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Re-evaluating the Local Compton-thick AGN Fraction

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We study the N_H distribution in a complete sample of 88 AGN selected in the 20-40 keV band from INTEGRAL/IBIS observations. We find that the fraction of absorbed ($N_H > 10^{22}$ cm^{-2}) sources is 43% while Compton thick AGN comprise 7% of the sample. While these estimates are fully compatible with previous soft gamma-ray surveys, they would appear to be in contrast with results reported from an optically selected sample. This apparent difference can be explained as being due to a selection bias caused by the reduction in high energy flux in Compton thick objects rendering them invisible at our sensitivity limit. Taking this into account we estimate that the fraction of highly absorbed sources is actually in close agreement with the optically selected sample. Furthermore we show that the measured fraction of absorbed sources in our sample decreases from 80% to $\sim$20-30% as a function of redshift with all Compton thick AGN having z < 0.015. We conclude that in the low redshift bin we are seeing almost the entire AGN population, from unabsorbed to at least mildly Compton thick objects, while in the total sample we lose the heavily absorbed 'counterparts' of distant and therefore dim sources with little or no absorption. Taking therefore this low z bin as the only one able to provide the 'true' distribution of absorption in type 1 and 2 AGN, we estimate the fraction of Compton thick objects to be >24%.

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1. Introduction

The cosmological evolution of the Active Galactic Nuclei (AGN) luminosity function and its implications on the Cosmic X-ray Background (CXB) is still a challenging issue for extragalactic science. While years ago the study of the cosmological and statistical properties of AGN was principally limited to the optical or soft X-ray regimes, and therefore dealing essentially with unabsorbed (type 1) AGN, it is now clear that a complete census of the entire AGN population and especially for the most obscured objects is the missing ingredient to come close to the true picture. Indeed the selection and the identification of obscured objects is a difficult task in the optical as well as in the soft X-ray (up to a few keV) band where hydrogen column densities (N_H) of the order of 10^{21}-10^{22} cm^{-2} strongly reduce the flux emitted from the nucleus. However, X-ray observations below 10 keV have extensively probed the so called Compton thin regime, i.e. column densities below 1.5×10^{24} cm^{-2} (the inverse of the Thomson cross-section) but still in excess of the Galactic value in the source direction. The Compton thick regime has been much less sampled either due to the lack of complete spectral coverage and/or all-sky surveys above 10 keV (for mildly Compton thick sources) or because the entire high energy spectrum is down scattered by Compton recoil and therefore depressed at all energies (heavily Compton thick sources). Until now, indirect arguments have been used to probe this regime: the intensity of the iron line at 6.4 keV (equivalent width typically of the order of 1 keV, Matt 1999), the signature of strong Compton reflection, or the ratio of the observed X-ray luminosity against an isotropic indicator of the source intensity, often the [OIII]5007 luminosity. However, sometimes iron line and Compton reflection diagnostics may lead to a wrong classification, caused by a temporary switching off of the primary continuum (Guainazzi et al. 2005) and not by thick absorption. Furthermore, the [OIII] luminosity is not always available and/or properly estimated so that the large uncertainties on the $L_X/L_{[OIII]}$ ratios can also lead to a misclassification.

The study of Compton thick AGN is important for various reasons: (i) about 80% of the active galactic nuclei in the local Universe are obscured (e.g., Maiolino et al. 1998; Risaliti et al. 1999); (ii) their existence is postulated in all AGN synthesis models of the X-ray background (Gilli et al 2007); (iii) they may constitute an important ingredient for the IR and the sub-mm backgrounds, where most of the absorbed radiation is re-emitted by dust (Fabian & Iwasawa 1999; Brusa et al. 2001) and (iv) accretion in these objects may contribute to the local black hole mass density (Fabian & Iwasawa 1999, Marconi et al. 2004).

Because of this interest and despite the limitations so far encountered, a sizable sample of Compton thick AGN is available for in depth studies (Della Ceca et al. 2008). However, this sample is by no means complete, properly selected and reliable in relation to the column density estimates. It is clear that for an unbiased census of Compton thick sources sensitive soft gamma-ray surveys/observations are needed.

2. The importance of hard X-ray surveys and the current scenario

A step forward in the census of Compton thick AGNs, is now provided by Swift/BAT and INTEGRAL/IBIS which are surveying the sky above 20 keV with a sensitivity better than a few mCrab and a point source location accuracy of 1-3 arcmin depending on the source strength and distance (Bird et al. 2007). These two surveys are complementary, not only because they probe the sky in a different way but also because they can be a check of each other's results. Together they will provide the best yet knowledge of the extragalactic sky at gamma-ray energies. Results obtained so far from these two instruments, point to a percentage of absorbed sources ($N_H > 10^{22}$ cm^{-2}) in the range 50-65%, while the fraction of Compton thick objects is constrained to be $< 20\%$, likely closer to 10% (see summary table in Ajello 2009). This percentage is clearly in contrast with results from optically selected samples (we will, in the following, refer to the Risaliti et al. 1999 sample) and with that postulated in the synthesis models of the cosmic X-ray background (Gilli et al. 2007).

3. The INTEGRAL Complete AGN sample

The complete sample of INTEGRAL selected AGN has been extracted from a set of 140 extragalactic objects detected in the 20-40 keV band and listed in the 3^{rd} IBIS survey (Bird et al. 2007). Most of these objects were already identified as active galaxies in the IBIS catalogue, while others were subsequently classified as such thanks to follow-up optical spectroscopy.[1]

From this list, a complete sample has been extracted by means of the V/V_{max} test (Schmidt, 1968) i.e. assuming that the sample is distributed uniformly in space (and that there is no evolution), it is possible to test if the sample is complete. The test consists of comparing the volumes contained within the distances where the sources are observed (V) with the maximum volumes (V_{max}), defined as those within the distance at which each source would be at the limit of detection. If the sample is not complete, the expected value for $<V/V_{max}>$ is less than 0.5, while when complete it should be equal to 0.5. In the case of the IBIS catalogue, the sky exposure, and therefore the limiting sensitivity is a strong function of position, as is shown in figure 1 (left panel). This can be taken into consideration by using the V_e/V_a variation of the test, introduced by Avni & Bahcall (1980). Once again the expected mean value m=$<V_e/V_a>$ will be 0.5 when the sample is complete.

Figure 1 (right panel) shows the value of $<V_e/V_a>$ as a function of limiting sensitivity. It can be seen that the increasing trend becomes flat above about 5.2σ at which point the ratio has a value of 0.47 ± 0.03, consistent with completeness.

There are 88 objects detected in the 20-40 keV band with a significance higher than this limit and they form our complete sample of INTEGRAL selected AGN: 46 objects are of type 1 (Seyfert 1-1.5, of which 5 Narrow Line Seyfert 1s) and 33 of type 2 (Seyfert 1.8-2); only 9 Blazars (BL Lac-QSO) are included in the catalogue. It is worth noting that for all the 88 objects we have class and redshift. The 2-10 keV flux and N_H measurements have been collected from literature for the well studied objects while XRT/XMM data analysis has been performed for the new INTEGRAL AGN (IGRJ sources) in order to get the X-ray parameters.

[1]For optical classification of *INTEGRAL* sources, please refer to Masetti's web page at http://www.iasfbo.inaf.it/extras/IGR/main.html

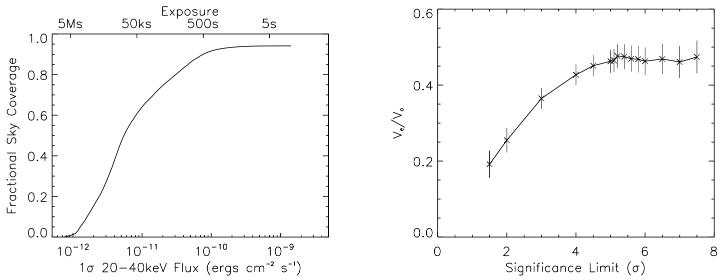

Figure 1: *Left panel*:The fraction of the sky seen as a function of both 1σ limiting flux and exposure for the complete 3^{rd} catalogue. It can be seen that large fractions of the sky have very different sensitivity limits. *Right panel*: The value of $<V_e/V_a>$ as a function of limiting significance.

4. Absorption Distributions

The column density distribution for the complete sample is shown in figure 2 (left panel). Assuming $N_H = 10^{22}$ cm^{-2} as the dividing line between absorbed and unabsorbed sources, we find that absorption is present in 43% of the sample. Within our catalogue we find 5 mildly (MKN 3, NGC 3281, NGC 4945, Circinus galaxy and IGR J16351-5806) and one heavily (NGC 1068) Compton thick AGN; we therefore estimate the fraction of Compton thick objects to be only 7%. Although the fraction of absorbed sources is lower than obtained in various Swift/BAT and INTEGRAL/IBIS surveys, the percentage of Compton thick AGN is fully consistent with these previous studies (see Table 1 in Ajello 2009).
To better investigate the absorption properties of our sample and to properly compare with optically selected ones, the distribution in the set of type 2 objects have also been plotted in figure 2 (right panel) where a peak at Log N_H=23 cm^{-2} is evident. Among our type 2 objects we have estimated that the fraction of absorbed (Log N_H >22 cm^{-2}) is 85% while that of Compton thick is 18%.

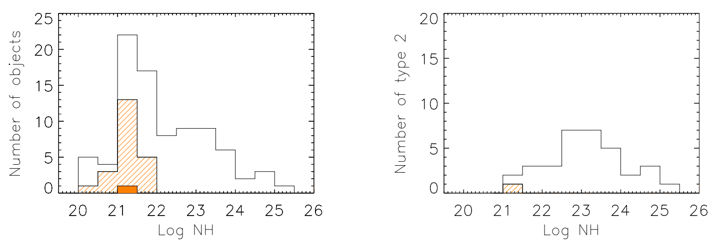

Figure 2: *Left panel*:Distribution of column density in the INTEGRAL complete sample. The dashed bins represent upper limit measurements (including Galactic values, see text), while the filled bin corresponds to GRS 1734-292 for which a lower limit is available. *Right panel*: Column density distribution in the 33 type 2 AGN of the complete sample. Dashed bin represents IGR J16024-6107 where no absorption in excess of the Galactic one has been measured.

5. Comparison and apparent disagreements with optically selected samples

While the estimates of the fraction of absorbed objects as well as the fraction of Compton thick sources are fully consistent with previous soft gamma-ray surveys, they would appear to be in contrast with results reported in optically selected samples. We will compare our results with the Risaliti et al. (1999) sample selected in O[III] 5007 which is still used nowadays as a reference work in the AGN absorption issue. This work provided the best estimates of the key parameters of the XRB spectral intensity around the 30 keV peak since it relied on Beppo/SAX PDS observations of nearby bright ($F_{10-100keV} > 10^{-11}$ erg cm^{-2} s$^{-1)}$ objects, it also provided the first unbiased N_H distribution of Seyfert 2 objects finding a fraction with Log(N_H)>22 of 95% and that of Compton thick AGN of 50%. Before comparing these results with ours, we first updated the values of the column densities of the sources in the Risaliti sample, finding more recent X-ray measurements for many objects and for the first time an absorption estimate for five sources. Our re-analysis of the Risaliti sample yields a fraction of absorbed objects of 90% but the Compton thick fraction is 36% (15 out of 41), i.e. smaller than found in the original paper but still a factor of two higher than our estimate.

It is possible that in our survey we have not recognized some Compton thick AGN because of the low statistical quality of the X-ray observations used to estimate N_H. To see if this has happened we can use the diagnostic diagram provided by Malizia et al. (2007). This diagram uses the N_H versus softness ratio ($F_{2-10\ keV}/F_{20-100\ keV}$) to look for AGN candidates and its validity has recently been confirmed by Ueda et al. (2007) and Malizia et al. (2009). Misclassified Compton thick objects populate the part of the diagram with low absorption and low softness ratios and none of our sources is located in this zone indicating that all the Compton thick sources in our complete sample have been included.

We have also verified that our sample, when viewed in OIII, is not significantly different to that of Risaliti et al. To this end, we have collected from the literature the [OIII] 5007 fluxes for all our type 2 objects. As noted by Maiolino and Rieke (1995) the host galaxy gaseous disk might obscure part of the narrow line region where the [OIII] 5007 emission originates. To correct for this effect we have used the prescription of Bassani et al. (1999) using the observed [OIII] 5007 fluxes and Balmer decrement H_α/H_β and when the latter was not available we based our correction on the H_β/H_γ ratio (see Gu et al. 2006).

In figure 3 (left) the distribution of [O III] 5007 fluxes for our sample (dashed bins) is compared with that of Risaliti et al. (1999): no difference is evident from the figure indicating that we are likely sampling the same population.

The most reasonable explanation for the difference in the fraction of Compton thick objects found in gamma and optically selected samples is due to bias introduced by obscuration which reduces the source luminosity by an amount depending on the column density. It is therefore more likely that, at a given distance, the most heavily absorbed AGN will have a flux below our sensitivity limit than unabsorbed ones and therefore will be lost from our sample.

A method of investigating the number of these 'missing' Compton thick sources is to calculate the reduction in the 20-40 keV flux as a function of N_H using a simple absorbed power-law model in XSPEC. The average flux reduction is negligible below Log N_H=24 and becomes progressively more important thereafter (8%, 25% and 64% reduction in the ranges 24-24.5, 24.5-25, and 25-25.5

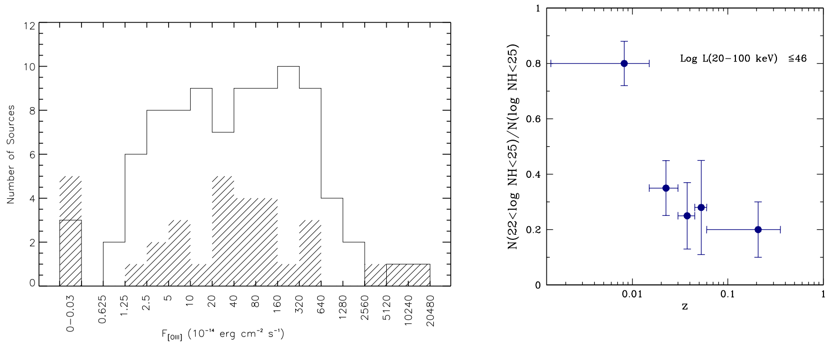

Figure 3: *Left pane*: [O III] flux distribution of the Risaliti et al. sample compared to the one in INTEGRAL complete sample (dashed bins). *Right panel*: Fraction of absorbed objects compared to the total number of AGN as a function of redshift.

respectively). Despite the simplicity of the fit adopted, the numbers do not change significantly for more complex models. Starting from the source numbers shown in figure 2 (right panel), we can calculate that this reduction in flux would lead to the 'loss' of around 15 sources in the Compton thick regime assuming a Euclidian LogN/LogS. This suggests that the true fraction of Compton thick sources among Seyfert 2 is around 40% in reasonable agreement with that found for the Risaliti et al. (1999) sample.
Another manner in which to examine the effect of absorption on source numbers is to calculate the fraction of absorbed ($N_H \geq 10^{22}$ cm^{-2}) objects compared to the total number of AGN (i.e. the number of objects with $N_H \leq 10^{25}$ cm^{-2}) as a function of redshift. We divided our sample into 5 bins of redshift (up to z=0.335) chosen in order to have a reasonable number of sources in each bin. The result is shown in figure 3 (right panel) where there is a clear trend of decreasing fraction of absorbed objects as the redshift increases. We interpret this evidence as an indication that in the low redshift bin we are seeing almost the entire AGN population, from unabsorbed to at least mildly Compton thick; while in the total sample we lose the heavily absorbed 'counterparts' of distant and therefore dim sources with little or no absorption.
It is then incorrect to look at the overall sample in order to estimate the role of absorption and one manner in which we can come closer to the true picture is by just adopting the first redshift bin for our estimates. Despite the lower statistics, we are now in the position to compare our result with that of Risaliti et al. in a more correct way. To do this, we use only the Seyfert 2's in our first redshift bin and then compare their column density distribution with that of all type 2 AGN in the Risaliti et al. sample having z$\leq$ 0.015. Up to this redshift, there are 17 objects in our sample compared to 39 in that of Risaliti et al. . Figure 4 (left) shows the results of this comparison: the similarity between the two distributions is striking with the fraction of objects having $N_H \geq 10^{23}$ cm^{-2} being similar in the two samples ($\sim$ 75%). The fraction of Compton thick objects is also remarkably close (35% compared to 36%).

In conclusion every method we use leads to an estimate of around 36%-40% for the true fraction of Compton thick AGN among Seyfert 2. Going from just the Seyfert 2 to the entire AGN population we note that the first bin, ranging up to z = 0.015, contains 25 AGN, of which 20 (80%)

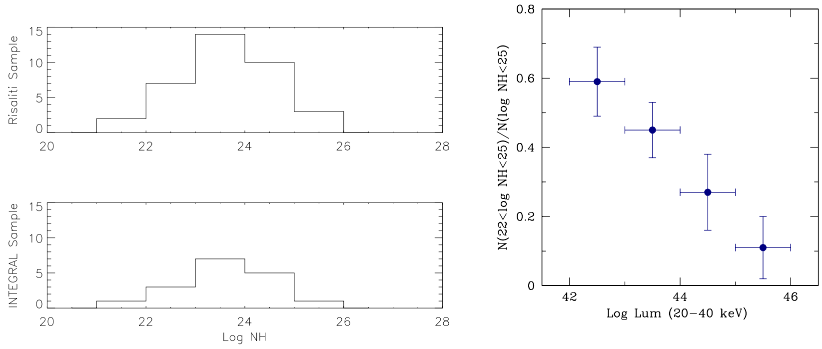

Figure 4: *Left pane*: Comparison of the distribution of column densities in the type 2 objects between Risaliti et al. sample (up) and INTEGRAL sample (bottom) with z≤0.015. *Right panel*: Fraction of absorbed objects compared to the total number of AGN as a function of luminosity

are absorbed and of these, 6 (24%) are Compton thick. It is still possible that the measured fraction of Compton thick objects is a lower limit, since some of the most heavily absorbed sources may not have sufficient luminosities to be detected even at the lowest redshifts.

We have also looked for a trend of decreasing fraction of absorbed AGN with increasing source gamma-ray luminosities. This effect, which is well documented in the X-ray band (La Franca et al. 2005), has also been observed in gamma-rays (Bassani et al. 2006, Sazonov et al. 2007 and references therein) and is also found in our sample as shown in figure 4 (right) Whether the redshift effect discussed here may have contaminated this result or this is a direct consequence of the evolution of AGN luminosity function with z, is not possible to discriminate here with the present data. In fact, dividing the 25 sources with z≤0.015 into two luminosity bins, we find comparable fractions of absorbed sources. This means that either our statistics are too low for a proper estimate or the effect is not real but only induced by the selection due to z. Only with the larger AGN sample that is now becoming available from the 4th IBIS survey (Bird et al. 2009), which will be even better if combined with Swift-BAT extragalactic survey, will we be able to go deeper at higher redshifts and provide the statistics which will allow us to discriminate between these two effects (Malizia et al. in preparation). Whatever the overall picture will be it is now clear from this work that the fraction of the Compton thick objects in the local Universe is 1 for every 4 AGN.

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