INTEGRAL/IBIS 20-100 KEV EXTRAGALACTIC SURVEY: AN UPDATE

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ABSTRACT

Analysis of INTEGRAL Core Program and public Open Time observations has recently provided a sample of 60 extragalactic sources selected in the 20-100 keV band above a flux of $1.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. As this band probes heavily obscured regions/objects, i.e. those that could be missed in optical, UV, and even X-ray surveys, our sample offers the opportunity to study the extragalactic sky from a different point of view with respect to surveys at lower energies. We present an update of our analysis, including the first sample of AGNs detected above 100 keV. We also discuss the results of follow up observations performed at optical and X-ray frequencies with the aim of classifying our objects and studying the effects of intrinsic absorption in gamma-ray selected AGNs. The average redshift of our sample is 0.134 while the mean 20-100 keV luminosity in Log is 43.84; if blazars are excluded these numbers become 0.022 and 43.48 respectively. Defining an absorbed object as one with $N_H$ above $10^{22}$ atoms cm$^{-2}$, we find that absorption is present in 60% of the objects with at most 14% of the total sample due to Compton thick active galaxies. Almost all Seyfert 2s in our sample are absorbed as are 24% of Seyfert 1s. We also present broad-band spectral information on a sub-sample of the brightest objects: our observations indicate a mean photon index of $\Gamma = 1.8$ spanning from 30-50 keV to greater than 200 keV. Finally, we discuss the LogN/LogS distribution in the 20-100 and 100-150 keV bands derived from our sample. The present data highlight the capability of INTEGRAL to probe the extragalactic gamma-ray sky, to discover new AGNs and to find absorbed objects.

Key words: galaxies: active - gamma rays: observations: surveys.

1. INTRODUCTION

Quantifying the fraction of AGNs missed by surveys which are affected by selection due to absorption is necessary if we want to fully understand the accretion history of the Universe and study a population of objects (absorbed AGNs) so far poorly explored. Furthermore, the measurement of the primary AGN continuum and its cut-off energy is crucial for understanding emission models and discriminating between them. Both information (spectral shape of AGN and column density distribution) are key parameters for estimating the contribution of AGNs to the X-ray cosmic diffuse background and for testing current unified theories. Only high energy observations (above 10 keV) can provide an unbiased knowledge of the column densities and high energy cut-off distributions of AGNs in the local Universe.

A step forward in both these issues is now provided by INTEGRAL/IBIS and SWIFT/BAT which are surveying a great fraction of the sky above 20 keV with a sensitivity better than a few mCrab and a point source location accuracy of the order of 1-3 arcminutes depending on the source strength. These two surveys are complementary to each other, as the first one concentrates mostly on mapping the galactic plane, while the second covers the high galactic latitude sky so that together they will provide the best yet sample of AGNs selected in the gamma-ray band. We have recently presented a catalogue of $\sim 60$ IBIS AGNs selected in the 20-100 keV band above a flux limit of $1.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ ([3] or paper I). The analysis was performed using INTEGRAL Core Program and public Open Time observation performed up to April 2005. Most sources in the sample were Seyfert galaxies almost equally divided between type 1 and 2 objects, 6 were blazars but 14 were still unclassified at the time of this first publication. Despite an initial attempt to study the role of absorption in the sample, a significant fraction (about 30%) of the objects did not have archival X-ray spectra to allow a full assessment of the column density distribution. Furthermore due to the highly inhomogeneous coverage of the INTEGRAL/IBIS survey a determination of the LogN-LogS relation had to await a proper study of the various corrections to be applied.

Here, we present an update on the first 20-100 keV IBIS catalogue of AGNs, with a number of identification/classification being provided in the meantime through optical spectroscopy; on the basis of further work we have eliminated a few sources from the initial list and added a couple of new objects. We also use available X-ray data to obtain information on the column density of a number of AGNs in the catalogue. Given the higher number of new information available, we have re-estimated the main conclusions of [3]. Furthermore on the basis of this update, we have evaluated the LogN-LogS relation...
in the 20-100 keV band. In the meantime, we have also performed broad band spectral analysis of a subsample of objects observed in the first INTEGRAL extragalactic survey using IBIS data in combination with archival X-ray data from other missions and have provided information on their primary continuum shape including the cut-off energy. Finally, we report the first catalogue of AGNs detected above 100 keV by INTEGRAL and provide the first extragalactic number counts in the 100-150 keV band.

2. CATALOGUE UPDATE AND OPTICAL CLASSIFICATION

Of all the excesses reported in paper I, 3 objects resulted a posteriori to be AGNs to be active galaxies mainly due to projection effects; these 3 sources (IGR J13009+2529, IGR J13057+2036 and UGC3142) have been removed from the initial sample. Two objects which were not listed but were detected in the survey, were found to be AGNs a posteriori through optical follow up observations (17 and references therein); due to the limited information available on these two excesses (IGR J17488-3253 and IGR J17513-2011) their AGNs nature was difficult to assess prior to optical spectroscopic work. It is important to stress that some other unidentified sources may turn out to be active galaxies but due to their location near the galactic plane it is difficult to assess their nature without a proper optical follow up work. We have estimated for these two objects the total exposure and 20-100 kev flux and luminosity as done in paper I for the other sources; ISGRI coordinates can instead be found in 17. We obtained an exposure of 737.0 and 571.8 ks, a flux of 2.18±0.17 and 2.04±0.22 mCrab and a luminosity of 3 and 15.5 × 10^{33} erg cm^{-2} s^{-1} for IGR J17488-3253 and IGR J17513-2011 respectively. We remind that between 20-100 keV, 1 mCrab corresponds, for a Crab like spectrum, to 1.6 × 10^{-11} erg cm^{-2}s^{-1} which is a value close to our detection limit; the fluxes have been converted to gamma-ray luminosities assuming H_0=71 Km sec^{-1} Mpc^{-1} and q_0=0.51. Finally one source (IGR J16194 -2810) has been removed as it is not clear at the present stage from our own follow up measurements (Masetti, private communication) if it is a galactic or an extragalactic source. A number of objects in the initial catalogue have been optically classified and confirmed to be active galaxies; at the moment only 5 objects have no classification nor redshift available. For all the objects in this initial survey, we report in Table 1 an update of the source classification and redshift either available from the literature or from our own work (17 at this conference and references therein); in some cases the optical classification has been revised allow intermediate Seyfert types to be also sampled. We have also updated information on the column density by using available X-ray data. In particular we have made use of public SWIFT/XRT observations and performed our own spectral analysis in order to estimate photon index and column density for a set of 8 sources. More detailed results of this analysis are presented in the contribution to this conference by Landi et al. (12). We have also used XMM data obtained very recently in conjunction with INTEGRAL data to quickly estimate the source column density. A more in depth analysis of these objects is on going but since we are only interested in estimating if the column density is above or below 10^{22} at cm^{-2} a simple modeling of the data (power law absorbed both by galactic and where required by intrinsic absorption) is sufficient to provide this information. Only in the case of IC4518A we find that an intrinsic column density above 10^{22} at cm^{-2} is required by the data. Results becoming available in the literature have also been used to update our database (23). Only 9 objects have no column density estimate at this stage.

3. RESULTS UPDATE

Our extragalactic survey comprises after this revision 60 objects securely identified with AGNs. For those objects with known distance, we plot in figure 1 the gamma-ray luminosity against redshift, to show the large range in these parameters sampled by the present survey. From this figure it is also evident that our sensitivity limit is around 1.5 × 10^{-13} erg cm^{-2}s^{-1} (straight line in the figure). Within the overall sample, 49 objects are classified as Seyfert galaxies, 6 are blazars and only 5 (8% of the sample) are still unclassified. Within the sample of Seyfert galaxies, 26 objects are of type 1-1.5 while 23 are of type 2, i.e. a ratio 1:1, which illustrates the power of gamma-ray surveys to find narrow line AGN. About 10% of our sample is made of radio loud objects. The average redshift of our sample is 0.134 while the mean 20-100 keV luminosity in Log is 43.84; if blazars are excluded,
Table 1. AGNs sample

| Source       | Type | z    | Log Nh |
|--------------|------|------|--------|
| QSOB0241+62  | S1   | 0.044| 22.2   |
| MCG+8-11-11  | S1.5 | 0.020| <20.3  |
| IGRJ07597-3842| S1.2| 0.040| <20.6  |
| ESO 209-12   | S1.5 | 0.040| <21.4  |
| Fairall 1146 | S1.5 | 0.031| 21.1†  |
| MCG-05-23-016| S2   | 0.008| 22.2   |
| IGR J10404-4625| S2 | 0.024| >22.0  |
| NGC4151      | S1.5 | 0.003| 22.47  |
| 4C04.42      | Bl   | 0.965| -      |
| NGC4388      | S2   | 0.008| 23.63  |
| 3C273        | Bl   | 0.158| <20.5  |
| NGC4507      | S2   | 0.012| 23.5   |
| LEDA 170194  | S2   | 0.037| 22.28  |
| NGC4593      | S1   | 0.009| <20.3  |
| 3C279        | Bl   | 0.536| <20.3  |
| NGC4945      | S2   | 0.002| 24.60  |
| CenA         | S2   | 0.002| 23.4   |
| 4U1344-60    | S1.5 | 0.013| 22.6∗  |
| IC4329A      | S1.2 | 0.016| 21.6   |
| Circinus     | S2   | 0.001| 24.6   |
| IGR J16482-3036| S1 | 0.031| 21.1†  |
| ESO138-G01   | S2   | 0.009| >24.0  |
| NGC6300      | S2   | 0.004| 23.5   |
| GRS1734-291  | S1.5 | 0.021| >21.7  |
| 2E1739.1-1210| S1   | 0.037| 21.2†  |
| IGR J17488-3253| S1 | 0.02 | 21.3†  |
| IGR J17513-2011| S1.9| 0.046| -      |
| IGRJ18027-1455| S1  | 0.035| 21.4‡  |
| PKS1830-211c | Bl   | 2.507| 21.4   |
| ESO103-G35   | S2   | 0.013| 23.2   |
| 2E1853.7+1534| S1.2 | 0.084| -      |
| NGC6814      | S1.5 | 0.005| <20.7  |
| Cygnus A     | S2   | 0.056| 23.6   |
| IGRJ21247+5058| S1? | 0.020?| -      |
| 1ES0033+595  | Bl   | 0.086| 21.6   |
| NGC788       | S2   | 0.014| 23.3   |
| NGC1068      | S2   | 0.004| >25.0  |
| NGC1275d     | S2   | 0.018| 22.2   |
| 3C111        | S1   | 0.049| <21.9  |
| LEDA168563   | S1   | 0.029| -      |
| MKN3         | S2   | 0.014| 24.0   |
| MKN6         | S1.5 | 0.019| 23.0   |
| IGR J07565-4139| S2 | 0.022?| 22.0   |
| QSO0836+710  | Bl   | 2.172| <20.5  |
| IGR J10206-5349| S2 | 0.027| 22.3   |
| IGR J12415-5750| S2 | 0.024| 21.0†  |
| ESO323-G077  | S1.2 | 0.015| 23.7   |
| MCG-06-30-15 | S1.2 | 0.008| <20.3  |
| ESO511-G030  | S1   | 0.022| <20.7  |
| IGR J14492-5535| -  | -    | 23.0†  |
| IGR J14552-5133| NLS1| 0.018| -      |

Table 1 - Continued

| Source       | Type | z    | Log Nh |
|--------------|------|------|--------|
| IGR J16119-6036| S1 | 0.016| -      |
| IC4518-Ac     | S2   | 0.016| 23.3‡  |
| NGC6221b      | S2   | 0.005| 22.0   |
| IGR J16558-5203| S1.2| 0.054| <20.0  |
| IGR J17204-3554| -  | -    | 23.1   |
| IGR J18249-3243| -  | -    | -      |
| IGR J20187+4041| -  | -    | 23.3   |
| IGR J20286+2544| S2  | 0.014| 23.6-24.0|
| IGR J21178+5139| -  | -    | -      |

† Landi et al. these proceedings
‡ Panessa et al. in preparation and De Rosa et al. in preparation
* Piconcelli et al. (2006), also absorption partially covering the source

these numbers become 0.022 and 43.48 respectively.
The column density distribution for our sources is presented in figure 2. Assuming $10^{22}$ atoms cm$^{-2}$ to be the dividing line between absorbed and unabsorbed sources, we find that absorption is present in nearly 60% of the sample of objects having a column density estimate. This result is in line with the Swift findings [16] and also with other INTEGRAL AGNs surveys [5], [25].

![Figure 2. Column density versus 20-100 keV Luminosity for AGNs in the survey with known intrinsic absorption](image-url)
possibly NGC6300 since this is an object which moves from thick to thin in time [19] and very likely IGR J20286+2544 [12], [17]. Therefore we estimate that at most 14% of the sample is Compton thick. Within the sub-sample of 22 Seyfert 2s with known \( N_H \), we find that 95% are absorbed and 50% are Compton thick; this is in line with previous estimates of the column density distribution of type 2 objects based on X-ray data [24], [1]. Interestingly we also find that 24% of type 1-1.5 objects with \( N_H \) values are absorbed. In some of these absorbed type 1 objects, the absorption is complex with multiple column density obscuring partially and/or totally the central nucleus; in same cases these absorptions could also vary in time. Typical examples of this complexity are MKN 6, NGC4151 and 4U1344-60 (see [23] and references therein). In figure 3 we show the contours of the column densities for 4U1344-60 [23] and MKN 6 [15]. Similar sources are also found in the SWIFT/BAT survey [13].

In figure 4 we show the column density of our sources as a function of IBIS luminosity. Although from this figure there is little evidence of any strong correlation, the few high luminosity objects in the survey all have low absorption. However, since high luminosity objects are mostly blazars, this evidence is not conclusive and more data are required to firmly establish this observational evidence. More in depth studies of the present sample require optical classification of all objects and a detailed analysis of their broad band behavior (particularly in the X-ray to gamma-ray band) in order to fully understand the role of absorption: in particular we want to establish if there is any other Compton thick object in the sample and how is the absorption (complex or not) in Seyfert 1-1.5 galaxies. Furthermore when all sources are properly characterized it will be possible to estimate the luminosity function and the role of gamma-ray selected AGNs with respect to the cosmic diffuse background (see also [25]).

4. STUDY OF THE PRIMARY CONTINUUM

The high energy emission of AGNs is often to first order well described by a power law of photon index 1.8-2.0, extending from a few keV to over 100 keV; at higher energies there is evidence of an exponential cut-off. Secondary features, which are also commonly present, are considered to be the effects of reprocessing of this primary continuum and are relatively well understood. Modeling of high energy AGN spectra has so far generally focused on how to reproduce and explain the observed primary continuum shape: however, while the photon index distribution has been well investigated [18], observational results on the cut-off energy have
so far been limited by the scarcity of measurements above 10-20 keV, with most information coming from BeppoSAX broadband spectra. Analysis of type 1 and 2 AGN provides evidence for a wide range of values in the cut-off energy, spanning from 30 to 300 keV and further suggests a possible trend of increasing cut-off energy as the power law index increases; it is not clear however if this effect is due to limitations in the spectral analysis or if it is intrinsic to the source population sampled.

Direct INTEGRAL measurements enable us to obtain further observational results on the primary continuum and high energy cut-off thus providing more refined parameters for AGN modeling. The sample of 12 AGNs first detected by INTEGRAL can be taken as a case study: they are representative of the larger sample of AGNs presented here and are detected with adequate statistics to allow more in depth analysis. In particular, they are ideal objects for the study of the primary power law component, the presence of any high energy cut-off and the existence of a relation (if any) between these two parameters. Spectral analysis has recently been reported for this entire sub-sample using INTEGRAL data alone or in conjunction with data from other satellites. Excluding PKS1830-211 which is a blazar, this sub-sample is primarily made of Seyfert galaxies. Indeed PKS 1830-211 shows a flat spectrum and a cut-off likely located at MeV energies as typical of a low frequency peaked or red blazar. For the remaining sources, the mean photon index is $1.83 \pm 0.07$, while the cut-off energy ranges from 30-50 keV to greater than 200 keV. In most cases the cut-off energy is well constrained at or below 100 keV: the contour plot of photon index versus cut-off energy for those Seyfert galaxies in the sub-sample for which we have information on these two parameters. Combining all our data, we can also test the correlation found by a number of authors between the photon index and the cut-off energy. In figure 6, we plot the photon index versus the high energy cut-off for those Seyfert galaxies in the sub-sample for which we have information on these two parameters. It is clear from this figure that our data do not show the correlation found by [22]: the values for the photon index, in fact, cluster around 1.8, while the values of the cut-off energy range over a wide interval. We can conclude that the correlation between the high energy cut-off and the photon index remains to be proved and that a diversity in cut-off energy is most likely a property of Seyfert galaxies. INTEGRAL will keep observing these AGNs and new ones for the duration of the mission and so we expect that more spectral data on this class of objects will become available; this will provide further information on the high energy cut-off in AGNs and a deeper insight into the primary continuum emission.

Figure 5. High Energy cut-off vs photon index for MCG-5-23-16 (right) and GRS 1734-292 (left).

Figure 6. Power law photon index versus cut-off energy for the sample of AGNs analyzed by Soldi et al. 2005 and Molina et al 2006.
5. AGNS DETECTED ABOVE 100 KEV

Recently Bazzano et al. [4] have presented the first census of IBIS objects with detection above 100 keV. This high energy survey includes 10 AGNs with detection above 4 sigma level in the 100-150 keV band of which only one (Cen A) is also visible in the 150-300 keV band. All objects are also detected at energies below 100 keV. Of these 10 AGNs, 2 are blazars and 8 are Seyfert galaxies; however this time the ratio of type 1 versus type 2 objects is 2:6, with Seyfert 2 outnumbering Seyfert 1 by a factor of 3, which is interestingly close to values found in optical spectroscopic surveys [14], [11]. However, this could be simply due to the limited number of AGNs present in this first extragalactic survey above 100 keV. In Figure 7, we plot for these 10 AGNs the hardness ratios $H_1$ versus $H_2$, where $H_1$ is defined as the 40-100 keV to 20-40 keV flux and $H_2$ as the ratio of the 100-150 keV to the 40-100 keV flux. It is clear from this figure that the 10 AGNs detected at high energies have photon index $\geq 1.5$ with some clearly showing a softening of the spectrum probably due to the presence of a cut-off at or around 100 keV as discussed in the previous section.

6. AGN LOGN-LOGS IN THE 20-100 KEV AND 100-150 KEV BANDS

In this section, we estimate the number counts relation for AGNs in two bands: 20-100 keV and 100-150 keV. Even though the number of sources in the second band is low, a LogN-LogS estimate is nevertheless a useful information to have if one wants to estimate the total number of objects which may become visible as the survey progresses. However before doing any evaluations, there are a number of complications involved in forming this relationship that must be taken into consideration. First, the sensitivity limit in any direction depends not only on the exposure at that point, which is extremely non-uniform due to the pointing strategy of INTEGRAL [7], but also on systematic variations/structures in the background. Another problem is the fact that our survey is not truly serendipitous as some of our objects have been the targets of INTEGRAL dedicated observations. Finally, our sample is probably incomplete again due to the peculiar nature of INTEGRAL observing strategy. Given these caveats, we first convert exposure to $1\sigma$ limiting sensitivity the flux errors and effective exposures for the sources found in each band. (see fig 8 for the case where the errors refer to 20-100 keV fluxes). From this we obtain the sky coverage as a function of $5\sigma$ (4$\sigma$) 20-100 keV (100-150 keV) limiting flux as shown in figure 9, again for the case of 20-100 keV band.

We then create the ‘raw’ logN-logS for the 60 AGNs detected in the 20-100 keV band (figure 10) and the 10 found in the 100-150 keV band (figure 11). This distribution is then corrected for the exposure limit and sky coverage assuming a-priori an isotropic underlying distribution. Both the ‘raw’ data and the corrected values normalized to full sky coverage are also shown in figures 10 and 11 where the horizontal bars indicate the errors on the flux of the $N^{th}$ source. The best-fit power law relationship and the ($1\sigma$) statistical limits are indicated by the solid lines. Unsurprisingly, we find that the best-fit power law is similar to, though rather flatter than an isotropic distribution. A deeper analysis will be performed as a greater number of sources and, most importantly, more uniform sky coverage become available.

Finally these number counts can be used to estimate the contribution of local AGNs to the cosmic diffuse background. The total AGNs emissivity measured in both bands above 1 mCrab accounts for approximately 1-3% of the total background intensity; extrapolation of our...
LogN-LogS by a factor of 100 towards lower flux will account for 15-20% of the extragalactic background. In short we are just start to unveil the source population responsible for the hardX/gamma-ray background.

7. FUTURE EXPECTATIONS

Future work will concentrate on the optical classification of objects in the present sample and of those new AGNs that will be detected in the future. We also want to progress in estimating the column densities for the 8 remaining sources in the 20-100 keV catalogue and prepare to obtain X-ray data on the new sources. In parallel, we expect to concentrate on detailed analysis of the spectral properties of all AGNs in the present sample in order to define the primary continuum (photon index and cutoff energy) using INTEGRAL data in combination with archival X-ray information and data obtained through proposal requests to the Chandra, XMM and Swift observatories. In figure 12 we plot the number of AGNs detected in our own previous INTEGRAL surveys [2], [7], [3] as a function of science windows analyzed. We are currently working at the third INTEGRAL survey which involves the analysis of around 24000 science windows. As evident in the figure we expect around 100 AGNs (even more as new part of the extragalactic sky will be observed for the first time) to be detected in this coming survey thus doubling the number of sources for which follow up optical and X-ray observations will be needed, investigation of their spectral properties required and statistical studies performed. The future looks good for extragalactic studies with INTEGRAL and busy for the observers.
Figure 12. The increase in AGN numbers as a function of accumulated science windows. When the 3rd IBIS/ISGRI survey becomes available around 110 AGN should be visible.

8. ACKNOWLEDGEMENTS

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