exposure, with any differences at higher exposures likely due to transient sources detected in one or other catalog.

Finally, we note that the current IBIS survey includes all sources reported by the SPI team except one, SPI J1720–49, for which no further information apart from that the source is variable is available until now (Bouchet et al. 2008). Since the usable SPI sensitivity extends to considerably higher energies than IBIS covers effectively, this implies that there are no sources emitting very hard spectra, or lines above $\sim$200 keV within the SPI sensitive range.
5.2. Concluding Comments

It is interesting to note the different aim of the INTEGRAL and Swift missions that are very clearly demonstrated by the different source populations in the two catalogs. We anticipate that the large difference in the numbers of AGNs with the two lists of sources will be reduced soon once the deep exposures obtained with the INTEGRAL Key Programs in AO6 become public and the new AO7 pointings are performed. The current survey shows that IBIS has sufficient sensitivity to detect weak AGNs when these exposures are carried out. Furthermore, the overall picture from the new unidentified sources, accounting for 30% of our list, indicates the existence of a large galactic population still to be discovered, and we are confident that even in this case the new deep pointings planned for next year (AO7) will result in new source discoveries, possibly new class of objects as in the case of the obscured ones. The hard X-ray sky requires dedicated observations to solve some of the critical issues currently debated such as the contribution of different types of sources to the X-ray background, the distribution of intrinsic absorption in sources, and diversity within the same class of objects. Swift and INTEGRAL have been shown to be complementary and have opened new windows of investigations. Moreover, complete and unbiased surveys are of great benefit to studies now being undertaken of the very high energy sky, acting alongside the large soft X-ray database to allow for identification and broadband analysis of HESS, MAGIC, VERITAS, AGILE, and now Fermi sources.

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