A&A 440, 637–646 (2005)
DOI: 10.1051/0004-6361:20052684

Astronomy & Astrophysics

Identification of the optical counterparts of high-mass X-ray binaries through optical photometry and spectroscopy

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Received 12 January 2005 / Accepted 8 May 2005

Abstract. We present the results of our search for optical counterparts to high-mass X-ray transient sources discovered by various X-ray missions. We obtained CCD images of the X-ray fields through BVR and Hα filters to identify early-type stars in the $R-$ Hα versus $B-V$ colour–colour diagram. We also obtained medium-resolution spectroscopy of the candidates in order to confirm the presence of Hα emission and perform spectral classification. We report on the discovery of the optical counterparts to two X-ray sources: XTE J1858+034 and IGR J01363+6610, and the follow-up observations of another two, newly identified by our group: SAX J2103.5+4545 and GRO J2058+42. For another source, IGR J00370+6122, we present the first detailed optical spectral analysis. The optical photometry and spectroscopy reveal B-type companions in all five sources; GRO J2058+42, SAX J2103.5+4545 and IGR J01363+6610 are positively identified with Be/X-ray binaries, IGR J00370+6122 with a supergiant X-ray binary, while the nature of the XTE J1858+034 is uncertain. We also study the relationship between the optical and X-ray emission during quiescent states.

Key words. X-rays: binaries – stars: neutron – stars: binaries: close – stars: emission-line, Be – stars: pulsars: general – X-rays: general

1. Introduction

The interest in X/γ-ray Astronomy has grown enormously in the last decades thanks to the ability to send X-ray space missions above the Earth's atmosphere. There are more than half a million X-ray sources detected and over a hundred missions (past and currently operational) devoted to the study of X/γ rays. With the improved sensibilities of the currently operational missions new detections occur very frequently. Among these, X-ray binaries form an important group because they contain neutron stars and black holes allowing the study of the physics of matter under strong gravity and the physics of accretion.

X-ray binaries consist of a compact object orbiting a companion star. They admit several classification schemes depending upon whether the emphasis is put on their optical or X-ray properties. This work focuses on the high-mass X-ray binaries (HMXB), that is, systems formed by a magnetised neutron star and a OB-type star (see Negueruela 2005, for a recent review). According to the luminosity class of the primary they can further be divided into supergiant X-ray binaries (SXRB) and Be/X-ray binaries (BeX). All but four HMXBs harbour X-ray pulsars. By far the most numerous group (about 70%) is that of BeX (Coe 2000; Ziolkowski 2002; Negueruela 2004).

The generally accepted definition of a Be star is that of a non-supergiant B-type star whose spectrum shows or, has at some time shown, Balmer lines in emission. An infrared excess when compared with non line-emitting B stars of the same spectral type is another observational characteristic of Be stars. The origin of these observational characteristics lies in a quasi-Keplerian circumstellar disk around the equator of the Be star. This disk is fed from material expelled from the rapidly rotating Be star in a manner that it is not yet understood (Porter & Rivinius 2003). Recombination radiation from ionised hydrogen in this hot ($T_{\rm disk}=0.5$–$0.8T_{\rm eff}$) extended envelope produces the Balmer line emission and the infrared excess. Be stars may appear as isolated objects or take part in binaries. While isolated Be stars have been observed to sample all B type subclasses, the spectral type of Be stars in galactic and LMC X-ray binaries is confined to the narrow range O9-B2 (Negueruela 1998). In the SMC, however, the spectral distribution of Be in BeX seems to show a better agreement with those of isolated Be stars (Coe et al. 2005).

In HMXBs, X/γ-rays are produced as the result of accretion of matter onto the neutron star. The way how matter is transferred from the massive star differs in each case. Among HMXBs with evolved companions there are disk-fed and wind-fed systems depending upon whether accreted matter is transferred through an accretion disk (with the mass donor star being close to filling its Roche lobe) or via the stellar wind of the evolved companion. In BeX, the reservoir of matter is provided by the circumstellar disk. Wind-fed SXRBs are persistent long-pulsing (>10^2 s) X-ray sources with luminosities of the order of $10^{35}-10^{36}$ erg s^{-1}. Occasionally they exhibit flaring variability on short time scales (seconds). With only one representative in the Galaxy (Cen X-3) and three in total (SMC X-1 and LMC X-4), disk-fed HMXBs display high X-ray luminosities ($L_X \sim 10^{38}$ erg s^{-1}) and short spin periods (a few seconds). The vast majority of BeX are transient sources showing either regular orbital modulated outbursts with $L_X = 10^{35}-10^{36}$ erg s^{-1}, or giant, unexpected outbursts with $L_X \gtrsim 10^{37}$ erg s^{-1}, or both. Persistent BeX also exist (Reig & Roche 1999). Transient BeX tend to contain fast rotating neutron star, while persistent BeX show pulse periods above ~200 s (Negueruela 2005).

A search in the *SIMBAD* database yields that only about one third of HMXBs in the Milky Way have well-established optical counterparts. One of the largest hindrances to the identification of optical counterparts is the size of the uncertainty in X-ray positions. This can be as small as a few arcseconds for imaging detectors (*ROSAT HRI*, *Chandra ACIS*, *XMM-Newton EPIC*), or as large as a few degrees for all sky monitors (*CGRO BATSE*). In addition, many identifications are based only upon positional coincidence. In regions with a high density of early type stars a danger exists that these identifications may be spurious. Furthermore, given the transient nature of these systems, many times only one detection of the source is available.

An optical identification is necessary to facilitate a complete study of these systems. Without a known counterpart, observations are limited to X-ray energies, and hence our understanding of the structure and dynamics of those systems that remain optically unidentified is incomplete. In this work we provide optical information of five HMXBs and compare the optical and X-ray properties during quiescence.

2. Observations

Unless otherwise stated the red-end spectra and the photometric observations were carried out from the 1.3 m Telescope of the Skinakas Observatory (SKI), located in the island of Crete (Greece). Optical photometry was made using a 1024 × 1024 SITe CCD chip with a 24 μm pixel size (corresponding to 0.5$''$ on sky). Standard stars from the Landolt (1992) and Oja (1996) lists were used for the transformation equations. Reduction of the data was carried out in the standard way using the IRAF tools for aperture photometry. For the optical spectroscopic observations the 1.3 m telescope was equipped with a 2000 × 800 ISA SITe CCD and a 1302 l mm^{-1} grating, giving a nominal dispersion of 1.04 Å/pixel, except for the June 2004 and July 2004 campaigns for which a 1024 × 1024 CH260 chip (1.3 Å/pixel) was employed. The reduction of the spectra was made using the STARLINK *Figaro* package (Shortridge et al. 2001), while their analysis was performed using the STARLINK *Dipso* package (Howarth et al. 1998). For IGR J00370+6122 and IGR J01363+6610 the Skinakas data were complemented with data from the 2.56-m Nordic Optical Telescope (NOT) and the 2.5-m Isaac Newton Telescope (INT). The results of our photometric and spectroscopic observations are summarised in Tables 1 and 2.

3. Methodology

In searching for the optical counterparts of new X-ray transients we have restricted our search to HMXB systems. If the only available information is that provided by an isolated X-ray detection then we select systems exhibiting properties of a magnetised neutron star, namely, X-ray pulsations in the range $1-10^3$ s and/or an absorbed power-law continuum spectrum with an exponential cutoff at 10–30 keV and possible cyclotron absorption features. Extra information on the nature of the source can be obtained if the long-term X-ray variability is known (information provided by all-sky monitors, like RXTE ASM or CGRO BATSE). The presence of regular and periodic outbursts or unexpected giant outbursts may indicate the presence of a Be star.

If the distance to the source is known, one can make use of the narrow spectral range of the optical companion in HMXBs, namely O9-B2, to apply selection criteria based on the photometric magnitudes and colours. But without prior knowledge of the distance, which is normally the case, the most obvious observational feature to look for is the presence of Hα in emission. Note that Hα in emission is not only a property of Be stars but also of many supergiant companions.

The size of the X-ray error circle determines the type of observational technique to use. If the X-ray uncertainty region is small (a few arcseconds) then the number of visible stars in the region is expected to be small and it is possible to perform narrow-slit spectroscopic observations and look for early-type, Hα emitting line stars. If the error radius is large, then it is likely to include a large number of sources and hence narrow-slit spectroscopy becomes impractical. Furthermore, uncertainty regions are given to a certain percentage of probability, what makes it possible that the true optical companion lies close but outside the X-ray error box.

The size of the X-ray error radius of the sources reported in this work at the time of the observations was relatively large, typically ~2$'$. Therefore we proceeded as follows: the fields around the best-fit X-ray position were observed through the *B*, *V*, *R* and *I* filters and a narrow filter centred at 6563 Å (Hα filter). The instrumental magnitudes corresponding to the *B*, *V*, *R* and Hα filters were used to define a "blue" colour ($B-V$) and a "red" colour ($R-$ Hα). Then a colour–colour diagram was constructed by plotting the red colour as a function of the blue colour. Stars with a moderately or large Hα excess can be distinguished from the rest because they deviate from the general trend and occupy the upper left parts of the diagram. Be star are expected to show low ($B-V$) colours because they are early-type stars (although they normally appear redder than non-emitting B stars due to the circumstellar disk) and also larger (i.e., less negative) $R-$ Hα colours because they show Hα in emission. This kind of diagrams have been successfully used to identify optical counterparts in the Magellanic Clouds (Grebel 1997; Stevens et al. 1999).

Table 1. Results of the photometric observations.

Date	MJD	*B*	*V*	*R*	*I*
		XTE J1858+034			
20-05-04	53 146.45	19.63 ± 0.01	18.01 ± 0.01	16.94 ± 0.01	–
27-07-04	53 214.38	19.60 ± 0.02	17.97 ± 0.03	16.92 ± 0.04	15.38 ± 0.04
24-08-04	53 242.41	19.61 ± 0.02	18.00 ± 0.02	16.95 ± 0.01	15.32 ± 0.02
		GRO J2058+42			
07-06-03[a]	52 798.50	16.03 ± 0.03	14.93 ± 0.03	14.23 ± 0.03	–
08-06-03[a]	52 799.50	16.07 ± 0.03	14.94 ± 0.02	14.24 ± 0.02	–
24-08-03[a]	52 876.38	16.03 ± 0.02	14.91 ± 0.03	14.26 ± 0.03	13.50 ± 0.04
05-07-04[a]	53 192.44	16.03 ± 0.02	14.89 ± 0.02	14.16 ± 0.02	13.35 ± 0.02
27-07-04[a]	53 214.51	16.07 ± 0.02	14.92 ± 0.03	14.19 ± 0.03	13.41 ± 0.04
24-08-04[a]	53 243.52	16.05 ± 0.02	14.96 ± 0.02	14.24 ± 0.02	13.46 ± 0.02
14-09-04	53 263.35	16.04 ± 0.02	14.92 ± 0.02	14.22 ± 0.02	13.47 ± 0.02
01-10-04	53 280.30	16.07 ± 0.02	14.96 ± 0.02	14.24 ± 0.02	13.47 ± 0.02
		SAX J2103.5+4545			
08-06-03[b]	52 799.47	15.34 ± 0.02	14.21 ± 0.02	13.48 ± 0.02	–
24-08-03[b]	52 876.41	15.35 ± 0.02	14.25 ± 0.03	13.57 ± 0.03	12.85 ± 0.03
20-05-04	53 146.56	15.40 ± 0.01	14.32 ± 0.01	13.63 ± 0.01	12.87 ± 0.01
05-07-04	53 192.37	15.42 ± 0.02	14.33 ± 0.02	13.64 ± 0.02	12.92 ± 0.02
24-08-04	53 243.48	15.39 ± 0.02	14.31 ± 0.02	13.61 ± 0.01	12.85 ± 0.02
14-09-04	53 263.38	15.39 ± 0.02	14.27 ± 0.02	13.58 ± 0.02	12.84 ± 0.03
01-10-04	53 280.37	15.40 ± 0.02	14.30 ± 0.02	13.61 ± 0.02	12.85 ± 0.02
		IGR J00370+6122			
20-05-04	53 146.57	10.21 ± 0.01	9.65 ± 0.01	9.36 ± 0.01	8.88 ± 0.01
14-09-04	53 263.52	10.24 ± 0.02	9.70 ± 0.02	9.36 ± 0.02	8.91 ± 0.03
		IGR J01363+6610			
27-07-04	53 214.55	14.68 ± 0.02	13.29 ± 0.03	12.32 ± 0.04	11.37 ± 0.04
14-09-04	53 263.44	14.70 ± 0.02	13.33 ± 0.02	12.35 ± 0.02	11.37 ± 0.03
01-10-04	53 280.40	14.62 ± 0.02	13.26 ± 0.02	12.28 ± 0.02	11.31 ± 0.02

[a] From Wilson et al. (2005).
[b] From Reig et al. (2004a).

Good candidates are then those that occupy the upper left parts of the colour-colour diagram *and* lie inside or very close to the X-ray uncertainty region. Under these conditions the colour-colour diagram restricts the possible candidates to a handful of sources (sometimes just one or two), hence making narrow-slit spectroscopy useful. The next step is to obtain Hα spectra of those potential candidates. In order to check for the usefulness of the diagram and secure our method we also obtained spectra of the brightest stars inside the X-ray error circles. With the appropriate instrumental set-up the red-end spectrum can extend beyond 6700 Å, hence the He I line at 6678 Å, if present, can be taken as evidence that the optical counterpart is indeed an early-type object. Nevertheless, a classification spectrum (i.e. around 4000–5000 Å) is desirable to pin down the exact spectral type.

Figure 1 shows the colour-colour diagrams and the optical images corresponding to the visual band of the field around the X-ray positions of XTE J1858+034 and IGR J01363+6610. The optical counterparts have been marked with a filled circle on the colour–colour diagrams and with an arrow on the images. The satellite uncertainty circles at the time when the optical observations were performed are also indicated.

In order to assess the statistical significance of this method we can estimate the expected number of Be/X-ray binaries present in a circular portion of the sky with 2′ radius (i.e., the typical size of the satellite uncertainties). Assuming that there are about 0.005–0.5 Be stars per arcmin^2 in the Galactic Plane and that about 2/9 of the Be stars take part in Be/X-ray binaries (Wilson et al. 2005), we estimate the total number of Be/X-ray binaries inside the typical error circles considered in this work in ~0.01−1. Given that Be/X-ray binaries represent more than 70% of the HMXBs and the uncertainty in the above calculation, we can assume that the range 0.01–1 is also representative of all types of HMXBs.

4. Results and discussion of individual sources

4.1. XTE J1858+034

XTE J1858+034 was discovered by the RXTE satellite in 1998 with an estimated uncertainty (90% confidence) of 6′. The peak flux, 24 mCrab (2–12 keV), was reached on 7 February 1998 (Remillard & Levine 1998). The X-ray position was later refined down to a 90% confidence error radius of 2.′5 (Marshall et al. 1998). X-ray pulsations with a

Table 2. Hα equivalent width measurements.

Date	MJD	EW(Hα) (Å)	Profile
	XTE J1858+034		
23-06-03	53 180.44	–6.3 ± 0.8	single peak
25-06-04	53 182.40	–6.8 ± 0.9	single peak
06-07-04	53 193.38	–8.2 ± 1.5	single peak
07-07-04	53 194.37	–7.3 ± 1.0	single peak
08-07-04	53 195.37	–7.5 ± 1.0	single peak
25-08-04	53 243.27	–5.5 ± 0.5	single peak
	GRO J2058+42		
25-06-04[a]	53 182.44	–4.2 ± 0.6	double peak
06-07-06[a]	53 193.38	–5.0 ± 0.9	double peak
25-08-04[a]	53 243.52	–4.7 ± 0.5	double peak
13-09-04	53 262.49	–4.9 ± 0.5	double peak
03-10-04	53 282.38	–4.6 ± 0.6	double peak
24-10-04	53 303.39	–3.7 ± 0.4	double peak
	SAX J2103.5+4545		
01-08-03[b]	52 853.50	–2.2 ± 0.3	$V > R$
17-08-03[b]	52 869.53	–1.1 ± 0.2	shell
14-09-03[b]	52 897.36	+2.3 ± 0.2	absorption
06-10-03[b]	52 919.33	+2.2 ± 0.3	absorption
08-10-03[b]	52 921.32	+2.0 ± 0.3	absorption
23-05-04	53 149.56	+2.6 ± 0.3	absorption
27-05-04	53 153.57	+2.5 ± 0.3	absorption
28-05-04	53 154.52	+2.4 ± 0.3	absorption
23-06-04	53 180.52	+1.8 ± 0.5	absorption
25-06-04	53 182.47	+2.2 ± 0.3	absorption
07-07-04	53 194.54	+2.7 ± 0.3	absorption
26-08-04	53 244.44	+2.1 ± 0.3	absorption
27-08-04	53 245.44	+1.6 ± 0.5	absorption
12-09-04	53 261.36	+2.1 ± 0.3	absorption
13-09-04	53 262.35	+2.1 ± 0.3	absorption
25-10-04	53 304.35	+2.1 ± 0.5	absorption
	IGR J00370+6122		
21-05-04	53 147.56	+1.1 ± 0.1	absorption
22-05-04	53 148.55	+1.06 ± 0.05	absorption
24-06-04	53 181.54	+1.17 ± 0.05	absorption
07-07-04	53 194.57	+0.81 ± 0.03	absorption
13-09-04	53 262.39	+0.93 ± 0.03	absorption
24-10-04	53 303.49	+0.71 ± 0.02	absorption
	IGR J01363+6610		
06-07-04	53 193.53	52 ± 2	single peak
26-08-04	53 244.56	51 ± 2	single peak
12-09-04	53 261.46	51 ± 2	single peak
13-09-04	53 262.40	53 ± 4	single peak
03-10-04	53 282.47	48 ± 3	single peak
04-10-04	53 283.57	48 ± 2	single peak
24-10-04	53 303.58	49 ± 3	single peak

[a] From Wilson et al. (2005).
[b] From Reig et al. (2004a).

pulse period of 221.0 ± 0.5 s (Takeshima & Corbet 1998) and quasi-periodic oscillations centred at 0.11 Hz (Paul & Rao 1998) were also detected. The pulsations and transient nature of XTE J1858+034 suggested that it is a Be/neutron star binary. Molkov et al. (2004) reported the detection of a new X-ray outburst in April 2004 with INTEGRAL and an improvement of its coordinates. The average flux was ~20 mCrab and ~15 mCrab in the 3–15 keV and 18–60 keV energy bands, respectively. The uncertainty of the INTEGRAL IBIS and JEM-X detectors was 2′ and 1′, respectively.

Optical photometric observations of the field around the best-fit INTEGRAL position were carried out on the nights 20 May 2004, 27 July 2004 and 24 August 2004. Based on positional coincidence several candidates were identified (see Fig. 1). Subsequent spectroscopic observations revealed that only one exhibited Hα emission. The position of the proposed candidate is RA = 18h58m36s, Dec = 03d26m09s, consistent with the ISGRI/IBIS uncertainty, although outside the JEM-X error circle. No photometric or spectroscopic variability has been detected during the three months covered by our observations (Tables 1 and 2). Unfortunately, the weakness of the source in the blue band prevented us from obtaining a good enough S/N spectrum, hence, no spectral classification analysis has been made so far. Although the identification of XTE J1858+034 with a HMXB is apparent we cannot tell the spectra subtype nor the luminosity class. Some spectra seem to show a trough bluewards of the central peak, reminiscent of a P-Cygni profile and possibly indicating a supergiant companion (Fig. 2). The relatively long spin period (221 s) would give further support to the presence of an evolved companion as transient BeX systems tend to have shorter spin periods ($P_{\rm spin} \lesssim 100$ s). However, the strength of the Hα line (~−7 Å) is somehow larger than average values found in SXRBs (≲5 Å). Strong Hα emission and P-Cygni profiles has been reported for the hypergiant system Wray977/2S 1223-624 (Kaper et al. 1995). Blue-end spectra and higher quality red-end spectra are needed to determine the nature of XTE J1858+034.

4.2. GRO J2058+42

GRO J2058+42 was discovered in September 1995 by GRO BATSE during a giant outburst that lasted for 46 days (Wilson et al. 1998). The total flux reached about 300 mCrab in the energy range 20–50 keV. Based on the regularity of a series of smaller (15–20 mCrab) outbursts following the first giant outburst the orbital period was proposed to be 110 days. BATSE also detected shorter and weaker outbursts halfway between the intermediate outbursts, which opened the possibility that the orbital period was 55 days. Recent timing analysis with RXTE ASM data favour the value of 55 days as the correct orbital period (Wilson et al. 2005).

The uncertainty in the location of GRO J2058+42 given by BATSE was initially a 95% confidence box of 4° × 1°, which was improved by OSSE to 30′ × 60′ (95% confidence). The X-ray position was further refined by RXTE PCA to a radius error circle of 4′ (90% confidence). With this uncertainty in the finding charts we performed our optical observations resulting in the discovery of the optical counterpart (Reig et al. 2004b). A recent *Chandra* observation pinned down the

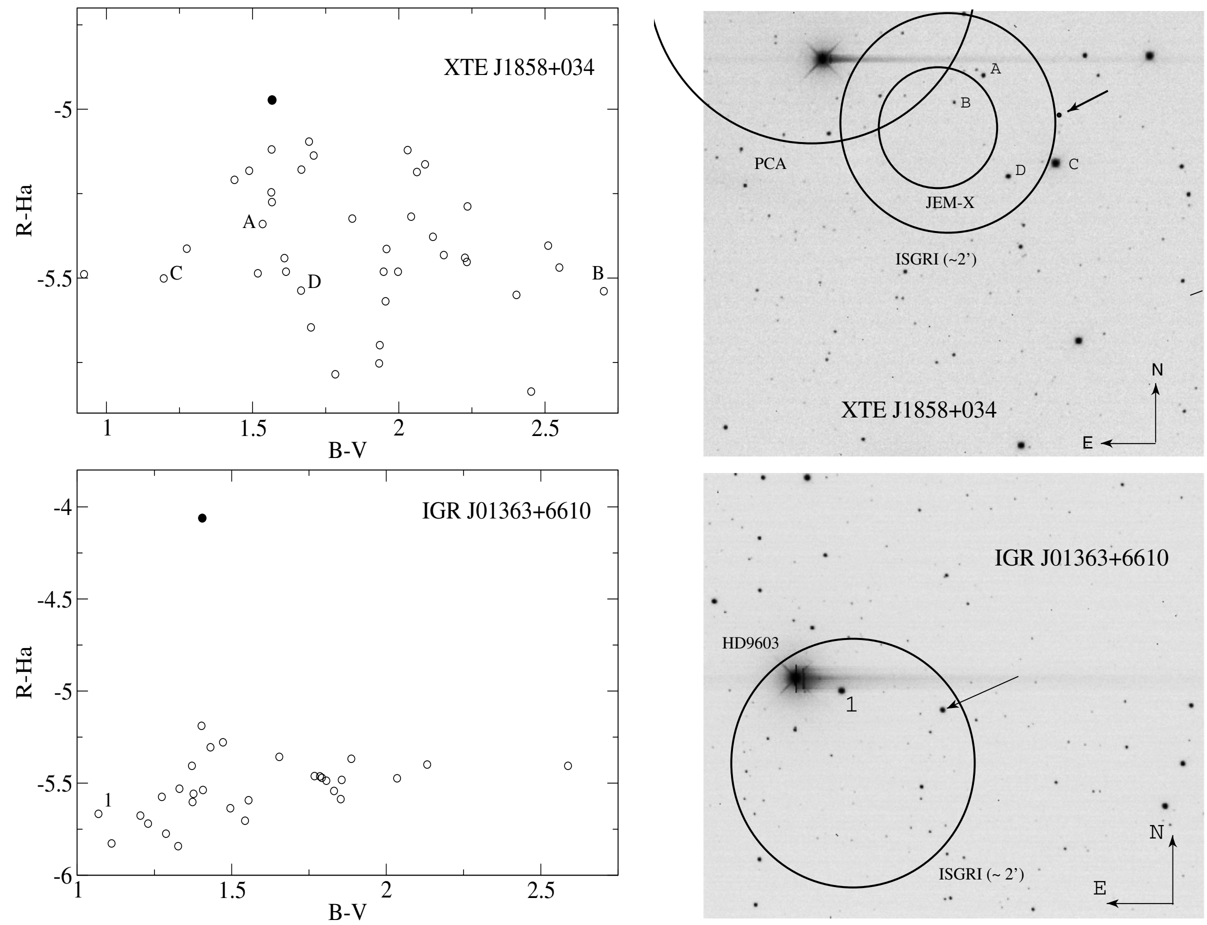

Fig. 1. Colour–colour diagrams and V-band images of the field around XTE J1858+034 (*top*) and IGR J01363+6610 (*bottom*). The images were taken from the 1.3 m telescope of the Skinakas observatory on 20 May 2004 and 27 July 2004, respectively and the diagrams used data obtained on 28 and 29 June 2004, respectively. Other potential (and subsequently rejected) candidates are also indicated. For XTE J1858+034, the 2.5′ PCA RXTE, 2′ ISGRI INTEGRAL and 1′ JEM-X INTEGRAL radius error circles are shown. For IGR J01363+6610, the 2′ ISGRI INTEGRAL error circle is shown. The proposed optical counterparts are marked with a filled circle on the diagrams and with an arrow on the images.

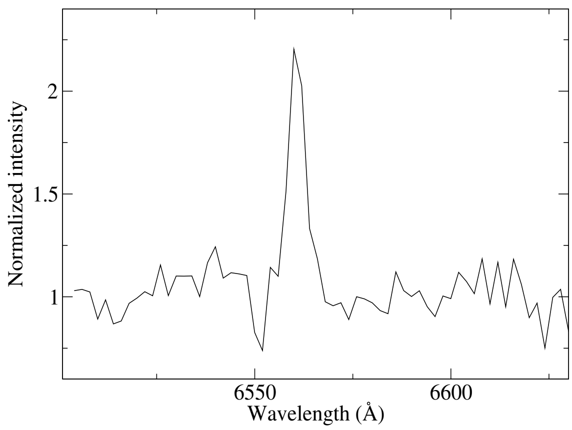

Fig. 2. Average Hα profile of XTE J1858+034. The spectrum was re-binned with a bin size of 2 Å.

position of GRO J2058+42 to just 0.″41 (68% confidence radius), consistent with our optical position (Wilson et al. 2005).

The optical counterpart to GRO J2058+42 has been identified with a V = 14.9 O9.5-B0IV-Ve star located at a distance of ~9 ± 1 kpc. After a period of high X-ray activity (1995–2002) GRO J2058+42 entered a quiescent phase in mid 2002 that continues up to the present. The *Chandra* observations of February 2004 failed to detect pulsations and estimated the unabsorbed 2–10 keV flux to be $(3-9) \times 10^{33}$ erg s^{-1}. No optical variability is apparent during the four months (June–October 2004) that we monitored the source. The photometric magnitudes remained unchanged at mean values of B = 16.05, V = 14.93, R = 14.22 and I = 13.44.

Despite the fact that the X-ray observations showed a quiescent state, the Be star did not lose the disk completely. The Hα line exhibited always a double-peak emission profile with a mean equivalent width of −4.7 Å and a peak separation of 400 ± 30 km s^{-1}. The presence of the disk can also explain the higher scatter of the photometric magnitudes as the wavelength increases. The standard deviation of the observations of Table 1 for the various photometric bands are: σ_B = 0.018, σ_V = 0.023, σ_R = 0.030 and σ_I = 0.050.

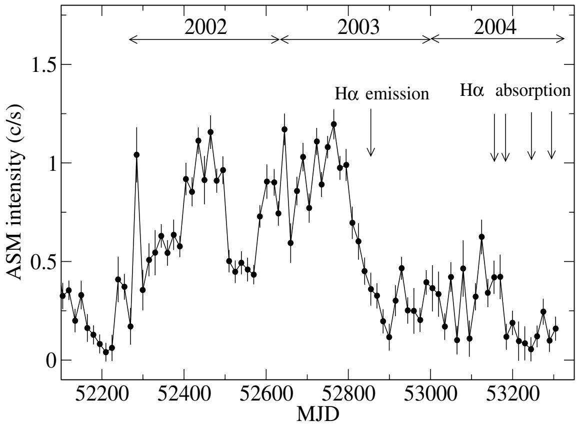

Fig. 3. X-ray/optical evolution of SAX J2103.5+4545. Absorption Hα profiles correspond with low X-ray activity states.

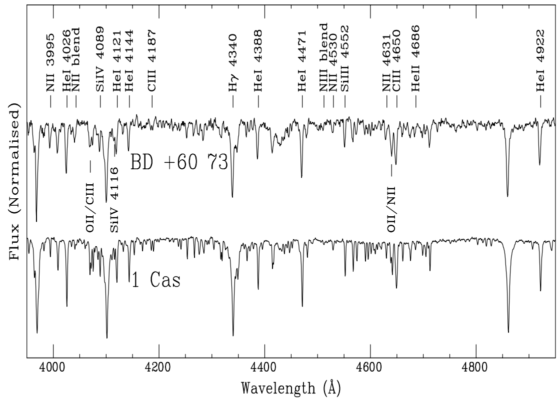

Fig. 4. Blue-end spectrum of IGR J00370+6122. A comparison with a B0.5III standard is provided.

4.3. SAX J2103.5+4545

The X-ray transient SAX J2103.5+4545 was discovered by the BeppoSAX Wide Field Camera (WFC) during an outburst in February 1997, reaching a peak intensity of 20 mCrab (2–25 keV). The source was found to be an X-ray pulsar with a 358.61 s pulse period (Hulleman et al. 1998). Since its discovery SAX J2103.5+4545 has been detected by other three satellites: RXTE observations allow the determination of the orbital parameters: $P_{\rm orb} = 12.68$ d, $e = 0.4 \pm 0.2$ (Baykal et al. 2000); XMM-Newton observations detected quasi-periodic oscillations at 0.044 Hz and estimated the magnetic field of the neutron star to be $\sim 7 \times 10^{12}$ G (Inam et al. 2004); INTEGRAL observations provided the first broad-band spectrum and showed significant emission up to 150 keV (Blay et al. 2004).

Optical observations reporting on the identification of the optical counterpart with a $V = 14.2$ B0Ve star at 6.5 kpc has been reported elsewhere (Reig et al. 2004a). Here we present new photometric and spectroscopic observations performed in 2004. At the time of the optical identification (mid 2003) the source was caught in the final stages of a disk-loss phase. All new observations show Hα in absorption, indicating that the Be star has not recovered the circumstellar disk. The source is known to go through high and low X-ray states (Baykal et al. 2000). Although the optical coverage is still scarce, a loose correlation between the X-ray and optical data is present. As can be seen in Fig. 3, where a portion of the RXTE ASM of SAX J2103.5+4545 is plotted, the emission profiles were observed at the end of a high X-ray state, whereas the absorption profiles correspond to a low activity state which SAX J2103.5+4545 entered at the end of 2003 and still continues. This is quite a puzzling situation since without the disk no X-ray emission should be detected – the material in the disk constitutes the fuel that powers the X rays. However, the source is still active in X-rays as can be noticed from the RXTE ASM. We discuss this issue further in Sect. 5.

4.4. IGR J00370+6122

The X-ray source IGR J00370+6122 was detected by *INTEGRAL* during December 2003. The error circle (∼2′) included the position of the *ROSAT* source 1RXS J003709.6+612131 (den Hartog et al. 2004), which had been identified with the OB star BD +60°73 = LS I +61°161 (Rutledge et al. 2000). A search of *RossiXTE*/ASM data from this position revealed the presence of a variable X-ray source, displaying a clear modulation with a period of 15.665 ± 0.006 d. When the light curve is folded on this period, the source is only clearly detected as a single peak close to the phase of maximum (den Hartog et al. 2004).

We performed five spectroscopic and two photometric runs from Skinakas observatory during the summer 2004 (see Tables 1 and 2). Additionally, an intermediate-resolution spectrum of this object was taken on the night of 2003 July 7th with the 2.5-m Isaac Newton Telescope (INT), at La Palma, Spain. The INT was equipped with the Intermediate Dispersion Spectrograph (IDS) and the 235-mm camera. The R900V grating and EEV#13 camera were used, resulting in a nominal dispersion of ≈0.65 Å/pixel. This spectrum is shown in Fig. 4, together with that of HD 218376 (1 Cas), given as B0.5 III standard by Walborn (1971). In both stars, the only He II line visible is 4686 Å, implying a spectral type earlier than B1 but later than B0.2 (Walborn & Fitzpatrick 1990). BD +60°73 was classified as B1Ib by Morgan et al. (1955).

Comparison of the two spectra clearly shows BD +60°73 to be more luminous than 1 Cas (the Balmer lines are less deep and have narrower wings) in spite of the higher rotational velocity indicated by the broader He I and metallic lines. However, the moderate strength of Si IV 4089 Å and Si III 4552 Å prevents a supergiant classification. The most adequate classification appears to be B0.5 II-III, where the composite luminosity class indicates an intermediate luminosity. Though BD +60°73 appears slightly earlier than 1 Cas (as it displays stronger He II), a spectral type B0.2 cannot be given because of the absence of the He II 4541 Å line. The low-resolution spectra covering the yellow/red region of the spectrum obtained from the Skinakas Observatory show that He I 5875 Å, He I 6678 Å and Hα are all strongly in absorption, as is morphologically normal for the spectral type. BD +60°73 has thus not entered a Be phase. Another interesting different between the spectrum of BD +60 73 and that of the standard is the greater strength of all the N II and N III lines in the former. This N enhancement does not seem to be accompanied by any C depletion, perhaps suggesting the accretion of CNO processed material during a previous evolutionary phase, when the progenitor of the compact object was a giant or supergiant.

UBV photometry of BD +60°73 is reported by Hiltner (1956) and Haug (1970). Their values are identical within the errors (the photometry of Haug is transformed to Hiltner's system) and give $V = 9.64$, $(B-V) = 0.57$, in complete agreement with our photometric measurements (Table 1). Assuming the intrinsic colours of a B0.5 giant (Wegner 1994) and $M_V = -5.2$, intermediate between the values for luminosity class II and III, we obtain $E(B-V) = 0.78$ and $DM = 12.4$, corresponding to a distance $d = 3.0$ kpc. Such values are typical of Perseus Arm objects in the Cassiopeia region and suggest that BD +60°73 may belong to the "far" component of Cas OB5 (cf. Ampel 1964).

Because of the spectral type of its counterpart, IGR J00370+6122 appears difficult to fit within the classification scheme of massive-X-ray binaries. The counterpart is neither a Be star nor a supergiant. It is not surrounded by a circumstellar disk and it is expected to have only a moderate wind, rising the question of how the X-ray emission originates. The fact that the X-ray light curve seems to be very strongly peaked supports the idea of a very eccentric orbit. If this is the case, the compact object could come very close to the B-type star at periastron, allowing accretion from the inner regions of its wind, or perhaps triggering some extra mass loss. In this sense, IGR J00370+6122 shares some similarity with the extreme LMC X-ray transient A 0538−66 (Charles et al. 1983), though obviously the X-ray activity is much lower. Depending on the orbital parameters, IGR J00370+6122 could evolve toward a Roche-lobe overflow system such as LMC X-4 (if the orbit circularises on a time-scale smaller than the evolutionary time for the mass donor) or, more likely, a SXB, if the mass donor swells to supergiant size while the orbit is still relatively broad. Though no pulsations have been detected from IGR J00370+6122, the lack of radio emission (Cameron et al. 2004) hints at the presence of a neutron star in this system.

4.5. IGR J01363+6610

IGR J01363+6610 was discovered by INTEGRAL imager IBIS/ISGRI on April 19, 2004 during observations dedicated to the Galactic Plane Scan. The source position was provided with an uncertainty 2′. The average flux over 2.3 h of observations was 17 mCrab in the 17–45 keV band. The source was not detected with IBIS/ISGRI during a Galactic Plane Scan of the region on May 1, 2004 (Grebenev et al. 2004).

Our optical observations revealed that the star located at RA = 01h35m50s, Dec = 66d12m40s, consistent with the INTEGRAL uncertainty circle (see Fig. 1), shows a very strong Hα emission (Reig et al. 2004c). Other potential candidates (star 1 in Fig. 1) showed Hα in absorption.

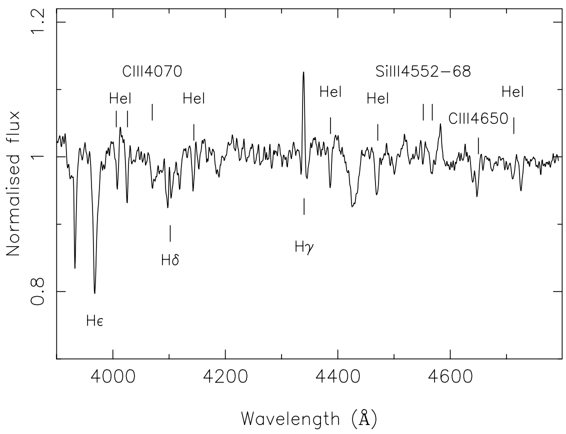

Fig. 5. Blue-end spectrum of IGR J01363+6610. The He I lines are 4006 Å, 4026 Å, 4144 Å, 4387 Å, 4471 Å and 4713 Å.

In addition to the Skinakas observations IGR J01363+6610 was also observed with the Nordic Optical Telescope on 2004 October 4th using the Andalucia Faint Object Spectrograph and Camera (ALFOSC). The instrument was equipped with a thinned 2048 × 2048 pixel E2V CCD. Observations of the field of IGR J01363+6610 were taken in slitless spectroscopy mode using the Bessell *R*-band filter and grism #4. Spectra of the candidate were taken with grisms #16 and #7 which cover the 3500–5100 Å and 3800–6870 Å range respectively, with nominal dispersions of 0.8 Å/pixel and 1.5 Å/pixel respectively.

The classification spectrum (4000–5000 Å) shows the presence of Hβ and Hγ in emission and the metallic and He I lines typical of an early B-type star of low luminosity (Fig. 5). More precisely, the absence of He II lines indicates an spectral type later than B0.5. He I lines dominate the spectrum (together with the hydrogen lines), indicating a B1 or B2 star. However, the presence of some amount of Si III 4552–68 Å and the carbon blends (C III 4070–4650 Å) favours the B1 spectral type. On the other hand, the weakness of the oxygen and silicon lines points toward a main-sequence star, although the strength of C III 4650 Å is more typical of giant companion. Thus we conclude that the optical counterpart to IGR J01363+6610 is a B1V star, although a more luminous companion cannot be ruled out. This object is probably identical with the catalogued emission line star [KW97] 6-30 (Kohoutek & Wehmeyer 1999), though the coordinates listed in this catalogue locate the source about 2′ south-west of our proposed candidate and outside the INTEGRAL error circle. IGR J01363+6610 shows the second strongest, after A 1118-616, Hα emission among galactic BeX with an equivalent width of ~50 Å.

Measured photometric magnitudes are given in Table 1. Taking the typical colour of a B1V star, $(B-V)_0 = -0.23$ (Wegner 1994), and comparing with the observed colour $(B-V)_{\rm obs} = 1.38$, we derived an excess colour of $E(B-V) = 1.61$. Assuming an absolute magnitude of $M_V = -3.2$ (Jaschek & Jaschek 1987), we estimate the distance to be ~2 kpc, compatible with the near side of the Perseus Arm.

Table 3. Optical and X-ray properties of the sources.

Source	Optical data RA (2000)	Dec (2000)	Spectral type	$E(B-V)$	Distance (kpc)	X-ray data P_{spin} (s)	QPO (Hz)	Peak flux (mCrab)/ Energy range
XTE J1858+034	18 58 36	03 26 10	B?e			221	0.11	24 (2–12 keV)
GRO J2058+42	20 58 47	41 46 36	O9.5-B0IV-Ve	1.40	9.0	192		300 (20–50 keV)
SAX J2103.5+4545	21 03 36	45 45 04	B0Ve	1.35	6.5	358	0.044	27 (2–12 keV)
IGR J00370+6122	00 37 10	61 21 35	BN0.5II-III	0.75	3.3			15 (2–28 keV)
IGR J01363+6610	01 35 50	66 12 40	B1IV-Ve	1.61	2.0			19 (17–45 keV)

5. BeX-ray binaries in quiescence

The study of BeX in quiescence is still an unexplored field. So far only a handful of BeX systems have been observed in quiescence: A0538-66, 4U 0115+63, V0332+53 (Campana et al. 2002), A0535+262 (Negueruela et al. 2000) and GRO J2058+42 (Wilson et al. 2005).

In the X-ray band the limited number of observations (Campana et al. 2002; Wilson et al. 2005) show very soft spectra, absence of pulsations (except in A0535+262) and luminosities well below 10^{34} erg s^{-1}. Quiescent states are generally related to the propeller effect (Illarionov & Sunyaev 1975). There exists a minimum X-ray luminosity below which the propeller effect sets in. This luminosity is given by (see e.g. Campana et al. 2002)

$$L_{\rm min}(R_{\rm NS}) = 3.9\times10^{37}\left(\frac{B}{10^{12}\,{\rm G}}\right)^{2}\left(\frac{P_{\rm spin}}{1\,{\rm s}}\right)^{-7/3} \times\left(\frac{M_{\rm X}}{1.4\,M_\odot}\right)^{-2/3}\left(\frac{R_{\rm X}}{10^{6}\,{\rm cm}}\right)^{5}\ {\rm erg\,s^{-1}}.$$

Below this limiting luminosity the accreting matter can no longer reach the neutron star surface because it is spun away by the fast rotation of the magnetosphere. For rapid rotating pulsars like 4U 0115+63 or V0332+53 $L_{\rm min}(R_{\rm NS})$ is relatively high, $\sim10^{36}$ erg s^{-1}. For long pulsing systems like GRO J2058+42, SAX J2103.5+4545 and A0535+262, $L_{\rm min}(R_{\rm NS}) \sim 10^{32}$–$10^{33}$ erg s^{-1}. When the propeller effect is at work, X-rays can still be produced through accretion onto the magnetosphere (Corbet 1996), as opposed to onto the neutron star surface, or through leakage through the magnetosphere (Campana et al. 2001). A third model that has been put forward to explain X-ray emission during quiescence, namely, cooling of the neutron star surface after crustal heating (Brown et al. 1998), can be ruled out as the general mechanism since in order to achieve the observed luminosities it requires prior events of intense accretion, that is, a high outbursting activity before entering the quiescent state, which was not seen in A0538-66, V0332+53 or A0535+262. It, however, might still contribute in part to the total quiescent luminosity.

In this work we focus on the optical state of BeX during X-ray quiescence. In the standard model of BeX systems, the circumstellar disk around the Be star's equator provides the reservoir of matter that ultimately is accreted onto the neutron star. Thus, one would expect that during the X-ray quiescent state the disk would be missing or largely debilitated. This seems to be the case for GRO J2058+42, for which optical observations during the X-ray quiescent state showed Hα in emission, i.e., the disk was still present. Given the relatively low $L_{\rm min}(R_{\rm NS})$ for GRO J2058+42, mass transfer may still be going on during quiescence states from a weak disk and there is no need to invoke thermal emission from crustal heating or accretion onto the magnetosphere.

The cases of SAX J2103.5+4545 and A0535+262 are particularly interesting because despite the complete loss of the circumstellar disk X-ray emission was detected (for a detailed discussion of A0535+262 see Negueruela et al. 2000). All optical spectra of SAX J2103.5+4545 taken during 2004 exhibit Hα in absorption. Still, the source shows X-ray activity with a mean flux of $\sim$3–5 $\times$ 10^{35} erg s^{-1} ($\sim$0.25 ASM c s^{-1}), as can be seen in Fig. 3. We assume a distance of 6.5 ± 0.9 kpc (Reig et al. 2004a). This luminosity is above $L_{\rm min}(R_{\rm NS})$, hence accretion is likely to be the mechanism that powers the X-rays but contrary to GRO J2058+42, SAX J2103.5+4545 has completely lost the disk.

SAX J2103.5+4545 is a moderately eccentric, $e \approx 0.4$, system with the narrowest orbit, $P_{\rm orb} = 12.6$ days, among the Galactic BeX (Baykal et al. 2000). Interestingly, SAX J2103.5+4545 occupies the region of the wind-fed supergiant binaries in the $P_{\rm spin} - P_{\rm orb}$ diagram (Reig et al. 2004a). In principle, then, accretion from the stellar wind of the B0 companion might be at the origin of the observed luminosity, as much the same way as we proposed to be the case in IGR J00370+6122, for which $L_{\rm X}(1.5$–12 keV$) \approx (0.5$–$2) \times 10^{35}$ erg s^{-1} (den Hartog et al. 2004). We can make an estimate in order of magnitude of the expected luminosity using a simple wind-fed model. Assuming that all the gravitational energy is converted into X-rays, the X-ray luminosity is given by (see e.g Waters et al. 1989)

$$L_{\rm X} \approx 4.8\times10^{37}\left(\frac{M_{\rm X}}{1.4\,M_\odot}\right)^{3}\left(\frac{R_{\rm X}}{10^{6}\,{\rm cm}}\right)^{-1}\left(\frac{M_*}{1\,M_\odot}\right)^{-2/3} \times\left(\frac{P_{\rm orb}}{1\,{\rm day}}\right)^{-4/3}\left(\frac{\dot{M}_*}{10^{-6}\,M_\odot\,{\rm yr}^{-1}}\right)\left(\frac{v_{\rm w}}{10^{8}\,{\rm cm\,s^{-1}}}\right)^{-4}\ {\rm erg\,s^{-1}}.$$

Taking $M_* = 20\,M_\odot$ (Vacca et al. 1996), the canonical mass and radius for a neutron star, $M_{\rm X} = 1.4\,M_\odot$ and $R_{\rm X} = 10^6$ cm, the corresponding orbital periods of 12.68 d for SAX J2103.5+4545 and 15.66 d for IGR J00370+6122, and wind velocities in the range 400–1000 km s^{-1} (Snow 1981; Prinja 1989) we note that mass-loss rates of the order

$10^{-7}\ M_\odot$ yr^{-1} are needed to reproduce the observed X-ray luminosity. This mass-loss rate is not unusual for early-type giants and supergiants (Prinja et al. 1990).

For SAX J2103.5+4545 one has to invoke the asymmetry of mass outflows that characterise Be stars if the observed X-ray luminosity is to be explained by wind accretion. The structure of the stellar winds in Be stars is highly asymmetric and contains two components: at higher latitudes, mass is lost through the high-velocity, low-density wind; in the equatorial regions a slower and denser wind operates and ultimately forms the disk. Equatorial mass-loss rates are of the order of $10^{-7}\ M_\odot$ yr^{-1} and are a factor 10–100 larger than polar mass-loss rates (Waters et al. 1988, and references therein). Note that in the case of SAX J2103.5+4545 there is no need to reach $\dot{M} \sim 10^{-7}\ M_\odot$ yr^{-1} due to its narrow orbit and the strong dependence of the luminosity on the wind velocity ($L_{\rm X} \propto v_{\rm w}^{-4}$). Stellar winds are generally modelled with a wind velocity field of the form (Castor et al. 1975)

$$v_{\rm w}(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$$

where β is normally taken to vary in the range 0.7–1 and R_* is the star radius (8.3 $R_\odot$ for a B0). The relatively narrow orbit of SAX J2103.5+4545 implies that the wind, at the position of the neutron star, does not reach its terminal velocity, v_∞, but varies in the range $v_{\rm w} \sim [0.7–0.9]v_\infty$.

6. Summary and conclusions

We have presented the results of our search for optical counterparts to high-mass X-ray transients. We have used a method based on the combination of photometric colour–colour diagrams with medium-resolution spectroscopy. This method rests on two observational properties of this type of systems, namely, the narrow range of spectral types and the fact that the vast majority of the optical companions in high-mass X-ray binaries show Hα in emission. This method has proved to be very useful in cases where the uncertainty in the position of the X-ray source is large (a few arcminutes). We found the optical counterparts to XTE J1858+034, GRO J2058+42, SAX J2103.5+4545 and IGR J01363+6610. Three systems, GRO J2058+42, SAX J2103.5+4545 and IGR J01363+6610 harbour main-sequence or subgiant B stars and hence constitute new BeX binaries. The nature of XTE J1858+034 is not clear: its Hα line resembles a P-Cygni profile reminiscent of very luminous stars with strong stellar winds but its transient nature is more typical of BeX systems. If it contains an evolved companion, then the large equivalent width might be indicative of a hypergiant star. We have carried out a detailed spectroscopic analysis of IGR J00370+6122 and IGR J01363+6610 and found that the systems contain an evolved BN0.5 II-III and a main-sequence B1 companion, respectively. The production of X-rays in IGR J00370+6122 is difficult to explain unless a very eccentric orbit is invoked. Determination of the orbital parameters of IGR J00370+6122 could provide important clues on the evolutionary path leading to the formation of high-mass X-ray binaries. Finally, a study of the correlated X/optical data of SAX J2103.5+4545 and GRO J2058+42 during quiescence shows that while quiescent emission in GRO J2058+42 can still proceed via accretion from the circumstellar disk onto the surface of the neutron star, in SAX J2103.5+4545 it must come from the stellar wind.

With these new findings we have increased the number of known traditional HMXBs. However, not all the new suspected HMXBs that are being discovered fit into the known subgroups of the population of massive binaries. Since its launch, and mainly thanks to its continual monitoring of the Galactic plane, *INTEGRAL* has detected a large number of new X-ray sources, most of which are HMXBs (Lutovinov et al. 2005; Kuulkers 2005). Most of them seem to have interesting new properties, which set them aside from previously known HMXBs. A few sources display very high variable absorption, indicative of a very dense local environment. Among them, IGR J16318−4848 has been identified with a very peculiar IR counterpart by Filliatre & Chaty (2004), who suggest that it may be a B[e] supergiant. Another subset of sources, less obscured, appear to be transients with very short outbursts. Three of them are associated with OB supergiants (Smith 2004; Negueruela et al. 2005), and hence are likely to belong to a new class of HMXB transients.

Other new *INTEGRAL* sources seem to belong to well established classes of HMXB. This is the case of IGR J01363+6610 or IGR J11435–6109 (Torrejón & Negueruela 2004), which appear to be typical Be/X-ray transients. This last source, like IGR J00370+6122, had already been observed by other satellites, although not recognised as a HMXB. In this sense, it is unlikely to be coincidental that obscured sources belonging to new classes are mainly being found in the areas covered by the Galactic Centre scans, which are deeper and more frequent. This suggests that deep continuous monitoring of other regions of the Galactic disk would result in the discovery of many new HMXBs.

Acknowledgements. I.N. is a researcher of the programme *Ramón y Cajal*, funded by the Spanish Ministerio de Educación y Ciencia and the University of Alicante, with partial support from the Generalitat Valenciana and the European Regional Development Fund (ERDF/FEDER). This research is partially supported by the MEC through grant ESP-2002-04124-C03-03. Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology-Hellas and the Max-Planck-Institut für Extraterrestrische Physik. The Nordic Optical Telescope is operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Part of the data presented here have been taken using ALFOSC, which is owned by the Instituto de Astrofísica de Andalucía (IAA) and operated at the Nordic Optical Telescope under agreement between IAA and the NBIfAFG of the Astronomical Observatory of Copenhagen. The INT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias. Some of the WHT spectra were obtained as part of the ING service programme. This research has made use of NASA's Astrophysics Data System Bibliographic Services.

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