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Soft X-ray observations of unidentified *INTEGRAL* sources

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The 4^{th} *INTEGRAL*/IBIS sky survey catalog contains more than 700 sources in the 17-100 keV energy range. About 30% of the catalogued sources are as yet unidentified and/or unclassified. We report on the results of the soft X-ray observations performed by ACIS/*Chandra*, EPIC/*XMM-Newton* Newton and XRT/*Swift* of an unidentified source sample. This study has allowed us to characterize these objects in terms of spectral shape, variability and absorption properties and to localize them with a positional uncertainty of a few arcsec to identify their optical, IR and UV counterparts. This information is a mandatory first step towards determining the nature of, and the physical processes, powering these high energy emitters.

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1. Introduction

In 7 years of operation, *INTEGRAL*/IBIS (Ubertini et al. 2003) has surveyed almost the whole high energy sky, accumulating more than 20 Msec in the Galactic Centre and mapping more than 90% of the hard X-ray sky with an exposure of at least 100 ks and down to a flux limit of about 1 mCrab ($\sim 2\times10^{-11}$ $erg\ cm^{-2}\ s^{-1}$) in the 20-100 keV band using data collected between October 2002 and April 2008. The number of high energy emitters of various nature detected in the 20-100 keV band has greatly increased over the years with a total of 723 listed in the 4th IBIS catalogue (Bird et al 2010). New hard X-ray source typologies have been discovered such as Supergiant Fast X-ray Transient (SFXT) and highly absorbed High Mass X-Ray Binaries. Within this catalog about 210 objects, i.e. 30% of the detections, have an unidentified or poorly known nature. Many of these unidentified objects have no obvious counterpart at other wavelengths and cannot be associated with any known class of high energy emitting objects. Searching for counterparts of these unidentified gamma-ray sources is very difficult due to the relatively large *INTEGRAL* error boxes. Thanks to the current generation of soft X-ray telescopes, improved localization at the arcsec level allow us to pinpoint their counterparts and provide the optical spectroscopy needed to assess their nature/class. Furthermore, these instruments allow measurement of the soft X-ray energy emission of the source, providing information on the spectral shape and level of absorption that are both important in determining the nature of the unidentified object.
Classification and knowledge of the nature of these unidentified objects is very important to the study of several astrophysical questions. In particular, we need to understand if they belong to new classes of objects, and define their timing and spectral characteristics. The construction of a large complete sample of hard X-ray objects belonging to specific object classes (such as AGNs detected with *INTEGRAL*, Malizia et al. 2009) will also allow the study of the spatial distribution and the luminosity function of various classes of objects.

With this aim, we report on the results of the cross-correlation of the IBIS sources included in the fourth catalog with the ACIS/CHANDRA, EPIC/*XMM-Newton* and XRT/*Swift* data archive.

2. *CHANDRA* observations of unidentified *INTEGRAL*/IBIS sources

The cross correlation of the unidentified hard X-ray emitters listed in the 4th IBIS survey with the archive of all *CHANDRA/ACIS* pointings finds a set of 5 objects. The detailed analysis of the ACIS images, light curves and spectra has allow us to identify four of the five investigated objects (Fiocchi et al 2010).
The source IGR J10447-6027 was associated with the IR source 2MASS J10445192-6025115 and IGR J12562+2554 with SDSS J125610.42+260103.5 source, although their nature remains unclear.
IGR J14193-6048 is associated with the pulsar and surrounding wind nebula PSR J1820-6048 in the Kookabarra region. Pulsars and pulsar wind nebulae are strong emitters from radio to TeV energies and *INTEGRAL* already detected 13 of these objects in the 20-100 keV energy band (Bird et al. 2010).
IGR J16377-6423 is clearly identified with the cluster of galaxies CIZA J1638.2-6420. This is the 4^{th} galaxy cluster observed by IBIS at high energies showing that *INTEGRAL* preferentially detects hot and bright members of this class of objects. In fact, Bird et al. (2010) reported only four bright

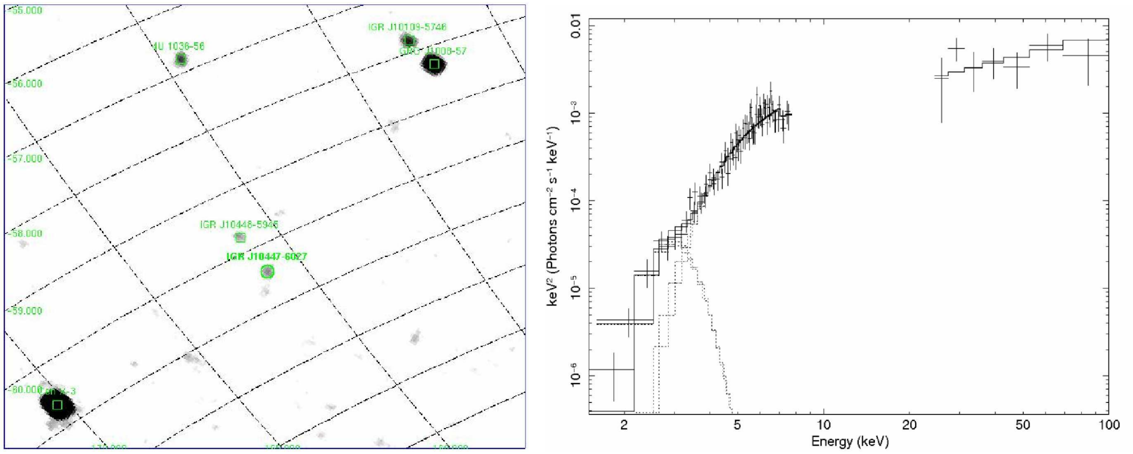

Figure 1: Left: The *INTEGRAL* IBIS/ISGRI mosaic significance image around IGR J10447-6027 in the 18-60 keV energy band for a total exposure of 2189 ks. Right: ACIS and IBIS spectrum of Source #1 in the region surrounding IGR J10447-6027, fitted with a simple power law model plus a thermal BREMS model.

clusters out of 723 sources, while the CIZA (Clusters In the Zone of Avoidance) survey found 73 bright clusters at $|b| < 20^0$ in the 0.1–2.4 keV energy range (Ebeling et al. 2002).
For IGR J12288+0052, the association is doubtful because the ACIS field of view does not cover the entire IBIS 99% confidence error box and unfortunately no other X-ray image is so far available to provide full coverage. We however suggest that a possible counterpart could be the Seyfert type 2 object SDSS 122845.74+005018.7 detected above 4 keV by *Chandra*.

Here, we describe in detail the object IGR J10447-6027 as a intriguing example of unidentified IBIS sources observed with XRT and ACIS instruments. This source was discovered by Leyder, Walter & Rauw (2008) during the analysis of the region surrounding Eta Carinae and associated to a young stellar object (YSO, IRAS 104236011 RA:10 44 17.9; DEC:-60 27 46); it has been included in the IBIS 4^{th} catalog as a faint persistent object detected in the 18-60 keV energy band at 5.8 sigma level (Bird et al. 2010). The IBIS/ISGRI mosaic significance image around IGR J10447-6027 in the 18-60 keV energy band (total exposure of 2189 ks) is shown in Figure 1 (left panel). Within the most recent IBIS error box of 4.1 arcmin at 90% confidence level (Bird et al. 2010), we find many soft X-ray sources, 11 objects in the 2-8 keV energy band but only two in the 4-8 keV energy range (see Figure 2); Source #1 is by far the most intense and coincides with the source detected in the *Swift*/XRT image (Landi et al. 2010), although the XRT localization was not sufficient to pinpoint a unique counterpart. Its spectrum across a very broad energy band (1-100 keV) when fitted with a simple power law model with galactic absorption does not give an acceptable fit (χ^2/d.o.f.=550/81), but the addition of an intrinsic absorber reduces the χ^2/d.o.f. to 105/80. This model gives an acceptable fit to the data, although a soft excess is also visible below 3 keV in the residuals obtained with respect to the fitted model. Adding a thermal component (modeled in XSPEC with BREMSS) resulted in a substantial fit improvement, reducing the χ^2/d.o.f. from 105/80 to 65/78. With this two-component model we obtain the following parameters: a very high column density $N_{\rm H} = (30^{+3}_{-5}) \times 10^{22} {\rm cm}^{-2}$, a spectral index $\Gamma = 1.2 \pm 0.4$, a temperature of the

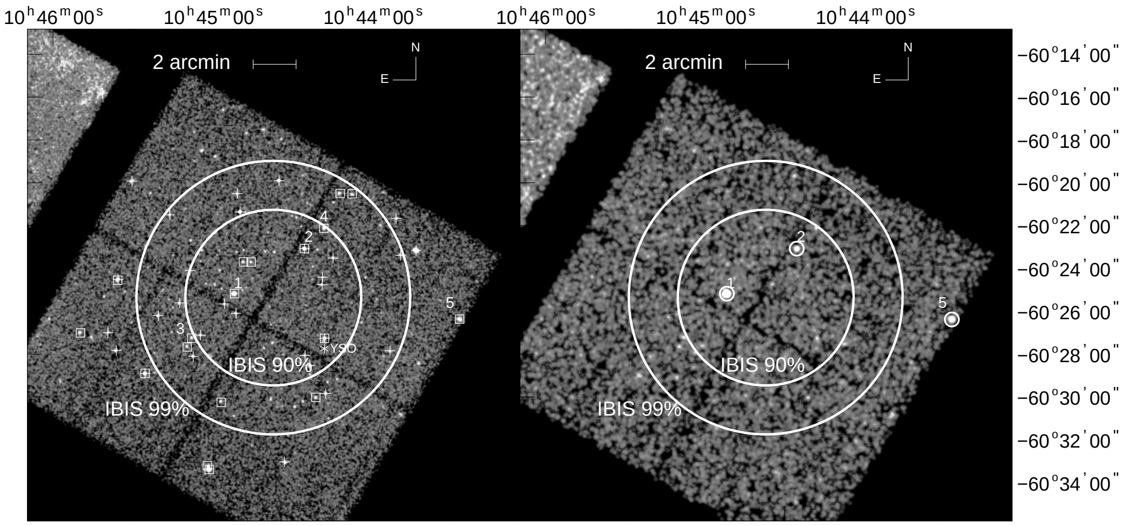

Figure 2: Left: ACIS 0.5−8 keV image of the region surrounding IGR J10447-6027. A Gaussian smoothing was applied to the counts distribution with a width of 2 pixels. The large circles represent the IBIS position and uncertainties expressed as 90% and 99% confidence circles (as reported by Bird et al. 2010). Crosses indicate detections in the 0.5−2.0 keV band, squares detections in the 2.0−8.0 keV band and numbers indicate the position of the X-ray sources detected within the IBIS error box in the hard X-ray band (4−8 keV). The asterisk is the position of the YSO, IRAS 104236011. Right: ACIS 4−8 keV image of the region surrounding IGR J10447-6027. A Gaussian smoothing was applied to the counts distribution with a width of 4 pixels. The large circles represent the IBIS position and uncertainties expressed as 90% and 99% confidence circles (as reported by Bird et al. 2010). Circles represent sources detected in the 4−8 keV energy band.

thermal component of 0.21 ± 0.07 keV and unabsorbed fluxes of $\sim 1.2 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 0.3-10 keV energy band. The high energy flux ($\sim 5.7 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 20-40 keV energy band) is in full agreement with the IBIS detection ($\sim 4.7 \times 10^{-12}$ erg cm^{-2} s^{-1} in 20–40 keV energy range). The ACIS and IBIS spectrum of this source is shown in figure 1 (right panel). Source #2 has a softer continuum ($\Gamma \sim 2.4$) and a lower unabsorbed 0.3–10 keV flux ($\sim 0.4 \times 10^{-12}$ erg cm^{-2} s^{-1}) than Source #1; its extrapolated high energy flux is a factor of $\sim$50 lower than that reported by Bird et al. (2010) and so it cannot be considered a likely counterpart of the IBIS object. Sources #3 and #4 are both much weaker and so very unlikely to be the counterparts of the IBIS source. This leads us to discard the association between the YSO and the IBIS object proposed by Leyder, Walter & Rauw (2008) and to conclude that Source #1 is the only possible counterpart. Contrary to the XRT observation, the *Chandra* restricted position allows us to pinpoint the infrared counterpart of the source to the object 2MASSJ10445192-6025115.

3. *Swift* observations of unidentified *INTEGRAL*/IBIS sources

The cross-correlation of the list of IBIS sources included in the fourth IBIS catalogue with the *Swift*/XRT data archive finds a sample of 20 objects, for which XRT data allows us to search for the X-ray and hence optical counterpart and/or study of the source spectral and variability properties below 10 keV (Landi et al. 2010). Four objects (IGR J00465–4005, LEDA 96373, IGR J1248.2–5828 and IGR J13107–5626) are confirmed or likely absorbed active galaxies, while two (IGR J14080–3023 and 1RXS J213944.3+595016) are unabsorbed AGN. Three are peculiar extragalactic objects, NGC 4728 being a Narrow Line Seyfert galaxy, MCG+04–26–006 a type 2 LINER and PKS 1143–693 probably a QSO. IGR J08262+4051 and IGR J22234–4116 are candidate AGN, that require further optical spectroscopic follow-up observations to be fully classified. The source 1RXS J080114.6–462324 is a Galactic object. For IGR J10447–6027, IGR J12123–5802 and IGR J20569+4940 XRT observations allow us to pinpoint one X-ray counterpart and define their spectral shape. There are five objects for which no obvious X-ray counterparts are reported (IGR J07506–1547 and IGR J17008–6425) or even no detection (IGR J17331–2406, IGR J18134–1636 and IGR J18175–1530).

4. *XMM-Newton* observations of unidentified *INTEGRAL*/IBIS sources

The cross-correlation of the list of the still unidentified hard X-ray emitters listed in the 4th IBIS survey with the archive of all *XMM-Newton* pointings finds a set of 6 objects with archival data (Malizia et al. 2010). In four cases, Malizia et al. 2010 found a convincing X-ray counterpart in the IBIS error circle for which it has been possible to search for counterparts in other wavelength bands and also perform the spectral data analysis in the 0.5–10 keV band. The spectral parameters obtained together with the possible IR/optical/radio counterpart found allowed investigation on the nature of each source. IGR J15359-5750 is an AGN of intermediate type, AX J1739.3-2923 and AX J1740.2-2903 are two absorbed Galactic sources, probably two persistent HMXB systems. More uncertain is the case of IGR J18538-0102 which is spatially coincident with a hot spot in the supernova remnant G32.1-0.9 detected previously by ROSAT and ASCA. From the broad band spectral analysis, Malizia et al. 2010 conclude that this object is an unrelated compact object which happens to coincide with the supernova remnant, probably a background AGN that is coincidentally aligned.

In a couple of cases, IGR J173331–2406 and IGR J17445-2747, no obvious X-ray counterpart has been found from the *XMM-Newton* observations. In the first case, no X-ray source has been detected. This is in perfect agreement with the IBIS survey data where this source has been found to be transient. Extrapolating the spectrum seen by IBIS during the source outburst to low energies (0.5-10 keV) and comparing it with the *XMM-Newton* upper limit, Malizia et al. reported a dynamical range of the order of 3000. Such a high value strongly suggests that IGR J17331–2406 could be either a transient black hole in the Galactic bulge or a SFXT.

For IGR J17445-2747, *XMM-Newton* observation does not provide a secure X-ray counterpart but suggests that the *XMM-Newton* slew source XMMSL1 J174429.4-274609 is a possible counterpart of this IBIS object. In fact it is well inside the high energy positional uncertainty and it was seen only once by *XMM-Newton*, in perfect agreement with the high energy survey data which classified this source extremely variable.

5. Conclusions

One of the more difficult tasks associated with the observation of the high energy sky, though with non focussing optics, is associated to the identification of a substantial fraction of the newly discovered sources. In fact, in spite of the forward steps achieved in the imaging capability of the new generation high energy instruments (e.g. SWIFT and *INTEGRAL* in the hard X-ray range, FERMI and AGILE in the gamma-ray domain and Cherenkov ground telescopes at TeV energies) optical identification remain a very difficult task. This task becomes almost impossible whenever timing information or evident source variability are not detected at high statistical significance at different wavelengths (e.g. GRBs, Pulsar, AGNs etc). In particular, for weak sources the optical and/or IR identification remain a challenge if arcsec X-ray counterpart positions are not available.

To overcome this problem a robust programme has started in parallel with the *INTEGRAL*/IBIS survey production to obtain, whenever possible, X-ray fields containing counterparts for the high energy unknown detected objects. This approach has been successful using archival data from ROSAT, and TOO dedicated observation and archival data from *Swift*, *XMM-Newton* and CHANDRA. These data were essential to trigger a robust programme of ground based optical observations and identification that has been very succesful so far (Masetti et al. 2009 and references therein). In fact up to now 181 unidentified IBIS sources have been optically or IR classified thanks to localization of the soft X-ray counterparts of the hard X-ray objects, with the following classification:

- 59% AGN
- 22% HMXBs (often obscured and SFXT)
- 11% CVs
- 2% Symbiotic stars

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