Searching for Orbital Periods of Supergiant Fast X-ray Transients

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Abstract Building on the currently active program of observing High Mass X-ray Binaries (HMXBs), we describe here a challenging extension of the project for experienced AAVSO observers who want to push their observing to the limit. A new subclass of HMXBs, the Supergiant Fast X-ray Transients (SFXTs), have been recently discovered in *INTEGRAL* data and are still poorly understood. In these systems, a neutron star is accreting matter from the strong wind of its supergiant companion (typically of spectral type O–B), resulting in a conspicuous emission of x-ray radiation. At odds with the other previously known HMXBs, the SFXT sources display an extreme variability in x-ray output. The origin of this variability is presently unknown, and has led in the past three years to the suggestion that the SFXT sources might host neutron stars with ultra-strong magnetic fields or supergiant stars with peculiar ultra-dense clumpy winds. Our new program aims at determining the orbital parameters of all the known systems in this class (fifteen objects) in order to distinguish between the different theoretical models proposed to interpret the behavior of the SFXTs.

1. Description of the proposed program and scientific rationale

One of the most important results in high-energy astronomy was the discovery of x-ray binary systems; these systems comprise a compact object (a white dwarf, a neutron star, or a black hole) and a companion star, typically a main sequence star. In these systems, the compact object (if it is not a white dwarf) is formed during the final stages of the evolution of the binary through a supernova explosion (although a neutron star might also be formed by the accretion, induced collapse of a white dwarf). We consider in the following only the case in which the compact object is a neutron star. The mechanism that makes these binary systems very bright in x-rays is the accretion of matter from the companion star onto the compact object. Due to evolutionary processes, the companion star in these systems tends to lose a conspicuous fraction of its mass through the emission of a strong stellar wind and/or through so called Roche-lobe overflow. The strong gravitational field of the neutron star channels the inflowing matter toward its surface, where the gravitational potential energy is finally converted into electromagnetic radiation. Due to the compactness of the star and the relatively high velocity of the infalling matter (~1000 km/s), most of the radiation is emitted in the x-ray domain (0.1–100 keV). The accretion of matter onto a neutron star is thus a very efficient mechanism for converting gravitational energy into radiation, and it allows astronomers to study the nearby environment of an otherwise invisible compact object.

The study of x-ray emission from neutron star binary systems has proven to be very useful in past years for gaining information into the physics of accretion, the nuclear physics of neutron stars, and electromagnetic phenomena in the presence of a very strong magnetic field (the oldest neutron stars might have magnetic fields lower than 10^8 G, but for young objects the magnetic field can be > 10^{12} G and can reach 10^{15} G in the most extreme cases).

Among the large variety of binary systems with neutron stars, we propose to concentrate on the so-called supergiant high mass x-ray binaries (SgHMXBs). These systems are relatively young (< 10^7 years), are mostly distributed near the Galactic plane, and are characterized by circular orbits with relatively short orbital periods (from a few days up to ~30 days). Their companion stars are supergiants of spectral type O or B and they possess strong stellar winds, which are accelerated by the absorption in the wind itself of UV radiation from the star (line-trapping mechanism). Part of the stellar wind is captured and accreted onto the compact object which gives rise to a strong x-ray emission (x-ray luminosities can be up to few 10^{37} erg/s). In a few peculiar systems with very short orbital periods, accretion can also take place through a transient accretion disk that is formed around the neutron star during periods of intense mass loss rate from the supergiant companion. Due to the irregular and intense mass loss rate that characterize the supergiant stars, the majority of the SgHMXBs are persistent bright emitters in x-rays (10^{35}–10^{36} erg/s) and display a typical x-ray variability of a factor 10–50 along the neutron star orbit. Because of the large size of the companion stars, x-ray eclipses are commonly observed in many of the SgHMXBs, thus giving direct evidence of the binary nature of the system. In a large fraction of SgHMXBs, periodic x-ray pulsations are also observed;

these pulsations are due to the beamed radiation that is produced close to the magnetic poles of the accreting NS. The pulsation periods are distributed over a wide range from milliseconds up to few thousand seconds, and are observed to increase and/or decrease over time due to the interaction of the neutron star with the inflowing matter.

Recently, a new subclass of SgHMXBs, collectively termed *Supergiant Fast X-ray Transients* (SFXTs), have been discovered thanks to the x-ray observatory *INTEGRAL*. These sources are composed of an accreting neutron star and a supergiant companion, similar to the classical SgHMXBs (see Figure 1). However, at odds with the classical SgHMXBs, they display a much more pronounced variability in x-rays. SFXTs undergo sporadic outbursts which reach ~10^{37} erg/s^{-1} and last only a few hours; they then return to a quiescent state in which the x-ray luminosity decreases by up to a factor of ~10^5. Optical studies have already provided some detail about the supergiant stars in these systems, and in a few cases x-ray monitoring has been able to determine a rough orbital period (3–50 days) from the recurrence of the outbursts and from the x-ray eclipses (so far only in two sources). In five systems x-ray pulsations have also been discovered which provide the spin period of the neutron stars. All of these measurements have not revealed any peculiarity with respect to the classical SgHMXBs. Given the close similarity between SgHMXBs and SFXTs, the extreme x-ray variability of the latter sources remains, so far, unexplained.

In the past three years, several different models have been proposed in order to interpret the behavior of the SFXT sources. One of these models suggests that the accretion onto the neutron stars takes place from an extremely clumpy wind environment (see, for example, Walter and Zurita Heras 2007). According to this interpretation, the wind of the supergiant star in the SFXT is characterized by the presence of very dense "clumps" of material, which produce short and bright x-ray flares when they are accreted onto the neutron star. In this model, the orbital period of the system fixes the separation of the two stars and thus the probability of having an encounter between the neutron star and the clumps. Eccentric orbits were introduced to explain why the majority of the bursts are observed close to periastron in many SFXTs. Indeed, in an eccentric orbit one should expect that the probability for the neutron star to intercept one of the clumps along its orbit is larger close to the companion at periastron. Other models predict that the magnetic field of neutron stars in SFXTs are extremely high ($\gtrsim 10^{14}$ G), and this field regulates the duration and peak luminosity of the outbursts (Bozzo *et al.* 2008). In this model, the orbital period of the system plays a key role since it fixes the average value of the mass inflow rate that is interacting with the neutron star magnetic field along the orbit, causing the onset of the sporadic outbursts. A third model suggests that neutron stars in SFXTs might have transient accretion disks around them whose formation and extension is also dependent on the orbital period of the system (Ducci *et al.* 2010).

In all the suggested models, the orbital parameters of the SFXT sources play a fundamental role. Determining the orbital periods of the SFXTs, along with a measurement of their orbital eccentricity, is crucial for distinguishing among the different models to finally unveil the mechanism behind the peculiar x-ray variability of these sources.

2. Scientific objectives and the role of the AAVSO

Due to their unique behavior in x-rays, the SFXTs have gained much interest in the astronomical community over the past five years. This interest is also testified to by the high number of publications dedicated to the SFXTs during this period. However, despite the large amount of x-ray observing time that has been devoted in the past few years to investigate the SFXT sources, the origin of their extreme variability is still a matter of debate. The time is now propitious for beginning an in-depth investigation of these sources in the optical and infrared domain.

Up to now, both deep pointed and long-term monitoring programs using all the available x-ray observatories have been done for a large sample of the SFXT sources, and a systematic long-term optical monitoring of these sources is now required to bring our knowledge in this field a further step forward.

With our proposed program, we aim at investigating, in the optical and infrared domain (I, R, and V bands), the whole sample of the presently confirmed members in the SFXT class (fifteen objects). Useful details on all these sources are provided in Tables 1, 2, and 3. Our immediate objectives are:

• *Identify and measure the magnitudes of the SFXT counterparts in the optical and infrared domain.* Most of the SFXT spectral types have been determined in these energy bands (see Table 3), but some values are still missing (see the cases of, for example, IGR J17354-3255 and IGR J17407-2808). Filling in the missing magnitude values in Table 1 will be useful for improving our knowledge of the nature of the supergiant stars in the SFXT systems which, in turn, will give us further insight into the nature of these objects.

• *Determining, through optical and infrared monitoring, the orbital periods of all the selected candidates.* We are particularly interested in discovering the orbital periods of those sources for which the period is presently unknown. However, providing a confirmation and an improved estimate of the orbital period of those systems for which the period is already known will be useful as well. Indeed, the known orbital periods are still affected by rather large errors and thus do not allow us to predict, with the required accuracy, the time of periastron passage that would allow us to perform follow-up observations at longer wavelength infrared bands (especially the K band) and at x-ray wavelengths during different parts of their orbits.

• *Determining the value of the eccentricity of the orbit (if any).* This will be of particular interest in order for us to distinguish among the different models and clarify if there exists a significant difference between the orbital parameters of the SFXTs and the SgHMXBs (which mostly have circular orbits with negligible eccentricities). A measurement of the eccentricity is possible only if a sufficiently detailed (daily observations with relatively small errors on the estimated magnitudes) dataset for each source can be obtained.

• *Measuring the terminal velocity of the stellar wind, calculating the companion OB mass-loss rate, and making radial velocity measurements.* These parameters will be determined by us through spectroscopic observations with large telescopes. As with previous HMXB observations, *AAVSO Special Notices* will be issued to alert observers of the times when the spectroscopic observations are planned. Simultaneous light curve and spectroscopic radial velocity data are useful, for example, to separate periodicity due to pulsations of the primary from periodicity due to orbital motion (Sarty *et al.* 2009).

We remark that, in order to achieve the scientific aims presented above, *the contributions of AAVSO members and observers are critical*, since no single institutional telescope can afford such a large amount of observation time with the time spacing implied by an effective monitoring of the seventeen proposed candidate sources. (Two of the objects listed in the Tables are not SFXTs *per se* but "obscured HMXBs," another class of new HMXBs discovered by *INTEGRAL*. Our objectives for observing the obscured sources are the same as for the SFTXs although the astrophysical models are different.) Here we propose to observe the primary stars in SFXTs, which are generally faint in the visual domain (*V* band) due to the high extinction in the direction of these systems (and absorption intrinsic to the systems as well). For this reason, observations will need to be done in the *I* and possibly *R* bands (see section 3).

3. Feasibility: observing methods

This project extends the observational program for AAVSO observers described by Sarty *et al.* (2007) to the realm of the new class of SFXTs. The complete listing of program SFXTs is given in Tables 1, 2, and 3. The magnitude listing given in Table 1 is especially important to note. In the visual bands, the SFXTs are mostly beyond the reach of amateur-sized telescopes, although at least one, IGR J08408-4503, appears to be bright enough to be observed in the *V* band. Inspection of Table 1 reveals that the determination of two SFXT candidate optical counterparts will comprise the first stage of the observational program. The following stage will be to monitor as deeply and as frequently as possible all the proposed sources, in order to obtain at least daily estimates of their visual and/or infrared magnitudes and to determine their orbital periods. For this long term light curve monitoring, most of the observing will need to be done in the *I* and possibly *R* bands, where, even then, many objects will be faint. Since the amplitude of any periodicities in the light curves are currently unknown, the highest precision possible is required. This means longer exposures that maximize the signal-to-noise ratio are required as opposed to densely sampled time-series. A goal of 0.01 magnitude precision or better is ideal but this may not be achievable for some of the dimmer sources. However, all data free from systematic error, of any precision, are valuable since so little is known about the optical properties of the SFXTs. For example, the x-ray flares may be accompanied by fairly large amplitude optical flares that would be visible in lower precision data. Some techniques for achieving the highest possible precision are given by Castellano *et al.* (2004) where topics like pixel scale choices (typically two or three pixels across the seeing disk) are discussed. To ensure a homogeneous set of comparison and check stars, standardized observing charts will be posted to:

http://homepage.usask.ca/ges125/AAVSO_HMXB_Charts.html.

With every observer using the same comparison star, or stars for ensemble differential photometry, we hope to reduce the systematic differences between observers. Generally, there should be a suitable comparison star within 10 arc minutes of the SFXT of interest. It will take some preparatory observations with the AAVSO Photometric All-Sky Survey (Henden *et al.* 2009), or some all-sky photometry by others, to define comparison stars having similar magnitude and color to the target SFXT. In the meantime, observers will be able to record useful differential photometry that can be shifted once the comparison star magnitudes are standardized. As with the wider HMXB observing project, observers will submit their reduced data directly to the AAVSO International Database. The authors of this manuscript will then download the data for period analysis, using software such as PERIOD04 (Lenz and Breger 2005), to discover the orbital periods in your data. If we discover periods, or other interesting phenomena such as flares, in your data you will be offered authorship on the resulting discovery paper.

If you are interested in participating in this challenging new observing project, please watch for the *AAVSO Special Notices* and/or contact author G. E. Sarty (AAVSO observer SGE) and M. Falanga.

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Table 1. Positions and magnitudes of the program SFXTs.

Source	*Coordinates* *R.A.*	*Dec.*	*B*	*V*	*R*	*I*	*K*
IGR J08408–4503	08:40:47.79	–45:03:30.2[1]	7.8	7.6[2]	—	—	6.8[3]
IGR J16195–4945	16:19:32.20	–49:44:30.7[4]	18.1	17.2	16.4	15.5[5]	11.0[6]
IGR J16207–5129	16:20:46.26	–51:30:06.0[4]	19.8	17.7	15.4	13.6[5]	9.2[7]
IGR J16318–4848*	16:31:48.31	–48:49:00.7[8]	>25.4	>21.1	17.7	16.1[9]	7.6[3]
IGR J16358–4726	16:35:53.8	–47:25:41.1[10]	—	—	—	12.6[3]	—
IGR J16465–4507	16:46:35.26	–45:07:04.6[11]	15.2	—	13.0	—	9.8[12]
IGR J16479–4514	16:48:06.56	–45:12:06.8[11]	—	20.4[13]	—	—	9.8[14]
IGR J17354–3255*	17:35:25	–32:55:18 [11]	—	—	—	—	10.3[3]
XTE J1739–302	17:39:11.58	–30:20:37.6[15]	17.0	14.9	12.9	11.4[16]	7.4[12]
IGR J17407–2808	17:40:42	–28:08:00[17]	—	—	—	—	—
XTE J1743–363	17:43:01.324	–36:22:22.2[18]	—	—	—	—	7.6[19]
IGR J17544–2619	17:54:25.27	–26:19:52.7[20]	14.4	12.7	<11.9	—	8.0[21]
SAX J1818.6–1703	18:18:37.89	–17:02:47.9[22]	—	—	17.2	—	7.9[23]
AX J1820.5–1434	18:20:29.5	–14:34:24[24]	16.5	—	14.7[25]	—	—
AX J1841.0–0536	18:41:00.43	–05:35:46.5[11]	—	—	—	—	8.9[3]
AX J1845.0–0433	18:45:02.1	–04:33:55[26]	16.2	14.0	12.7	11.4	8.9[27]
IGR J18483–0311	18:48:17.17	–03:10:15.54	>25.2	21.9[28]	19.3	15.3[29]	8.6[30]

[1]Coordinates of the optical counterpart HD 74194 (Leyder et al. 2007). [2]B and V mags from Drilling (1991). [3]K mag from SIMBAD based on identification with 2MASS object listed in Table 3. [4]Coordinates from Chandra (Tomsick et al. 2006). [5]BVRI mags from Tomsick et al. (2006). [6]K mag based on identification with 2MASS J16193220–4944305 (Tomsick et al. 2006). [7]K mag based on identification with 2MASS J16204627–5130060 (Tomsick et al. 2006). [8]Position of optical counterpart identified by Filliâtre and Chaty (2004). [9]BVRI mags from Filliâtre and Chaty (2004). [10]Rahoui et al. (2008b). [11]Coordinates from Simbad based on 2 MASS object listed in Table 3. [12]BRK mags from Smith (2004). [13]Kennea et al. (2005). [14]Chaty et al. (2008). [15]Chandra localization (Smith et al. 2006). [16]VI mags from Negueruela et al. (2006). [17]Sguera et al. 2006. [18]Position of I band optical candidate identified by Ratti et al. 2010. [19]K mag of 2 MASS object (see Table 3) identified by Ratti et al. 2010. [20]Position of optical counterpart identified by Pellizza et al. (2006), see Table 3. [21]BVRK mags from Pellizza et al. (2006); Naik et al. (2010) found K=8.2. [22]Chandra coordinates (in't Zand et al. 2006). [23]RK mags from Negueruela and Smith (2006). [24]Kinugasa et al. (1998). [25]BR mags based on identification given in Table 3 (Negueruela and Schurch 2007). [26]Halpern and Gotthelf (2006). [27]BVRIK mags from Coe et al. (1996). [28]BV mags from Rahoui and Chaty (2008a). [29]Position and RI mags from Sguera et al. (2007). [30]Chaty et al. (2008). [*]Note that these two sources are not part of the SFXT class. However, given their peculiar behavior in the x–ray domain, we included them in our observational program.

Table 2. Physical characteristics of the program SFXTs.

Source	*Orbital Period(d)*	*Spin Period(s)*	*Spec Type*	*Remarks*
IGR J08408-4503	24[1]	—	O8.5Ib(f)[2]	5% microvar[3]
IGR J16195-4945	16[4]	—	O, B or A[5]	Near HD 146628[5]
IGR J16207-5129	—	—	B0I[7]	No x-ray period <12 hr[8]
IGR J16318-4848	80[9]	—	sgB[e][10]	Almost edge-on obscuring matter[11]
IGR J16358-4726	—	5871[12]	sgB[e][13]	
IGR J16465-4507	30.32[14]	228[15]	B0.5I[16]/O9.5Ia[17]	
IGR J16479-4514	3.32[18]	—	O8.5Ib[19]	x-ray eclipses[20]
IGR J17354-3255	8.452[21]	—	—	x-ray eclipses[21]
XTE J1739-302	51.47[22]	—	O8.5Iab(f)[23]	
IGR J17407-2808	—	—	—	No Opt Cpt[24]
XTE J1743-363	—	—	late sg or OI[25]	No radio src at 4.9 and 8.5 GHz[26]
IGR J17544-2619	4.926[27]	—	O9Ib[28]	
SAX J1818.6-1703	30[29]	—	O9-B1I[30]	
AX J1820.5-1434	—	152.26[31]	O9.5-B0Ve[32]	
AX J1841.0-0536	—	4.7[33]	B1Ib[34]	
AX J1845.0-0433	—	—	O9Ia[35]	
IGR J18483-0311	18.55[36]	21.05[37]	B0.5Ia[38]	

[1]Based on recurring x-ray flares (Sidoli et al. 2009). [2]Spectral type of HD 74194 as reported in Sidoli et al. (2009). [3]Microvariable (from Hipparcos) with period of 7.8d (Leyder et al. 2007). [4]Based on a model of the fraction of an orbit spent in an x-ray flare (Morris et al. 2009). [5]Tomsick et al. (2006). [6]Possible blended optical source (Tomsick et al. 2006). [7]Based on I-band spectrum (Negueruela and Schurch 2007). [8]Tomsick et al. (2009b). [9]Based on x-ray outburst intervals (Jain et al. 2009). [10]Chaty and Filliâtre (2005). [11]Ibarra et al. (2007). [12]Variable spin (Patel et al. 2007). [13]Rahoui et al. (2008b). [14]Based on x-ray light curves (Clark et al. 2010). [15]Lutovinov et al. (2005). [16]Negueruela et al. (2005). [17]Nespoli et al. (2008). [18]Period based on x-ray light curves (Bozzo et al. 2009). [19]Nespoli et al. (2008). [20]Bozzo et al. (2009). [21]D'Ai' et al. (2010). [22]From x-ray light curve (Drave et al. 2010). [23]Rahoui et al. (2008b). [24]Need to follow up an x-ray outburst with optical observations to identify the counterpart; may be an unusual LMXT (Heinke et al. 2009). [25]Ratti et al. (2010). [26]Rupen et al. (2004). [27]Clark et al. (2009). [28]Pellizza et al. (2006). [29]Based on x-ray outburst intervals (Bird et al. 2009, Zurita Heras et al. 2009). [30]Zurita Heras et al. (2009) and Torrejón et al. (2010). [31]Kinugasa et al. (1998). [32]Belczynski and Ziolkowski (2009). [33]Bamba et al. (2001). [34]Nespoli et al. (2008). [35]Coe et al. (1996). [36]Levine and Corbet (2006), Jain et al. (2009). [37]Sguera et al. (2007). [38]Rahoui et al. (2008b).

Table 3. Name cross references for the program SFXTs.

Source	*Other Names*
IGR J08408-4503	LM Vel, HD 74194, 2MASS J08404780-4503302[1]
IGR J16195-4945	2MASS J16193220-4944305[2]
IGR J16207-5129	2MASS J16204627-5130060, USNO-B1.0 0384-0560875[2]
IGR J16318-4848	2MASS J16314831-4849005[3]
IGR J16358-4726	2MASS J16355369-4725398[4]
IGR J16465-4507	2MASS J16463526-4507045, USNO-B1.0 0448-00520455[5]
IGR J16479-4514	2MASS J16480656-4512068, USNO-B1.0 0447-0531332[6]
IGR J17354-3255	2MASS J17352760-3255544, Possible gamma-ray transient AGL J1734-3310[7]
XTE J1739-302	IGR J17391-3021, 2MASS J17391155-3020380, USNO-B1.0 0596-0585865[8]
IGR J17407-2808	CXOU J174042.0-280724[9]
XTE J1743-363	2MASS J17430133-3622221[10]
IGR J17544-2619	2MASS J17542527?2619526, USNO-B1.0 0636-0620933[11]
SAX J1818.6-1703	2MASS J18183790-1702479, USNO-B1.0 0729-0750578[12]
AX J1820.5-1434	2MASS J18203114-1434193, USNO-B1.0 0754-0489829[13]
AX J1841.0-0536	2MASS J18410043-0535465[14]
AX J1845.0-0433	IGR J18450-0435[15]
IGR J18483-0311	2MASS J18481720-0310168[16]

[1]Identification of HD 74194 with LM Vel and 2MASS J08404780-4503302 is based on SIMBAD data. [2]Tomsick et al. (2006). [3]Filliâtre and Chaty (2004). [4]Kouveliotou et al. (2003). [5]Zurita Heras and Walter (2004), Nespoli et al. (2008). [6]Walter et al. (2006). [7]Tomsick et al. (2009a). [8]Rahoui et al. (2008b). [9]Chandra counterpart suggested by Heinke et al. (2009); however Tomsick et al., 2008 find no Chandra counterparts. [10]Ratti et al. (2010). [11]Pellizza et al. (2006). [12]Negueruela and Smith (2006). [13]Negueruela and Schurch (2007) but identification is uncertain. [14]Halpern et al. (2004). [15]Halpern and Gotthelf (2006). [16]Sguera et al. (2007).

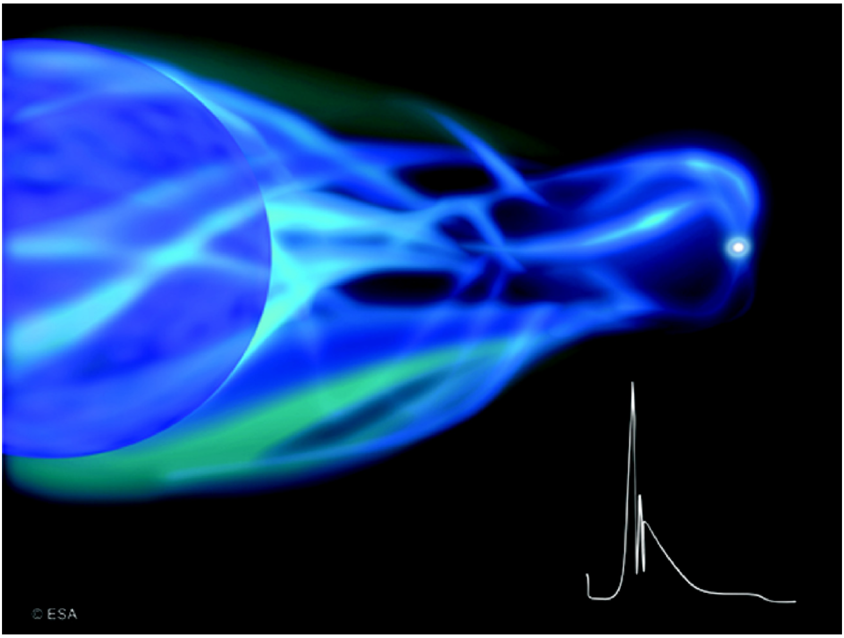

Figure 1. This artist's impression shows a high-mass binary system, composed of a supergiant luminous star (on the left) and a neutron star as the compact stellar object. These supergiant systems show strong and exceptionally fast-rising x-ray outbursts lasting a few hours, hence their name "supergiant fast x-ray transients." A typical x-ray flare light curve is shown at the bottom-right. The discovery story can be found on the ESA Space Science News from 16 November 2005: http://www.esa.int/esaSC/SEM20VJBWFE_index_0.html. *Picture copyright ESA, used with permission.*