PROCEEDINGS OF SCIENCE

Study of three puzzling sources among Compton-thick candidates in the deep INTEGRAL 3C273/Coma survey

L. Gibaud[1,2], **S. Paltani**[1,2], **T.J-L. Courvoisier**[1,2], **T. Dwelly**[3], **N. Masetti**[4], **I. McHardy**[3], **P. Parisi**[4], **R. Walter**[1,2]

[1] *ISDC Data Centre for Astrophysics, University of Geneva*
[2] *Astronomical Observatory of the University of Geneva*
[3] *School of Astronomy Astrophysics, University of Southampton*
[4] *INAF − Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna*

Compton-thick AGN are detected in hard X-ray surveys, but their space density is significantly lower than expected. In order to test the possibility that the Compton-thick AGN population would emerge at lower fluxes, we performed follow-up observations of candidate sources detected in a very deep *INTEGRAL* survey. From the obtained hard X-ray mosaic and from *Chandra* follow-up and *XMM-Newton* observations, we find five objects with quite hard spectra, pointing to the possibility that they could be highly absorbed. We present the results for three of these objects for which we obtained optical spectra. The reflection-dominated interpretation of their spectra is not convincing, in particular because of the absence of strong iron features. Optical classification and absence of iron features point to the possibility that these objects are LINER. However the photon index is, in each case, too hard to support this interpretation. In NGC 4224, it is of 1.2 and compatible with Fanaroff-Riley type I galaxies, or even a FSRQ (Flat Spectrum Radio Quasar). ESO 575-G059 and LEDA 104441 have still harder spectral indices, respectively of 0.3 and 0.2, which remain extremely puzzling.

8th INTEGRAL Workshop "The Restless Gamma-ray Universe"
September 27-30 2010
Dublin Castle, Dublin, Ireland

PoS(INTEGRAL 2010)079

1. Introduction

Active Galactic Nuclei (AGN) are characterized by accreting processes occuring around supermassive black holes (10^6-10^9 $M_\odot$). The different classes of AGN were established from the various observed properties which, according to the unified model [1], depend primarily on the orientation of the source. Because of the presence of gas structures, AGN can be affected by absorption. Depending on the level of absorption, we distinguish unabsorbed AGN ($N_H < 10^{22}\,cm^{-2}$), absorbed Compton-thin AGN ($10^{22} < N_H < 10^{24}\,cm^{-2}$) and absorbed Compton-thick objects ($N_H > 10^{24}\,cm^{-2}$). Some studies [2, 3, 4] showed evidence that the extragalactic X-ray background requires the existence of a large population of Compton-thick AGN that has not yet been properly observed in X-ray surveys in the local universe. The fraction of Compton-thick sources detected in hard X-ray surveys could be as low as 5% [5], which is two times smaller than the needed fraction in some cosmic X-ray background synthesis models [4].

The fraction of Compton-thick objects in hard X-ray surveys is also very low compared to what is observed in the population of local Seyfert 2 galaxies [6, 7]. We attempt to resolve this discrepancy by investigating whether the population of Compton-thick AGN would emerge if one could lower the sensitivity limit of hard X-ray surveys. Using the hard X-ray imager IBIS on board *INTEGRAL*, a very deep hard X-ray survey of 2500 deg^2 in the 3C273/Coma field was performed in the 20-60 keV energy band [8]. In order to test this possibility using this survey, we search for objects just below the formal limit of detection and observe them at lower energy with *Chandra* and *XMM-Newton*. After studying these *Chandra* and *XMM-Newton* fields, we focus on the brightest sources for which we know the **optical characteristics**. We report here on the broad-band study of three objects.

2. Study of the *Chandra* and *XMM-Newton* fields

INTEGRAL performed a hard X-ray survey in the 3C273/Coma field in the 20-60 keV energy band totaling 4 Ms of observation. From this hard X-ray survey, we selected candidate sources just below the 5 σ detection limit. 16 candidate sources were found (nine sources with possible identification and seven unidentified objects). Bright counterparts were found in four *Chandra* snapshot observations and were subsequently reobserved in much deeper *XMM-Newton* observations. In the four *XMM-Newton* fields, we found 31 sources (including the four selected targets) for which we extracted the 0.1-12 keV spectra, using the standard analysis software *SAS* (Science Analysis System).

We first check if these objects are compatible with being AGN by fitting the spectrum of each source with a simple absorbed power-law with an index typical of AGN X-ray spectra. 26 sources are compatible with being unabsorbed AGN, as we obtained good fits with an index Γ around 1.9 and $N_H < 2\ 10^{22}$ cm^{-2}. Most of the sources being very weak, the fits are however not very constraining. Sometimes a soft component with a kT of about 0.1-0.5 keV is required. The remaining five sources, which include the four targeted objects, exhibit hard spectra: $0.2 \leq \Gamma \leq 1.2$. In addition to having very hard spectra, they are the brightest objects in each field, which confirms that they are the probable counterparts of the *INTEGRAL* detections if they are real. The *Chandra* positions allowed us to identify unambiguously three of the five sources with known local galaxies.

Table 1: List of candidate sources observed with *Chandra* and *XMM-Newton*.

Sources	z^a	*INTEGRAL*	*Chandra*		*XMM-Newton*		Class
		Exp. time^b	obs. ID	Exp. time^b	obs. ID	Exp. time^b	
NGC 4224	0.0087	1715	9436	2	0604310201	29	LINER*
ESO 575-G059	0.0152	289	9439	2	0604310101	21	Normal**
LEDA 104441	0.1323	980	9447	2	0604310401	25	LINER**

^{a}Redshifts were taken from the *Simbad* database and the NASA Extragalactic Database

^{b}Exposure times in kiloseconds

*cf NED ; our optical observations do not show any activity. **Our optical observations

We concentrate below on these three sources (see Table 1), for which we also obtained optical spectra with the 1.9 m Radcliffe telescope based in South Africa and the 2.1 m telescope of the San Pedro Mártir Observatory in Mexico.

3. Individual sources

We reanalyzed data taken from the ISGRI detector of the IBIS imager with the software *OSA* (Off-line Scientific Analysis), version 9 in order to extract spectra. Combining *INTEGRAL*/IBIS and *XMM-Newton*/PN observations, we obtain X-ray spectra covering a broad energy band, from soft to hard X-rays. The reanalysis of the ISGRI data did not provide any improvement in the source detection significances, so by themselves the *INTEGRAL* detections are not significant ($\sigma < 3.5$). We keep anyway the *INTEGRAL* data points in the analysis below as an illustration, since they have negligible weight on the fits.

The luminosities in the 2-10 keV energy band provide a first indication whether the source is an AGN or not. The X-ray luminosities we found, ranging from 10^{41} to 10^{43} erg/s, are too high for normal galaxies [9] and are the signature of nuclear activity [10]. Moreover, *Chandra* coordinates are coincident with the nucleus in the three cases, although the small extension of LEDA 104441 makes the case less convincing. We can therefore safely assume that we are detecting the nuclear emission and not another object in the galaxy or even in our Galaxy.

Our optical spectra reveal that LEDA 104441 is a LINER (Low Ionization Nuclear Emission Region). NGC 4224 is also classified as a LINER in NED and ESO 575-G059 presents signs of activity in a quite prominent [NII] double. NGC 4224 and LEDA 104441 could be starburst galaxies but also AGN [11]. Furthermore, NGC 4224 and ESO 575-G059 are characterized by dust obscuration on large scales, a dark dust layer is particularly visible in the case of NGC 4224. Dust lanes are linked to star formation regions, so could be due to starbursts [12]. The hypothesis of a starburst-AGN connection is supported in [13].

The first characterization of the X-ray spectra of these sources showed that they have very hard spectra. Such hard spectra can be the signature of a dominant reflection component, which results from the incident power-law continuum being strongly absorbed. Therefore we also try to model these objects by adding a reflection component [14] (*pexrav* model in *xspec*) to a very absorbed power-law. In our fits with reflection, we fix the cut-off energy at 200 keV, following the values found in an analysis of all *BeppoSAX* observations [15]. As the spectra are very hard, we fix

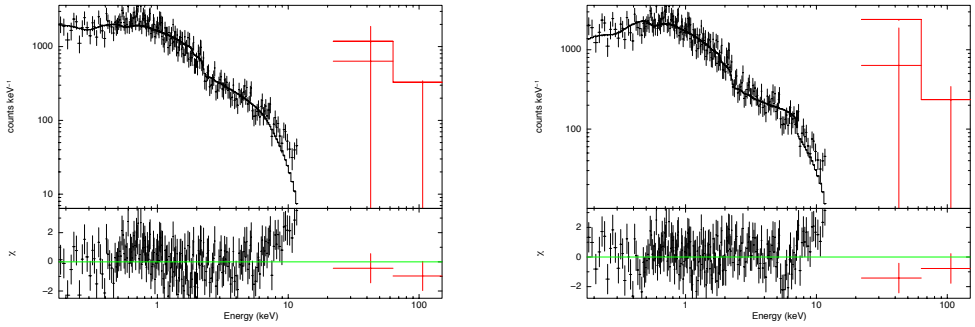

Figure 1: Combined *XMM-Newton* and *INTEGRAL* spectra of NGC 4224 in the 0.1-200 keV energy band. *Left*: Fit with an absorbed power-law. *Right*: Fit with an absorbed cut-off power-law plus reflection.

$\Gamma = 1.7$ in the fits with reflection, which corresponds to a rather hard spectrum for an AGN. We discuss the fit results for each object separately.

3.1 NGC 4224

A simple absorbed power-law fit to the source spectrum (see Fig. 2 left) gives an index $\Gamma = 1.2$ and a value of N_H of 1.8 10^{20} cm^{-2}, corresponding roughly to the galactic value. The fit is however not really good as the χ^2 is 293 for 205 degrees of freedom and the null hypothesis probability is of the order of 10^{-5}. Its X-ray luminosity in the 2-10 keV energy band is of 8.3 10^{40} erg/s. If it is an AGN, NGC 4224 is part of the class of low-luminosity AGN.

Adding a reflection component and fixing Γ to 1.7 and the energy cut-off to 200 keV (see Fig. 2 right), the fit is better with a χ^2 of 263 with 203 degrees of freedom and a null hypothesis probability of the order of 10^{-3}. The reflection fraction is about 20, indicating that we do not detect any direct component but that a scattered component at a level of a few percent might be present. This would make NGC 4224 a Compton-thick reflection-dominated AGN [16]. But while the fit is acceptable, the iron emission line is not detected. This casts serious doubts on this interpretation as reflection-dominated AGN are expected to show strong neutral iron lines at 6.4 keV with equivalent widths of the order of 0.3-1.0 keV [10].

3.2 ESO 575-G059

We fitted the spectrum adding a soft component with $kT = 0.30$ keV using the *apec* model and fixing the N_H to the galactic value. This object presents an extremely hard unabsorbed power-law, as we obtained a $N_H < 10^{22}$ cm^{-2} and a photon index Γ of 0.3 (see Fig. 3 left). We obtained an unsatisfactory fit with χ^2/dof=168/80 and null hypothesis probability of about 10^{-8}. The X-ray luminosity is of 2.8 10^{41} erg/s, which is still rather low for an AGN.

The fit with an absorbed cut-off power-law plus a soft component and reflection gives a worse result with a $\Delta\chi^2$ of 9 with 78 degrees of freedom and a smaller null hypothesis probability (see Fig. 3 right). In this model, the reflection fraction R of about 174 implies that the continuum is

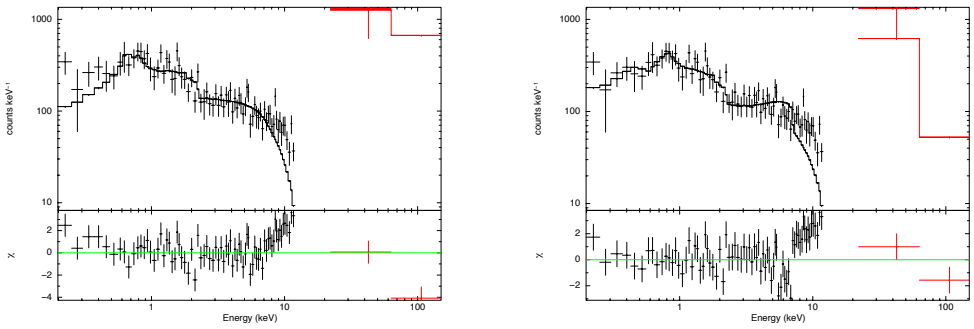

Figure 2: Combined *XMM-Newton* and *INTEGRAL* spectra of ESO 575-G059 in the 0.1-200 keV energy band. *Left*: Fit with an absorbed power-law plus a soft component. *Right*: Fit with an absorbed cut-off power-law with a reflection and a soft component.

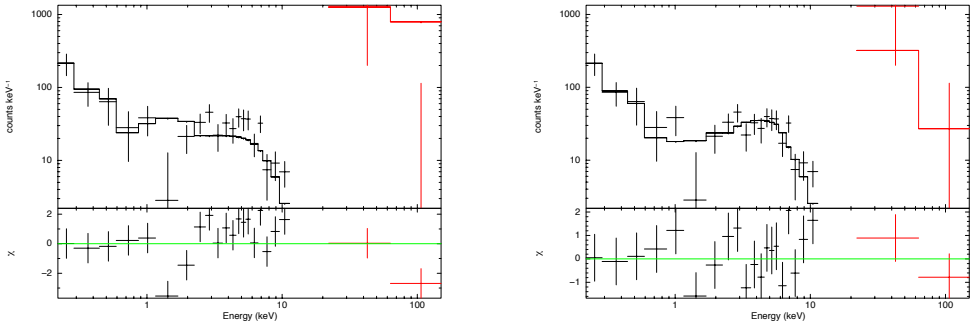

Figure 3: Combined *XMM-Newton* and *INTEGRAL* spectra of LEDA 104441 in the 0.1-200 keV energy band. *Left*: The source is fitted with an absorbed power-law plus a soft component. *Right*: Fit with an absorbed reflection plus a soft component model.

completely absorbed in the *XMM-Newton* spectrum. As in the case of NGC 4224, in the *XMM-Newton* spectrum, there is no evidence for iron line or absorption edges, making very improbable the reflection-dominated interpretation of this spectrum.

3.3 LEDA 104441

Fitting LEDA 104441 with an absorbed power-law plus a soft component with $kT = 0.05$ keV, using the *apec* model, we obtain an extremely hard photon-index with $\Gamma = 0.2$ (see Fig. 4 left). The value of N_H is 8.6 10^{20} cm^{-2}, higher than the galactic value. The fit is not good as the χ^2 is 52 for 24 degrees of freedom and a null hypothesis probability of about 10^{-4}. The X-ray luminosity in the 2-10 keV energy band is 4.3 10^{42} erg/s, typical of AGN.

The fit with an absorbed cut-off power-law with $\Gamma = 1.7$ plus a reflection and a soft component (shown in Fig. 4 right) gives a better result as the previous fit: χ^2/dof=28/22 and null hypothesis

probability of about 10^{-1}. The reflection fraction R is about 398, implying again a complete absorption of the continuum. As the previous spectra of NGC 4224 and ESO 575-G059, we do not find any evidence of the presence of the iron fluorescence line, which should be particularly prominent in very absorbed AGN.

4. Nature of the hard sources

The fits obtained with an absorbed power-law do not show any evidence for strong absorption. While absorbed power-law fits are not very good, there is no evidence for important X-ray complexity. We found however extremely hard spectra for ESO 575-G059 and LEDA 104441 for which respectively $\Gamma = 0.3$ and $\Gamma = 0.2$. We checked the presence of similar sources in the BAT AGN catalog [17]. Among the sources showing a hard photon index, we found no objects without strong absorption and simple spectra.

The fits with an absorbed cut-off power-law and a reflection give better fits than the ones without reflection, except in the case of ESO 575-G059 (for which χ^2/dof=177/78). In particular, the reflection-dominated models are roughly able to explain the very hard spectral indices. However, the expected iron features are absent in all spectra. The interpretation of these objects in terms of extremely absorbed AGN is therefore very unlikely. We notice, in the lower panels of NGC 4224 and ESO 575-G059 spectra, residuals with more or less the same shape, with in particular same excess above 7 keV. The situation might be similar in the case of LEDA 104441, but the lower signal/noise ratio and correspondingly better fit prevent us from drawing any conclusion regarding the residuals.

The optical spectra show that NGC 4224 and LEDA 104441 are LINER, while ESO 575-G059 shows strong [NII] emission lines. The weakness or even the absence of the iron line is characteristic of LLAGN and LINER [11]. But the hard photon indices remain puzzling. LLAGN normaly exhibit photon indices of 1.79, similar to Seyfert galaxies [18].

Assuming an AGN origin, we check if the sources could be radio-loud objects, as their spectra are too hard to be radio-quiet objects. The typical FSRQ-type (Flat Spectrum Radio Quasar) blazar photon index is about 1.4 [20]. The Γ of 1.2 obtained in the case of NGC 4224 is therefore compatible with this mean value. Fanaroff-Riley (FR) type I radio-galaxies usually show spectral indices of 1.1-2.6 [21]. Again, only the photon index in NGC 4224 is coincident with such range of values. The two other cases remain very puzzling. With extremely hard photon indices (0.3 for ESO 575-G059 and 0.2 for LEDA 104441), these objects are not compatible with a blazar or a FR type I radio-galaxy. NGC 4224 is detected in radio with a flux of 4.2 mJy. The two sources ESO 575-G059 and LEDA 104441 have however never been detected in the radio domain up to now.

5. Conclusion

We have presented broadband spectral analysis of three Compton-thick AGN candidates, using *XMM-Newton* and *INTEGRAL* data. We have tried to model the very hard spectra of these sources with "standard" reflection-dominated Compton-thick AGN model.

The absence of iron line in any of those objects makes this interpretation very unlikely. These sources all show evidence of LINER-type activity, which is compatible with the absence of iron features. However, such hard spectra are not expected in these objects.

The spectral index in the source NGC 4224 is compatible with those of FR type I radio-galaxies or of FSRQ. ESO 575-G059 and LEDA 104441 remain mysterious because of their extremely hard spectra. Further investigations are therefore needed, especially in the radio domain.

References

[1] Antonucci, R. , 1993, ARA&A, 31, 473

[2] Gilli & al., 1999, A&A, 347, 424

[3] Treister, E., & Urry, C. M., 2005, ApJ, 630, 115

[4] Gilli & al., 2007, A&A, 463, 79

[5] Tueller & al., 2008, ApJ, 681, 113

[6] Risaliti & al., 1999, ApJ, 522, 157

[7] Guainazzi & al., 2005, MNRAS, 356, 295

[8] Paltani & al., 2008, A&A, 485, 707

[9] Prestwich & al., 2009, ApJ, 705, 1632

[10] Ueda & al., 2003, ApJ, 598, 886

[11] Ho, L.C., 2008, ARA&A, 46, 475

[12] Dalcanton, J. J., Yoachim, P., & Bernstein, R. A. 2004, ApJ, 608, 189

[13] Ptak, A., 2000, arXiv:astro-ph/0008459v1

[14] Magdziarz, P., & Zdziarski, A. A., 1995, MNRAS, 273, 837

[15] Dadina, 2008, A&A, 485, 417

[16] Ueda & al., 2007, ApJ, 664, L79

[17] Winter & al., 2009, ApJ, 690, 1322

[18] Terashima & al., 1997, ASP Conference Series, 113, 54

[19] Mereghetti, S., 2008, A&A Rev., 15, 225

[20] Gianni & al., 2010, arXiv:1010.5713v1

[21] Donato & al., 2004, ApJ, 617, 915