SUPERGIANT FAST X-RAY TRANSIENTS: A NEW CLASS OF HIGH MASS X-RAY BINARIES UNVEILED BY *INTEGRAL*

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ABSTRACT

INTEGRAL monitoring of the Galactic Plane is revealing a growing number of recurrent X-ray transients, characterised by short outbursts with very fast rise times ($\sim$ tens of minutes) and typical durations of a few hours. Here we show that several of these transients are associated with OB supergiants and hence define a new class of massive X-ray binaries which we call Supergiant Fast X-ray Transients. Many other transient X-ray sources display similar X-ray characteristics, suggesting that they belong to the same class. Since they are difficult to detect and their number is growing fast and steadily, they could represent a major class of X-ray binaries.

Key words: binaries: close — stars: supergiants – X-rays: binaries.

1. INTRODUCTION

High Mass X-ray binaries (HMXBs) are X-ray sources composed of an early-type massive star and an accreting compact object. Most known HMXBs are Be/X-ray binaries, systems consisting of a neutron star accreting from the disc around a Be star. Even though a few Be/X-ray binaries are persistent weak X-ray sources (with $L_{\rm X} \sim 10^{34}\ {\rm erg\,s^{-1}}$), the majority are transients, displaying bright outbursts with typical duration on the order of several weeks.

The second major class of HMXBs contains early-type supergiants. The compact object is fed by accretion from the strong radiative wind of the supergiant. These objects are persistent sources, with luminosities around $L_{\rm X} \sim 10^{36}\,{\rm erg\,s^{-1}}$, very variable on short timescales, but rather stable in the long run. Because of their relative brightness and persistent nature, it has been generally assumed that Supergiant X-ray Binaries (SGXBs) were easy to detect. About a dozen SGXBs were known before the launch of *INTEGRAL*, most of them having been discovered in the early days of X-ray astronomy. This low number was generally attributed to a real scarcity of such systems, as the short duration of the supergiant phase would result in very short lifetimes.

Since the launch of *INTEGRAL*, the situation is changing dramatically. Several new sources have been detected displaying the typical characteristics of SGXBs (Walter, these proceedings). In most cases, the sources had not been detected by previous missions due to high absorption, which renders their spectra very hard. Here we show that an even larger population of X-ray sources with OB supergiant companions may lie hidden in the Galaxy, undetected because of its transient nature.

2. X-RAY SOURCES WITH FAST OUTBURSTS

XTE J1739−302 = IGR J17391−3021

XTE J1739−302 was discovered during an outburst in August 1997 (Smith et al., 1998). Further observations, mostly with *RossiXTE*, but also with *ASCA* showed it to be a strange transient with very short outbursts, lasting only a few hours (Smith et al., 2006). Monitoring of the Galactic Centre region with *INTEGRAL* reveals that flares are rare, with typical intervals between outbursts of several months (Sguera et al., 2005).

The outbursts start with a very sharp rise (with a timescale < 1 h) and sometimes show complex structure, with several flare-like peaks (Lutovinov et al., 2005a; Sguera et al., 2005). The X-ray spectrum during the outbursts is generally very absorbed, though the absorption is variable. Good fits can be achieved with either a power law with a high-energy cut-off or a thermal bremsstrahlung

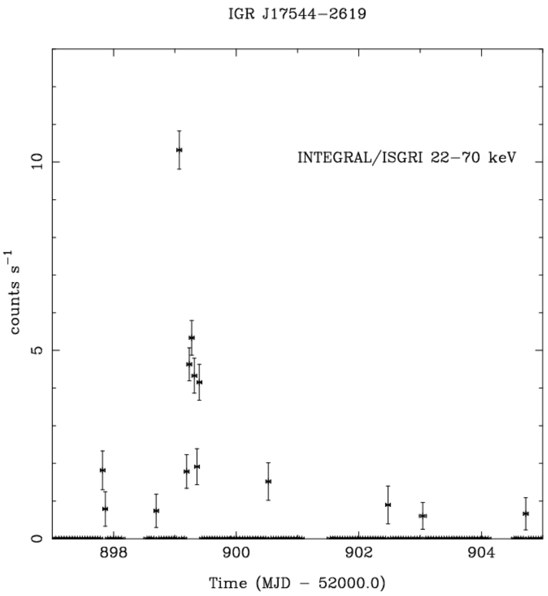

Figure 1. A typical outburst from a SFXT. INTEGRAL lightcurve for IGR J17544−2619 during the flare on 2003 September 17th. The data have been downloaded from the public data archive at the ISDC.

model with $kT \sim 20$ keV (Smith et al., 2006; Lutovinov et al., 2005a). Such spectra are typical of accreting neutron stars in a HMXB. The luminosity at the peak of the outbursts approaches $L_{\rm X} \sim 10^{36}\ {\rm erg\,s^{-1}}$, also typical of HMXBs.

The source was not detected during most of an *ASCA* pointing in March 1999 (with an upper limit $L_{\rm X} < 10^{33}\ {\rm erg\,s^{-1}}$), but went into outburst at the end of the same observation. *Chandra* detected the source at a moderate luminosity $L_{\rm X} \sim 10^{34}\ {\rm erg\,s^{-1}}$, allowing the identification of the counterpart (Smith et al., 2006). VLT/FORS1 spectra taken in May 2004 show the counterpart to be an O8 Iab(f) star, placed at a distance ≈ 2.6 kpc (Negueruela et al., 2006). Interstellar absorption is much lower than the absorption implied by X-ray spectral fits.

IGR J17544−2619

IGR J17544−2619 was discovered by *INTEGRAL* during a short flare ($\sim$ 2 h; see Fig. 1) on 2003 September 17th (Sunyaev et al., 2003). Six hours later, it showed a longer (8 h) double-peaked outburst (Grebenev et al., 2003). On 2004 March 8th, it showed a complex outburst lasting more than 8 h (Grebenev et al., 2004).

The source was observed by *XMM-Newton* on 2003 September 11th and 17th and in both cases seen at $L_{\rm X} \sim 10^{35}\ {\rm erg\,s^{-1}}$ (González-Riestra et al., 2004), though it was not detected during a serendipitous observation in March 2003 ($L_{\rm X} \lesssim 2 \times 10^{32}\ {\rm erg\,s^{-1}}$). *Chandra* may have observed its quiescent state on 2004 July 3rd, as it was detected at only $L_{\rm X} \sim 5 \times 10^{32}\,{\rm erg\,s^{-1}}$ and displaying a soft spectrum (In't Zand, 2005). In outburst, the spectrum is hard and moderately absorbed, with evidence for some variation in the amount of absorbing material.

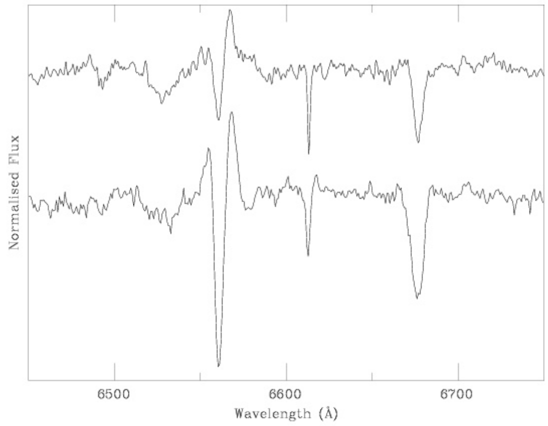

Figure 2. Hα spectra of the counterparts to IGR J17544−2619 (top) and IGR J16465−4507 (bottom). Both display weak P-Cygni profiles, indicative of moderate mass loss.

The counterpart to the source has been unambiguously identified with the *XMM-Newton* and *Chandra* positions. Spectra taken with NTT/EMMI show it to be an O9 Ib supergiant, with a weak wind (see Fig. 2) at a distance of $\sim$ 3 kpc (Pellizza et al., 2006).

IGR J16465−4507

IGR J16465−4507 was discovered by *INTEGRAL* during an X-ray flare on 2004 September 7th (Lutovinov et al., 2004). A subsequent *XMM-Newton* observation (Lutovinov et al., 2005b) revealed that the source is a pulsar with $P_{\rm spin} = 228$ s and is extremely absorbed ($N_{\rm H} \sim 7 \times 10^{23}\ {\rm cm^{-2}}$).

No further flares have been reported, but the *XMM-Newton* error circle contains only one star. NTT/EMMI spectra of this object were taken in February and March 2005. The blue spectrum, displayed in Fig. 3, is rather noisy, but allows an approximate classification. While the object is very obviously an early B-type star, the strength of all metallic lines indicates that it is a supergiant. Comparison to the spectrum of the B1 Ib supergiant ζ Per rebinned to the same dispersion clearly shows that the lines are very broad for a supergiant, suggesting a very high rotational velocity, a typical characteristic of HMXBs.

The presence of strong C III 4650Å and moderate Si III lines, while He II 4686Å is absent, is only compatible with a luminous star in the B0−B1 range. Unfortunately, the signal to noise of the spectrum falls below ~ 20 around λ4100Å and we cannot determine the strength of the Si IV lines that would allow an exact classification. The Hα spectrum (see Fig. 2) shows evidence for a moderate mass loss.

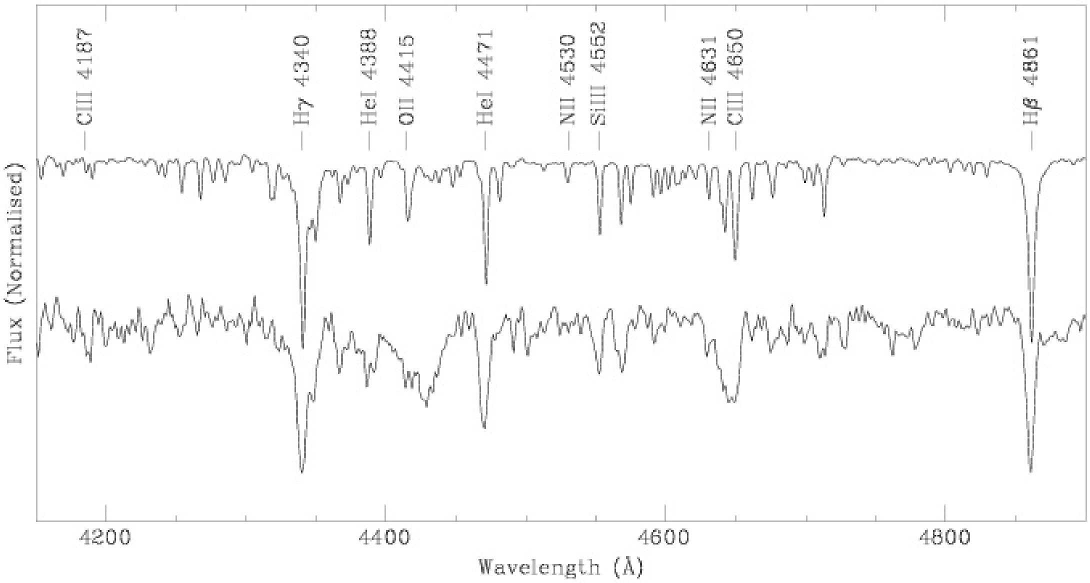

Figure 3. The spectrum of the optical counterpart to IGR J16465−4507 (bottom), compared to that of the B1 Ib supergiant ζ Per, rebinned to the same dispersion. The strength of the metallic lines indicates that the counterpart is a supergiant.

AX 1845.0−0433

AX 1845.0−0433 was discovered by *ASCA* during a strong flare in 1993. The outburst consisted of a very fast rise (on the order of a few minutes) followed by a number of peaks during the next few hours. The spectrum was well fit by an absorbed power law (Yamauchi et al., 1995). No further X-ray activity has been reported.

The *ASCA* error circle was studied by Coe et al. (1996), who found only one remarkable object, a late O-type supergiant. This star has been monitored with the 1.3-m telescope at Skinakas observatory. Some of the spectra are shown in Fig. 4. The star shows strong $H\alpha$ emission, typical of a luminous supergiant. Both the shape and strength of the line are variable, sometimes from night to night. Such variability is a typical signature of an interacting binary.

AX J1841.0−0536

AX J1841.0−0536 was observed as a violently variable transient by *ASCA* in April 1994 and then again in October 1999 (Bamba et al., 2001). The source showed multi-peaked flares with a sharp rise (tenfold increase in count-rate over $\sim$ 1 h). Analysis of the *ASCA* data revealed that the source is a pulsar with $P_{\rm spin} = 4.7$ s. The spectrum can be fit by an absorbed power law plus iron line (Bamba et al., 2001). Based on the detection of X-ray flares with a sharp rise, Bamba et al. (2001) suggested that AX 1845.0−0433, AX J1841.0−0536 and XTE J1739−302 could be members of a class with common physical features.

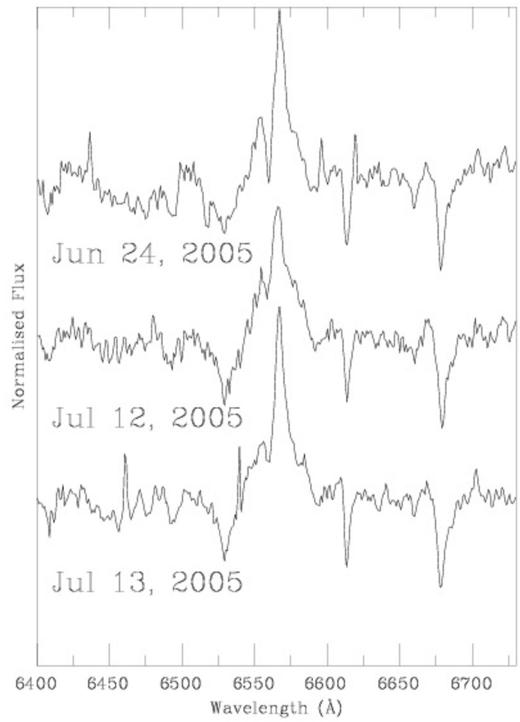

Figure 4. $H\alpha$ spectra of the proposed counterpart to AX 1845.0−0433, displaying strong variability, even between consecutive nights, a typical signature of an interacting binary.

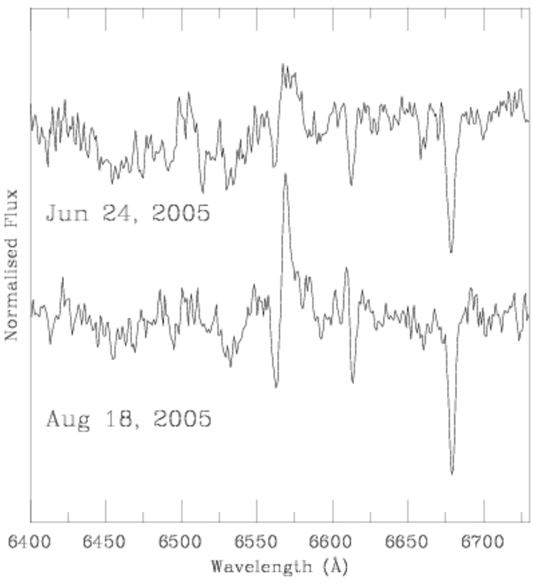

Figure 5. Hα spectra of the counterpart to AX J1841.0−0536, showing P-Cygni profiles indicative of the stellar wind of a luminous star.

A *Chandra* observation of the field revealed the counterpart to AX J1841.0−0536, a reddened star with Hα in emission (Halpern et al., 2004). We have taken spectra of this star with the 2.2-m at Calar Alto and the 1.9-m at SAAO. Though the spectra are very noisy, they strongly resemble that of the counterpart to IGR J16465−4507, displaying a very strong C III 4650Å line and no He II 4686Å. Therefore, it is also likely to be a luminous star in the B0−1 range.

Some red spectra have been taken with the 1.3-m telescope at Skinakas observatory (see Fig. 5). Again we find a shape reminiscent of a P-Cygni profile and strong variability, lending support to the idea that the object is a supergiant rather than a Be star. A fast outburst observed by *INTEGRAL* (IGR J18410−0535) has been attributed to this source (Halpern & Gotthelf, 2004).

3. SUPERGIANT FAST X-RAY TRANSIENTS: A NEW CLASS?

The five sources described in the previous section are characterised by the occurrence of X-ray outbursts of a very different nature from those seen in other X-ray binaries. These outbursts are very short (lasting from ~ 3 to ~ 8 hours) and present very sharp rises, reaching the peak of the flare in $\lesssim 1$ h. The decay is generally characterised by a complex structure, with two or three further flares. Three of the sources are associated with O-type supergiants. Though no pulsations have been detected, they display spectra typical of accreting neutron stars. The other two sources are X-ray pulsars and are associated with luminous early B-type stars. In all cases, the spectra show moderate or high absorption. In the case of XTE J1739−302 and IGR J17544−2619, which are better studied, the amount of absorbing material is variable.

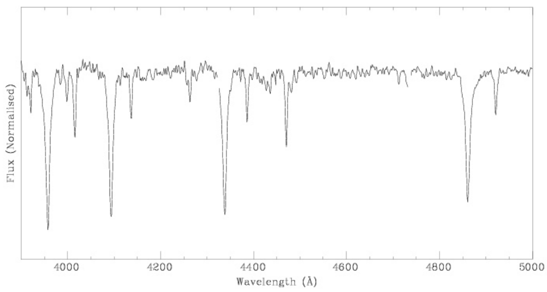

Figure 6. Optical spectrum of HD 168078.

We therefore propose that all these objects form a class of HMXBs which we call Supergiant Fast X-ray Transients (SFXTs), because of the fast outbursts and supergiant companions. They differ from classical wind-fed SGXBs, whose X-ray luminosity is variable but always detectable around $L_{\rm X} \sim 10^{36}\,{\rm erg\,s^{-1}}$. Quiescent fluxes of SFXTs have been near the sensitivity limit of focusing observatories, with values or upper limits in the range of $\sim 10^{32}$ to $\sim 10^{33}\,{\rm erg\,s^{-1}}$.

In spite of this difference, it must be noted that the commonalities between SFXTs and SGXBs are strong. As a matter of fact, at least three classical SGXBs have been observed to undergo bright flares on the same timescale: Vela X-1 (Laurent et al., 1995; Krivonos et al., 2003), 1E 1145.1−6141 (Bodaghee et al., 2004) and Cyg X-1 (Golenetskii et al., 2003, and references therein).

4. OTHER SOURCES DISPLAYING FAST OUTBURSTS

SAX J1818.6−1703

SAX J1818.6−1703 was discovered by *BeppoSAX* during a strong short outburst (with a rise time of ~ 1 h), in March 1998 (In't Zand et al., 1998). *INTEGRAL* detected a double-peaked outburst in September 2003 (Grebenev & Sunyaev, 2005) and two more in October 2003 (Sguera et al., 2005). Other fast outbursts have been observed with the ASM on *RossiXTE* (Sguera et al., 2005).

The X-ray lightcurve of SAX J1818.6−1703 is typical of a SFXT. The X-ray spectrum is very hard (Grebenev & Sunyaev, 2005). The optical counterpart to SAX J1818.6−1703 is not known. A bright early type star, HD 168078, is within both the *BeppoSAX* and *INTEGRAL* error circles. Spectra of this object, taken with the 1.3-m at Skinakas and the 1.9-m at SAAO show a normal B3 IV star, without indications of emission (see Fig. 6). As HD 168078 is not a convincing counterpart to SAX J1818.6−1703, it might be worthwhile to search the error circle for a reddened supergiant.

IGR J16479−4514

IGR J16479−4514 was discovered by *INTEGRAL* during an outburst in August 2003 (Molkov et al., 2003). Several other short outbursts with very fast rise times were observed by *INTEGRAL* during 2003 (Sguera et al., 2005). The X-ray spectrum of IGR J16479−4514 is a power-law with high-energy cut-off, typical of a HMXB with a neutron star (Lutovinov et al., 2005b). All these characteristics are strongly suggestive of a SFXT.

XTE J1901+014

XTE J1901+014 was discovered by *RXTE* during a very bright outburst (reaching 0.9 Crab) that lasted less than 8 h, in 2002 (Remillard & Smith, 2002). Analysis of *RXTE*/ASM data revealed another fast outburst in 1997 (Remillard & Smith, 2002). Several outbursts have been observed by *INTEGRAL*. The *INTEGRAL* error circle contains two *ROSAT* sources and one *Einstein* source, one of which could represent the quiescent state of XTE J1901+014 (Stephen et al., 2005).

AX J1749.1−2733

AX J1749.1−2733 was observed by *ASCA* at a relatively low luminosity on several occasions (Sakano et al., 2002). It has recently been reported to show fast X-ray outbursts during *INTEGRAL* observations (Grebenev, quoted in In't Zand 2005).

5. DISCUSSION & CONCLUSIONS

Most X-ray transients, whether Be/X-ray binaries or low mass X-ray binaries (having either neutron star or black hole companions), display outbursts typically lasting from a few weeks to months. Such durations are compatible with viscous timescales in a typical accretion disc. Fast outbursts, with much shorter durations, must be due to a completely different physical mechanism. Here we have shown that at least a fraction of the recurrent fast X-ray transients are associated with luminous OB stars, suggesting that the mass transfer mechanism feeding the accreting compact object is a radiative wind, and therefore have identified the class of SFXTs.

We must note that not every source displaying short X-ray outbursts may be assigned to the class of SFXTs. Flare stars and RS CVn binaries display short X-ray flares and superbursts from low mass X-ray binaries have similar durations, though rather different luminosities and lightcurves (e.g. Grebenev & Sunyaev, 2005). The HMXB 1A 0535−668, in the LMC, has shown very bright X-ray outbursts lasting only a few days, but these outbursts are locked in phase with the orbital period of the system and may be related to periastron passage in a very eccentric orbit (cf. Charles et al., 1983). IGR J00370+6122 could be a similar system (Reig et al., 2005). The black hole transient V4641 Sgr should not be grouped with SFXTs either. In this system, the mass donor is a B9 III giant (Orosz et al., 2001), which is not a massive star and cannot have a radiative wind. Moreover, its 1999 outburst was highly super-Eddington and accompanied by a huge optical brightening, properties that set it completely apart from SFXTs (Revnivtsev et al., 2002).

However, there are strong reasons to believe that the class of SFXTs comprises a much larger number of sources than the five objects described above. In Section 4, we list four reliable candidates, but other known sources might belong to this class. For example, the X-ray transient IGR J11215−5952 was observed by *INTEGRAL* during the decaying phase of an outburst. It is likely to be related to SFXTs if its association to the B1 Ia supergiant HD 306414 is confirmed (cf. Negueruela et al., 2005).

If only some of these candidates are confirmed, the number of SFXTs would already be comparable to that of classical SGXBs. We must consider, however, that classical SGXBs are persistent bright X-ray sources, while SFXTs are transient sources with very short duty cycles. Most of them are detectable, unless directly pointed at by *Chandra* or *XMM-Newton*, only for a few hours every several months. It is hence not surprising that most of the SFXTs so far found lie on the vicinity of the Galactic Centre, a region extensively monitored by *INTEGRAL* and other satellites.

But, if SFXTs are very difficult to detect, and we already know several of them in the region around the Galactic Centre, the implication is that the population of SFXTs in the Galaxy is much larger than the ten or so objects already known. As a matter of fact, it is difficult to avoid concluding that most binaries containing a supergiant and a compact object **must** be SFXTs or entirely quiescent. If we take into account the large number of obscured persistent HMXBs that *INTEGRAL* is discovering, it seems clear that the numbers of HMXBs must have been severely underestimated.

The physical reason for fast outbursts is still unknown. Golenetskii et al. (2003) speculated that the outbursts in Cyg X-1 could be due to some form of discrete mass ejection from the supergiant donor. In't Zand (2005) also suspects that wind variability is the cause of fast outbursts. As we have shown here, an important fraction of fast transients have supergiant companions and at least three classical SGXBs have shown fast outbursts. It seems then that the fast outbursts are related to the mass transfer mode, wind accretion. They cannot be related to the nature of the companion, as they are seen in black hole systems (Cyg X-1), slow X-ray pulsars (IGR J16465−4507) and faster X-ray pulsars (AX J1841.0−0536).

There is increasing evidence suggesting that the winds of B-type supergiants are highly structured and may have a fundamentally clumpy nature (Prinja et al., 2005, and references therein). If these clumps survive to the distance at which the compact object is orbiting, they could give rise to sudden episodes of increased accretion rate. Alternatively, the outbursts could be related to the instability believed to be intrinsic to the wind accretion process (e.g. Foglizzo et al., 2005).

On the other hand, there is nothing in the optical properties of SFXTs setting them apart from classical SGXBs. It is therefore difficult to understand why their quiescent X-ray luminosities are rather lower. A possibility would be that SFXTs have wider orbits than SGXBs, and the compact object (in most cases, a neutron star) accretes from a less dense environment. This, however, would not explain why the sources spend some (still not quantified) fraction of time below detectability. If highly eccentric, wide orbits are invoked in order to explain the periods of very low X-ray luminosity, one would naïvely expect some (quasi-)periodicity in the recurrence of the outbursts, that has not been observed, as they would have to occur always relatively close to periastron.

Clearly, a more complete investigation of all the sources presented here is needed before common trends start to emerge and a characterisation of the group of SFXTs can be achieved. Understanding the reasons for their X-ray behaviour and the source of the difference with classical SGXBs will undoubtedly increase our knowledge of the accretion process and very likely provide valuable insights into the different paths leading to the formation of HMXBs and their subsequent evolution.

ACKNOWLEDGMENTS

IN is a researcher of the programme *Ramón y Cajal*, funded by the Spanish MCyT and the University of Alicante. This research is partially supported by the Spanish MCyT under grants AYA2002-00814 and ESP-2002-04124-C03-03.

Partly based on observations collected at the European Southern Observatory, La Silla, Chile (ESO 73.D-0081; 274.D-5010) and observations collected at the DSAZ, Calar Alto, operated by the MPI für Astronomie Heidelberg jointly with the Spanish CNA. We thank Calar Alto for allocation of director's discretionary time to this programme. Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology-Hellas and the MPI für Extraterrestrische Physik. This research has made use of the Simbad data base, operated at CDS, Strasbourg, France.

We are very grateful to Jorge Casares for carrying out the observations at SAAO. We also thank Leonardo Pellizza for advancing results on IGR J17544−2619.

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