High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
Proceedings IAU Symposium No. 346, 2019
L. M. Oskinova, E. Bozzo, T. Bulik & D. Gies, eds.

doi:10.1017/S1743921319001285

On the nature of Supergiant Fast X-ray Transients

Ignacio Negueruela

Departamento de Física Aplicada, Facultad de Ciencias, Universidad de Alicante
Carretera de San Vicente del Raspeig s/n, E03690, San Vicente del Raspeig, Alicante, Spain
email: ignacio.negueruela@ua.es

Abstract. More than a decade after fast x-ray transients with an OB supergiant counterpart were identified as a distinct class of wind-accreting sources, we still have not reached a consensus on the physical origin of their similarities and differences with persistent sources. Both kinds seem to extend over the same range of every relevant parameter. Here I argue that, despite this overall overlap, persistent sources have – on average – later-type, more evolved counterparts, and discuss the hypothesis that SFXTs are – on average – a younger population, as well as some of its possible implications.

Keywords. accretion, stars: atmospheres, stars: early-type, stars: mass loss, stars: neutron, stars: winds, outflows, X-rays: binaries

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1. Introduction

It is now more than a decade since Supergiant Fast X-ray Transients (SFXTs) were identified as a distinct class of x-ray sources with blue supergiant donors (Negueruela *et al.* 2006a; Smith *et al.* 2006). These objects spend most of the time at very low x-ray luminosity (or simply undetected), and occasionally present flares lasting a few hours, which normally consist of a few short (several hundred seconds) peaks, with large flux changes on a timescale of minutes (Sguera *et al.* 2006; Blay *et al.* 2008). The nature of their counterparts, together with their x-ray spectral properties, suggested that, just like the majority of Supergiant X-ray Binaries (SGXBs), they are fed by the radiation-driven wind of the companion. SGXBs are persistent x-ray sources, always detected by pointing instruments with adequate sensitiveness, typically displaying $L_X \approx 10^{36}$ erg s^{-1} with moderate short-time variability. Several ideas were put forward to provide an explanation for the obvious differences (together with many similarities) between SGXBs and SFXTs: accretion from a clumpy wind (Walter & Zurita Heras 2007), clumpy winds combined with orbital geometry (Negueruela *et al.* 2008a), inhibition of accretion by very strong magnetic fields in the neutron stars (Bozzo *et al.* 2008). However, it soon became clear that, although these hypotheses could explain the behaviour of a given source, none of them on its own can account for the wide variety of behaviours observed (see, e.g., discussion in González-Galán *et al.* 2014). A combination of several factors needs to be invoked.

Progress towards a global solution has been slow. One key difficulty is inherent to the very nature of SFXTs: they are only detectable as x-ray sources for very short time spans. As a consequence, it is very hard to obtain accurate information about them, because data tend to have low signal to noise ratio. For example, spectral evolution with luminosity is poorly constrained, as the sources rarely show high luminosity. Likewise, pulsation periods have been claimed for many SFXTs, but they have proved very difficult to confirm, as long intervals of good data cannot be obtained. Careful analysis of several

Table 1. Persistent SGXBs with known counterparts, ordered by increasing $P_{\rm orb}$. Spectral types in boldface are consistent with results of quantitative spectral analysis, while those in italics are less secure than the others, as they are based on K-band spectra only. The reference for the spectral type is given.

System	Spectral Type	$P_{\rm orb}$ (d)	e	Ref.
4U 1700−37	**O6 Iafcp**	3.4	≈ 0	(1)
4U 1538−52	B0 I	3.7	$\lesssim 0.2$	(2)
4U 1909+07	**B1 − 3 I**	4.4	~ 0	(3)
SAX J1802.7−2017	B1 Ib	4.6	$\lesssim 0.2$	(4)
Cyg X-1	**O9.7 Iab**	5.6	≈ 0	(5)
XTE J1855−026	BN0.2 Ia	6.1	< 0.04	(6)
IGR J16493−4348	*∼B0.5 Ib*	6.8	~ 0	(7)
4U 1907+097	**O8-9 I**	8.4	~ 0.3	(8)
Vela X-1	**B0 Iab**	8.9	0.09	(9)
IGR J16320−4751	*BN0.5 Ia*	9.0	~ 0.2	(10)
EXO 1722−363	B0 − 1 Ia	9.7	~ 0.2	(11)
OAO 1657−415	Ofpe/WN9	10.4	0.11	(12)
2S 0114+65	B1 Ia	11.6	≈ 0.18	(13)
IGR J19140+0951	B0.5 Ia	13.6	?	(4)
1E 1145.1−6141	B2 Ia	14.4	0.2	(14)
GX 301−2	**B1 Ia$^+$**	41.5	0.46	(15)

References: (1) Clark *et al.* (2002); (2) Reynolds *et al.* (1992); (3) Martínez-Núñez *et al.* (2015); (4) Torrejón *et al.* (2010); (5) Herrero *et al.* (1995); (6) Own data; (7) Pearlman *et al.* (2018); (8) Cox *et al.* (2005); (9) Giménez-García *et al.* (2016); (10) Coleiro *et al.* (2013); (11) Mason *et al.* (2010); (12) Mason *et al.* (2012); (13) Reig *et al.* (1996); (14) Densham & Charles (1982); (15) Kaper *et al.* (2006).

years of monitoring with *INTEGRAL* (Sidoli & Paizis 2018) and *Swift* (Romano 2015) have finally allowed a good characterisation of SFXTs as a class. Following Sidoli (2017), SFXTs are hard x-ray sources with OB supergiant donors presenting:

- A low duty cycle ($<5\%$) in bright x-ray flares (where bright means $L_{\rm X} \gtrsim 10^{36}$ erg s^{-1}).
- A high dynamical range ($L_{\rm max}/L_{\rm min} \gtrsim 100$).
- A low time-averaged luminosity ($L_{\rm X} \lesssim 10^{36}$ erg s^{-1}, below the typical time-averaged luminosity of SGXBs.)

Moreover, comparison of these large datasets with homogeneous observations of SGXBs shows that the behaviour of SFXTs as x-ray sources is different from that of classical SGXBs at a statistically significant level (Bozzo *et al.* 2015; Romano 2015) in terms of the properties listed above.

2. The optical counterparts

What are then the reasons for this difference? Both SFXTs and SGXBs are binaries consisting of a compact object (in fact, with the exception of Cyg X-1, all confirmed systems contain, or are believed to contain, a neutron star) and an OB supergiant. Table 1 lists (most of) the SGXBs with well-characterised counterparts, together with some of their orbital properties. The earliest spectral type is seen in 4U 1700−37, with a luminous O6 supergiant companion. The latest type counterparts are around B2. Most counterparts are moderate-luminosity B0 − 1 supergiants. Table 2 lists the same parameters for SFXTs and related objects. The counterparts to SFXTs do not show significantly different spectral types (see Sidoli 2017; fig. 2). The spin periods of the neutron stars in SGXBs range from a few hundred seconds to about one thousand, with only two exceptions: OAO 1657−415 has a shorter period of only 38 s, while 2S 0114+65 has a very long 2.6 h period. The spin periods of neutron stars in SFXTs, as noted, are not known. The neutron stars in SGXBs typically have surface magnetic fields between 10^{12} and 10^{13} G (Revnivtsev & Mereghetti 2015; although the long spin period of 2S 0114+65

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Table 2. Objects that have been classified as SFXTs with known counterparts. The top panel lists systems that likely are high-eccentricity SGXBs. The second panel lists intermediate systems (though those in italics have also been classified within other categories). The bottom panel includes objects with typical SFXT behaviour. Spectral types in boldface are consistent with results of quantitative spectral analysis, while those in italics are less secure than the others, as they are based on K-band spectra only. The reference for the spectral type is given.

System	Spectral type	P_{orb} (d)	e	Ref
IGR J11215−5952	**B0.5 Ia**	165	High	(1)
IGR J00370+6122	**BN0.7 Ib**	15.7	0.6	(2)
IGR J16465−4507	**B0.5 Ibn**	30.2	Unknown	(3)
IGR J18483−0311	B0 – 1 Iab	18.5	High?	(4)
IGR J17354−3255	*O9 Iab*	8.4	Unknown	(5)
SAX J1818.6−1703	B0.5 Iab	30	0.3 – 0.4	(4)
IGR J16418−4532	*BN0.5 Ia*	3.7	Unknown	(5)
IGR J16328−4726	*O8 Iaf*	10.1	Unknown	(5)
IGR J16479−4514	**O8.5 Ib**	3.3	Moderate?	(6)
AX J1841.0−0536	B0.2 Ibp	6.5?	Low?	(7)
IGR J08408−4503	O8.5 Ib-II(f)p	9.5	0.63	(8)
XTE J1739−302	O8 Iab(f)	51.5??	Unknown	(9)
IGR J17544−2619	**O9 Ib**	4.9	Moderate?	(10)
AX J1845.0−0433	O9 Ia	5.7?	Low to moderate	(7)

References: (1) Lorenzo *et al.* (2014); (2) González-Galán *et al.* (2014); (3) Chaty *et al.* (2016); (4) Torrejón *et al.* (2010); (5) Coleiro *et al.* (2013); (6) Negueruela *et al. in prep.*; (7) Negueruela *et al.* (2008b); (8) Gamen *et al.* (2015); (9) Negueruela *et al.* (2006b); (10) Giménez-García *et al.* (2016)

has sometimes be interpreted in terms of a higher magnetic field). Spectral properties of SFXTs suggest similar values, with the detection of a cyclotron line in the prototypical IGR J17544−2619 (Bhalerao *et al.* 2015) providing strong evidence in this sense. The orbital periods of SGXBs range from 3.4 d to 14.4 d and almost all have low eccentricity (GX 301−2 is a very peculiar case: with a longer orbital period and higher eccentricity, and a very massive and luminous hypergiant companion, it cannot be considered typical of SGXBs). The orbital periods of SFXTs cover approximately the same range, although there is a possible 51.5 d period in XTE J1739−302 (Drave *et al.* 2010). In all, the average properties of both kinds of system seem very similar. The only possibility of a systematic difference lies in the spin periods, but there is no *a priori* strong reason to expect it. In fact, the theory of quasi-spherical accretion on to magnetised neutron stars (Shakura *et al.* 2012), the most widely accepted model for the production of x-rays in wind-accreting systems, assumes that the neutron stars rotate slowly.

Since the global x-ray behaviour must be determined by the interaction of the stellar wind and the neutron star magnetosphere (see Sander in this proceedings and references therein), the properties of mass donors should play a role in setting the differences. The possibility that the donors in SFXTs are not true supergiants has recently been raised. This is not a straightforward question, as O-type supergiants are still H-core burning objects and thus not fundamentally different from O-type dwarfs. Their morphological differences are mostly due to higher mass loss rates at higher luminosities (see, e.g., Holgado *et al.* 2018), and so a lower luminosity would imply weaker winds. To test this possibility, we collected high-quality VLT/ISAAC spectra of the IR counterpart to IGR J16479−4514, the SFXT with the shortest orbital period. In fact, this heavily-reddened eclipsing transient presents the shortest (by little) orbital period for any wind-accreting system, $P_{orb} = 3.32$ d (Sidoli *et al.* 2013). Rahoui *et al.* (2008) estimated an early spectral time around O8.5 I. According to calibrations (e.g. Martins *et al.* 2005), such a star has a

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radius of $\approx 22\,R_\odot$, while a dwarf of the same spectral type only has $R_* \approx 8\,R_\odot$, allowing for a wider orbit. Using tailored CMFGEN models, we find stellar parameters typical of an O8.5 Ib star (Negueruela *et al.* in prep.), confirming that even in this extreme case the counterpart is a supergiant. The neutron star cannot be further away from the surface of the donor than in most classical SGXBs. Therefore the environmental conditions for the neutron star must be quite similar to those in some classical SGXBs. This is strong evidence for the existence of gating mechanisms close to the surface of the neutron star, and joins similarly strong evidence coming from analysis of x-ray data (Romano 2015; Bozzo *et al.* 2015; Pradhan *et al.* 2018).

Of course, the key to this discussion lies on the accuracy of the spectral types and the reliability of the stellar parameters derived from them. The counterparts to many x-ray binaries are distant and highly obscured by intervening material along the line of sight and thus obtaining high-quality optical spectra is not always feasible. Moreover, different groups use different techniques for spectral classification. The MK system is based on features lying in the blue side of the spectrum, which is much more heavily reddened than the red side and thus not always accessible. A good spectral classification of OB stars is possible with near-IR spectra if a wide spectral range is observed, so that many features can be used for the classification. On the other hand, classifications based on a small spectral range (e.g. K-band spectra only, as in Nespoli *et al.* 2008) have a much higher uncertainty, because there are very few features in the range and most are sensitive to more than one physical parameter, including the mass loss rate. Even when spectral types are accurate, their calibration against stellar parameters is necessarily loose, because of physical reasons (see Simón-Díaz *et al.* 2014; Holgado *et al.* 2018). Therefore stellar parameters based on quantitative spectral fitting with suitable model atmospheres (see the contribution by Sander) are always more reliable. To take these difficulties into account, the spectral types in Tables 1 and 2 have been coded: spectral types in boldface are supported by quantitative spectral analysis. Spectral types in roman type are based on blue spectra or a combination of several red and near-IR bands, while spectral types in italics are derived from single-band IR spectra or indirect methods.

3. A working hypothesis

When the reliability of spectral types is taken into account, we can see some interesting trends emerging. Given the size of existing samples, such trends cannot be considered statistically significant†, but are still highly suggestive. When we look at the SGXBs, two systems have donors with very strong winds, 4U 1700−37 with an O6 Iaf supergiant (pressumably a very massive star; see Clark *et al.* 2002) and OAO 1657−415, which likely has followed a different evolutionary path from most other systems (Mason *et al.* 2012). A third one, 4U 1907+097, has on O-type supergiant as companion. All the other ones have companions in a very narrow spectral range, from O9.7 to B2, with the vast majority concentrated between B0 and B1. Objects with orbital periods below 8 d have essentially circular orbits, while longer periods imply moderately eccentric orbits. The exception is again 4U 1907+097, with a higher eccentricity, only surpassed by the peculiar system GX 301−2.

If we look now at Table 2, we find in the top panel three objects that have been associated with SFXTs, but seem more closely related to SGXBs. They all have companions in the B0−1 range. The difference with the main SGXB group lies in their wide (and

† Indeed, if we take into account the many difficulties in obtaining reliable spectral types, it is quite possible that the whole Galactic population of wind-fed systems is insufficient to give a statistically significant sample (see Tabernero *et al.* 2018, for a robust estimation of the sample sizes needed to ascertain a difference in average spectral type between two populations).

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eccentric) orbits. These subset most likely consists of the SGXBs with the widest orbits, for which orbital geometry alone likely leads to the transient-like behaviour, as has also been proposed by Walter *et al.* (2015) for a number of objects. The second panel contains objects that have sometimes been classified as intermediate between SGXBs and SFXTs. Their counterparts are again in the same spectral range and there are reasons to at least suspect that their orbits are eccentric. The third panel contains those objects that have been confirmed as SFXTs, following Romano (2015). The spectral types are decidedly earlier. With the exception of the peculiar counterpart to AX J1841.0−0536, all fall within O8 and O9.

Although the difference in spectral type is small and likely lacks statistical significance, it seems too well defined to be due to random sampling. If the counterparts of SFXTs are consistently earlier, this implies somewhat smaller stars and – crucially – faster, less dense winds. While the counterparts to SGXBs straddle the bi-stability jump – a sudden change in wind conditions happening at temperatures cooler than 25 000 K that results in higher mass loss rates and slower winds (e.g. Vink 2018), two conditions that favour accretion – the counterparts to SFXTs lie well to the hot side, with temperatures $> 30\,000$ K. These faster, less dense winds imply that – on average – conditions will be less favourable for accretion over a wide range of orbital parameters and neutron star properties. Interestingly, this small difference in spectral types also implies that, according to standard evolutionary tracks, the average donor in an SFXT will evolve into the average donor in an SGXB. This does not necessarily mean that all SGXBs must have had an earlier phase as SFXTs†, but is strongly suggestive of the idea that SFXTs, as a population, are younger than SGXBs.

What would this hypothesis of SFXTs as a younger population than SGXBs mean? In fact, there are two interpretations – not at all mutually exclusive – to such a statement. On the one hand, this youth may refer to the evolutionary status of the mass donor, as discussed in the previous paragraph. But it can also mean that the neutron star is younger, i.e. that the supernova explosion took place more recently. If so, the binary system has had less time to evolve. For example, assuming that all O star + NS systems form with some eccentricity due to mass loss and a kick during the explosion, the fact that all SGXBs with short ($\lesssim 10$ d) orbital period have (almost) circular orbits suggests an efficient mechanism for circularisation (see González-Galán *et al.* 2014). The very high eccentricity of a system like IGR J08408−4503, on the other hand, indicates that there has not been time for circularisation. Even the short-period systems IGR J16479−4514 and IGR J17544−2619 seem to require some eccentricity to explain their lightcurves (Ducci *et al.* 2010; Bozzo *et al.* 2016), again pointing to a relatively recent formation‡. If this second sense of youth also applies to SFXTs, then the properties of

† This idea of late-O supergiants evolving into B-type supergiants must be interpreted in a broad, general sense. According to the models in Martins & Palacios (2017), late-O supergiants are spread between the $30\,M_\odot$ and $40\,M_\odot$ tracks, with observations showing some objects at slightly lower masses. In the absence of dynamical mass determinations, we assume that counterparts to SFXTs lie in this range – those of Ib luminosity class not very far above $30\,M_\odot$, and perhaps even less massive, given the tendency of counterparts in HMXBs to be undermassive. Such objects evolve into B1 – 2 Ia supergiants. On the other hand, objects with classifications B0 – 1 Ib probably come from stars with masses $\approx 25\,M_\odot$, which have luminosity class II-III when late-O stars. IGR J00370+6122 has a B0.7 Ib counterpart (verging on luminosity class II) with a moderately low mass $\approx 15\,M_\odot$, a bit lower than expected for a star of its spectral type. This object cannot have been an O-type supergiant earlier in its life, but probably had a spectral type close to O9.5 III.

‡ This scenario is further reinforced by the high eccentricity of 4U 1907+097, the only SGXB whose counterpart is similar to those of SFXTs. It could be argued that these systems with short orbital periods and moderate eccentricity are the descendents of binaries that formed with such a high eccentricity that they required more time than the others to circularise. Again, we

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the neutron stars in these systems may also show some differences with respect to those in classical SGXBs, having had less life time for spin down and magnetic field decay – with fast rotation and high fields again contributing to make accretion less effective. In this respect, it is worth remembering that the spin periods of neutron stars in wind-accreting systems are thought to be determined by evolution during the propeller phase, i.e. before accretion begins (see Li *et al.* 2016 and references therein). If the system formed when the mass donor was close to the O-supergiant phase – which, we should not forget, is still H-core burning – the equilibrium period may be noticeably different from that in a system formed when the mass donor was still a dwarf. In any case, in order to understand the effect of system age on its x-ray properties, we still need a much better knowledge of the different evolutionary pathways leading to HMXB formation and the consequences of rejuvenation on O-type stars that accrete substantial amounts of mass from their binary companions (cf. Dray & Tout 2007, and references therein.)

4. Conclusions

The main ideas discussed in this paper are:

• Gating mechanisms must be at work to explain the existence of SFXTs as a separate class. These mechanisms are seen to operate very differently in systems with similar orbital and wind parameters overall. The theory of quasi-spherical accretion on to magnetised neutron stars (Shakura *et al.* 2012) provides a firm base for such mechanisms, either through magnetic-field interaction (Shakura *et al.* 2014), or the accumulation mechanism proposed by Drave *et al.* (2014).

• In consequence, differences in behaviour must be due to specific parameter combinations, which are hard to identify and test. We are limited by small sample size in a very large parameter space.

• The idea that SFXTs represent an earlier stage for (some) SGXBs is probably worth exploring.

Acknowledgements

I would like to thank all my collaborators in binary work, especially David Smith, Sylvain Chaty and J. Simon Clark, for many fruitful discussions. This research is partially supported by MinECO/FEDER under grant AYA2015-68012-C2-2-P and Ministerio de Educación y Ciencia under grant PRX14-00169.

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lack the numbers to show a statistically significant effect, but the sample available is suggestive of evolution, with 4U 1907+097 qualifying as a SGXB once its eccentricity has decreased below a threshold for which its stellar wind is strong enough to favour accretion.

https://doi.org/10.1017/S1743921319001285 Published online by Cambridge University Press

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Discussion

Sander: Knowing that the amount of existing spectroscopic analyses for mass donors is very limited, did you take a look at the abundances of the donors from what you would define as the "true" SFXTs? Do they differ from the other ones?

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Negueruela: So far there are analyses for only two SFXTs. In the case of IGR J16479−4514, the data are only good enough for stellar parameter determination. Giménez-García *et al.* (2016) calculated CNO abundances for IGR J17544−2619 and the prototypical SGXB Vela X-1, finding almost identical values in the two objects. If the connection between the two types of object is indeed evolutionary, differences are likely to be marginal, in the sense of the B-type supergiants showing a slightly more advanced stage, with a higher He fraction, more N and less C. In most of the cases analysed, the CNO abundances clearly display the effects of evolution, but at values that are compatible with the effect of fast rotation on an isolated O-type star. The most obvious signs of recent binary interaction are the very high rotational velocities of some systems, most notably IGR J16465−4507 (Chaty *et al.* 2016).

Pradhan: Would it be possible to distinguish the age of SGXBs and SFXTs from the nature of the companion stars?

Negueruela Not really. The difference pointed out here is in terms of average spectral type, not the types of individual stars. In fact, this difference is quite small and it can be quite difficult to show its statistical significance even if larger samples of wind-accreting systems are discovered.

Karino: Even though donors in SFXTs are young and emit fast winds, the wind condition should have a large variety, since orbital periods show large differences. So, how does the fact that donors are young affect the accretion properties?

Negueruela: I have to stress again that I am using the term "younger" in a broad sense and that I am talking about the bulk properties of the population. The accretion conditions depend on the interaction between the wind and the neutron star. My hypothesis is that fast, low density winds allow gating mechanisms to work more effectively than dense, slow winds. But the efficiency of gating mechanisms must depend on orbital parameters and very likely also on neutron star parameters. Whether a system behaves like an SGXB, an SFXT or something intermediate will depend on the specific combination of all these variables in that system.

Pradhan: So can we say that the difference between SFXTs and HMXBs lies in the wind velocity?

Negueruela: Not quite. I think that your recent paper (Pradhan *et al.* 2018) provides strong evidence for the existence of gating mechanisms. But wind conditions very likely determine whether these mechanisms act effectively. Unfortunately, directly measuring wind velocities is in practice impossible for most wind-accreting system, as it can only be done with UV spectra, which cannot be obtained for highly obscured sources.