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Obscured Sources and Supergiant Fast X-ray Transients: New Classes of High Mass X-ray Binaries

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Abstract A new type of high-energy binary systems has been revealed by the *INTEGRAL* satellite. These sources are in the course of being unveiled by means of multi-wavelength optical, near- and mid-infrared observations. Among these sources, two distinct classes are appearing: the first one is constituted of intrinsically obscured high-energy sources, of which IGR J16318–4848 seems to be the most extreme example. The second one is populated by the so-called supergiant fast X-ray transients, with IGR J17544–2619 being the archetype. We report here on multi-wavelength optical to mid-infrared observations of a sample of 21 *INTEGRAL* sources. We show that in the case of the obscured sources our observations suggest the presence of absorbing material (dust and/or cold gas) enshrouding the whole binary system. We finally discuss the nature of these two different types of sources, in the context of high energy binary systems.

Key words: X-ray binaries — visible — near infrared — infrared — *INTEGRAL* — IGR J16318–4848; IGR J17544–2619

1 INTRODUCTION

The *INTEGRAL* observatory has performed a detailed survey of the galactic plane and the ISGRI detector on the IBIS imager has discovered many new high energy sources, most of all reported in Bird et al.(2007) (and *http://isdc.unige.ch/∼rodrigue/html/igrsources.html*). The most important result of *INTEGRAL* to date is the discovery of many new high energy sources –concentrated in the Galactic plane, and some in the Norma arm (see e.g., Chaty & Filliatre 2005) –, exhibiting common characteristics which previously had rarely been seen. Most of them are high mass X-ray binaries (HMXBs) hosting a neutron star orbiting around an O/B companion, in most cases a supergiant star. They divide into two classes: some of the new sources are very obscured, and exhibiting a huge intrinsic and local extinction, and the others are HMXBs hosting a supergiant star and exhibiting fast and transient outbursts: an unusual characteristic among HMXBs: they are therefore called Supergiant Fast X-ray Transients (SFXTs, Negueruela et al. 2006). High-energy observations are not sufficient to reveal the nature of the newly discovered sources, since the *INTEGRAL* localisation ($\sim 2''$) is not accurate enough to unambiguously pinpoint the source at other wavelengths. Once X-ray satellites such as *XMM-Newton*, *Chandra* or *Swift* provide an arcsecond position, the hunt for the optical counterpart of the source is open. However, the high level of absorption towards the galactic plane makes the near-infrared (NIR) domain more efficient to identify these sources. We first report on multi-wavelength observations of two sources belonging to each class described above, then give general results on *INTEGRAL* sources, before discussing them and concluding.

Based on observations collected at the European Southern Observatory, Chile (proposals ESO N° 070.D-0340, 071.D-0073, 073.D-0339, 075.D-0773 and 077.D-0721).

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2 OBSERVATIONS AND RESULTS

The multiwavelength observations described here were performed at the European Southern Observatory (ESO), using Target of Opportunity (ToO) and Visitor modes, in 3 domains: optical ($400 - 800$ nm) with the EMMI instrument on the 3.5 m New Technology Telescope (NTT) at La Silla, NIR ($1 - 2.5\,\mu$m) with the SOFI instrument on the NTT, and MIR ($5 - 20\,\mu$m) with the VISIR instrument on Melipal, the 8m Unit Telescope 3 (UT3) of the Very Large Telescope (VLT) at Paranal (Chile). These observations include photometry and spectroscopy on 21 *INTEGRAL* sources in order to identify their counterparts, the nature of the companion star, derive the distance, and finally characterise the presence and temperature of their circumstellar medium.

2.1 IGR J16318–4848: Extreme Among the Obscured High-Energy Sources

IGR J16318–4848 was the first source to be discovered by IBIS/ISGRI on *INTEGRAL* on 29 January 2003 (Courvoisier et al. 2003). *XMM-Newton* observations showed a strong absorption of $N_{\rm h} \sim 2 \times 10^{24}$ cm^{-2} (Matt & Guainazzi 2003). The accurate localisation by *XMM-Newton* allowed Filliatre & Chaty (2004) to rapidly trigger ToO photometric and spectroscopic observations in optical and NIR, leading to the discovery of the optical counterpart and to the confirmation of the NIR one found by Walter et al. (2003). The extremely bright NIR source (Ks$=7.20$ magnitudes) exhibits an unusually strong intrinsic absorption in the optical of $A_v = 17.4$ magnitudes, much stronger than the absorption along the line of sight of $A_v = 11.4$ magnitudes, but still 100 times lower than the absorption in X-rays. This led Filliatre & Chaty (2004) to suggest that the material absorbing in the X-rays was concentrated around the compact object, while the material absorbing in the optical/NIR was enshrouding the whole system. The NIR spectroscopy revealed an unusual spectrum, with many strong emission lines, originating from a highly complex and stratified circumstellar environment, of various densities and temperatures, suggesting the presence of an envelope and strong stellar outflow, responsible for the absorption. Only luminous early-type stars such as supergiant sgB[e] show such extreme environments, and Filliatre & Chaty (2004) concluded that IGR J16318–4848 was an unusual HMXB. By combining these optical and NIR data with MIR observations, and fitting these observations with a model of a sgB[e] companion star, Rahoui et al. (2007) showed that IGR J16318–4848 exhibits a MIR excess (see Fig. 1), that they interpret as being due to the strong stellar outflow emanating from the sgB[e] companion star. They found that the companion star had a temperature of $T = 23\,500$ K, radius $R_\star = 20.4\,R_\odot$, and an extra component of temperature $T = 900$ K, radius $R = 12\,R_\star$ and $A_v = 17.6$ magnitudes. By taking a typical orbital period of 10 days and a mass of the companion star of $20\,M_\odot$, we obtain an orbital separation of $50\,R_\odot$, smaller than the extension of the extra component, suggesting that this component enshrouds the whole binary system, as would do a cocoon of gas/dust (see Fig. 2). In summary, IGR J16318–4848 is an HMXB system, located at a distance between 1 to 6 kpc, hosting a compact object (probably a neutron star) and a sgB[e] star (it is therefore the second HMXB with a sgB[e] star, after CI Cam). The most striking facts are i. the compact object seems to be surrounded by absorbing material and ii. the whole binary system seems to be surrounded by a dense and absorbing circumstellar material envelope or cocoon, made of cold gas and/or dust. This source exhibits so extreme characteristics that it might not be fully representative of the other obscured sources.

2.2 IGR J17544–2619: Archetype of the Supergiant Fast X-ray Transients

The Supergiant Fast X-ray Transients (SFXTs) constitute a new class of sources identified among the recently discovered *INTEGRAL* sources, whose common characteristics are: they exhibit rapid outbursts lasting only hours, a faint quiescent emission, their high energy spectra require a BH or NS accretor, and they host O/B supergiant companion stars. IGR J17544–2619, a bright recurrent transient X-ray source discovered by *INTEGRAL* on 17 September 2003 (Sunyaev et al. 2003), seems to be the archetype of this class of sources. Observations with *XMM-Newton* have shown that it exhibits a very hard X-ray spectrum, and a faint intrinsic absorption (10^{22} cm^{-2}, González-Riestra et al. 2004). Its bursts last for hours, in-between bursts it exhibits long quiescence periods, which can reach more than 150 days (Zurita Heras et al. in prep.). The nature of the compact object is probably a neutron star (in't Zand 2005). Pellizza et al. (2006) managed to get optical/NIR ToO observations only one day after the discovery of this source. They identified a likely counterpart inside the *XMM-Newton* error circle, confirmed by *Chandra* accurate localization. Spectroscopy showed that the companion star was a blue supergiant of spectral type O9Ib, with a mass of 25–28 $M_\odot$ and

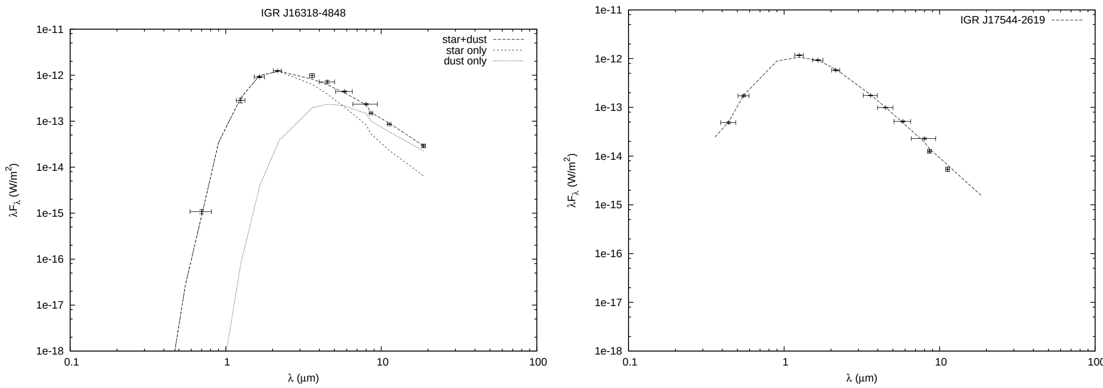

Fig. 1 Optical to MIR SEDs of IGR J16318–4848 (left) and IGR J17544–2619 (right), including data from ESO/NTT, VISIR on VLT/UT3 and *Spitzer* (Rahoui et al. 2007). IGR J16318–4848 exhibits a MIR excess, interpreted by Rahoui et al. (2007) as the signature of a strong stellar outflow coming from the sgB[e] companion star (Filliatre & Chaty 2004). On the other hand, IGR J17544–2619 is well fitted with only a stellar component corresponding to the O9Ib companion star spectral type (Pellizza et al. 2006).

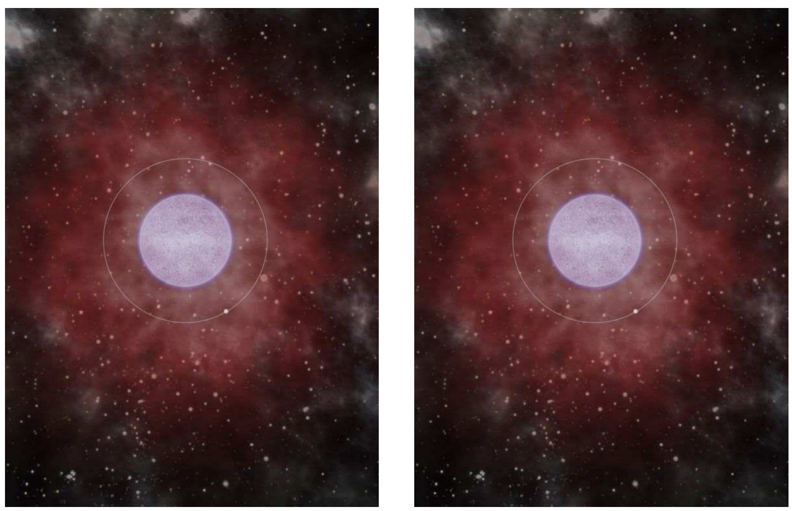

Fig. 2 Scenarii illustrating two possible configurations of *INTEGRAL* sources, with a neutron star orbiting around a supergiant star on a circular orbit (left image), and on an excentric orbit (right image), accreting from the clumpy stellar wind of the supergiant. The accretion of matter is persistent in the case of the obscured sources, as in the left image, where the compact object orbits inside the cocoon of dust enshrouding the whole system. On the other hand, the accretion is intermittent in the case of SFXTs, which might correspond to a compact object on an excentric orbit, as in the right image. A 3D animation of these sources is available on the website *http://www.aim.univ-paris7.fr/CHATY/Research/hidden.html.*

temperature of $T \sim 31\,000$ K: the system is therefore an HMXB (Pellizza et al. 2006). Rahoui et al. (2007) combined optical, NIR and MIR observations and showed that they could accurately fit the observations with a model of an O9Ib star: temperature $T = 30\,500$ K and radius $R_\star = 21.9 R_\odot$. They derived an absorption $A_v = 5.9$ magnitudes and a distance $D = 3.9$ kpc. The source does not exhibit any MIR excess (see Fig. 1, Rahoui et al. 2007). In summary, IGR J17544–2619 is an HMXB at a distance of ∼4 kpc, constituted of an O9Ib supergiant, with a mild stellar wind and a compact object which is probably a neutron star, without any MIR excess.

2.3 General Results on *INTEGRAL* Sources and Discussion

To better characterize this population, Chaty et al. (2007) and Rahoui et al. (2007) studied a sample of 21 *INTEGRAL* sources belonging to both classes described above. All the results of this study are reported in Table 1.

Table 1 Results on our sample of *INTEGRAL* sources. We indicate respectively the name of the sources, the region of the Galaxy in the direction of which they are located, their spin and orbital period, the interstellar column density, the absorption derived from optical-IR and X-ray observations respectively, their spectral type, their type, and the reference about their spectral type. More details on each source are given in Chaty et al. (2007). Type abbreviations: AGN = Active Galactic Nucleus, B = Burster, BHC = Black Hole Candidate, D = Dipping source, HMXB = High Mass X-ray Binary System, LMXB = Low Mass X-ray Binary, NS = Neutron Star, O = obscured source, S = Supergiant Fast X-ray Transient, T: Transient source, XP: X-ray Pulsar. c: Chaty et al. (2007), co: Combi et al. (2006), f: Filliatre & Chaty (2004), m: Masetti et al. (2006), n1: Negueruela et al. (2005), n2: Negueruela et al. (2006), n3: Nespoli et al. (2007), p: Pellizza et al. (2006), t: Tomsick et al. (2006).

Source	Reg	P_s(s)	P_o(d)	Nh_{is}	$Nh_{\rm IR}$	$Nh_{\rm X}$	SpT	Type	Ref
		(s)	(d)	10^{22} cm^{-2}	10^{22} cm^{-2}	10^{22} cm^{-2}			
IGR J16167–4957	No					0.5	A0	CV/IP	t
IGR J16195–4945	No			2.18	2.9	7	OB	H?/S?/O	t
IGR J16207–5129	No			1.73	2.0	3.7	BOI	H/O	t
IGR J16318–4848	No			2.06	3.3	200	sgB[e]	H/O/P	f
IGR J16320–4751	No	1250	9	2.14	6.6	21	sgOB	H/XP/T/O	c
IGR J16358–4726	No	5880		2.20	3.3	33	sgB[e]?	H/XP/T/O	c
IGR J16393–4643	No	912	3.6875	2.19	2.19	24.98	BeV	H?/XP/T	c
IGR J16418–4532	No	965	3.75	1.88	2.7	10	OB	H/XP/S	c
IGR J16465–4507	No	228		2.12	1.1	60	B0.5I	H/S	n1
IGR J16479–4514	No			2.14	3.4	7.7	sgOB	H/S?	c
IGR J16558–5203	No						Sey1.2	AGN	m
IGR J17091–3624	GC			0.77	1.03	1.0	BeV	H/BHC	c
IGR J17195–4100	GC					0.08		CV/IP	t
IGR J17252–3616	GC	413	9.7	1.56	3.8	15	sgOB	H/XP/O	c
IGR J17391–3021	GC			1.37	1.7	29.98	O8Iab(f)	H/S/O	n2
IGR J17544–2619	GC	NS	165?	1.44	1.1	1.4	O9Ib	S	p
IGR J17597–2201	GC			1.17	2.84	4.50	LMXB	L/B/D/P	c
IGR J18027–1455	GC						Sey1	AGN	co
IGR J18027–2016	GC	139	4.6	1.04	1.53	9.05	sgOB	H/XP/T	c
IGR J18483–0311	GC	21.05	18.52	1.62	2.45	27.69	HMXB	H	c
IGR J19140+0951			13.55	1.68	2.9	6	sgB0.5I	H/O	n3

The optical/NIR study, through an accurate astrometry, photometry and spectroscopy, allowed Chaty et al. (2007) to identify or confirm the identification of the counterpart, and to show that most of these systems are HMXBs, containing massive and luminous early-type companion stars. By combining MIR photometry, and fitting their optical–MIR spectral energy distributions, Rahoui et al. (2007) showed that i. most of these sources exhibit an intrinsic absorption and ii. three of them exhibit a MIR excess, that they suggest to be due to the presence of a cocoon of dust and/or cold gas enshrouding the whole binary system (see also Chaty & Rahoui 2006c). Nearly all the *INTEGRAL* HMXBs for which both spin and orbital periods have been measured are located in the upper part of the Corbet diagram (Corbet 1986): they are wind accretors, typical of supergiant HMXBs, and X-ray pulsars exhibiting longer pulsation periods and higher absorption (by a factor ~ 4) as compared to the average of previously known HMXBs (Bodaghee et al. 2007). This extra absorption might be due to the presence of a cocoon of dust and/or cold gas enshrouding the whole binary system in the case of the obscured sources: the intrinsic properties of the supergiant star in the binary system could therefore explain some properties of these sources. However, fundamental differences exist between obscured sources and SFXTs, which might be explained by the geometry of the binary systems, and/or the extension of the wind/cocoon enshrouding either the companion star or the whole system. Indeed, obscured sources are naturally explained by a compact object orbiting inside a cocoon of dust and/or cold gas, while the fast X-ray behaviour of SFXTs needs a clumpy stellar wind environment, to account for fast and transient accretion phenomena (see Fig. 2, and Chaty & Rahoui 2006c). These results show the existence in our Galaxy of a dominant population of a previously rare class of high-energy binary systems: supergiant HMXBs, some exhibiting a high intrinsic absorption (Chaty et al. 2007; Rahoui et al. 2007). A careful study of this population, recently revealed by *INTEGRAL*, will provide a better understanding of the formation and evolution of short-living HMXBs. Furthermore, stellar population models will henceforth have to take these objects into account, to assess a realistic number of high-energy binary systems in our Galaxy. Our final word is that only a multiwavelength study can allow to reveal the nature of such obscured high-energy sources.

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DISCUSSION

NIELS LUND: Are all the SFXT sources heavily absorbed? The animation seems to indicate a connection between the heavily absorbed sources and the SFXT sources.

SYLVAIN CHATY: No, the SFXTs are not all heavily absorbed. The animation shows two possible configurations for INTEGRAL sources. The first one, where the neutron star is on a circular orbit inside the cocoon of dust, well corresponds to the obscured sources. The second one, where the neutron star on an excentric orbit only periodically crosses the clumpy environment of its companion supergiant star, could explain some properties of the SFXTs.