NEW RESULTS ON OPTICAL IDENTIFICATIONS OF *INTEGRAL* SOURCES

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ABSTRACT

Optical spectroscopic identification of the nature of 21 unidentified southern hard X–ray objects is reported here in the framework of our campaign aimed at determining the nature of newly-discovered and/or unidentified sources detected by *INTEGRAL*. Our results show that 12 of these objects are Active Galactic Nuclei (AGNs), 5 are magnetic Cataclysmic Variables (CVs), and 4 are High-Mass X–ray Binaries (HMXBs), one of which is in the Large Magellanic Cloud. These identifications further underscore the importance of *INTEGRAL* in the study of the hard X–ray spectrum of AGNs, HMXBs and CVs, and the usefulness of a strategy of catalogues cross-correlation plus optical spectroscopy to unveil the nature of the X–ray sources detected with *INTEGRAL*.

Key words: Galaxies: Seyfert — Stars: novae, cataclysmic variables — X–rays: binaries — Techniques: spectroscopic — X–rays: individuals.

1. INTRODUCTION

Since its launch in October 2002, the *INTEGRAL* satellite [35] is boosting our knowledge of the hard X–ray sky above 20 keV in terms of both sensitivity and positional accuracy of the detected sources. Thanks to the capabilities of the IBIS instrument [28], *INTEGRAL* is effectively detecting hard X–ray objects at the mCrab level with a typical localization accuracy of 2–3′ [6]. This has made it possible, for the first time, to obtain all-sky maps in the 20–100 keV range with arcminute accuracy and down to mCrab sensitivities (e.g., [2]).

Most of the sources detected by *INTEGRAL* are known Galactic X–ray binaries ($\sim$50% of the total number of detected objects), plus a fraction of known Active Galactic Nuclei (AGNs; $\sim$10%) and Cataclysmic Variables (CVs; $\sim$5%). However, a large majority of the remaining objects (about 25% of all detections achieved with IBIS) has no obvious counterpart at other wavelengths and therefore cannot immediately be associated with any known class of high-energy emitting objects.

Recently, in order to fill this identification gap, we started a campaign aimed at identifying the nature of these still unknown sources through optical spectroscopy at northern and southern telescopes [13, 14, 15, 16, 17]. Our results indicate that, despite *INTEGRAL* doubled the number of Galactic High Mass X–ray Binaries (HMXBs; see [32]) and despite the expectation according to which most of these unidentified objects should be HMXBs [5], about half of them are identified in the optical as nearby ($z \lesssim 0.1$) AGNs [13, 14, 15, 16].

In the framework of our continuing effort to identify unknown *INTEGRAL* sources, we present here the optical spectroscopic observations obtained on 21 southern objects at the 1.5-metre telescope of the Cerro Tololo Interamerican Observatory (CTIO) located in Cerro Tololo (Chile). Preliminary analysis of part of the data presented here can be found in Masetti et al. [18]. A detailed presentation of the results reported here is available elsewhere [17].

2. SAMPLE SELECTION AND OBSERVATIONS

In order to continue our program [13, 14, 15, 16] of optical spectroscopic identifications of *INTEGRAL* sources with unknown nature, we first collected all objects belonging to the 2$^{\rm nd}$ IBIS Galactic Plane Survey [2], to the Crux arm Tangent Survey [22], to the AGN minisurvey of Sazonov et al. [25] and to the Circinus-Carina arm Survey [12], and which are visible from the southern hemisphere.

We then positionally cross-correlated the IBIS error circles of the selected southern unidentified *INTEGRAL* objects with catalogues of soft ($<$10 keV) X–ray sources. This was made in order to reduce the X–ray error box size to some ($\lesssim$ 10) arcsec at most. For the present sample, we selected *INTEGRAL* objects with a single *ROSAT* source [30, 31, 24], or a single *Swift*/XRT archival X–ray source (available at `http://www.asdc.asi.it`), or a single *Chandra* source [7, 11, 25] within the IBIS error box. This approach was chosen because Stephen et al.

[26] showed that, from a statistical argument, these are very likely to be the soft X–ray counterparts of the positionally corresponding *INTEGRAL* sources; besides, the results of Masetti et al. [13, 14, 15, 16] prove that this approach is very effective, when combined with optical spectroscopy.

For the cross-correlation searches, we considered 90% confidence level *INTEGRAL*/IBIS error circles. To this aim, a conservative 90% confidence level error box radius of $2'$ was assumed for the objects belonging to the $2^{\rm nd}$ IBIS Galactic Plane Survey [2], and of $6'$ for the Crux arm Survey objects (as stated in Revnivtsev et al. [22]). For the Circinus-Carina Survey sources, the 90% confidence level error radius as reported in Kuiper et al. [12] regarding each object was considered.

In this way we could select 18 unidentified *INTEGRAL* sources associated with a single arcsec-sized soft X–ray error box which, when overlaid onto the corresponding DSS-II-Red survey[1] images, is seen to contain a single or few (3 at most) relatively bright ($R < 18$) possible optical counterparts. Three additional sources (IGR J14175−4641, IGR J14552−5133 and IGR J18244−5622) were added to our sample as their IBIS error circle includes bright field objects which were suggested as their possible counterparts [22, 23]. The list of selected *INTEGRAL* sources is shown in the first column of Table 1.

All objects were observed spectroscopically between March 21 and April 6, 2006, with the 1.5-metre CTIO telescope of Cerro Tololo (Chile) equipped with the R-C spectrograph. Spectra were extracted and analyzed using IRAF[2]. Wavelength calibration was performed using He-Ar lamps acquired soon after each spectroscopic exposure; the spectra were then flux-calibrated using the spectrophotometric standards LTT 3218 and LTT 7379 [9]. Finally, and when applicable, different spectra of the same object were stacked together to increase the S/N ratio.

3. RESULTS

Optical spectroscopy allowed us to find that our sample of 21 unidentified objects is composed of 12 AGNs, 5 CVs and 4 HMXBs. The classification for each object is reported in Table 1.

3.1. AGNs

It is found that 12 objects of our sample show optical spectra which are dominated by redshifted broad and/or narrow emission lines typical of AGNs. For their classification, we used the criteria of Veilleux & Osterbrock [29] and the line ratio diagnostics of Ho et al. [10]; moreover, for the subclass assignation of Seyfert 1 nuclei, we used the H_β/[OIII]λ5007 line flux ratio criterion as in [34].

In detail, we found that, of the 12 AGNs of the sample, 6 of them are classified as Seyfert 2 galaxies, and the other 6 are Seyfert 1 galaxies. Of these latter objects, 2 are classified as Seyfert 1.2, one as Seyfert 1.9 and two as Narrow-Line (NL) Seyfert 1; for the case of IGR J17488−3253 only a general Seyfert 1 classification can be given due to the lower quality of the spectrum.

Their redshifts range between 0.016 and 0.076, indicating that with *INTEGRAL* we are sampling the hard X–ray emission from new AGNs in the nearby Universe. Assuming a cosmology with H_0 = 65 km s^{-1} Mpc^{-1}, Ω_Λ = 0.7 and $\Omega_{\rm m}$ = 0.3, these redshifts correspond to distances between 74.7 and 370.6 Mpc. This in turn implies that their hard X–ray luminosities detected with *INTEGRAL* are between $\sim 1\times10^{43}$ and $\sim 3\times10^{44}$ erg s^{-1}.

3.2. CVs

Five objects of our sample were identified as CVs through the appearance of their optical spectra, which show Balmer emissions up to at least H_δ, as well as several He I and He II lines in emission. All of the detected lines are consistent with being at z = 0, indicating that these objects belong to our Galaxy.

The facts that, in the spectra of all these 5 objects, the Balmer decrement clearly appears negative, the HeIIλ4686/H_β Equivalent Width (EW) ratio is $\gtrsim$ 0.5 and the EWs of He II and H_β are around (or larger than) 10 Å indicate that these sources are magnetic CVs belonging to the Intermediate Polar (IP) subclass (see [33]).

Assuming for the CVs an absolute magnitude $M_V \sim 9$ and an intrinsic color index $(V-R)_0 \sim 0$ mag [33], from their USNO-A2.0[3] optical magnitudes we determined their distances to be in the range 110–220 pc; this implies hard X–ray fluxes observed with *INTEGRAL* in the $(0.4–1.4)\times10^{32}$ erg s^{-1}.

3.3. HMXBs

Finally, we identify the remaining 4 *INTEGRAL* sources of our sample as HMXBs by their overall spectral appearance, which is typical of this class of objects (see e.g. [15]), with narrow H_α emission at a wavelength consistent with that of the laboratory frame, superimposed on an intrinsically blue continuum with Balmer absorptions.

In three cases, however, the stellar continuum appears strongly reddened and almost undetected blueward of 5000 Å, implying the presence of substantial interstellar dust along the line of sight. This also is quite typical of HMXBs detected with *INTEGRAL* (e.g., 2RXP J130159.6−635806 [15]) and indicates that these objects are relatively far from Earth.

In the remaining case (IGR J05007−7047) we detect the H_α line in emission, and the rest of the Balmer series (up to H_ζ) in absorption, all redshifted of ∼6 Å with respect to the corresponding laboratory wavelengths. This is consistent with the redshift of the Large Magellanic Cloud (LMC; see [3]). This information implies for this source an X–ray luminosity of 3.6×10^{36} erg s^{-1} in the 17–60 keV band as seen by *INTEGRAL*.

[1] http://archive.eso.org/dss/dss

[2] http://iraf.noao.edu/

[3] http://archive.eso.org/skycat/servers/usnoa/

Table 1. List of unidentified INTEGRAL sources observed at the 1.5m CTIO telescope on March-April 2006, along with the spectroscopic optical classification derived from these observations.

Object	Classification
IGR J05007−7047	HMXB in LMC
IGR J07565−4139	Sy2 AGN
IGR J07597−3842	Sy1.2 AGN
IGR J10101−5654	HMXB
IGR J12026−5349	Sy2 AGN
XSS J12270−4859	IP CV
IGR J14175−4641	Sy2 AGN
IGR J14471−6319	Sy2 AGN
IGR J14515−5542	Sy2 AGN
IGR J14536−5522	IP CV
IGR J14552−5133	NL Sy1 AGN
IGR J15094−6649	IP CV
IGR J16167−4957	IP CV
IGR J16185−5928	NL Sy1 AGN
IGR J16207−5129	HMXB
IGR J16558−5203	Sy1.2 AGN
IGR J17195−4100	IP CV
IGR J17200−3116	HMXB
IGR J17488−3253	Sy1 AGN
IGR J17513−2011	Sy1.9 AGN
IGR J18244−5622	Sy2 AGN

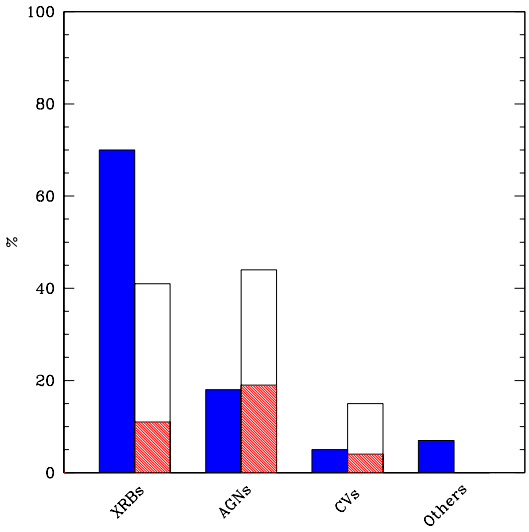

Figure 1. Histogram, subdivided into source types, showing the percentage of INTEGRAL objects of known nature and belonging to the 2nd IBIS Galactic Plane Survey ([2]; left-side, darker columns), and INTEGRAL sources from various surveys and identified through optical spectroscopy (right-side, lighter columns). The latter columns also show (as shaded areas) the percentage of sources identified thanks to optical spectroscopy and which belong to 2nd IBIS Galactic Plane Survey.

Likewise, from the available multiwavelength information on IGR J16207−5129 [27], we could determine a distance of ∼4.6 kpc and a 20–100 keV *INTEGRAL* X–ray luminosity of $\sim 1 \times 10^{35}$ erg s^{-1}.

Unfortunately, due to the lack of reliable optical photometry for the optical counterparts of IGR J10101−5654 and IGR J17200−3116, no significant information concerning distance, spectral type and X–ray luminosity can be determined for these two objects.

4. STATISTICAL CONSIDERATIONS

We can now briefly recover the statistical approach made in Masetti et al. [14], updating the numbers presented there with recent discoveries [8, 15, 16, 17, 19, 20, 21] and with the sample of sources illustrated in the present work. It is now found that, presently, of the 54 *INTEGRAL* sources identified through optical spectroscopy, 22 (41%) are X–ray binaries (with a large majority, i.e. more than 90%, of HMXB), 24 (44%) are AGNs (half of which were presented in this paper for the first time) and 8 (15%) are CVs (5 of which were shown in Masetti et al. [17] for the first time), with at least 6 of them belonging to the IP subclass (see [16, 17]).

One can compare, for instance, these numbers with those for the group of the 153 identified objects belonging to the largest catalogue of *INTEGRAL* sources published up to now, i.e., the 2nd IBIS Galactic Plane Survey [2]. In this survey we have 107 (70%) X–ray binaries (of which, only one third are HMXBs), 27 (18%) AGNs and 8 (5%) CVs, with at least 6 of them of magnetic nature (IPs or Polars).

From these numbers, graphically reported in percentage terms in the histogram in Fig. 1, one can immediately see that the CV sample detected with *INTEGRAL* has been doubled thanks to the optical spectroscopy identification approach. This also stresses *INTEGRAL*'s sensitivity in detecting hard X–ray emission from this class of objects. One of the reasons for this may be found in the fact that the bulk of the X–ray emission from magnetic CVs falls in the 20–40 keV band (e.g., [1, 4]), which is the one in which *INTEGRAL* has the strongest sensitivity.

The number of *INTEGRAL*-detected AGNs also has nearly doubled thanks to these optical studies; besides, it is apparent that an important fraction of the *INTEGRAL* sources identified by means of optical spectroscopy and lying on the Galactic Plane is composed of background AGNs. This once again underscores the extraordinary capabilities of *INTEGRAL* of piercing through the Zone of Avoidance of the Galaxy for the exploration of this part of the extragalactic sky.

As a final corollary, we would like here to stress the extreme effectiveness of the strategy of catalogues cross-correlation plus optical spectroscopy we are pursuing to securely pinpoint the actual nature of the X–ray sources detected with *INTEGRAL*: for instance, of the 56 unidentified objects belonging to the 2nd IBIS Galactic Plane Survey [2], this observational approach led to the discov-

ery of the nature of 18 sources (10 AGNs, 6 HMXBs and 2 CVs), i.e., nearly one third of the total, 15 of which being reported in Masetti et al. [14, 15, 16, 17]. The corresponding source type percentages are represented as shaded areas in Fig. 1.

The lack of known accurate (up to $\sim 10''$) soft X–ray position is the main cause of failure in this identification task; therefore, observations with high-resolution imaging X–ray satellites (such as *Chandra*, *XMM-Newton* and/or *Swift*) are of paramount importance for the continuation of this program aimed at identifying the nature of unknown *INTEGRAL* hard X–ray sources.

5. CONCLUSIONS

In our continuing work of identification of *INTEGRAL* sources by means of optical spectroscopy [13, 14, 15, 16], we have identified and studied 21 southern hard X–ray objects of unknown nature by means of the 1.5m CTIO telescope of Cerro Tololo (Chile).

We found that the selected sample is made of 12 AGNs (6 of which are of Seyfert 1 type and 6 are Seyfert 2 AGNs), 5 magnetic CVs and 4 HMXBs (one of which in the LMC). In terms of relative sizes of the three groups, we notice the absolute majority of AGNs in the sample, and a comparatively large fraction ($\sim$25%) of CVs.

We recall that in three cases (IGR J14175$-$4641, IGR J14452$-$5133 and IGR J18244$-$5622), all identified as AGNs, only a tentative albeit likely optical counterpart was given because of the the lack of an univocal arcsecond-sized soft X–ray position. Thus, for them an observation with soft X–ray satellites affording arcsecond localizations (such as *Chandra*, *XMM-Newton* or *Swift*) is needed to confirm the proposed association.

The results presented in this work further indicate the capabilities of *INTEGRAL* to reveal not only high- and low-mass X-ray binaries, but also (if not mostly) extragalactic objects in the nearby Universe ($z < 0.1$) and magnetic dwarf novae.

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