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Searching for active galactic nuclei among unidentified *INTEGRAL* sources

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ABSTRACT

We report on a new method to identify active galactic nuclei (AGNs) among unidentified *INTEGRAL* sources. This method consists of cross-correlating unidentified sources listed in the fourth Imager on Board the *INTEGRAL* Satellite (IBIS) Survey Catalogue first with infrared and then with radio catalogues and a posteriori verifying, by means of X-ray and optical follow-up observations, the likelihood of these associations. In order to test this method, a sample of eight sources has been extracted from the fourth IBIS catalogue. For seven sources of the sample, we obtained an identification, whereas the last one (IGR J03103+5706) has insufficient information for a clear classification and deserves more in-depth study. We identified three objects (IGR J08190−3835, IGR J17520−6018 and IGR J21441+4640) as AGNs and suggest that three more (IGR J00556+7708, IGRJ17219−1509 and IGR J21268+6203) are likely active galaxies on the basis of their radio spectra, near-infrared photometry and location above the Galaxy plane. One source (IGR J05583−1257) has been classified as a starburst galaxy, but it might have been spuriously associated with the *INTEGRAL* detection.

Key words: catalogues – surveys.

1 INTRODUCTION

A key strategic objective of the *INTEGRAL* mission (Winkler et al. 2003) is a survey of the sky at high energies (>20 keV), the domain where fundamental changes from primarily thermal to non-thermal sources/phenomena are expected, where the effects of absorption are drastically reduced and where most of the extreme astrophysical behaviours are taking place. To survey the high-energy sky, *INTEGRAL* makes use of the unique imaging capability of the IBIS instrument (Ubertini et al. 2003), which allows the detection of sources at the mCrab flux level with an angular resolution of 12 arcmin and a point source location accuracy of typically 1–3 arcmin within a large (29° × 29°) field of view.

So far, several surveys produced from data collected by IBIS have been reported in the literature, the most complete being that of Bird et al. (2010), which lists more than 700 sources of a diverse nature (Galactic and extragalactic) and class. However, a large fraction (∼30 per cent) of these new *INTEGRAL* sources have no obvious counterpart in other wavebands and cannot be firmly classified; their classification is a primary objective of the survey work, but it is made very difficult by the large IBIS error circles. Improved arcsecond-sized localization is therefore necessary to pinpoint the optical counterpart and through spectroscopic observations assess its nature/class (Masetti et al. 2010). For source identification one relies mostly on X-ray observations, but data in other wavebands can be used as well for counterpart search, in particular in those cases where the *INTEGRAL* unidentified source may be associated with an active galactic nucleus (AGN).

Within this framework, in the present paper we present a new method for AGN identification in the fourth IBIS catalogue, which relies on cross-correlating unidentified sources first with infrared (IR) and then with radio catalogues. The method is a posteriori verified by means of X-ray and optical follow-up observations of

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some of the sources discussed in the paper, which allow exploring their nature.

In the first step we use a set of extended IR objects [Two Micron All Sky Survey (2MASS) Extended (2MASX) Source Catalogue; Skrutskie et al. 2006], 97 per cent of which are associated with galaxies; we note that this is one of the most complete lists of galaxies available as it also covers the Galactic plane. Then we search for radio emission from these galaxies in order to identify likely AGNs. This second step is justified by the fact that almost all AGNs detected so far by *INTEGRAL* have a radio counterpart, which is not necessarily radio loud but can emit at a few mJy level.

An object which is extragalactic in nature and radio emitting could also be a starburst galaxy, but, in this case, we would not expect a bright X-ray luminosity as typically seen above 20 keV with currently operating hard X-ray detectors; indeed, so far, no starburst galaxy has been detected by IBIS in the 20–100 keV energy band.

Hence we use the IR, or better the information on source extension provided by the 2MASX Source Catalogue, to pinpoint galaxies and then the information available from radio and hard X-ray emissions to look for AGNs. We emphasize that many unidentified objects in the IBIS survey are on the Galactic plane, so identification of these sources as AGNs is not straightforward. Our method, however, provides a way to overcome problems related to the identification of active galaxies in the 'zone of avoidance'. Our choice of IR and radio catalogues is not intended to be a way to select special types of AGNs, but rather a simple way to find galaxies among Galactic and extragalactic sources and to select, among them, AGNs associated with hard X-ray-selected objects. X-ray follow-up observations are instead used to provide confirmation of the proposed IR/radio and hard X-ray association, while optical spectroscopy is performed to test the source AGN nature and class.

The paper is organized as follows. Section 2 describes the sample selection criteria and gives an overview of the extracted sample. The multiwavelength observations and analyses are reported in Section 3, while results and discussion are shown in Section 4. Finally, conclusions are presented in Section 5. The present work supersedes the analysis carried out in Maiorano et al. (2010), in which preliminary results for only three sources of the sample were presented.

2 SAMPLE SELECTION

Historically, AGNs were discovered with radio observations, i.e. the radio selection is often a way to recognize active galaxies, except at lower luminosities where star formation in galaxies can produce radio emission. Therefore, for bright objects, a mere detection in radio provides support for the presence of an active galaxy. Sample contamination from Galactic sources may, however, come from pulsars, microquasars and cataclysmic variables (CVs). In many cases, association with a galaxy via cross-correlation with galaxy catalogues can help in selecting only extragalactic objects and, by means of the radio detection, pinpointing those sources that are likely AGNs.

So, while a mere radio detection does not imply an identification with an AGN, its combination with high-energy X-ray/gamma-ray emission, together with the association with a galaxy, strongly argues in favour of the identification of an unclassified *INTEGRAL* source with an active galaxy. Following this reasoning we have cross-correlated our set of unidentified *INTEGRAL* sources in the fourth IBIS catalogue (Bird et al. 2010) with IR/radio catalogues, in order to extract a small sample of objects likely associated with an AGN.

For the IR bands, we have used the 2MASX Source Catalogue (Skrutskie et al. 2006) which is a powerful tool to identify, within the sample of unidentified *INTEGRAL* sources, those possibly associated with galaxies. For this survey, the entire sky was uniformly scanned in three near-IR (NIR) bands (J, H, K) to detect and characterize sources brighter than about 1 mJy in each band, with a signal-to-noise ratio (S/N) greater than 10 and which are resolved and extended beyond the 2MASS beam/point spread function (PSF). The absolute astrometric accuracy of the 2MASX catalogue is better than 1 arcsec. The extended source catalogue consists of 1647 599 objects, 97 per cent of which are galaxies, while the remaining $\sim$3 per cent is made of sources in the Milky Way (mostly double and triple stars, H II regions, planetary and reflection nebulae), which are not expected to emit at high energies. Therefore, the presence of a 2MASX object inside the IBIS error circle suggests an association with a galaxy.

As radio catalogues we have used the National Radio Astronomy Observatories Very Large Array Sky Survey (NVSS; Condon et al. 1998) and the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003) which are particularly well suited for finding counterparts of unidentified *INTEGRAL* sources: they are similar in sensitivity and spatial resolution, and together they cover the whole sky. The NVSS catalogue covers the sky north of the J2000.0 Declination of -40° (82 per cent of the celestial sphere) at 1.4 GHz (20 cm). The catalogue consists of almost 2 million discrete sources stronger than a flux density of about 2.5 mJy. The NVSS images have 45-arcsec full width at half-maximum angular resolution and nearly uniform sensitivity. The rms uncertainties in right ascension (RA) and declination (Dec.) vary from about 1 arcsec for the 400 000 sources stronger than 15 mJy to 7 arcsec at the survey limit. The SUMSS catalogue covers instead the sky south of the J2000.0 Dec. of -30° ($\sim$20 per cent of the celestial sphere) and is carried out at 843 MHz (36 cm). The survey consists of $4\overset{\circ}{.}3 \times 4\overset{\circ}{.}3$ mosaic images with a resolution of 45×45 cosec$|\delta|$ arcsec^2 and a rms noise level of 1–2 mJy beam^{-1}. Positions in the catalogue are accurate to within 1–2 arcsec for sources with peak brightness >20 mJy beam^{-1} and are always better than 10 arcmin. The internal flux density scale is accurate to within 3 per cent. The radio detection of a 2MASX emitting galaxy strongly indicates that the source is an AGN if also detected above 10 keV.

To perform the correlation, we used the standard statistical technique which has been employed very successfully in other cases (Stephen et al. 2005, 2006, 2010). This consists of simply calculating the number of *INTEGRAL* sources for which at least one 2MASX counterpart was within a specified distance, out to a distance where all *INTEGRAL* sources had at least one NIR counterpart. To have a control group we created a list of fake 'anti-*INTEGRAL*' sources. For every object in the *INTEGRAL* list, we made a corresponding source in the fake list with coordinates mirrored in Galactic longitude and latitude (this mirroring was chosen due to the strong Galactic component evident in the *INTEGRAL* distribution), and the same correlation algorithm was then applied between this list and the 2MASX catalogue. Subtracting from the number of correlations in the true list those obtained in the false sample, it is possible to estimate the number of true associations. We see that the radius at which the first correlations between the 'anti-*INTEGRAL*' sources sample and 2MASX catalogue appear is about 6 arcmin. This is comparable with the size of the IBIS error circle radius; therefore, we expect at most one spurious correlation within the lot of selected sources (see below). The sample of associations extracted in this way, i.e. a list of objects likely associated with galaxies, was then cross-correlated to the radio catalogues following the same method.

By means of this sequence of cross-correlations we extracted a final sample of eight objects which are seen in all three wavebands (hard X-rays, NIR and radio); all eight can be considered as AGN candidates because they are classified as galaxies in the 2MASX catalogue and are detected both in radio and hard X-rays. Note that in one case we have two radio/NIR objects associated with a unique *INTEGRAL* source (IGR J21441+4640); both are detected in the 2MASX and radio catalogues and so are equally possible counterparts of the *INTEGRAL* source and as such will be considered in the following sections. In NASA/IPAC Extragalactic Database (NED) these two objects form a galaxy pair.

2.1 Overview of the extracted sample

All objects in the sample are reported in Table 1; for each source we list the *INTEGRAL* name, the IBIS position with relative error, the IR (2MASX) and radio (NVSS or SUMSS) positions and associated errors of the putative counterparts. In our sample, seven sources have a counterpart in the NVSS catalogue, while only one has an association in the SUMSS.

The 2MASX catalogue provides *J, H, K* magnitudes for all sources in the sample which are reported in Table 2; note that all objects listed in Table 2 are classified as galaxies in NED. In Table 2 we also show the NIR colour indices $J - H$ and $H - K$; these can be used as a tool to confirm the AGN nature of our sources. Indeed, all objects but one (2MASX J03095498+5707023) have NIR colours compatible with those of nearby active galaxies (see fig. 1 of Kouzuma & Yamaoka 2010). Despite the uncertainties introduced by this method [i.e. it is not obvious from the work of Kouzuma & Yamaoka (2010) which is the efficiency of finding an AGN via IR photometry], it is re-assuring that almost all of our objects are compatible with NIR AGN colour indices.

Hard X-ray information concerning the sources of our sample is reported in Bird et al. (2010). We note here that all but two objects are classified as variable in the fourth IBIS catalogue since they are detected at the level of revolution, revolution sequence or through the bursticity analysis; the only exceptions are IGR J05583−1257 and IGR J08190−3835 which are reported as persistent objects in the IBIS survey. All but three objects (IGR J03103+5706, IGR J08190−3835 and IGR J21441+4640) are at Galactic latitude $>10^{\circ}$, an additional argument in favour of their extragalactic nature.

In order to provide radio images and fluxes, we have used the standard procedure employed within the software package AIPS,[1] release 31DEC10 (Astronomical Image Processing System). NVSS/SUMSS fluxes extracted from the radio maps are reported in Table 3.

Figs 1 and 2 show the collection of NVSS/SUMSS image cutouts for all of our sources with overimposed IBIS error circle and 2MASX source positions. For two sources (IGR J00556+7708 and IGR J21268+6203) in our sample, the radio and NIR positions are significantly different from each other, being separated by 22 and 24 arcsec, respectively. In both cases we searched among the optical and NIR catalogues selected in the Vizier Catalogue Selection Page[2] (USNO-B1, Monet et al. 2003, USNO-A2.0,[3] 2MASS), but we could not find any optical or NIR counterparts within the radio error circle; furthermore, we note that the 2MASX galaxies lie in each case within the edge of the radio contours and are obviously extended in the NIR band (semimajor axis of 16.6 and 13.7 arcsec, respectively). Indeed, in both cases the 2MASX and radio objects are associated with each other in NED on the basis of a sophisticated cross-identification analysis which takes into account not only the positional uncertainty, but also the source extension (Mazzarella et al. 2001). Taking all this evidence into account, we decide to keep both *INTEGRAL* sources in the sample also in view of the fact that either the NIR or the radio object (or in the best case both) is a likely counterpart to the high-energy emitter.

By looking for further radio information in the data archives of different radio telescopes and also in the literature, we found that some sources in the sample have been observed at more than one radio frequency. In these few cases, we have calculated the radio spectral index using the available data points and the usual relation $F_{\nu} \propto \nu^{-\alpha}$ (see Section 3). Furthermore, when the redshift is available, we have calculated the radio power at 1.4 GHz; all these values are reported in Table 3. Note that all objects in Table 3 have compact morphology in radio.

3 FOLLOW-UP OBSERVATIONS

In order to test the validity of our method, as well as to confirm the AGN nature of our objects, we have obtained a set of X-ray and optical follow-up observations. The X-ray observations, carried out with *Swift*/X-ray Telescope (XRT),[4] were useful to confirm the association between the NIR/radio source and the IBIS hard X-ray emission and hence to pinpoint the optical counterpart, while optical spectra of this counterpart allowed us to assess the source AGN nature and class.

For four objects in our sample (see Table 4), we have X-ray observations acquired with the XRT (0.2–10 keV; Burrows et al. 2005) onboard the *Swift* satellite (Gehrels et al. 2004). XRT data reduction was performed using the XRTDAS standard data pipeline package (XRTPIPELINE v. 0.12.4), in order to produce screened event files. All data were extracted only in the photon-counting (PC) mode (Hill et al. 2004), adopting the standard grade filtering (0–12 for PC) according to the XRT nomenclature.

Events for spectral analysis were extracted within a circular region of radius 20 arcsec, centred on the source position, which encloses about 90 per cent of the PSF at 1.5 keV (see Moretti et al. 2004).

The background was taken from various source-free regions close to the X-ray source of interest, using circular regions with different radii in order to ensure an evenly sampled background. In all cases, the spectra were extracted from the corresponding event files using the XSELECT software and binned using GRPPHA in an appropriate way, so that the χ^2 statistic could be applied. We used version v.011 of the response matrices and created individual ancillary response files *arf* using XRTMKARF v. 0.5.6.

The data have been fitted using an absorbed power-law model; due to the poor statistical quality of the X-ray data, we have fixed the photon index to 1.8 in order to evaluate the presence of absorption and the 2–10 keV flux.

[1] http://www.aips.nrao.edu/

[2] http://vizier.u-strasbg.fr/viz-bin/VizieR

[3] http://www.nofs.navy.mil/projects/pmm/USNOSA2doc.html

[4] The *Swift*/XRT observations were performed in the context of the approved follow-up programme in collaboration with the *Swift* team.

Table 1. IBIS, 2MASX and radio positions (and corresponding errors) for each source in the sample. The radio positions come from the analysis carried out in this work (Section 2.1).

Source	IBIS position RA (J2000) Dec. (J2000)	IBIS error circle (arcmin)	2MASX object	2MASX position RA (J2000) Dec. (J2000)	Radio object	Radio position RA (J2000)(err) Dec. (J2000)(err)
IGR J00556+7708	00:55:34.8	4.9	2MASX J00570148+7708505	00:57:01.482	NVSS J005700+770911	00:57:00.016 (0.181 s)
	+77:08:24			+77:08:50.50		+77:09:11.81 (0.62 arcsec)
IGR J03103+5706	03:10:16.8	4.9	2MASX J03095498+5707023	03:09:54.987	NVSS J030954+570704	03:09:54.955 (0.128 s)
	+57:06:07.2			+57:07:02.34		+57:07:04.29 (1.04 arcsec)
IGR J05583−1257	05:58:17.04	4.8	2MASX J05580231−1255477	05:58:02.313	NVSS J055802−125545	05:58:02.416 (0.172 s)
	−12:57:43.2		(LCSB 0289O)	−12:55:47.78		−12:55:45.54 (3.30 arcsec)
IGR J08190−3835	08:19:02.16	3.5	2MASX J08191136−3833104	08:19:11.365	NVSS J081910−383307	08:19:10.929 (0.219 s)
	−38:34:58.8			−38:33:10.46		−38:33:06.78 (3.00 arcsec)
IGR J17219−1509	17:21:55.68	4.2	2MASX J17215337−1505384	17:21:53.379	NVSS J172153−150532	17:21:53.273 (0.155 s)
	−15:09:39.6			−15:05:38.49		−15:05:32.02 (3.70 arcsec)
IGR J17520−6018	17:52:02.16	5.0	2MASX J17515581−6019430	17:51:55.818	SUMSS J175155−601943	17:51:55.585 (0.142 s)
	−60:18:18			−60:19:43.08		−60:19:43.87 (1.30 arcsec)
IGR J21268+6203	21:26:46.08	4.4	2MASX J21262644+6204410	21:26:26.440	NVSS J212628+620457	21:26:28.707 (0.027 s)
	+62:03:43.2			+62:04:41.03		+62:04:57.58 (0.19 arcsec)
IGR J21441+4640	21:44:04.08	4.9	2MASX J21441345+4637169	21:44:13.455	NVSS J214413+463718	21:44:13.419 (0.092 s)
	+46:40:51.6		(UGC 11806)	+46:37:16.97		+46:37:17.79 (0.98 arcsec)
			2MASX J21435408+4637048	21:43:54.082	NVSS J214354+463705	21:43:54.055 (0.074 s)
			(UGC 11802)	+46:37:04.84		+46:37:04.99 (0.66 arcsec)

Table 2. IR magnitudes as quoted in the 2MASX Source Catalogue for all objects in the sample. In the case of IGR J21441+4640, we report the IR magnitudes and colours of both galaxies in the pair individually.

Source	*J*-mag	*H*-mag	*K*-mag	$J-H$	$H-K$
2MASX J00570148+7708505	14.922 ± 0.222	14.291 ± 0.333	13.270 ± 0.173	0.63	1.02
2MASX J03095498+5707023	15.497 ± 0.301	13.831 ± 0.143	12.772 ± 0.096	1.67	1.06
2MASX J05580231−1255477	13.192 ± 0.080	12.608 ± 0.119	12.111 ± 0.133	0.58	0.50
2MASX J08191136−3833104	12.529 ± 0.058	11.303 ± 0.037	10.818 ± 0.049	1.23	0.49
2MASX J17215337−1505384	15.563 ± 0.237	>14.520	13.985 ± 0.181	1.04	0.53
2MASX J17515581−6019430	14.525 ± 0.133	13.564 ± 0.126	13.408 ± 0.166	0.96	0.15
2MASX J21262644+6204410	14.777 ± 0.185	14.172 ± 0.234	13.314 ± 0.174	0.6	0.86
2MASX J21441345+4637169 (UGC 11806)	12.106 ± 0.051	11.530 ± 0.062	11.312 ± 0.074	0.57	0.22
2MASX J21435408+4637048 (UGC 11802)	11.814 ± 0.055	11.088 ± 0.060	10.743 ± 0.064	0.73	0.34

For four sources in the sample (see Table 5) optical spectroscopy of the proposed counterparts were obtained from data collected at the 1.5-m telescope of the Cerro Tololo Inter-American Observatory (CTIO), Chile, at the 2.1-m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir (SPM), Mexico, and from the Six-degree Field Galaxy Survey[5] (6dFGS) archive (Jones et al. 2004) containing spectra acquired with the 4-m Anglo-Australian Telescope (AAT) in Siding Spring, Australia. Table 5 reports the log of these observations.

The spectroscopic data acquired at these telescopes were optimally extracted (Horne 1986) and reduced following standard procedures using IRAF.[6] Calibration frames (flat-fields and bias) were taken on the day preceding or following the observing night. The wavelength calibration was performed using lamp data acquired soon after each on-target spectroscopic acquisition; the uncertainty in this calibration was ∼0.5 Å in all cases, according to our checks made using the positions of background night sky lines. Flux calibration was performed using catalogued spectrophotometric standards.

As mentioned above an additional spectrum, for 2MASX J05580231−1255477, was retrieved from the 6dFGS archive. Since this archive provides spectra that are not flux calibrated, we used the optical photometric information in Jones et al. (2005) to calibrate the 6dFGS spectrum presented in this work.

The flux calibration was obtained by normalizing the count spectrum and by multiplying it by a cubic spline constructed with the fluxes extracted from the *BRI* optical magnitudes available for the source using the conversion formulae of Fukugita, Shimasaku & Ichikawa (1995).

The results of these X-ray and optical follow-up observations are presented in Tables 4 and 6.

[5] http://www.aao.gov.au/local/www/6df/

[6] IRAF is the Image Reduction and Analysis Facility made available to the astronomical community by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under contract with the US National Science Foundation. It is available at http://iraf. noao.edu.

4 RESULTS

In the following, the results of all available archival information gathered on each individual source are discussed together with the X-ray and optical data when available.

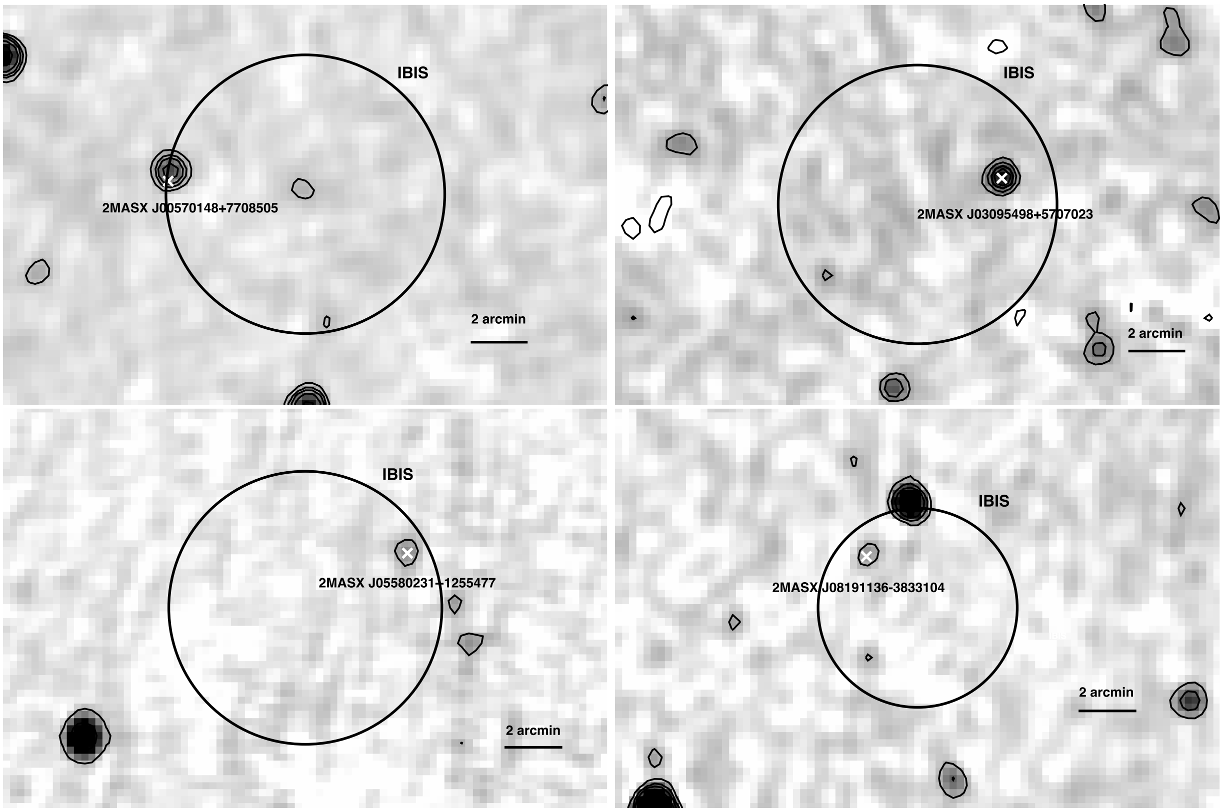

Figure 1. NVSS image cut-outs for four sources in our sample with overimposed IBIS error circle and 2MASX source positions. In all images, north is up and east is to the left. The scale is reported at the bottom right-hand corner.

Table 3. Radio information of all objects in the sample. NVSS 1.4 GHz (20 cm) and SUMSS 843 MHz (36 cm) fluxes are from this work. Other flux values are from the Westerbork Northern Sky Survey (WENSS) at 92 cm and the Parkes–MIT–NRAO (PMN) Surveys at 6 cm. All the redshifts reported in the table are from NED, except for NVSS J081910−383307 (2MASX J08191136−3833104) that is derived from the spectroscopic data analysis carried out in this work (Section 3).

Source	Redshift	325 MHz 92 cm (mJy)	843 MHz ∼36 cm (mJy)	1400 MHz 20 cm (mJy)	4850 MHz ∼6 cm (mJy)	Spectral index $\alpha^{1.4\,\mathrm{GHz}}_{325\,\mathrm{MHz}}$ ($F_\nu \propto \nu^{-\alpha}$)	Radio power at 1.4 GHz (W Hz^{-1})
NVSS J005700+770911		51 ± 2.1		16.0 ± 1.2		$0.79^{+0.09}_{-0.08}$	
NVSS J030954+570704		21 ± 3.8		10.2 ± 1.0		$0.50^{+0.18}_{-0.20}$	
NVSS J055802−125545	0.003042			4.7 ± 0.8			9.31×10^{19}
NVSS J081910−383307	0.009			2.7 ± 0.7			4.71×10^{20}
NVSS J172153−150532				5.2 ± 1.0			
SUMSS J175155−601943			25.2 ± 2.2				
NVSS J212628+620457		29 ± 4.8		45.1 ± 1.4	19 ± 4	$-0.30^{+0.13}_{-0.16}$	
NVSS J214413+463718 (UGC 11806)	0.011081	23 ± 4		11.0 ± 1.1		$0.51^{+0.17}_{-0.19}$	2.92×10^{21}
NVSS J214354+463705 (UGC 11802)	0.010517	40 ± 4		22.9 ± 1.2		$0.38^{+0.09}_{-0.10}$	5.47×10^{21}

As for the X-ray data, we note that in three cases (IGR J08190−3835, IGR J17520−6018 and IGR J21441+4640) the X-ray measurements confirm the proposed counterpart; in the case of the galaxy pair only one of the two objects, UGC 11806, was detected, while an upper limit was set on the other, UGC 11802. Only in one case (IGR J05583−1257) no X-ray source is detected within the *INTEGRAL* error circle (see the section on this source) and an upper limit is reported for the proposed counterpart.

For the optical spectra categorization, as they all refer to extragalactic sources (see below), we used the criteria of Veilleux & Osterbrock (1987) and the line ratio diagnostics of both Ho et al. (1993, 1997) and Kauffmann et al. (2003) which are generally used for emission-line AGN classification. The spectra of the galaxies shown here were not corrected for starlight contamination (see e.g. Ho, Filippenko & Sargent 1993, 1997) because of the limited S/N and spectral resolution. In this case, we do not expect this to affect any of our main results and conclusions.

Of the four objects for which we have obtained optical spectra, one was found to be a type 2 AGN (IGR J08190−3835), two (i.e. those belonging to the galaxy pair) were classified as

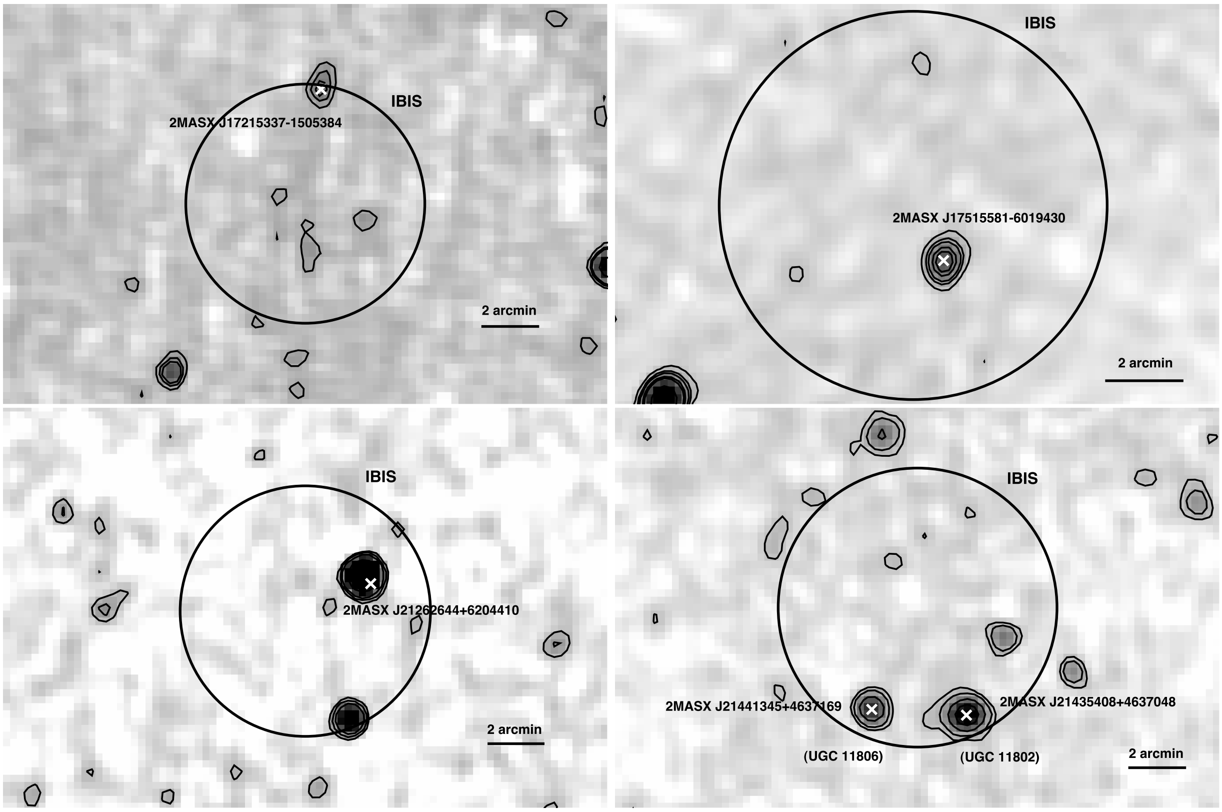

Figure 2. NVSS or SUMSS image cut-outs for four sources in our sample with overimposed IBIS error circle and 2MASX source positions. In all images, north is up and east is to the left. The scale is reported at the bottom right-hand corner.

Table 4. Spectral parameters derived from the X-ray data analysis of four sources observed by *Swift*/XRT. The values of the Galactic column densities are from Kalberla et al. (2005).

Source	Exposure (s)	Count rate (count s^{-1})	Γ Photon index	N_H(Gal) (cm^{-2})	N_H(intr) (cm^{-2})	Flux(2–10 keV) (erg cm^{-2} s^{-1})
IGR J05583−1257						
(LCSB 0289O)	4623	$<0.7 \times 10^{-3}$	1.8 (fixed)	1.63×10^{21}		$<5.8 \times 10^{-14}$
IGR J08190−3835	10310	$(18.6 \pm 1.3) \times 10^{-3}$	1.8 (fixed)	9.6×10^{21}	13.6×10^{22}	1.49×10^{-12}
IGR J17520−6018	11883	$(18.2 \pm 1.2) \times 10^{-3}$	1.8 (fixed)	7.0×10^{20}	13×10^{22}	2.55×10^{-12}
IGR J21441+4640	2755					
(UGC 11806)		$(3.3 \pm 1.2) \times 10^{-3}$	1.8 (fixed)	2.57×10^{21}		1.2×10^{-13}
(UGC 11802)		$<1.2 \times 10^{-3}$	1.8 (fixed)	2.8×10^{21}		$<8.3 \times 10^{-14}$

Table 5. Log of the spectroscopic observations presented in this paper.

Object	Date	Telescope + instrument	Exp. start time (UT)	Disp. (Å $pixel^{-1}$)	Exposure time (s)
LCSB L0289O	2005 Jan 13	AAT+6dF	12:15	1.6	1200 + 600
USNO-A2.0 0450_06519994	2010 Jan 18	CTIO 1.5m + RC Spec.	03:54	5.7	2 × 1200
UGC 11802	2009 Sep 15	SPM 2.1m + B&C Spec.	04:37	4.0	2 × 1800
UGC 11806	2009 Sep 15	SPM 2.1m + B&C Spec.	05:59	4.0	2 × 1800

low-ionization nuclear emission line regions (LINERs) and one shows the features typical of a starburst galaxy (IGR J05583−1257).

In the following, we consider a cosmology with $H_0 = 71\,km\,s^{-1}\,Mpc^{-1}$, $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$; the luminosity distances of the extragalactic objects reported in this paper were computed for these parameters using the cosmology calculator of Wright (2006).

4.1 IGR J00556+7708

This source, located at high Galactic latitude, is detected by IBIS in a revolution sequence, suggesting that it might be variable on long time-scales. As said above, in this case the radio and NIR positions are significantly different, and the objects are located on the left edge of the IBIS error box (Fig. 1, top left-hand panel). The radio object is detected at 20 and 92 cm and has a steep spectrum with index

$\alpha = 0.79$, typical of a radio-loud AGN; no optical counterpart is found within the radio source positional uncertainty. The NIR source is also listed in the USNO-A2.0 catalogue[7] with name USNO-A2.0 1650_00208794 and optical magnitudes $R \sim 17.4$ and $B \sim 19.5$; the NIR colour indices are typical of an active galaxy (Kouzuma & Yamaoka 2010).

Overall, we conclude that the radio and NIR objects are both likely AGNs and, as such, are both possible counterparts of the IBIS detection.

4.2 IGR J03103+5706

This object is also likely variable as it was detected by IBIS during just one revolution (3 d). The radio/NIR counterpart suggested in this work is located within the IBIS error circle (Fig. 1, top right-hand panel). It is detected in radio at 20 and 92 cm and has $\alpha = 0.50$, which is characteristic of a radio flat-spectrum galaxy. The source has no optical counterpart in USNO-B1.0 (Monet et al. 2003), suggestive of a highly reddened/absorbed object. Its NIR photometry, as well as its location on the Galactic plane, is not typical of an AGN, so the nature of this object remains dubious.

4.3 IGR J05583−1257

This is one of the two persistent sources in the sample; the radio/NIR source is identified in NED with LCSB L0289O, a low brightness galaxy at $z = 0.003$. This source is fairly bright in the far-IR being detected by *IRAS* at 60 μm with a flux of 0.6 Jy (IRAS 1988). The available radio data (Fig. 1, bottom left-hand panel) for this source only consist of a flux at 20 cm; thus, no information on the spectral index can be obtained. The 6dFGS optical spectrum (Fig. 4, first panel from top; see also DSS-II-red image in Fig. 3, left-hand panel) shows several permitted and forbidden narrow emission lines at the above redshift; their ratios (see also Table 6) indicate that this is a starburst galaxy with no noticeable nuclear activity.

There is no X-ray detection within the 90 per cent IBIS error box, but at the border of the 99 per cent positional uncertainty we find a detection at low significance level, 2.6σ. This source is located at RA(J2000) = $05^{h}57^{m}59\overset{s}{.}9$, Dec.(J2000) = $-12°51'33.0''$ ($6''$ uncertainty). The X-ray flux is 7.3×10^{-14} erg cm^{-2} s^{-1}, with photon index fixed to 1.8. At this position no optical or IR or radio source is found. On the other hand, we do not find any X-ray emission at the location of LCSB 0289O. The 2–10 keV flux upper limit provides an indication on the source luminosity which is $<10^{39}$ erg s^{-1}, i.e. quite low for an AGN, unless the source is extremely variable (but this is not evident in the IBIS data), or extremely absorbed (thus masking a Compton thick AGN in a starburst galaxy).

The persistent nature of the source, the stringent upper limit in X-rays and the optical spectrum suggest that this is probably not the counterpart of the IBIS source, which either is a spurious detection or has a different association than LCSB 0289O.

4.4 IGR J08190−3835

This is the second persistent source in our sample. Within the IBIS uncertainty, XRT detects only one source with a statistical significance of 5.8σ in the energy range 0.3–10 keV. This object is positionally coincident with both 2MASX and NVSS sources (Fig. 1, bottom right-hand panel). The radio analysis provides a flux of

Table 6. Fluxes (in units of 10^{-14} erg cm^{-2} s^{-1}) of the main emission lines detected in the spectra of the objects reported in Fig. 4. The correction for the Galactic reddening was computed a colour excess $E(B - V)$ = 0.479, 1.54, 0.404 and 0.403 mag for LCSB L0289O, USNO-A2.0 0450_06519994, UGC 11802 and UGC 11806, respectively (from Schlegel, Finkbeiner & Davis 1998). Uncertainties and upper limits for the fluxes are reported at 1σ and 3σ confidence levels, respectively.

Line	Observed flux	Corrected flux
LCSB L0289O ($z = 0.003$)		
Hβ	17.5 ± 0.9	87 ± 4
[O III] λ5007	92 ± 3	428 ± 13
[O I] λ6300	<0.5	<2.2
Hα	34.2 ± 1.0	105 ± 3
[N II] λ6583	1.0 ± 0.3	3.3 ± 1.0
[S II] λ6716	1.8 ± 0.3	5.5 ± 0.9
[S II] λ6731	1.2 ± 0.2	3.6 ± 0.6
USNO-A2.0 0450_06519994 ($z = 0.009$)		
Hβ	<0.07	<9
[O III] λ5007	<0.07	<9
[O I] λ6300	<0.17	<7
Hα	0.32 ± 0.08	11 ± 3
[N II] λ6583	0.12 ± 0.03	4.1 ± 1.0
[S II][a]	0.26 ± 0.04	8.3 ± 1.2
UGC 11802 ($z = 0.0105$)		
Hβ	1.41 ± 0.14	5.4 ± 0.5
[O III] λ5007	0.76 ± 0.11	2.7 ± 0.4
[O I] λ6300	0.24 ± 0.06	0.55 ± 0.14
Hα	9.5 ± 0.3	24.1 ± 0.7
[N II] λ6583	2.47 ± 0.12	6.4 ± 0.3
[S II] λ6716	2.26 ± 0.16	5.6 ± 0.4
[S II] λ6731	1.58 ± 0.11	3.9 ± 0.3
UGC 11806 ($z = 0.0110$)		
Hβ	1.22 ± 0.12	4.8 ± 0.5
[O III] λ5007	0.76 ± 0.08	2.8 ± 0.3
[O I] λ6300	0.21 ± 0.05	0.70 ± 0.18
Hα	7.0 ± 0.2	17.7 ± 0.5
[N II] λ6583	2.88 ± 0.14	7.2 ± 0.4
[S II] λ6716	1.53 ± 0.11	3.7 ± 0.3
[S II] λ6731	1.24 ± 0.09	3.1 ± 0.3

[a]The doublet is blended due to the low spectral S/N and resolution.

∼3 mJy at 20 cm. The source is fairly bright at NIR frequencies (see Table 2), and it is also detected in the optical band, where is listed in the USNO-A2.0 catalogue with name USNO-A2.0 0450_06519994 (see Tables 5 and 6) and magnitudes $R \sim 14.6$ and $B \sim 16.8$. From a comparison with the NIR magnitudes in Table 2, the $R - K$ colour is therefore ∼4, which suggests a red or obscured galaxy (Fig. 3, central panel and Table 6).

The X-ray data analysis is described by an absorbed power law with photon index fixed to 1.8 and an observed 2–10 keV flux of 1.5×10^{-12} erg cm^{-2} s^{-1}; the intrinsic column density is $N_{\rm H}$(intr) $\sim 1.4 \times 10^{23}$ cm^{-2}, which exceeds the Galactic value of 9.6×10^{21} cm^{-2} (Kalberla et al. 2005). Optical spectroscopy (Fig. 4, second panel from top) shows that the source displays Hα, [N II] and [S II] narrow emission lines at redshift $z = 0.009 \pm 0.001$ superimposed on a very reddened continuum. The flux ratios among these emission features suggest that the object is a type 2 AGN.

[7] http://www.nofs.navy.mil/projects/pmm/USNOSA2doc.html

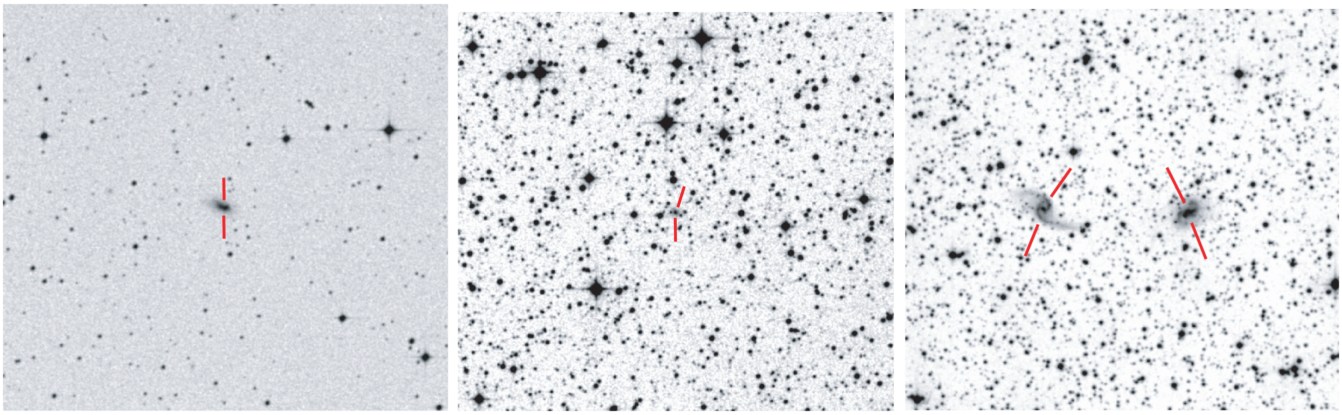

Figure 3. Optical images of the fields of three of the *INTEGRAL* hard X-ray sources selected in this paper for optical spectroscopic follow-up: IGR J05583−1257 (left-hand panel), IGR J08190−3835 (central panel) and IGR J21441+4640 (right-hand panel). The proposed optical counterparts are indicated with tick marks (see text). Field sizes are 10 × 10 arcmin^2 and are extracted from the DSS-II-red survey. In all cases, north is up and east is to the left.

Overall, we conclude that the proposed 2MASX/NVSS/XRT source is the actual counterpart of the IBIS-detected object and it is a narrow-line (obscured) AGN.

4.5 IGR J17219−1509

The radio/NIR source is located at the edge of the IBIS error circle (Fig. 2, top left-hand panel); it is very weak in radio, being close to the flux limit of the NVSS map (∼5 mJy). Very little is known about this source except that it is strongly variable in the IBIS waveband, being detected only in one revolution (R403, i.e. for a few days) and showing a large bursticity factor of 4 (see Bird et al. 2010, for details). The source has an optical magnitude of 18.2 in R; the NIR colours, as well as its location above the Galaxy plane, are compatible with the source being a nearby AGN (Kouzuma & Yamaoka 2010).

We conclude that this is an extragalactic object, most likely an AGN, on the basis of the above considerations, and it is a good association for the *INTEGRAL* source.

4.6 IGR J17520−6018

This source can also be considered as variable by Bird et al. (2010). An X-ray source is well detected at 13.6σ confidence level in the range 0.3–10 keV by XRT within the IBIS uncertainty and is located at RA(J2000) = $17^{\mathrm{h}}51^{\mathrm{m}}55\overset{\mathrm{s}}{.}9$ and Dec.(J2000) = $-60^{\circ}19'44''$ (4 arcsec uncertainty). It coincides with both the 2MASX object and the radio source reported in the SUMSS (Fig. 2, top right-hand panel). The source has only one detection in radio at 36 cm. Besides being detected in the NIR, the galaxy is also listed in the USNO-B1 catalogue with optical B and R magnitudes of 15.5 and 14.7, respectively. The X-ray data analysis provides an absorbed power-law spectrum with fixed photon index of 1.8 and an observed 2–10 keV flux of 2.6×10^{-12} erg cm^{-2} s^{-1}; the intrinsic column density is $N_{\mathrm{H}}(\mathrm{intr}) = 1.3 \times 10^{23}$ cm^{-2}, which exceeds the Galactic value (see Table 4). This source is also reported in the Burst Alert Telescope (BAT) 58-Month catalogue[8] as SWIFT J1751.8−6019, with flux 1.7×10^{-11} erg cm^{-2} s^{-1} in the range 14–195 keV.

Based on all the above information, we conclude that this galaxy is the likely counterpart of the IBIS/BAT source, and, on the basis of the detected X-ray absorption, we further suggest that it is a type 2 AGN.

4.7 IGR J21268+6203

This IBIS source is also highly variable, being reported with a high bursticity factor by Bird et al. (2010); it is also likely an extragalactic source being located above the Galactic plane. As said in Section 2.1, in this case the radio and NIR positions are significantly different (Fig. 2, bottom left-hand panel). The NIR object (Table 2) has an optical counterpart in USNO-B1.0 1520_0331686 listed in USNO-B1.0 catalogue with magnitudes $B \sim 20.3, R \sim 17.5$ and $I \sim 16.4$; no optical association was found for the radio object. The NIR colours are also in this case typical of a nearby AGN (Kouzuma & Yamaoka 2010). The radio data available provide a spectral index $\alpha = -0.3$ between 20 and 92 cm, indicative of a probable GHz-peaked-spectrum (GPS) radio source, i.e. a source characterized by a convex radio spectrum peaking near 1 GHz (O'Dea 1998; Lister 2003; Stanghellini 2006). GPSs are compact powerful young radio galaxies that reside in gas-rich environments at the centre of active galaxies.

Thus, the observational evidence suggests that the radio and NIR objects are both likely AGNs and, as such, are good candidates for an association with the *INTEGRAL* source.

4.8 IGR J21441+4640

This also is a strongly variable source in IBIS (Bird et al. 2010) with a bursticity larger than 4. Within the IBIS positional uncertainty of this source, there are two galaxies (see Fig. 3, right-hand panel), UGC 11802 and UGC 11806, at the same redshift ($z = 0.011$), which form the galaxy pair KPG559. Both galaxies are detected at radio frequencies in the NVSS catalogue (NVSS J214354+463705 and NVSS J214413+463718) and are also listed in the 2MASX Source Catalogue (2MASX J21435408+4637048 and 2MASX J21441345+4637169) (see Fig. 2, bottom right-hand panel). The radio data analysis provides a 20-cm flux for both objects, which are also detected at 92 cm and have spectral indices $\alpha = 0.38$ and 0.51, respectively; both radio power and spectral index are typical of low-luminosity AGNs. The optical B (R) magnitudes of the two objects are 14.5 (9.5) and 14.7 (12.9). Both are detected with *AKARI* in the far-IR, from 90 to 160 μm at the few jansky flux

[8] http://swift.gsfc.nasa.gov/docs/swift/results/bs58mon/

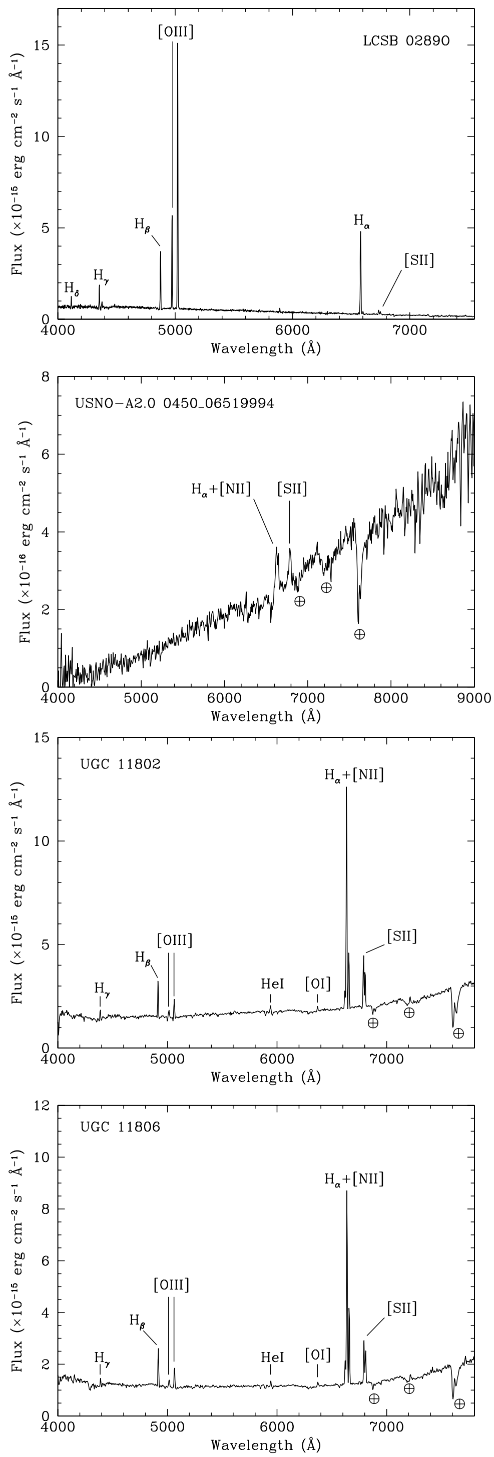

Figure 4. Spectra (not corrected for the intervening Galactic absorption) of the possible optical counterparts of some of the *INTEGRAL* sources presented in this paper (IGR J05583−1257, IGR J08190−3835 and IGR J21441+4640; see text). For each spectrum, the main spectral features are labelled. The symbol ⊕ indicates atmospheric telluric absorption bands.

level (Murakami et al. 2007). Within the IBIS uncertainty, XRT finds only one galaxy (UGC 11806) of the pair, with a low statistical significance of 2.5σ in the range 0.3–10 keV. The XRT spectrum can be described by an unabsorbed power law with fixed photon index of 1.8 and an observed 2–10 keV flux of 1.2×10^{-13} erg cm^{-2} s^{-1}. The upper limit of the X-ray flux in the 2–10 keV band for the companion galaxy UGC11802 is 8.3×10^{-14} erg cm^{-2} s^{-1}.

Optical spectroscopy (Fig. 4, bottom panel) indicates that UGC 11806 is a narrow emission-line galaxy with flat continuum and prominent Balmer, [N II], [O III] and [S II] lines at a redshift consistent with the one found in the literature. Emission-line ratios suggest that this is a transition object, i.e. a LINER (Heckman 1980) with a possible contamination from an underlying starburst event. The optical spectrum of UGC 11802 (Fig. 4, third panel from top) indicates instead that this galaxy is a starburst, with no indication of AGN activity (which explains the absence of detectable X-ray emission from its nucleus).

The low significance detection in X-rays of UGC 11806 may be due to the variable nature of the source (Bird et al. 2010) rather than to the high absorption, which is not readily apparent from the optical spectrum. To this aim we can infer the reddening local to the source by considering an intrinsic $H\alpha/H\beta$ line ratio of 2.86 (Osterbrock 1989). The corresponding colour excess, obtained by comparing the intrinsic line ratio with the measured one by applying the Galactic extinction law of Cardelli, Clayton & Mathis (1989), is $E(B-V) = 0.25$ mag. This, using the formula of Predehl & Schmitt (1995), corresponds to a hydrogen column density $N_{\rm H} = 1.4 \times 10^{21}$ cm^{-2} local to the AGN.

Overall we conclude that UGC 11806 is the counterpart of the IBIS source; it is probably a low-luminosity and highly variable AGN of LINER type.

5 CONCLUSION

The basic idea of this work is to propose a way whereby AGNs can be easily found out among a set of unidentified objects detected in hard X-ray surveys. The method, which consists of two consecutive steps of cross-correlations between hard X-ray objects and IR/radio catalogues, is tested here for the unidentified sources contained in the fourth IBIS Survey Catalogue.

Following this procedure, we first used the 2MASX Source Catalogue to identify galaxies in the IBIS error circle and then we extracted those which were also radio emitters, in order to isolate AGN candidates by means of NVSS and SUMSS radio catalogues. As a result, we obtained a set of eight objects for which we performed a more in-depth study, and in some cases optical and/or X-ray follow-up observations, in order to verify their true association with the *INTEGRAL* source as well as their AGN nature and class.

The purpose of this work is not to search out for AGNs using different selection criteria, but rather to confirm how a multiwavelength (radio, IR, optical and X-ray) study of these eight sources can be used to test the level of reliability and accuracy of the proposed method.

In three cases (IGR J08190−3835, IGR J17520−6018 and IGR J21441+4640) we found the X-ray counterparts of the IBIS sources. The optical spectra obtained for two of these sources (IGR J08190−3835 and IGR J21441+4640) allowed us to identify them as AGNs belonging to the type 2 and LINER class. The third one (IGR J17520−6018) is most likely a type 2 AGN on the basis of the high X-ray absorption measured. We further suggest that three sources (IGR J00556+7708, IGR J17219−1509 and IGR J21268+6203) are likely active galaxies on the basis of the radio spectra, NIR photometry and location above the Galactic plane: they are all likely associated with the IBIS objects. LCSB 0289O is instead a starburst galaxy, which is at most a very weak X-ray source and so unlikely to emit at high energies; we conclude that it is an improbable association of IGR J05583−1257. The nature of this *INTEGRAL* source is therefore still open. In only one case (IGR J03103+5706), we have not enough information for a clear classification of the radio/NIR source as an AGN; the nature of this *INTEGRAL* object remains dubious.

Overall, detailed information and follow-up measurements confirm the goodness of our method in the search for AGNs among unidentified hard X-ray emitters. On the basis of this work, we have classified in the fourth IBIS catalogue the sources discussed in this paper as AGNs, and the same approach can be used to pinpoint AGN candidates among *Swift*/BAT or future *NuSTAR* (Harrison et al. 2010) unidentified objects.

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