High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Spectroscopic identication of INTEGRAL high-energy sources with VLT/ISAAC†

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Abstract. *INTEGRAL* has been observing the γ-ray sky for 15 years and has discovered many high-energy sources of various nature. Among them, active galactic nuclei (AGN), low or high-mass X-ray binaries (LMXB and HMXB) and cataclysmic variables (CV) are rather difficult to differentiate from one another at high energies and require further optical or near-infrared observations to constrain their exact nature. Using near-infrared photometric and spectroscopic data from ESO VLT/ISAAC, we aim to reveal the nature of 14 high-energy INTEGRAL sources and improve the census of X-ray binaries. By comparing their spectral features to stellar spectra atlases, we identified 5 new CVs, 2 low or intermediate mass X-ray binaries, 2 HMXBs and 5 AGNs.

Keywords. infrared: stars, X-rays: binaries, binaries: general

1. Introduction

The *INTEGRAL* satellite has been looking at the high-energy sky between 15 keV and 10 MeV for 15 years. The nature of the high-energy sources is often ambiguous and further observations in optical and near-infrared (nIR) are required to constrain it. This is why a significant fraction ($\sim$20%) of the *INTEGRAL* sources (IGR) need lower energy followups. According to the catalogue of *INTEGRAL* sources (Bird *et al.* 2016), we expect that a majority of the unknown IGR sources are accreting binaries or active galactic nuclei (AGN); the former are binary stars in which one component is an accreting compact object.

We distinguish three main categories of accreting binaries depending on the compact object and the mass of the companion star: cataclysmic variables (CV), low-mass X-ray binaries (LMXB), and high-mass X-ray binaries (HMXB). LMXBs host either a neutron star (NS) or a black hole (BH); CVs host a white dwarf. Both have a low-mass companion star ($M \leqslant 1\,M_\odot$). Roche lobe overflow allows the accretion of matter from the companion star and releases high-energy photons. Compact objects can be surrounded by an accretion disc, which may lead to transient behaviours. Intermediate-mass X-ray binaries (IMXBs) are less common, and have a companion of mass between 1 and $10\,M_\odot$.

† Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 089.D-0181(A).

The accretion mechanisms are similar to that of LMXBs. For the sake of consistency with the literature and especially Bird *et al.* (2016), we group IMXBs and LMXBs in the same class of binaries.

High-mass X-ray binaries host a massive star ($M \geqslant 10\,M_\odot$) with a NS or a BH as primary component. Among HMXBs are two sub-categories, based on the evolutionary state of the companion star. In Be binaries (BeHMXB), the secondary is a fast-rotating main-sequence O/B star that loses matter as a consequence of high centrifugal force, forming a decretion disc around itself. Accretion occurs when the compact object crosses through the decretion disc. Supergiant binaries (sgHMXB) host an evolved O/B supergiant star with an intense stellar wind driven by its luminosity. The compact object thus feeds off that wind. *INTEGRAL* made it possible to differentiate two new subclasses of sgHMXBs thanks to its increased sensitivity at high energies, as reviewed in Chaty (2013). Obscured HMXBs have intrinsic absorption ($N_H > 10^{23}\,\mathrm{cm}^{-2}$), while supergiant fast X-ray transients (SFXTs) have short bursts of high-energy radiation with low quiescent states.

To accurately identify high-energy sources, further observations are required, for which nIR is well adapted. Firstly, many *INTEGRAL* sources (IGR) are located near the Galactic plane, where optical photons are absorbed by dust while infrareds are not. Secondly, most of the nIR emission of a binary comes from the companion star or the accretion disc, which is ideal to pinpoint their nature by deriving their spectral type.

We worked on a sample of 14 IGR sources for which nIR photometry and/or spectroscopy was performed. We aim to confirm unambiguous nIR counterparts for each of these IGR sources and provide constraints on their nature, such as the spectral type of companion stars in X-ray binaries.

2. Observations

The observations were carried out in 2012 (P. I. S. Chaty) on 14 *INTEGRAL* sources (programme ID 089.D-0181). Near-infrared photometry and spectroscopy were performed at ESO in Chile on the 8 m Very Large Telescope Unit 3 Nasmyth A (VLT/UT3) using the near-infrared spectro-imager ISAAC.

2.1. *Photometry - Finding nIR counterparts*

2.1.1. Data reduction

Near-infrared images were taken with a K_s filter ($1.98 - 2.35\,\mu$m) with a $2'5 \times 2'5$ field of view. For each source, five frames were taken with a random spatial offset following the jitter procedure standardly used in nIR ESO acquisitions.

We performed the data reduction with standard Image Reduction and Analysis Facility (IRAF†) routines. After subtracting dark and correcting the flat-field, the sky background was subtracted through the median of five jittered images for each source. Images were then aligned based on precise astrometry and averaged.

We performed aperture photometry with the *IRAF.apphot.qphot* tool to derive the apparent K_s magnitudes. The radii of the integration circle and background annulus were chosen to minimize sky background and pollution from nearby bright stars. We used eight photometric standard stars to derive the average zero-point of photometry ($Z_p = 0.972 \pm 0.056$). Extinction was corrected by using the value‡ given by ESO for Paranal: $\kappa_{K_s} = 0.07\,\mathrm{mag\,airmass}^{-1}$.

† IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

‡ http://www.eso.org/sci/facilities/paranal/decommissioned/isaac/tools/imaging_standards.html#Extinction

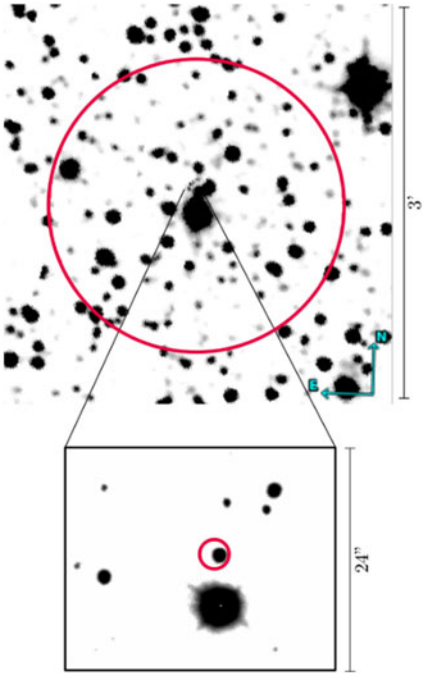

Figure 1. K-band field of view of IGR J13020-6359 from 2MASS (Skrutskie *et al.* 2006) along with the *INTEGRAL* error circle in red. The insert is the ISAAC K_s field of view around the Swift position (Rodriguez *et al.* 2009).

2.1.2. Finding nIR counterparts of IGR sources

Finding nIR counterparts to high-energy detections requires good astrometry. We refined the astrometric solution of ISAAC images using GAIA (Graphical Astronomic Image Analysis) by matching the positions of the stars in each field of view with 2MASS sources from the 2MASS Point Source Catalogue (PSC) and/or Gaia DR1.

The IBIS instrument on board *INTEGRAL* has a wide field of view, but does not have enough spatial resolution to associate accurately an optical/nIR counterpart to the high-energy detections. Precise X-ray localization is thus given by either *Chandra*, *XMM-Newton,* or *Swift* telescopes. We used available positions from these facilities in the litterature to associate an unambiguous nIR counterpart to the *INTEGRAL* sources (see example in Fig. 1).

2.2. *Spectroscopy*

2.2.1. Data reduction

Spectroscopy was performed with ISAAC with a long slit in short wavelength spectroscopy low resolution mode (SWS-LR). The 0.6" slit allowed us to obtain a spectral resolution of $R = 750$ in the K band (1.8–2.5 μm). We measured the width of narrow OH lines from sky emission to be 26±1 Å at 22 000 Å, which is compatible with the theoretical instrumental resolution of $R = 750$. For each source, eight spectral frames were taken. A slight spatial offset ($\sim$30") along the slit was added between each spectral acquisition, following the standard ESO nodding procedure.

We performed data reduction with standard IRAF tools. Each spectrum was corrected by dark and flat frames, and the overall sky value was estimated with the median of the

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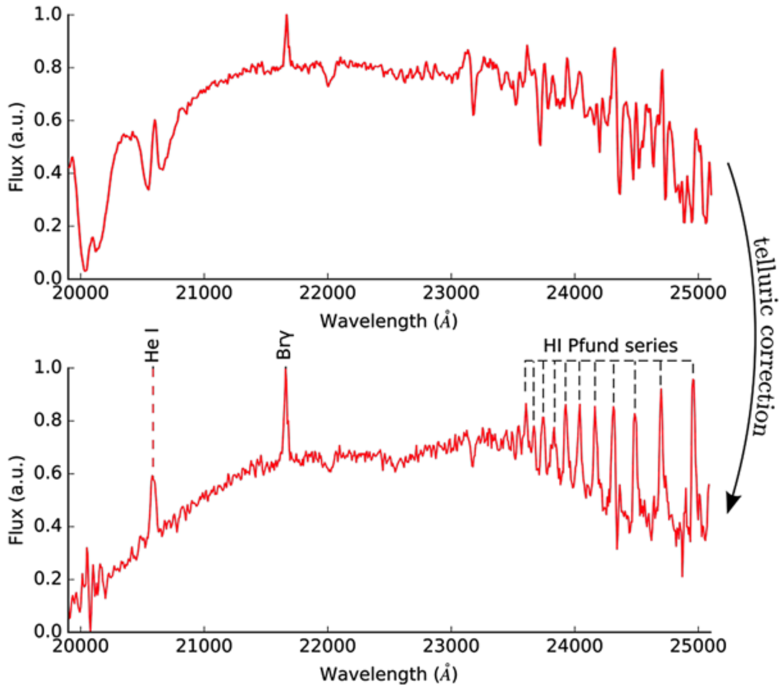

Figure 2. IGR J13020-6359 K-band ISAAC spectrum before (*top*) and after (*bottom*) telluric correction. Molecfit allows us to exploit deeply absorbed parts of the spectrum, revealing in this case HI Pfund emission lines, a feature that is distinctive of early-type stars.

eight spectra. We extracted 1D spectra via *IRAF.apall* package. The extracted spectra were stacked using a median to remove cosmic rays.

Telluric absorption was corrected on each reduced spectrum using *Molecfit* (Kausch *et al.* 2015, Smette *et al.* 2015). This software fits atmospheric features based on meteorological conditions on the date acquisitions were performed. This method was used instead of the classical telluric standard star correction, since it might have introduced artifacts because of the difference in spectral types between the target and the standard star.

The wavelength solution was derived using the argon and xenon lamp spectra provided by the standard calibration procedure in ESO for ISAAC. We derived a solution with a RMS of 0.15Å, and then derived individual wavelength zero-point correction for each source using eight OH lines from the sky spectra.

2.2.2. Deriving spectral types

We compared the features in the spectrum of our 14 IGR sources to spectral atlases (Kleinmann & Hall 1986, Hanson *et al.* 1996, 2005, Ramirez *et al.* 1997, Lenorzer *et al.* 2002, Harrison *et al.* 2004) to derive their spectral type (see example Fig. 2).

3. Results

Among our 14 sources, we identified 5 AGNs, 5 CVs, 2 I/LMXBs and 2 HMXBs (see Tab. 1). All but one are situated within the Galactic plane. Two AGNs (IGR J18457+0244 and IGR J18532+0416) were identified through imaging (extended sources) since their spectrum did not show any feature, which could be associated to synchrotron emission from flaring AGNs. Two CVs (IGR J12489-6243 and IGR J174004-3655) lack the typical

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Table 1. Summary of the identifications derived in this study with VLT/ISAAC nIR data.

RAJ2000 (nIR)	DEJ2000 (nIR)	Unc. (")	Previous identification (comment)	Our identification (spectral type / comment)
IGR J00465	**−4005**			
00:46:20.681	−40:05:49.26	0.060	AGN Sey 2 (z=0.201)	AGN (Sey 2, z=0.202±0.002)
IGR J10447	**−6027**			
10:44:51.925	−60:25:11.78	0.080	?	AGN (Sey 2, z=0.047±0.001)
IGR J12489	**−6243**			
12:48:46.422	−62:37:42.53	0.053	CV / HMXB ?	CV (K/M companion)
IGR J13020	**−6359**			
13:01:58.723	−63:58:08.88	0.164	HMXB (NS)	BeHMXB (B0–6Ve companion)
IGR J13186	**−6257**			
13:18:25.041	−62:58:15.66	0.072	HMXB ?	BeHMXB (B0–6Ve companion)
IGR J15293	**−5609**			
15:29:29.394	−56:12:13.42	0.136	CV (K-type giant ?)	CV (K5V–III companion)
IGR J17200	**−3116**			
17:20:05.920	−31:16:59.62	0.056	HMXB	Symbiotic CV (KIII companion)
IGR J17404	**−3655**			
17:40:26.862	−36:55:37.39	0.125	HMXB (NS) ?	CV (K3–5V companion)
IGR J17586	**−2129**			
17:58:34.558	−21:23:21.55	0.092	HMXB ?	Symbiotic CV (KIII companion)
IGR J17597	**−2201**			
17:59:45.518	−22:01:39.48	0.110	LMXB (NS) ?	LMXB (G8–K0III companion)
IGR J18457	**+0244**			
18:45:40.388	+02:42:08.88	0.043	Pulsar / AGN ?	AGN
IGR J18532	**+0416**			
18:53:16.028	+04:17:48.24	0.037	HMXB / AGN ?	AGN ($z = 0.051$)
IGR J19308	**+0530**			
19:30:50.756	+05:30:58.12	0.252	IMXB (F4V companion)	IMXB (F8-G0V-III companion)
IGR J19378	**−0617**			
19:37:33.029	−06:13:04.76	0.204	Sey1.5 (z=0.011)	AGN (Sey1.5, z=0.011±0.001)

CO bandheads that usually are the signature of cooler stellar atmospheres from the companion star. This may be due to the dominant emission from an accretion disc, or to the possibility of the secondary to have depleted part of its atmosphere were CO banheads arise.

4. Conclusion

The photometric and spectroscopic data allowed us to find unambiguous nIR counterparts to the high-energy detections and identify or better constrain the nature of these sources. Among them, we find 5 AGNs, 5 CVs, 2 BeHMXBs, and 2 I/LMXBs. Even though the proportions between the different types of sources are not in full agreement with those published in Bird *et al.* (2016), we still expect that the remaining unidentified *INTEGRAL* sources are mainly AGNs, X-ray binaries, and CVs. The current census of binaries would benefit from having more candidates with a well-constrained nature, hence the need to identify the rest of the IGR sources. This will help population studies and answer general questions on binary evolution in the context of gravitational wave astronomy and compact mergers.

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