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Optical and Infrared characterisation of High Mass X-ray Binaries discovered by *INTEGRAL*

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Over the last few years, *INTEGRAL* has discovered many high mass X-ray binaries. A significant fraction of those shows properties differing from previously known systems, increasing the areas of the parameter space filled by high mass X-ray binaries. In order to understand the physical properties of these systems and the evolutionary paths that lead to their formation, we need a good characterisation of their mass donors and accurate distances. We discuss some of the problems encountered when trying to achieve these ends and the procedures used to overcome them. We also present results on a number of sources.

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1. Introduction

High Mass X-ray Binaries (HMXBs) are interacting binaries where copious X-ray emission is produced by accretion of material from a donor OB star on to a compact object (neutron star or black hole). They are considered targets of prime astrophysical interest, because they can be used as laboratories to study issues as diverse as the equation of state of neutron stars, the structure of radiation-driven winds or the formation of binary black holes, expected to be strong sources of gravitational waves.

A particularly interesting subset of HMXBs contains OB supergiants. In these systems, the neutron star or black hole accretes from the dense radiation-driven wind of the supergiant, resulting in a persistent moderately bright X-ray source ($L_X \sim 10^{36}\,\mathrm{erg\,s^{-1}}$). The ~ 12 systems known before 2005 have been the subject of considerable study (e.g., Kaper & van der Meer, 2007, and references therein). The other major class of HMXBs contains Be stars close to the main sequence (Negueruela, 2007).

Since 2004, and thanks to its high sensitivity to hard X-ray sources, the ESA *INTEGRAL* space observatory has discovered a large number of previously unknown X-ray sources, characterised by very high absorption, which renders them almost invisible in the softer X-ray bands (e.g., Bodaghee et al., 2007). Most of these sources show X-ray characteristics typical of HMXBs (Lutovinov et al., 2005; Walter et al., 2006), and indeed many of them have been identified with stars which are likely to be OB supergiants (e.g., Chaty et al., 2008).

Because of the high obscuration, the counterparts are difficult to study. Most of them are not accessible in the classification region even for 10-m class telescopes. Their characterisation therefore represents a challenge, and different approaches have been taken to address it.

2. What do we need to know?

The characterisation of the counterparts to HMXBs is a fundamental part of the study of these sources. But, given the difficulties inherent to observing highly obscured sources, we may want to ask ourselves how well we really need to study them. For a start, characterisation of the primary is a first fundamental step towards understanding of a HMXB. Unlike in LMXBs, the properties of HMXBs are strongly dependent on the class of mass donor, because different donors imply different mass transfer mechanisms. Simply knowing if the counterpart is a Be star or a supergiant is already providing us valuable information.

However, if we want to understand the properties of the new sources discovered by *INTEGRAL*, we need a deeper study. Based on fits to the X-ray spectra, some authors argued that the high obscuration observed must be intrinsic to the sources and that the counterparts must be undergoing extremely heavy mass loss (e.g., Dean et al., 2005). Other evidence, however, suggests that these systems are similar to the non-obscured supergiant X-ray binaries, but lie behind large obscuring clouds (e.g., Kuulkers, 2005). Optical spectroscopy of the few systems that are bright enough to be observed in the blue reveals typical OB supergiants (Negueruela et al., 2006b; Pellizza et al., 2006), strongly supporting the second option. Moreover, infrared spectro-photometry reveals that most obscured *INTEGRAL* sources show spectral energy distributions compatible with purely

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interstellar reddenings (Chaty et al., 2008). Multiwavelength observations have been the only way to solve this issue.

In addition, we need pretty accurate distances to these sources. The discovery of new properties in sources with supergiant counterparts, like the fast-outburst behaviour (Negueruela et al., 2006a; Smith et al., 2006; Walter & Zurita Heras , 2007) has led to the development of many new models that try to explain the transient behaviour of some sources, while allowing others to be persistent. Several groups have given strong emphasis to the clumpy nature of OB supergiant winds (Walter & Zurita Heras , 2007; Negueruela et al., 2008a), but other authors have proposed alternative models, based on the existence of putative disks around the OB supergiants (Sidoli et al., 2007) or the presence of a magnetic gating mechanism (Grebenev & Sunyaev, 2007; Bozzo et al., 2008). Indeed, more than one of these mechanisms may be necessary to explain the complex behaviour of the increasing variety of sources.

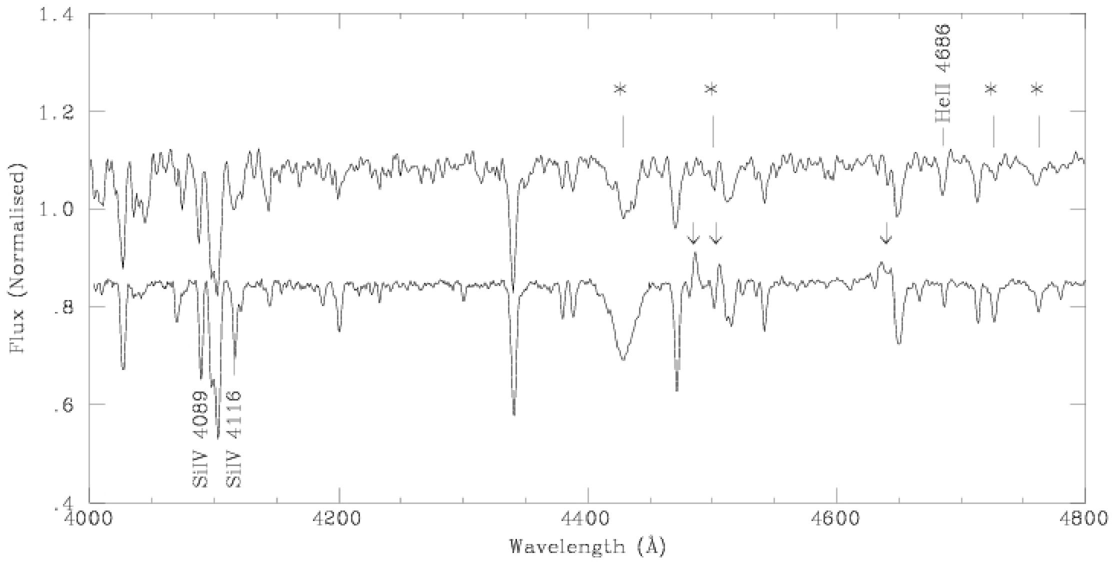

Figure 1: Classification spectra of the counterparts to IGR J17544−2619 (O9 Ib, top) and AX J1845.0−0433 (O9 Ia, bottom). These two objects have the same spectral type, but very different luminosities. The main luminosity criteria are the strength of the Si IV lines compared to neighbouring He I and the in-filling of He II 4686Å. This in-filling is caused by the extended atmosphere. Other wind features, due to N III and S IV, are indicated by arrows on the spectrum of AX J1845.0−0433. Interstellar features are marked with a '*'.

As the differences between models may be subtle with respect to the expected properties, the observed X-ray luminosity and its dependence on other parameters may turn out to be the fundamental discriminant. If we want accurate X-ray luminosities, we have to make sure that uncertainties in the distances are decidedly better than a factor of two.

In principle, when the sources are visible in the optical range, it is relatively straightforward to classify them. Unfortunately, as the counterparts are generally faint, in many cases only low resolution spectra exist. Low-resolution spectroscopy allows, in most cases, only an estimate of the luminosity class of the mass donor and perhaps an educated guess at its distance. This approach is necessary when a survey of many sources is conducted to allow broad classification. A good example is the successful recent series by Masetti et al. (2008, and references therein). However, low-resolution spectroscopy is not enough to obtain accurate distances. As an example, Fig. 1 shows intermediate-resolution spectra of two supergiants of the same spectral type, but different luminosity class. As seen, the spectral differences are subtle. However, they imply a difference in luminosity of order $\gtrsim 5$.

Simply to give an idea of the sort of uncertainties faced, let us consider the situation in which we cannot go any further than saying that the counterpart is, as widely used, a "typical B1 supergiant". If we look at the M_V calibration of Humphreys & McElroy (1984), we will find that a B1 Ib star has typically $M_V = -5.8$ and a B1 Ia star has $M_V = -7.0$. The intrinsic dispersion of the calibration is estimated at ± 0.5 and so a "typical B1 supergiant" may have M_V anywhere between -5.5 and -7.3. Assuming a B1 Iab star at a nominal distance of 7 kpc ($DM = 14.2$) the error bar in its distance would go from 4.4 kpc to 10 kpc *only* from not knowing the exact luminosity class.

3. The extinction law

However, the lack of accuracy in the spectral and luminosity class may not be the main cause of uncertainty in the determination of distance. If the sources are affected by high obscuration, the amount of extinction in our line of sight is difficult to know. The usual approach is simply assuming a "standard" law, where $A_V = 3.1E(B-V)$. The extinction A_V can then be determined from the colour excess, which we can calculate if we know the spectral type. Unfortunately, this "standard" law is simply an approximation to an average law. Extinction laws are very variable (Fitzpatrick & Massa, 2007) and polynomial representations, such as that of Cardelli et al. (1989) are only approximations.

When the sources are only moderately absorbed, the extinction law is generally problematic in the UV range. However, many *INTEGRAL* sources have very high optical extinction and variability in the extinction law becomes an issue, as distance determination depend *very* strongly on A_V. An interesting attempt at solving this problem is fitting the whole spectral energy distribution, as in (Rahoui et al., 2008). Unfortunately, introducing the possibility of several spectral components (such as, for example, a global infrared excess), results in far too many free parameters to allow a well-constrained fit. Further information (such as a spectral type) is required to reduce the number of free parameters.

Our preferred approach when broadband coverage is possible is determining the spectral type from intermediate-resolution blue spectra and then using the χ^2 code for parametrised modelling and characterisation of photometry and spectroscopy CHORIZOS implemented by Maíz-Apellániz (2004). This code generates synthetic photometry from a stellar model (chosen to provide the best fit to the observed spectral type) and convolves it with extinction laws from Cardelli et al. (1989). A fit to the real photometric data determines the values of R and $E(B-V)$ that would most likely result in the observed photometry for a star with the given spectrum. This procedure also has its complications. At high values of extinction, the polynomial fits of Cardelli et al. (1989) stop being good approximations to the extinction law (Maíz-Apellániz et al., 2007). However, the fits still produce a good estimate of the slope of the extinction law in the optical (R).

Following this method, we have been able to obtain rather accurate parameters for several *INTEGRAL* sources. We used optical spectroscopy performed with the VLT + FORS1/2 (ESO pro-

Table 1: Observed magnitudes and derived parameters for counterparts to SFXTs.

Object	Spectral Type	$T_{\rm eff}$ (K)	V	$K_{\rm S}$	$E(B-V)$	M_V^a	d (kpc)
IGR J17544−2619	O9 Ib	31 500	12.78	7.99	2.1	−6.0	3
SAX J1818.6−1703	∼B0 I	27 500	20.58	7.85	4.9	−6.3	∼ 2
AX J1841.0−0535	B0.2 Ibp	27 500^b	14.29	8.93	2.3^b	−5.7	∼ 4^b
AX J1845.0−0433	O9 Ia	31 000	14.14	8.93	2.5	−6.9	7
IGR J08408−4503	O8.5 Ib	32 000	7.57	6.81	0.5	−6.0	2.4
XTE J1739−302	O8 Iab	32 500	14.89	7.43	3.4	−6.3	2.3

$^{(a)}$ Absolute magnitude derived from the spectral type and used to calculate the distance.

$^{(b)}$ Under the assumption that the counterpart is a normal B0.2 Ib supergiant.

gramme 077.D-0055) in service mode (April & May 2006). We also used photometry obtained with the 2.6-m NOT telescope (La Palma) + ALFOSC (June 18th 2006) and the 1.3-m Skinakas telescope (at several dates). Additional spectra were taken from the NOT (several dates), Skinakas (several dates) and 1.9-m SAAO (May 4th-8th 2006). We also used IR photometry and spectroscopy from the 3.5-m TNG (La Palma) + NICS (July 7th 2006, May 1st 2007) or taken from 2MASS. The values obtained are displayed in Table 1.

One final issue to take into account when determining the extinction to a source is the use of interstellar lines as a measure of extinction. As is well known, the strength of many interstellar lines (atomic or molecular) and of diffuse bands is well correlated to reddening, measured, for example, as $E(B-V)$ (Herbig, 1995). The fact that this correlation saturates for high values is less well known. However, most lines stop increasing their strength at moderate reddening (e.g., Munari & Zwitter, 1997). Even at moderately high reddenings allowing optical spectroscopy, like those seen to sources such as 4U 1907+09 (Cox et al., 2005) or XTE J1739-302 (Negueruela et al., 2006b), all diffuse interstellar lines are in the saturated regime.

4. Infrared spectroscopy

For a sizable sample of *INTEGRAL* sources studies in the optical are simply not feasible. The high extinction puts the B band beyond the reach of spectrographs even on 10-m class telescopes. An obvious approach to the study of such obscured sources is near-infrared spectroscopy. There are several obvious advantages. For a start, extinction in the K band is ~ 10 times smaller than in the V band, meaning that the counterparts are much brighter in K even though they are intrinsically blue stars. Moreover the infrared extinction law is less variable than the optical/UV domain, meaning that much smaller errors are expected if a standard law is assumed (Indebetouw et al., 2005).

Moving to the K band also has its disadvantages, though. K-band spectra of early-type stars are pretty insensitive to temperature and very insensitive to luminosity (Hanson et al., 1996). Intermediate-resolution spectra can, in many cases, provide only very broad classifications, such as "early B supergiant". High resolution spectroscopy can provide better constraints, especially if combined with detailed modelling (Hanson et al., 2005). Unfortunately, obtaining such data requires large telescopes and is very expensive in terms of observing time.

If we want to provide moderately accurate information, we need to extend our wavelength coverage. For O-type stars, H-band spectra of moderately high resolution of are pretty sensitive to temperature (Lenorzer et al., 2004). Our own investigations (e.g. Negueruela et al., 2008b) show that I-band spectra are pretty sensitive to luminosity. In this case, moderate resolution is sufficient, if the signal-to-noise ratio is good. Luminous stars later than B1 can be classified pretty accurately in luminosity class and with some approximation in spectral type. Earlier stars can be classified with some accuracy, especially when complemented by K or H-band spectra . Naturally, an obscured source will be fainter in I than in K, but detectors are more sensitive in I (and also the sky contribution will not dominate our noise).

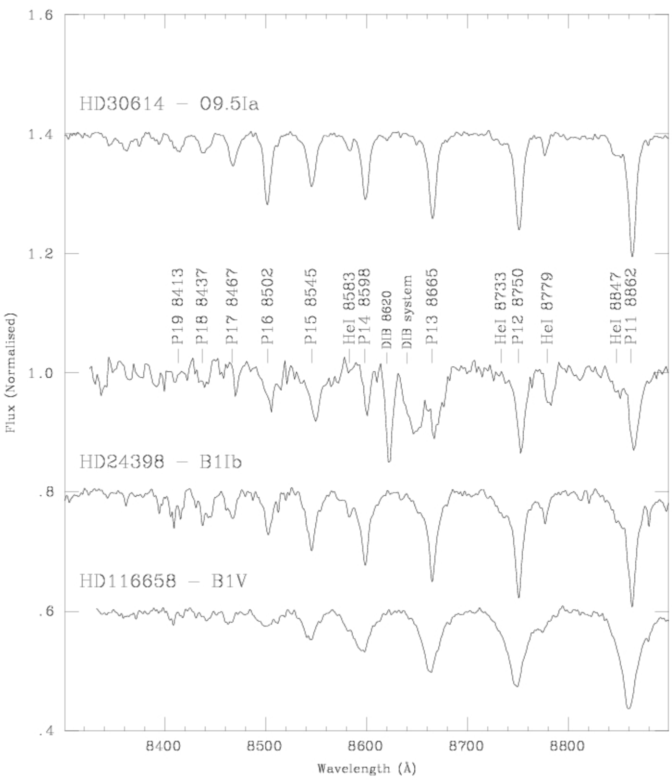

Figure 2: I-band spectrum of the counterpart to IGR J18483−0311 compared to several stars of known spectral type. The C III 8502Å line is very noticeable for stars of spectral type B0 or earlier (see the O9 Ia star). The counterpart to IGR J18483−0311 has spectral type around B1 and is a supergiant of moderate luminosity.

As an example, Fig. 2 shows a spectrum of the pulsar IGR J18483-0311, taken with the 4.2-m WHT (La Palma)+ISIS in May 2008. This *INTEGRAL* source shows X-ray pulsations with $P_{\rm spin} = 21.1$ s and regular outbursts, lasting a few days, every 18.5 d (Sguera et al., 2007). This characteristics were very suggestive of a Be/X-ray system. Even though the spectrum in Fig. 2 is of moderate resolution and has a low signal-to-noise ratio, the object is clearly a supergiant of moderate luminosity. A similar classification has recently been found from H and K-band spectra by Rahoui & Chaty (2008).

5. Conclusions

Multiwavelength observations are essential part of the study of obscured HMXBs. Fundamental information distance, extinction, and hence luminosity) can be obtained if sufficient wavelength coverage, resolution and SNR is achieved. The new sources discovered by INTEGRAL are filling up the parameter space for HMXBs and hence providing us with vital information to understand the physics and evolution of these systems, if we study them with the appropriate tools.

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