

Unveiling the Nature of *INTEGRAL* Sources Through Optical Spectroscopy

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Abstract Since its launch on October 2002 the *INTEGRAL* satellite is performing a deep survey of the hard X-ray sky with unprecedented sensitivity and positional accuracy. This allowed pinpointing, through positional cross-correlation with catalogs at longer wavelengths, possible optical/near-infrared candidates for the hard X-ray sources of still unknown nature. In this presentation I will describe this work as well as the observational activities aimed at determining, through optical spectroscopy, the nature of the unknown *INTEGRAL* sources, along with the main results of this search. Future prospects about this identification program will also be illustrated.

Key words: X-rays: binaries – X-rays: galaxies – Galaxies: Seyfert – Techniques: spectroscopic

1 INTRODUCTION

One of the main **aims** of satellites observing in the X-ray band is to obtain all-sky maps of celestial high-energy emission. This allows obtaining information on sky distribution and characteristics of X-ray objects. In the past years, several surveys were performed by various spacecraft such as, e.g., *HEAO-1* (13–180 keV, Levine et al. 1984), *ROSAT* (0.1–2.4 keV, Voges et al. 1999) and BATSE onboard *Compton-GRO* (25–160 keV, Shaw et al. 2004).

These surveys were mostly devoted to all-sky scannings, with particular attention to the Galactic Plane. In particular, the survey performed by *ROSAT* (Voges et al. 1999) allowed pinpointing, with a precision of few arcsecs, sources emitting in the soft X-ray band (below 2 keV). However, it could not detect heavily absorbed sources, in particular those located along the Galactic Plane, as the high amount of neutral hydrogen present in this strip of the sky severely hampers observations in this band. Likewise, the main drawbacks of the past hard X-ray surveys were the scarce positional accuracy (allowing source error boxes with radii not smaller than some degrees) and/or the low survey sensitivity (~ 30 mCrab).

In this sense, *INTEGRAL* (Winkler et al. 2003) produced a breakthrough in the all-sky mapping of hard X-ray sources in terms of both sensitivity and positional accuracy. Indeed, thanks to the capabilities of the IBIS instrument (Ubertini et al. 2003), *INTEGRAL* is able to detect hard X-ray sources at the mCrab level with a typical localization accuracy of $2'–3'$: this has made it possible, for the first time, to resolve crowded regions such as the Galactic Centre and the spiral arms, and to discover many new hard X-ray extragalactic objects beyond the Galactic Plane of the Milky Way, in the so-called ‘Zone of Avoidance’, where (as remarked above) the massive presence of interstellar neutral hydrogen disfavours observations in soft X-rays.

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2 THE 1st IBIS/INTEGRAL SURVEY

In its first year, during the 1st survey of the Galactic Plane, the IBIS instrument onboard *INTEGRAL* has detected 123 sources between 20 and 100 keV (Bird et al. 2004): within this sample of hard X-ray emitting objects, 53 low-mass X-ray binaries (LMXBs) and 23 high-mass X-ray binaries (MXRBs), 5 Active Galactic Nuclei (AGNs) and a handful of other objects such as pulsars, supernova remnants and cataclysmic variables (CVs) were **identified**. The remaining objects (28, or about 23% of the sample) have no obvious counterparts at other wavelengths and therefore cannot yet be associated with any known class of high-energy emitting objects. Only for a tiny fraction of these sources follow-up observations at X-ray energies as well as in the optical/near-infrared (NIR) wavebands **have** been carried out so far (Rodríguez 2005). Although the cross-correlation with catalogues or surveys at other wavelengths (especially soft X-rays, optical and radio) is of invaluable help in pinpointing the putative optical candidates, only accurate optical spectroscopy can confirm the association and reveal the nature of the object.

Most of these unidentified sources are believed to be X-ray binary systems, where one of the two members is either a black hole or a neutron star (NS). There is however the possibility that some of them could be AGN similar to those already detected (Bassani et al. 2004). However, since all these objects are hard X-ray selected and poorly known at other wavebands, there are possibilities that we are dealing with peculiar sources (e.g. Filliatre & Chaty 2004).

3 CORRELATIONS WITH CATALOGS AT OTHER WAVELENGTHS

Stephen et al. (2005) studied the positional correlation between the sources of the 1st IBIS survey and those in the larger *ROSAT* bright source catalogue (Voges et al. 1999). It was found that, assuming a (conservative) 3' radius for all *INTEGRAL* error boxes, there are 75 *INTEGRAL/ROSAT* positional associations. On purely statistical grounds, Stephen et al. (2005) moreover demonstrated that, if these catalogs were uncorrelated, the number of expected chance associations instead would have been 0.35, that is, a factor of about 200 times less than the actual number of associations found. This strongly indicates that a *ROSAT* source within an *INTEGRAL* error box corresponds to the soft X-ray counterpart of the hard X-ray object detected with IBIS; this fact allows one to reduce the error box of the X-ray source to few arcsecs, facilitating the searches of the optical counterpart.

Of the 75 *ROSAT* sources found associated with *INTEGRAL* detections, only 66 have an identified counterpart at longer wavelengths, in such a way that their nature is known (Stephen et al. 2005); this leaves 9 *INTEGRAL* objects not yet optically identified but for which, statistically, the corresponding *ROSAT* source should be the counterpart at softer X-rays.

Despite the strong correlation found between the two catalogues, a significant fraction (~40%) of the *INTEGRAL* sources have no association with a *ROSAT* bright survey object. This, as said in Sect. 1, may be due to strong absorption preventing detection in soft X-rays.

A similar, although less tight, correlation seems to be present (Stephen et al., in preparation) between the IBIS survey and radio catalogs such as the NVSS (Condon et al. 1998); thus, the presence of a radio object within the IBIS error box can be seen as an indication of an association between the radio and the *INTEGRAL* sources (see, e.g., Masetti et al. 2004).

4 OPTICAL/NIR IDENTIFICATIONS OF UNKNOWN INTEGRAL SOURCES

The first identification of the nature of an unknown source discovered with *INTEGRAL* was that of IGR J16138–4848, an object located in the Norma Arm of the Galaxy. Thanks to the refined (error radius: 4'') *XMM-Newton* soft X-ray position, Filliatre & Chaty (2004) pinpointed the using optical and NIR photometry. Then, through the use of NIR spectroscopy, these authors identified this source as an extremely reddened (with optical *V*-band absorption $A_V = 17.4$ magnitudes) MXRB, located at a distance between 0.9 and 6.2 kpc, and composed of a supergiant B[e] star losing mass onto a compact object, most likely a NS.

Motivated by the findings illustrated in Sect. 3, and in parallel with the above successful identification of the nature of IGR J16138–4848, we underwent a sample selection in order to pick out possible optical candidates over which optical spectroscopy could be done in order to unveil their nature.

We performed the sample selection following three steps: (i) we positionally correlated the IBIS survey with the *ROSAT* (X-ray) and NVSS (radio) catalogues in order to **substantially reduce** the error box size; (ii) within these reduced error boxes we searched for putative optical/NIR counterparts on DSS-II-Red

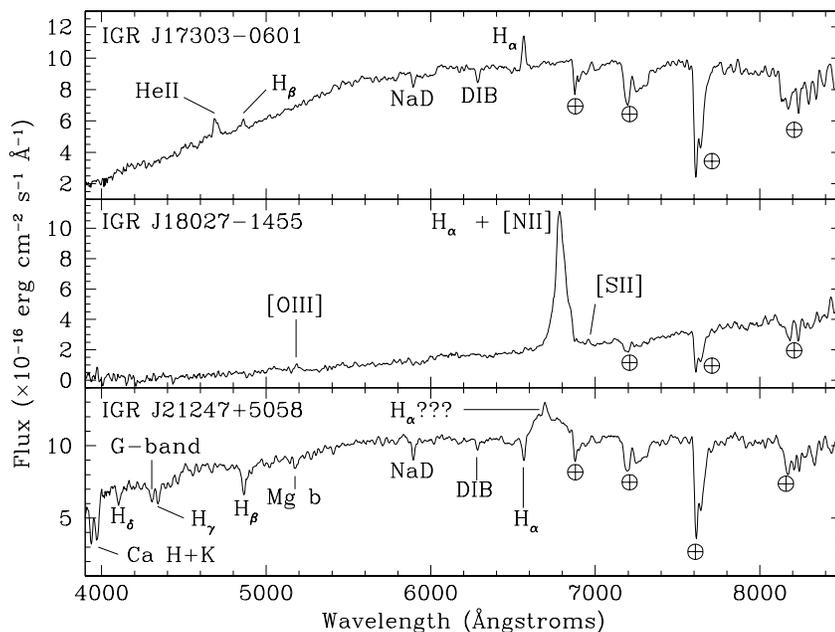


Fig. 1 Average optical spectra, **not corrected for Galactic or intrinsic absorption**, of the optical counterparts to IGR J17303–0601 (upper panel), IGR J18027–1455 (central panel) and IGR J21247+5058 (lower panel) acquired with the Cassini telescope at Loiano. The spectra, in the 3900–8500 Å range, are smoothed with a Gaussian filter with $\sigma = 4\text{Å}$ (i.e. comparable with the spectral dispersion). The main spectral features are labelled. The symbol \oplus indicates atmospheric telluric features. From Masetti et al. (2004a).

(optical) and 2MASS (NIR) surveys; (iii) we selected cases with few (3 or less) relatively bright optical/NIR candidates in the *ROSAT* and/or NVSS error boxes on which optical spectroscopy could be performed. We then started our campaign with three objects observable (in terms of both declination and optical brightness) with the 1.5-metre ‘Cassini’ telescope of the Astronomical Observatory of Bologna in Loiano (Italy): IGR J17303–0601 (*the Good*), IGR J18027–1455 (*the Bad*) and IGR J21247+5058 (*the Ugly*). For details, the reader is referred to the paper by Masetti et al. (2004a).

IGR J17303–0601. This source positionally coincides with an X-ray object detected earlier by *ROSAT*, *HEAO-A1* and *RXTE* from 0.1 to 30 keV. Within the small *ROSAT* error box ($7''$; Voges et al. 1999) our *R*-band imaging showed at least 5 objects. The spectrum of the brighter object in the error box (Figure 1, top panel) revealed the presence of Balmer and He II emissions and interstellar absorption features superimposed onto a reddened continuum. We therefore regarded the identification of this source as the optical counterpart to IGR J170303–0601 as secure. **All spectral lines are at redshift zero**, indicating that this object belongs to the Galaxy. Besides, the presence of the He II strongly indicates undergoing mass accretion onto a compact star (e.g. van Paradijs & McClintock 1995). We thus concluded that this source is very likely an X-ray binary system.

Using the strength of the Balmer emission lines we inferred a reddening of $E(B - V) = 0.45$ mag for the source. From this, and assuming a distance $d \sim 8$ kpc, we obtained an absolute optical *R*-band magnitude $M_R \sim 0$ for the object, which is typical of persistent LMXBs (van Paradijs & McClintock 1995). The *INTEGRAL* X-ray data (Bird et al. 2004) support this interpretation: at this distance, the 20–40 keV luminosity of the source is $1.8 \times 10^{35} \text{ erg s}^{-1}$. This also is typical of persistent LMXBs in the soft state (e.g., Masetti et al. 2004b).

Recently, Gänsicke et al. (2005) questioned the LMXB identification for IGR J17303–0601 on the (admittedly sole) basis of the detection of a 128-second optical periodicity from this source, which they attribute to the spin period of the accreting object. They conclude that, given this spin duration, the compact

source is a white dwarf and the system is actually an Intermediate Polar CV similar to AE Aqr. However, one should note that the NS hosted in the LMXB GX 1+4 has a comparable spin period (134 s; e.g., Makishima et al. 1988). Moreover, using the information in Gänsicke et al. (2005), one derives, in the CV hypothesis, a distance of ~ 3 kpc to the object: this implies an X-ray luminosity of $\sim 10^{34}$ erg s $^{-1}$, which is four orders of magnitude larger than that of AE Aqr (Mukai 2005). Thus the CV identification for this source is not certain and it is moreover problematic when compared to the LMXB interpretation.

IGR J18027–1455. Inside the 2' ISGRI error box of this source an X-ray and radio object is found (Combi et al. 2005); it also has NIR and optical ($R \sim 15$ mag) counterparts. The non-pointlike appearance of the optical source suggested that it has extragalactic origin. Indeed, its optical spectrum (Figure 1, central panel) showed a faint and reddened continuum dominated by a strong emission around 6800 Å which we identified with the line complex composed of H α plus [N II] at $z = 0.035 \pm 0.001$. Fainter and narrower emissions were also found at wavelengths consistent with this redshift. The spectrum allowed us to identify this source as a Type 1 Seyfert galaxy.

Assuming a cosmology with $H_0 = 65$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$, this redshift implies a distance of 166 Mpc, X-ray luminosities of 3×10^{42} erg s $^{-1}$ and 1.7×10^{44} erg s $^{-1}$ in the 0.1–2.4 keV and in the 20–100 keV bands, respectively, and an absolute optical B -band magnitude $M_B \sim -22$. These values place this source among the brightest Type 1 Seyfert galaxies detected so far (Malizia et al. 1999; Veron-Cetty et al. 2001).

IGR J21247+5058. This source was associated by Combi et al. (2005) with the radio source 4C50.55, which shows a morphology typical of a radio galaxy (Mantovani et al. 1982). The optical counterpart has magnitude $R \sim 15.5$. Its optical spectrum (Figure 1, bottom panel) has a puzzling appearance. It shows a smooth continuum, typical of a late F- or early G-type star in the Galaxy. However, superimposed to this stellar-like continuum, a broad emission bump around 6700 Å is apparent, topped by a narrow emission. By identifying the latter as H α , we obtained a redshift $z = 0.020 \pm 0.001$.

The hypothesis of a chance alignment between a Galactic F-type star and a background radio galaxy at $z = 0.02$ was thus suggested. In this occurrence, assuming the same cosmology as for IGR J18027–1455, the distance to this galaxy is 94 Mpc, and the extension of the radio lobes is ~ 200 kpc; the 20–100 keV luminosity would be 1.4×10^{44} erg s $^{-1}$, locating this source also at the bright end of the AGN luminosity distribution. One should note that, although Mantovani et al. (1982) suggested that optical spectroscopy would be able to disentangle the nature of this object, no observations of this kind have been reported in more than 20 years.

Therefore, our first campaign on the identification of the nature of unknown *INTEGRAL* sources through optical spectroscopy gave encouraging results, and indicates that the approach we used can indeed be remarkably successful in this identification task.

5 FUTURE PROSPECTS

Of course, *INTEGRAL* keeps monitoring the hard X-ray sky: the 2nd IBIS survey is about to be issued (Bird et al. 2005), and new sources are collected in the continuously updated *INTEGRAL* sources inventory of Rodríguez (2005). Up to the time of this meeting (late May 2005), among this new set of *INTEGRAL* sources, some have been optically identified as a LMXB containing a millisecond X-ray pulsar (Roelofs et al. 2004), three Be/X MXRBs (Reig et al. 2005; Halpern & Gotthelf 2004; Torrejón & Negueruela 2004), three supergiant MXRBs (Negueruela et al. 2005 and references therein) and a Type 1 AGN (Torres et al. 2004).

However, there is still a number of *INTEGRAL* sources which lack a firm optical/NIR identification of their nature: indeed, we have 13 transient or persistent hard X-ray sources with (basically *INTEGRAL*) error boxes which are still too large to allow sensible optical/NIR counterpart searches; moreover, there are also 23 new sources (to which 12 more, belonging to the 1st IBIS survey, should be added) which have soft X-ray or radio error boxes of size $\sim 10''$ but non-univocal optical/NIR localization.

Therefore, for most of the above objects, very precise localizations with arcsecond or subarcsecond positional accuracy are needed to remove the ambiguity in the optical/NIR identification of the counterpart, especially in crowded fields. At present, this task can be achieved with the use of the satellites *Chandra*, *XMM-Newton* and *Swift* in X-rays and with facilities sensitive at radio wavelengths, in particular the VLA.

Of course, our optical follow-up activities are ongoing: we are about to spectroscopically study northern and southern objects thanks to optical observing programmes approved at ESO (Chile), SAAO (South Africa), WHT (Canary Islands, Spain) and Loiano (Italy). These will secure new identifications of the nature of more *INTEGRAL* sources.

However, besides this identification task, more work is expected in the future on these sources. In the following I briefly outline the main objectives which should be pursued:

- cross-correlations with available catalogues at longer wavelengths is needed as soon as new *INTEGRAL* sources are discovered;
- a campaign of accurate X-ray astrometry of loose localizations with *Chandra*, *XMM-Newton* and *Swift* should be performed in order to pinpoint the soft X-ray counterparts of *INTEGRAL* sources;
- the study of the multiwavelength properties of the *INTEGRAL* sources, both considering each single case and grouping them into (sub)classes;
- the analysis of ‘Norma Arm sources’: is it, as suggested by some authors (e.g., Filliatre & Chaty 2004), a new class of objects? If so, it will disclose brand new information on heavily absorbed Galactic MXRBs;
- the study of statistical correlations between *INTEGRAL* and surveys at wavelengths longer than soft X-rays;
- a statistical analysis of the nature of the objects belonging to the IBIS survey;
- in-depth observations to obtain precise physical parameters of the identified *INTEGRAL* objects.

To conclude, I stress the fact that, in the era of large observatories, high-quality science on up-to-date astrophysical topics, such as the hunt for the nature of *INTEGRAL* sources, can be achieved using small- and medium-sized telescopes, as shown in Masetti et al. (2004a).

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References

- Bassani, L., Malizia, A., Stephen, J. B., et al. 2004, in: Schönfelder, V., Lichti, G., & Winkler, C. (eds.) *The INTEGRAL Universe*, ESA SP-552, p. 139
- Bird, A. J., Barlow, A. J., Bassani, L., et al. 2004, *ApJ*, 607, L33
- Bird, A. J., et al. 2005, *ApJ*, submitted
- Combi, J. A., Ribó, M., & Mirabel, I. F. 2005, *Ap. Space Sci.*, 297, 385
- Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, *AJ*, 115, 1693
- Filliatre, P., & Chaty, S. 2004, *ApJ*, 616, 469
- Gansicke, B. T., Marsh, T. R., Edge, A., et al. 2005, *MNRAS*, 361, 141
- Halpern, J. P., & Gotthelf, E. V. 2004, *ATel* 341
- Levine, A. M., Lang, F. L., Lewin, W. H. G., et al. 1984, *ApJS*, 54, 581
- Makishima, K., Ohashi, T., Sakao, T., et al. 1988, *Nature*, 333, 746
- Malizia, A., Bassani, L., Zhang, S. N., et al. 1999, *ApJ*, 519, 637
- Mantovani, F., Nanni, M., Salter, C. J., & Tomasi, P. 1982, *A&A*, 105, 176
- Masetti, N., Palazzi, E., Bassani, L., Malizia, A., & Stephen, J.B. 2004a, *A&A*, 426, L41
- Masetti, N., Foschini, L., Palazzi, E., et al. 2004b, *A&A*, 423, 651
- Mukai, K. 2005, <http://lheawww.gsfc.nasa.gov/users/mukai/iphone/iphone.html>
- Negueruela, I., Smith, D. M., & Chaty, S. 2005, *ATel* 429
- Roelofs, G., Jonker, P. G., Steeghs, D., Torres, M., & Nelemans, G. 2004, *ATel* 356
- Rodriguez, J. 2005, <http://isdcul3.unige.ch/~rodrigue/html/igrsources.html>
- Schlegel, D.J., Finkbeiner, D.P., & Davis, M. 1998, *ApJ*, 500, 525
- Shaw, S. E., Westmore, M.J., Hill, A. B., et al. 2004, *A&A*, 418, 1187
- Stephen, J. B., Bassani, L., Molina, M., et al. 2005, *A&A*, 432, L49
- Torrejón, J. M., & Negueruela, I. 2004, *ATel* 370
- Torres, M. A. P., Garcia M. R., McClintock J. E., et al. 2004, *ATel* 264

- Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A 411, L131
- van Paradijs, J., & McClintock, J.E. 1995, in *X-ray Binaries*, ed. W.H.G. Lewin, J. van Paradijs, & E.P.J. van den Heuvel (Cambridge Univ. Press), p. 58
- Veron-Cetty, M. P., Veron, P., & Goncalves, A. 2001, A&A, 372, 730
- Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
- Winkler, C., Courvoisier, T. J. -L., Di Cocco, G., et al. 2003, A&A, 411, L1

DISCUSSION

NINO PANAGIA: Can you comment on the fact that the spectrum of IGR J18027–1455 appears to be heavily reddened? Is this due to absorption intrinsic to the object?

NICOLA MASETTI: Most likely the observed reddening is mainly produced by foreground Galactic absorption, which is quite high along this line of sight as it passes right through the Galactic Plane (the Galactic latitude of the object is $b = +3^{\circ}7$). Indeed, according to Schlegel et al. (1998), a color excess $E(B - V) = 1.26$ mag (which implies a V -band extinction of nearly 4 magnitudes), induced by the Galactic dust, is present in the direction of this source.

ANATOLY IYUDIN: Can you tell me how the distance to IGR J16138–4848 was determined? As far as I know, its position is not exactly in the middle of the Norma Arm, so the absorption along the line of sight of this source should not be extremely high.

NICOLA MASETTI: Details on the determination of the distance to IGR J16138–4848 can be found in Filliatre & Chaty (2004); however, let me remark that, as stressed by these authors, most of this absorption is local to the binary system and not due to the interstellar medium along the line of sight.