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CHANDRA observations of four new INTEGRAL* sources

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The IBIS imager on board *INTEGRAL* has localized so far 723 hard X-ray sources in the 17–100 keV energy band with a point source location accuracy of a few arcminutes. The cross-correlation between the IBIS sources and the *Chandra*/ACIS data archive resulted in a sample of 4 not yet identified objects with a possible counterpart. We present here the results of *Chandra X-ray Observatory* observations of these hard X-ray sources discovered by the *INTEGRAL* satellite, providing the sub-arcsecond localizations necessary to pinpoint the optical and/or infrared counterpart and measuring their soft X-ray energy spectrum. All these informations are mandatory to disentangle the nature of these high energy emitters.

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PoS(extremesky2009)102

1. Introduction

Because of the mCrab sensitivity and the point source location accuracy of a few arcminutes, the IBIS instrument (Ubertini et al. 2003) has localized more than 723 hard X-ray in the 17–100 keV energy band (Bird et al. 2009); about 30% of these objects are still unidentified, unclassified and/or poorly studied in the X-ray band. The X-ray position with sub-arcsecond accuracy and the shape of the soft X-ray spectrum obtained with ACIS/*Chandra* instrument are crucial to obtain a firm identification. To determine the nature of some unidentified objects, we have cross-correlated the list of IBIS sources included in the fourth catalog, with the ACIS data archive and derived a sample of 4 unidentified objects.

2. Data reduction and images and spectra analysis

The log of all observations performed with the ACIS instrument in the 0.3–10 keV energy band is given in Table 1, where the observation code (ID), the observation date, the detector configuration and the exposure time are listed. Processing of ACIS data was done with the CIAO software (version 4.1.2) and CALDB version 4.1.2, following the science threads listed on the CIAO website[1].

In Table 2, we report all the sources detected by ACIS within the IBIS error circles and their position with the relative error. The positional uncertainty are 1-σ statistical errors as computed by the `wavdetect` software. A systematic pointing uncertainty should be added to this. The pointing uncertainties are 0.64 arcsec at 90% confidence and 1 arcsec at 99% confidence levels respectively (Weisskopf, 2005).

Using the restricted *Chandra* positions at 99% confidence level, we searched for optical/IR counterparts using various on-line archives such as as NED (NASA/IPAC Extragalactic Database), HEASARC (High Energy Astrophysics Science Archive Research Center) and Simbad (Set of Identifications, Measurements, and Bibliography for Astronomical Data).

Chandra energy spectra have been produced for those counterparts detected with a significant number of counts. For objects with more than one pointing, we fitted all the individual data contemporaneously. A simple power law model, absorbed by Galactic absorption, has been used to fit the 0.3–10 keV ACIS spectra, with XSPEC software v11.3.2. When required by the fit, a second absorber has been added to the model to study the intrinsic absorption. When we dealt with a cluster,

Table 1: *Chandra* Observation Log

IGR Name	ObsID	Start Time (UTC)	Detector	Exposure Time (s)
IGR J10447-6027	9495	2008-04-24 00:57:01	ACIS-I	31360
	9849	2008-04-26 16:31:04	ACIS-I	28840
IGRJ12288+0052	7754	2007-03-12 13:22:54	ACIS-S	9540
IGR J12562+2554	3212	2002-12-04 15:08:35	ACIS-S	28100
IGR J16377-6423	1227	1999-08-25 09:35:10	ACIS-I	12240
	1281	1999-08-25 05:45:39	ACIS-I	11530

[1] Available at http://cxc.harvard.edu/ciao/.

PoS(extremesky2009)102

a thermal model (BREMSS in XSPEC) has been tested. The result of this analysis is reported in Table 2.

3. Individuals sources

In the following section, results on each individual source is presented.

IGR J10447-6027

This source was associated by Leyder, Walter & Rauw (2008) to a young stellar object (YSO, IRAS 10423-6011 RA:10 44 17.9; DEC:-60 27 46) and 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. 2009). Within the IBIS error box, we find five *Chandra* sources with a signal to noise ratio >4 (see Figure 1). The analysis of the ACIS image, clearly indicates the presence of two bright X-ray objects and three weak sources, one of which is near to the YSO position ($\sim 0.5'$). Spectral analysis was possible only for the two brightest detections (Source #1 and #2). A simple power law model with two absorbers well fit Source #1 spectra and the extrapolated high energy flux 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). Source #2 has a softer emission ($\Gamma \sim 2.4$) and a lower unabsorbed 0.3–10 keV flux than Source #1; its extrapolated high energy flux is a factor of $\sim$ 50 lower than reported by Bird et al. (2009). Sources #3, #4 and #5 are all 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 likely counterpart. The *Chandra* restricted position allows us to pinpoint the infrared counterpart of the source as the 2MASS object 2MASSJ10445192-6025115; despite being outside the *Chandra* error box, the 2MASS uncertainty of few arcsec allows us to consider this infrared object as the most likely association.

IGR J12288+0052

This source is a new *INTEGRAL* detection reported as a possible AGN in the 4^{th} IBIS catalog (Bird et al. 2009), with a weak 20-40 keV flux corresponding to $\sim 4.5 \times 10^{-12}$ erg cm^{-2} s^{-1}. Within the IBIS error box there are two AGN reported in the Catalogue of Quasars and Active Galactic Nuclei by Veron-Cetty and Veron (12th edition): the Seyfert type 2 object SDSS 122845.74+005018.7 (RA=12 28 45.7, Dec=+00 50 18) at z=0.57 and the QSO 2QZJ122859+0054 (RA=12 28 59.1 Dec=+00 54 18) at z=1.2. This sky region is however full of other galaxies, some of which are also listed as quasar candidates (Richards et al 2009). Within the IBIS error box we detect three *Chandra* objects with a signal to noise ratio >4. Source #1 has no optical, infrared or radio counterpart; spectral analysis shows that it has a power law spectrum with photon index $\sim$1.8 and an unabsorbed 0.3–10 keV flux of $\sim 0.15 \times 10^{-12}$ erg cm^{-2} s^{-1}. Source #2 is coincident with a QSO candidate in the SDSS (SDSS J122903.62+005359.5 RA=12 29 03.628 Dec=+00 53 59.51); the count rate is not high enough for spectral extraction. Source #3 is instead coincident with the type 2 Seyfert at z=0.57; To discriminate between the 3 possible associations, we restricted the image analysis to the 5–10 keV energy band and found that only Source #3 was detected at these energies; this clearly suggests a hard spectrum or more likely a high absorption, given the source class. For these reasons, we consider the type 2 object SDSS 122845.74+005018.7 as the most likely counterpart of the *INTEGRAL* source.

PoS(extremesky2009)102

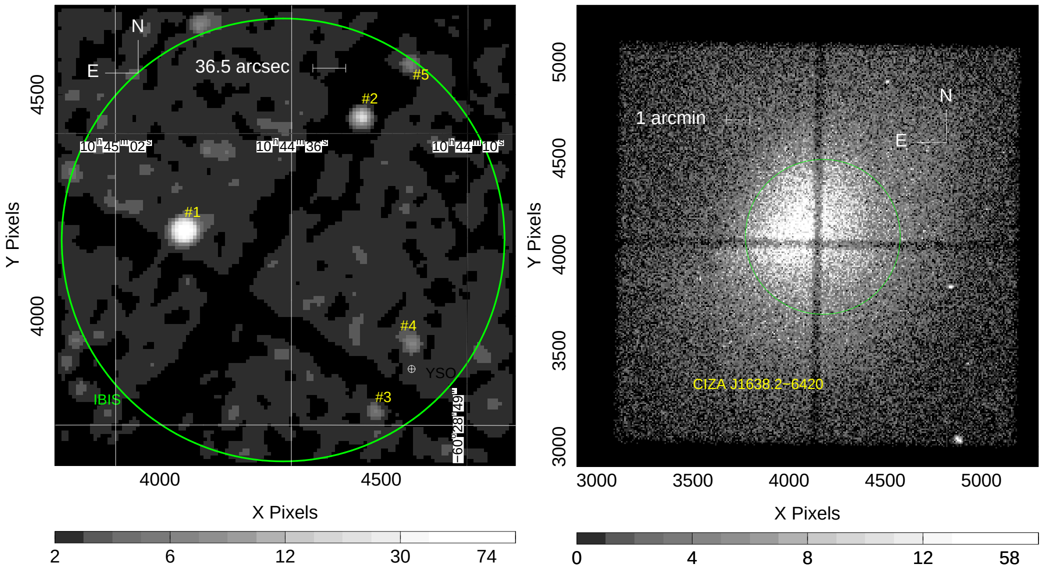

Figure 1: Left:ACIS 0.3-10 keV image of the region surrounding IGR J10447-6027. The circle represent the IBIS position and uncertainties as reported by Bird et al. (2009). The cross is the position of the YSO, IRAS 104236011. Right: The ACIS 5-10 keV image of the region surrounding IGRJ16377-6423.

IGR J12562+2554

This source is a new *INTEGRAL* detection reported in the 4th IBIS catalog (Bird et al. 2009); it has a 20-40 keV flux of 0.6 mCrab and is tentatively classified as a cluster of galaxies. An archival search of the IBIS error box provides evidence for the presence of the *fossil* group of galaxies RX J1256.0+2556 at z=0.232. Many galaxies reside in galaxy groups and towards the center there is a single giant central galaxy. The IBIS source could be associated to the cluster itself, the elliptical galaxy or any other member of the group. The *Chandra* image shows the presence of three sources within the IBIS positional uncertainty, although more X-ray objects could be present since the ACIS field is smaller than the IBIS error box (see Figure 2). Object #1 is coincident with SDSS J125600.78+255406.0, serendipitously detected by XMM (2XMM J125600.8+255406) and also listed as a *Chandra* QSO candidate (CXOMP J125600.7+255406). Object #2 is possibly the galaxy SDSS J125614.76+255535.4, also reported as 2XMM J125614.8+255529. Fits of the *Chandra* spectra of both sources with an galactic absorbed power law show that both sources are too dim to be the counterpart of IGR J12562+2554 as the extrapolated 20-40 keV flux is in each case lower than the measured one. Object #3 is the fossil group, also serendipitously detected by XMM as 2XMM J125602.2+255636. Recent analysis of the X-ray data from this system gives a gas temperature of $2.4-2.6$ keV using both XMM (Jeltema et al. 2006) and *Chandra* (Jones et al. 2003) data. We find a similar temperature indicative of a soft and weak X-ray source (see Table 2), again unlike to be the counterpart of the IBIS object.

Restricting the image analysis to the 5–9 keV band, we find that only Source #1 is still detected, suggesting that it is the harder of the 3 detected objects. The fact that the IBIS error box is not fully covered by *Chandra* together with the weak X-ray flux measured by all 3 objects detected, suggests that none of them is a likely counterpart, although object #1 could still be a possibility.

Table 2: INTEGRAL/IBIS position of the 4 selected sources (from Bird et al. 2009) with locations of the sources detected by CHANDRA/ACIS and ACIS spectral analysis results. Spectral parameters error are given at 90% confidence level for one parameter of interest ($\Delta\chi^2 = 2.71$). Unabsorbed 0.3–10 keV flux are reported in units of 10^{-12} erg cm^{-2} s^{-1}. The $N_{\rm H}$ values are the column densities in excess with to respect to the galactic value.

#	R.A. (J2000)	Decl. (J2000)	RA error arcsec	DEC error arcsec	$N_{\rm H}$ (10^{22} cm^{-2})	Γ or kT (keV)	X-ray Flux	$\chi^2/d.o.f.$
IGR J10447-6027, unidentified, (R.A.(J2000)=161.155, Dec(J2000)=-60.423, error radius=4.1′)								
1	161.2167	-60.4201	0.2	0.1	21 ± 3	$1.0^{+0.3}_{-0.6}$ [1]	1.7 ± 0.3	105/81
2	161.1060	-60.3850	0.7	0.2	4^{+3}_{-2}	$2.2^{+1.3}_{-0.7}$ [1]	$0.4^{+2.0}_{-0.3}$	19/14
3	161.0972	-60.4757	1.3	0.5	...	...	...	...
4	161.0816	-60.4536	1.5	0.8	...	...	...	...
5	161.0741	-60.3694	1.1	0.6	...	...	...	...
IGR J12288+0052, AGN?, (R.A.(J2000)=187.199, Dec(J2000)=0.870, error radius=5.3′)								
1	187.1369	0.8581	0.7	0.7	< 25	1.9 ± 0.5[1]	$0.15^{+0.09}_{-0.06}$	11/9
2	187.2652	0.9005	0.9	0.8	...	...	...	...
3	187.1900	0.8385	0.4	0.4	$2.5^{+6.5}_{-3.1}$	1.6 ± 0.8[1]	$0.3^{+3}_{-0.2}$	6/7
IGR J12562+2554, Cluster ? (R.A.(J2000)=194.051, Dec(J2000)=25.905, error radius=4.7′)								
1	194.0032	25.9019	0.3	0.3	...	2.1 ± 0.1 [1]	$0.10^{+0.02}_{-0.01}$	43/49
2	194.0616	25.9242	0.4	0.3	...	1.6 ± 0.3 [1]	0.06 ± 0.02	17/15
3	194.0103	25.9445	0.4	0.4	...	2.0 ± 0.9 [2]	0.02 ± 0.01	7/6
IGR J16377-6423, Cluster ?, (R.A.(J2000)=249.553, Dec(J2000)=-64.362, error radius=3.3′)								
1	249.5711	-64.3570	0.9	0.4	...	...	...	...

[1] this value is the spectral index of the power law model; [2] this value is the thermal temperature of the BREMSS model.

IGR J16377-6423

IGR J16377-6423 is a source detected by *INTEGRAL* in the 17-30keV energy band and associated by Bird et al. (2009) to a cluster of galaxies with a question mark. This was mainly due to the fact that ROSAT observations clearly indicate the presence of a bright galaxy cluster CIZA J1638.2-6420 (Stephen et al. 2006). Within the IBIS error box we find an extended and bright X-ray source clearly identified with the galaxy cluster even at high energies (see Figure 1). The analysis of the spectrum was performed by Snowden et al. (2008), showing that this cluster has a thermal spectrum with a very high plasma temperature in the range $8 - 13$ keV and a flux of $(0.1 - 3.3) \times 10^{-12}$erg cm^{-2}s^{-1}. Such high values of gas temperature could provide detectable emission in the IBIS waveband, making plausible the association with the *INTEGRAL* source.

4. Conclusions

We have identified and then measured the soft X-ray spectra of four IGR unidentified sources using *Chandra* observations. For two IGR sources we found the counterpart to be a weak AGN in *Chandra* images confirming that IBIS has sufficient sensitivity to detect weak AGNs: the first one, a QSO candidate named SDSS J125600.78+255406.0, is associated with IGR J12562+2554 while the second one is the QSO type 2 object SDSS 122845.74+005018.7 tentatively associated with IGR J12288+0052, i.e. the first type 2 QSO associated to an IGR source.
IGR J16377-6423 is clearly identified with the cluster of galaxies CIZA J1638.2-6420. This is the 4^{th} cluster of galaxies observed by IBIS at high energies.

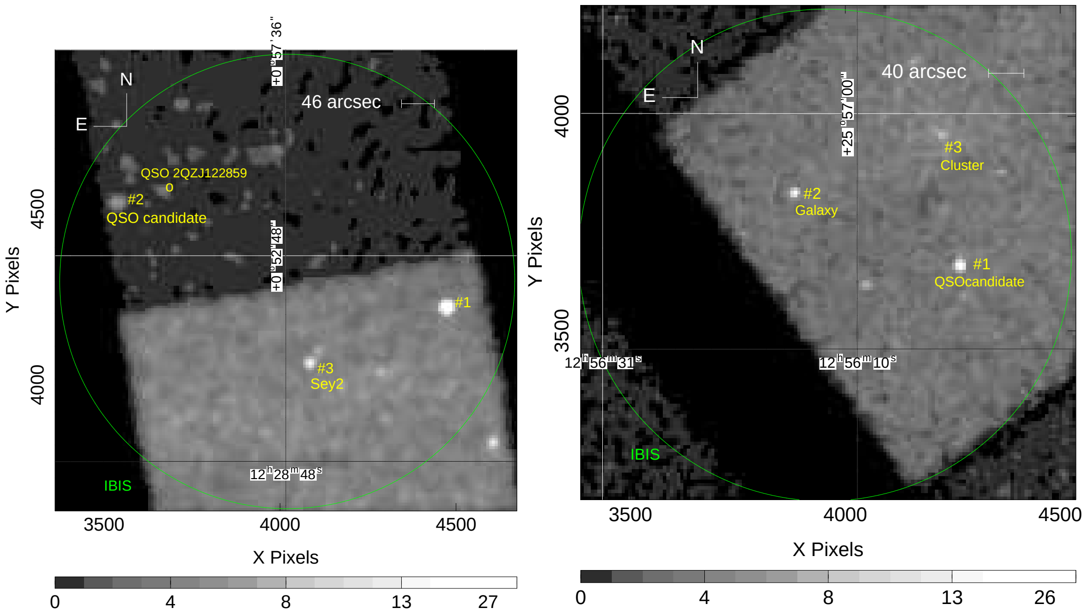

Figure 2: ACIS 0.3-10 keV image of the region surrounding IGRJ12288+0052. The circle represent the IBIS position and uncertainties as reported by Bird et al. (2009). Right: ACIS 0.3-10 keV image of the region surrounding IGRJ12562+2554. The circle represent the IBIS position and uncertainties as reported by Bird et al. (2009).

Concerning IGR J10447-6027, we associate this source with the IR source 2MASSJ10445192-6025115, but its nature remains unclear. Only follow-up observations with spectroscopic capabilities in lower energy bands could shed light on the nature of this intriguing source.

Acknowledgments

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