# STATISTICS OF LOCAL HARD X-RAY SELECTED AGN: OBSCURED ACCRETION ONTO MASSIVE BLACK HOLES

**Sergey Sazonov, M. Revnivtsev, R. Krivonos, E. Churazov, and R. Sunyaev**

*Space Research Institute, Russian Academy of Sciences, 117997 Moscow, Russia*

*Max-Planck-Institut für Astrophysik, 85740 Garching b. München, Germany*

## ABSTRACT

We have performed a statistical study of a representative sample of nearby AGN detected during the INTEGRAL all-sky hard X-ray survey. In broad agreement with previous studies, the fraction of obscured ($\log N_{\rm H} > 22$) AGN is found to drop with increasing luminosity, from $\sim 70\%$ at $\log L_{\rm hx} < 43.6$ to $\sim 25\%$ at $\log L_{\rm hx} > 43.6$. The local fraction of Compton-thick AGN proves to be less than 20%. We show that the spectral shape and intensity of the cosmic X-ray background can be accounted for if the X-ray absorption distribution of AGN has not changed during their dramatic downsizing since $z \sim 1.5$.

Key words: Surveys – Galaxies; active – Galaxies; evolution – Galaxies; Seyfert – X-rays; diffuse background.

## 1. INTRODUCTION

Deep extragalactic X-ray surveys [5] have revealed "AGN downsizing" – transition from powerful quasars at high redshift ($z \gtrsim 2$) to less luminous Seyfert galaxies at $z \lesssim 1$. They have also discovered numerous obscured AGN. Despite this progress, the census of AGN in the Universe is probably still significantly incomplete because typical surveys, performed at energies below $\sim 8$ keV, are biased against heavily obscured sources. Also, pencil-beam surveys cannot probe the bright end of the AGN luminosity function at low redshift ($z \lesssim 0.3$). In studying heavily obscured and luminous nearby AGN deep X-ray surveys could be efficiently complemented by all-sky hard X-ray surveys. The INTEGRAL/IBIS telescope [17] provides such a possibility owing to its good sensitivity above 20 keV, large field of view and good angular resolution.

By the spring of 2005 INTEGRAL observations had covered more than half of the sky, and we initiated a series of observations to cover the rest of the sky. This campaign has recently been completed. Approximately 75% (50%) of the sky have been covered down (see Fig. 1) to a limiting flux (for $5\sigma$ source detection) of 5 (3) mCrab, where 1 mCrab corresponds to $\sim 1.4 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ in the 17–60 keV band. Our source identification program includes follow-up X-ray observations with Chandra [14] (see an example of successful identification in Fig. 2) and optical spectroscopy on the Russian–Turkish 1.5-meter Telescope [4]. Similar identification programs are carried out by other teams [9, 2]. Based on the compiled all-sky source catalog [7] we have studied such key statistical properties of local AGN as their hard X-ray luminosity function and absorption distribution [15]. The results of this study are summarized below.

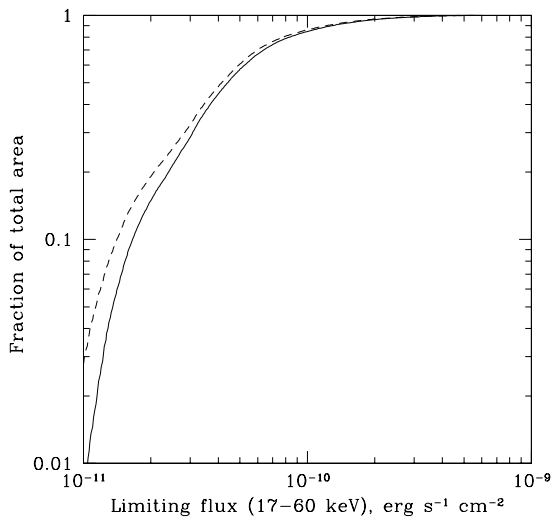


*Figure 1. Fraction of the total sky area as a function of the survey's sensitivity (the dashed line). The solid line shows the corresponding fraction for the $|b| > 5^\circ$ sky.*

## 2. THE AGN SAMPLE

Our all-sky catalog comprises 127 identified AGN, 33 of which were discovered by INTEGRAL [15]. This in-

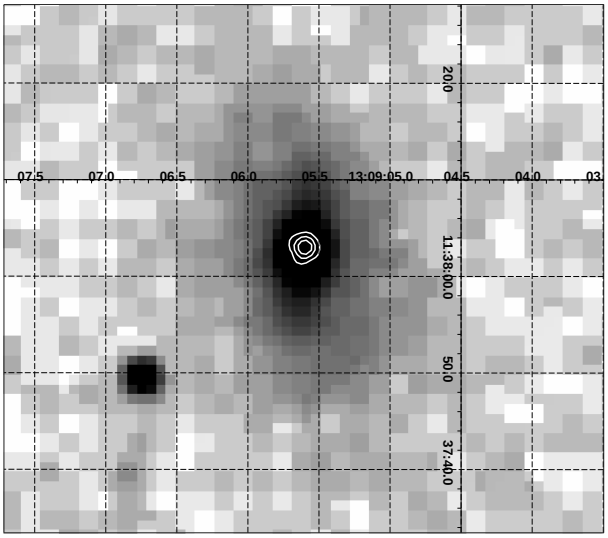


*Figure 2. Chandra X-ray brightness contours overlayed on the 2MASS J-band image of the galaxy NGC 4992 (at $z = 0.0251$) associated with the INTEGRAL source IGR J13091+1137.*

cludes 91 sources (82 Seyfert galaxies and 9 blazars) detected with more than $5\sigma$ significance on the average 17–60 keV map obtained with IBIS/ISGRI and 36 sources detected during individual observations but not on the average map; we excluded the latter from the statistical analysis.

There are published redshifts for all but 4 of our AGN and we used these to determine the observed source luminosities in the 17–60 keV energy band from the hard X-ray fluxes measured by IBIS/ISGRI. Both the statistical (photon counting statistics) and systematic (dependence on the spectral shape) uncertainties associated with the derived luminosities are small and do not significantly affect any of the statistical results presented below. We note that in the 17–60 keV energy range the observed luminosities of AGN are expected to be nearly equal to their intrinsic (unabsorbed) luminosities, except for the very Compton thick sources such as NGC 1068 and possibly few others (without measured absorption columns) in our sample.

All but one of the emission-line AGN are located at $z < 0.1$ (i.e. at luminosity distances smaller than 430 Mpc for our assumed cosmology with $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$), while there are several blazars as distant as $z \sim$ 1–2.5, with isotropic luminosities up to $\sim 10^{48}$ erg s$^{-1}$ (see Fig. 3).

Our all-sky AGN sample is probably incomplete because of the presence of 24 unidentified sources. Since most of them are located near the Galactic plane, we restricted our statistical study to the region $|b| > 5^\circ$ and also excluded blazars. The results presented below are thus based on 66 emission-line AGN located at $|b| > 5^\circ$.

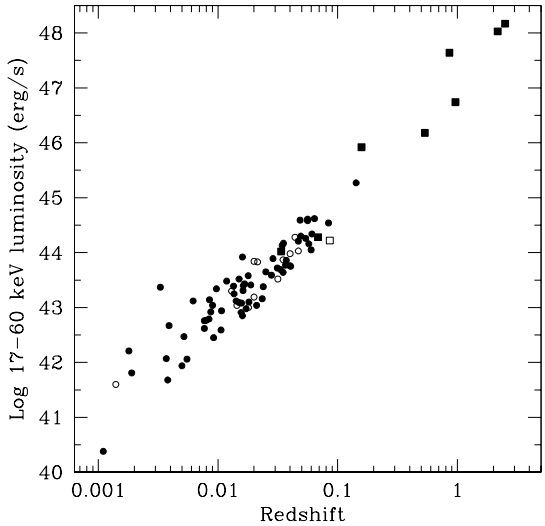


*Figure 3. Hard X-ray luminosity vs. redshift for the INTEGRAL AGN (excluding transiently detected sources). Circles and squares denote emission-line AGN and blazars, respectively. AGN located at $|b| < 5^\circ$ are shown by empty symbols.*

*Table 1. Parameters of the luminosity function*

| Parameter | Value and $1\sigma$ range |
|---|---|
| $\log L_*$ | 43.40 ($43.12 \div 43.68$) |
| $\gamma_1$ | 0.76 ($0.56 \div 0.94$) |
| $\gamma_2$ | 2.28 ($2.06 \div 2.56$) |
| $A$ (Mpc$^{-3}$) | $3.55 \times 10^{-5}$ |
| $n_{17-60\ \rm keV}(\log L_{\rm hx} > 40)$ ($10^{-3}$ Mpc$^{-3}$) | 9 ($4 \div 18$) |
| $\rho_{17-60\ \rm keV}(\log L_{\rm hx} > 40)$ ($10^{38}$ erg s$^{-1}$ Mpc$^{-3}$) | 14.1 ($11.8 \div 17.1$) |

## 3. HARD X-RAY LUMINOSITY FUNCTION

The measured hard X-ray (17–60 keV) luminosity function of nearby ($z \lesssim 0.1$) emission-line AGN (Fig. 4) is well fitted by a broken power law,

$$\frac{dN_{\rm AGN}}{d\log L_{\rm hx}} = \frac{A}{(L_{\rm hx}/L_*)^{\gamma_1} + (L_{\rm hx}/L_*)^{\gamma_2}}, \qquad (1)$$

with the parameters given in Table 1. In this table we also quote the inferred number density and luminosity density of local AGN with $\log L_{\rm hx} > 40$.

## 4. X-RAY ABSORPTION DISTRIBUTION

One of the interesting findings of the recent RXTE 3–20 keV slew survey of nearby AGN [10] was that the

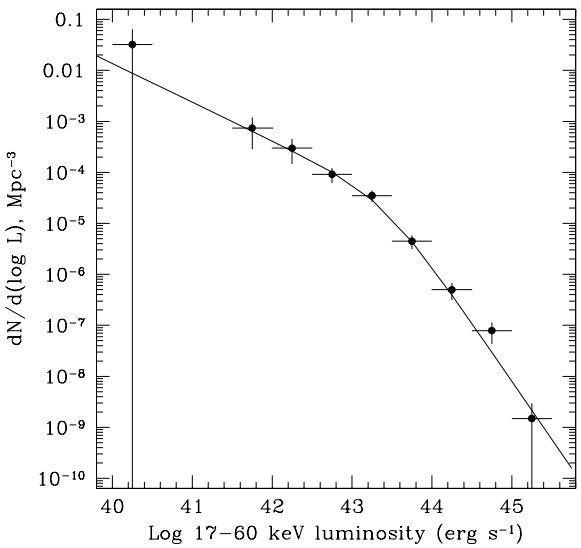


*Figure 4. Hard X-ray luminosity function of local emission-line AGN obtained with INTEGRAL. The analytic approximation given by Eq. (1) and Table 1 is shown by the solid line.*

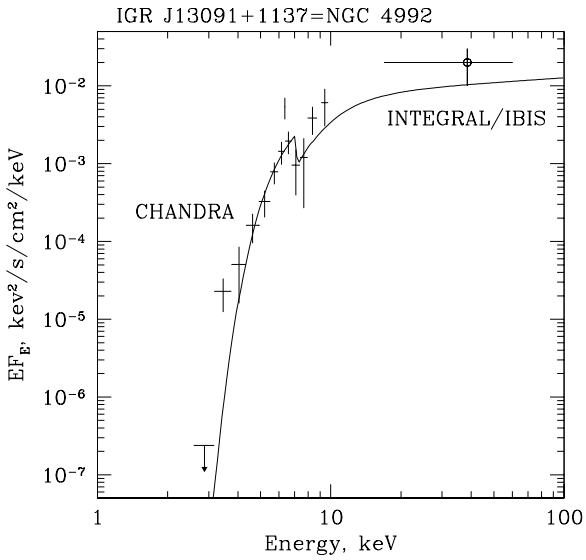


*Figure 5. Broad-band X-ray spectrum of a heavily obscured AGN discovered by INTEGRAL and Chandra. The spectrum is well fitted by an absorbed power law ($\Gamma = 1.8$) with $N_{\rm H} = 9 \times 10^{23}$ cm$^{-2}$.*

fraction of obscured ($\log N_{\rm H} > 22$) AGN drops with increasing luminosity [11]. To verify this we divided our INTEGRAL sample into two parts: 1) $\log L_{\rm hx} < 43.6$ and 2) $\log L_{\rm hx} > 43.6$, roughly representing the faint and bright ends of the AGN luminosity function. The source absorption columns were either adopted from the literature or found by analyzing spectral data from different X-ray astronomy missions (see an example in Fig. 5).

The derived $N_{\rm H}$ distributions (Fig. 6) confirm and strengthen the RXTE result that obscured AGN are much more frequent ($\sim 66\%$) in the faint end of the luminosity function than in its bright end ($\sim 24\%$). Another important result is that the local fraction of Compton thick AGN ($\log N_{\rm H} \gtrsim 24$) is less than 20%, at least over the luminosity range ($\log L_{\rm hx} \gtrsim 41$) effectively probed by INTEGRAL.

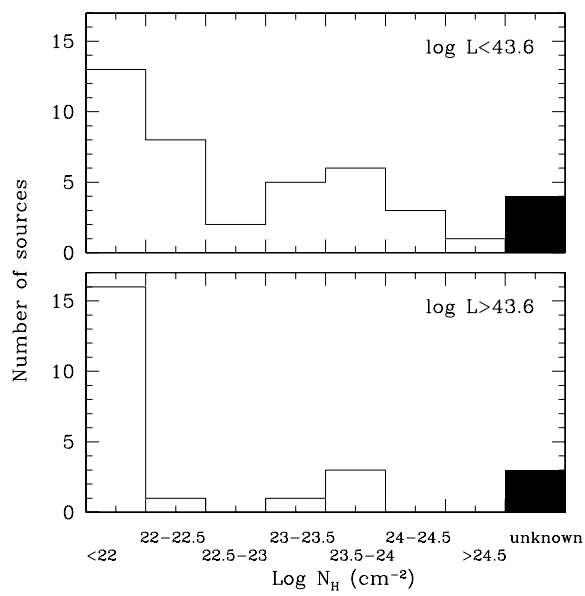


*Figure 6. Observed X-ray absorption distribution of AGN in the faint (top) and bright (bottom) ends of the luminosity function.*

## 5. IMPLICATIONS FOR THE COSMIC X-RAY BACKGROUND

It has become a common paradigm that the bulk of the cosmic X-ray background (CXB) is produced by all the AGN in the Universe. This conclusion is mainly based on the fact that deep extragalactic X-ray surveys have resolved $\sim 80\%$ of the CXB at energies below $\sim 8$ keV [5]. However, the maximum of the CXB $\nu F_\nu$ spectrum is located at $\sim 30$ keV, and at these energies not more than $\sim 3\%$ of the CXB is resolvable into point sources in the deepest INTEGRAL exposures. Therefore, resolving the CXB near its peak will certainly be one of the main objectives of future focusing hard X-ray telescopes. At present we may ask the following question: is the X-ray

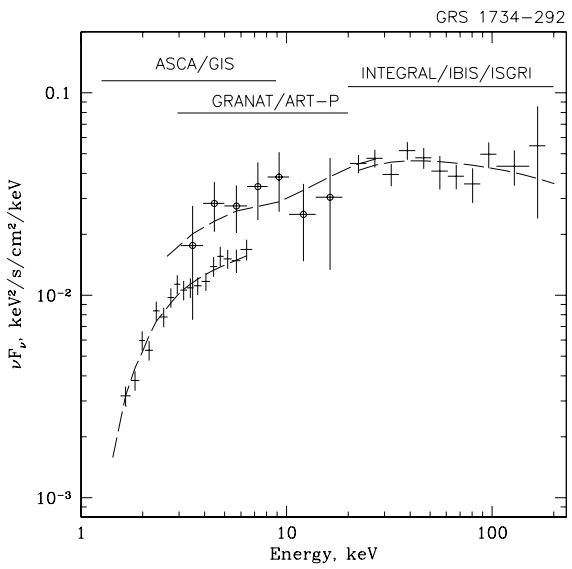


*Figure 7. X-ray spectrum of the Seyfert 1 galaxy GRS 1734−292 composed from non-simultaneous INTEGRAL, GRANAT and ASCA observations. The data are well fitted by an absorbed power-law+reflection model with $N_{\rm H} = 2.2 \times 10^{22}$ cm$^{-2}$ (probably of Galactic origin), $\Gamma = 1.9$, $E_{\rm f} > 120$ keV and $R = 1$.*

absorption distribution observed in local AGN by INTEGRAL compatible with that needed for distant quasars to explain the CXB spectrum?

To answer this question let us assume that all AGN, regardless of their redshift and luminosity, have the same intrinsic (unabsorbed) X-ray spectrum, consisting of a cutoff power law and a Compton reflection component with relative amplitude $R$:

$$\frac{dN_\gamma}{dE} = AE^{-\Gamma}\exp(-E/E_{\rm f}) + Rf(E). \qquad (2)$$

We adopt $\Gamma = 1.8$, $E_{\rm f} = 200$ keV and $R = 0.5$. These values are typical for well-studied bright Seyfert 1 galaxies, although the high-energy cutoff has been reliably measured only in few cases. As an axample we show in Fig. 7 a broad-band X-ray spectrum [12] of the luminous Seyfert 1 galaxy GRS 1734−292, which is famous for its location within 2 degrees of our Galactic Center.

We can now construct a composite spectrum $F(E)$ of local AGN by propagating the above fiducial intrinsic spectrum through different line-of-sight absorption columns and summing up the resulting spectra with weights inferred from the observed $N_{\rm H}$ distribution (Fig. 6). If we normalize this spectrum to the local AGN luminosity density measured with INTEGRAL (see Table 1), it will represent the spectral volume emissivity of all local emission-line AGN with $\log L_{\rm hx} > 40$.

If we now assume that AGN experience pure luminosity

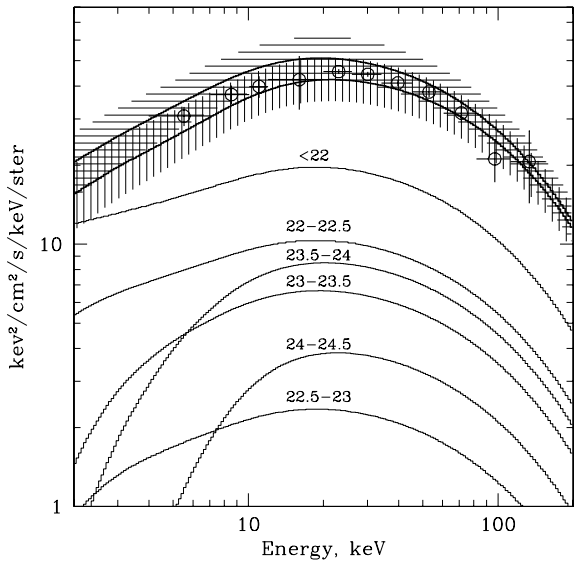


*Figure 8. Predicted CXB spectrum based on the absorption distribution measured in local AGN by INTEGRAL and the redshift evolution of AGN measured with Chandra. The upper thick line corresponds to the scenario of constant luminosity density at $z > 1$, the horizontally shaded region indicating the corresponding uncertainty. The lower thick line and the vertically shaded region correspond to the scenario of $\propto 1/z$ evolution at $z > 1$. Also shown are the predicted contributions to the CXB of AGN with different $\log N_{\rm H}$ (the labels next to the curves). The points with error bars represent the CXB spectrum measured by INTEGRAL [6].*

evolution with redshift, as appears to be approximately the case at $z \lesssim 1.5$ (where the bulk of the CXB is produced) [1], the cumulative AGN spectrum observed at $z = 0$ will (for a flat cosmology, [13]) be

$$I(E) = \frac{c}{4\pi H_0}\int_0^\infty \frac{\epsilon(z)F((1+z)E)}{(1+z)\left[\Omega_{\rm m}(1+z)^3+\Omega_\Lambda\right]^{1/2}}dz, \qquad (3)$$

where $\epsilon(z)$ describes the evolution of the AGN luminosity density. According to deep X-ray surveys [1], $e(z) \propto z^\alpha$ with $\alpha \sim 3$ at $z \lesssim 1$ while at higher redshifts $e(z)$ is bound between being $const$ and $\propto 1/z$.

Figure 8 shows the allowed range of CXB spectra arising in this scenario in comparison with the CXB spectrum recently measured by INTEGRAL [6]. One can see that the model is in very good agreement with the data. This suggests that AGN might have been evolving mainly in luminosity and much less in other properties such as the absorption distribution in the faint and bright ends of the luminosity function.

## 6. CONCLUSIONS

We have used the INTEGRAL all-sky hard X-ray survey to study some key properties of the local ($z \lesssim 0.1$) AGN

population. Since our source detection was based on 17–60 keV fluxes, the survey is equally sensitive to AGN with X-ray absorption up to several $10^{24}$ cm$^{-2}$, i.e. well into the Compton-thick domain ($N_{\rm H} > 1.5 \times 10^{24}$ cm$^{-2}$).

One of the most surprising results is that few Compton-thick AGN have been found. The observed fraction of Compton-thick objects is only $\sim 10\%$. This estimate may increase to at most $\sim 20\%$ once the currently missing absorption columns are measured. Clearly Compton-thick AGN are not as frequent as some have expected.

Another major result is confirmation of the finding of the RXTE slew survey that the local AGN absorption distribution is very different at low ($\log L_{\rm hx} < 43.6$) and high ($\log L_{\rm hx} > 43.6$) luminosities. While the fraction of obscured ($\log N_{\rm H} > 22$) objects is $\sim 70\%$ among the low-luminosity AGN, it is only $\sim 25\%$ among the high-luminosity ones. A similar result was recently reported based on HEAO-1 (2–10 keV) surveys [16] and is also emerging from the Swift all-sky hard X-ray survey [8].

We measured the hard X-ray luminosity function of local emission-line AGN. Its broken power-law shape is in good agreement with recent determinations in softer energy bands, in particular at 3–20 keV [11] and at 2–10 keV [16]. The cumulative luminosity density of AGN with $L_{\rm hx} > 10^{41}$ erg s$^{-1}$, $\rho_{17-60\ {\rm keV}}(> 41) = (12.4 \pm 1.5) \times 10^{38}$ erg s$^{-1}$ Mpc$^{-3}$, is somewhat (a factor of $\sim 1.9$) higher than the RXTE estimate assuming that typically $L_{17-60\ {\rm keV}}/L_{3-20\ {\rm keV}} = 1.25$. The hard X-ray luminosity function obtained in this work is in agreement with an earlier determination based on a smaller sample of INTEGRAL AGN [3].

In summary, the all-sky hard X-ray surveys conducted by RXTE, INTEGRAL, Swift, and HEAO-1 have already provided an accurate census of nearby unobscured and obscured AGN. This new information is not only interesting in its own right but also provides a reliable $z = 0$ point for the cosmic history of massive black hole growth.

As a first attempt to apply the local AGN statistics in a cosmological context, we demonstrated that the spectral shape and intensity of the CXB are consistent with the simple scenario in which the absorption distribution of AGN has not changed significantly since $z \sim 1.5$ while AGN have experienced strong downsizing. We came to this tentative conclusion using a fiducial (although realistic) intrinsic AGN spectrum. In future work we plan to perform a more rigorous investigation using INTEGRAL data on the hard X-ray spectra of nearby AGN.

## ACKNOWLEDGMENTS

This work was partly supported by the DFG-Schwerpunktprogramme (SPP 1177), the program of the Russian Academy of Sciences "Origin and evolution of stars and galaxies", and grant of the President of Russia NSh-1100.2006.2.

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