A Population Explosion: The Nature and Evolution of X-ray Binaries in Diverse Environments
28 Oct.–2 Nov. 2007, St. Petersburg Beach, FL
R.M. Bandyopadhyay, S. Wachter, D. Gelino, & C. R. Gelino, eds.
Session: *Obscured XRBs and INTEGRAL Sources*

A new explanation for the Supergiant Fast X–ray Transients outbursts

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Abstract. The physical mechanism responsible for the short outbursts in a recently recognized class of High Mass X-ray Binaries, the Supergiant Fast X-ray Transients (SFXTs), is still unknown. Recent observations performed with *Swift/XRT*, *XMM–Newton* and *INTEGRAL* of the 2007 outburst from IGRJ11215−5952, the only SFXT known to exhibit periodic outbursts, suggest a new explanation for the outburst mechanism in this class of transients; the outbursts could be linked to the possible presence of a second wind component in the supergiant companion, in the form of an equatorial wind. The applicability of the model to the short outburst durations of all other Supergiant Fast X-ray Transients, where a clear periodicity in the outbursts has not been found yet, is discussed. The scenario we are proposing also includes the persistently accreting supergiant High Mass X–ray Binaries.

1. Introduction: the SFXTs properties

Supergiant Fast X–ray Transients (hereafter SFXTs; Smith et al. 2006a) are a new class of hard X–ray sources mostly discovered by the *INTEGRAL* satellite (Negueruela et al. 2005a, Sguera et al. 2005). They are transient sources which seem to emit X–rays only during "short" outbursts (few hours, as observed with *INTEGRAL* or *RXTE*) and their optical counterparts are blue supergiant stars. Their X–ray spectra are similar to those of accreting pulsars, thus it is likely that they are High Mass X–ray Binaries (HMXBs) hosting neutron stars. In two SFXTs (among about twenty sources, comprising candidate SFXTs) X–ray pulsations have been indeed observed (IGR J18410-0535/AX J1841.0-0536,

P_{spin}=4.74 s, Bamba et al. 2001; IGR J11215–5952, $P_{spin} = 186.78 \pm 0.3$ s, Smith et al. 2006b, Swank et al. 2007).

SFXTs reach X–ray luminosities up to a few 10^{36} erg s^{-1}, while the quiescent level ($\sim 10^{32}$ erg s^{-1}) has been observed only in IGR J17391−3021/XTE J1739−302 (Smith et al. 2006a; Sakano et al. 2002), IGR J17544−2619 (in't Zand 2005) and probably IGR J18410−0535/AX J1841.0−0536 (Halpern et al. 2004; Bamba et al. 2001).

It is important to note that none of the SFXT sources has ever been caught to undergo a transition from quiescence to outburst and then back to quiescence in a few hours. The quiescent emission had always been observed well far away from the outbursts, except in one case: only in't Zand (2005) did observe the transition from quiescence to outburst with *Chandra* (in IGR J17544−2619), but the observation finished before the start of the declining phase to quiescence. Thus the real duration of this outburst could not be measured. The so-called "short" duration (a few hours) of the outbursts from SFXTs is indeed based on observations with instruments not sensitive enough to detect the quiescence level. The instruments onboard *RXTE* and *INTEGRAL* could only observe the brightest fast flaring activity (lasting a few hours, less than one day) reaching a few 10^{36} erg s^{-1}.

Hence, the definition of SFXTs as transient sources displaying "short" X–ray outbursts lasting only a few hours is strongly biased. This has been observationally demonstrated by our recent deep campaign with *Swift/XRT* (Romano et al. 2007, hereafter Paper II) of the outburst from the unique SFXT displaying "periodic outbursts", IGR J11215–5952 (Sidoli et al. 2006, hereafter Paper I). These very sensitive observations showed that the accretion phase in SFXTs lasts longer than what previously thought: a few days instead of only hours.

With these new observations at hand, we report on an alternative model to explain the outbursts from this new class of sources, based on *Swift/XRT* monitoring observations of IGR J11215–5952 during the last two outbursts (starting on February 9 and July 24, 2007; Sidoli et al. 2007, hereafter Paper III).

2. Swift/XRT observations of IGR J11215–5952

IGR J11215–5952 is an X–ray transient discovered by *INTEGRAL* during a fast outburst in April 2005 (Lubinski et al. 2005). The optical counterpart is a B1 supergiant, HD 306414, located at a distance of 6–8 kpc (Negueruela et al. 2005b, Masetti et al. 2006, Steeghs et al. 2006). From the analysis of *INTEGRAL* observations of the source field, we discovered (Paper I) that the outbursts are equally spaced by ∼330 days (although a half of this period could not be excluded, due to a lack of observations). This periodicity was later confirmed in March 2006 (outburst after 329 days; Smith et al. 2006c) during a monitoring with *RXTE/PCA*, and was related in a natural way to the orbital period of the system, with the outbursts triggered at (or near to) the periastron passage (Paper I).

Based on this known periodicity, a new outburst was expected for 2007 February 9 and we planned a monitoring campaign with *Swift/XRT*, starting on 2007 February 4 (Romano et al. 2007b). A second monitoring campaign was performed with *Swift/XRT* in July 2007, in order to monitor the quiescent level and the epoch of the supposed apastron passage (based on the 329 days period; Romano et al. 2007c). These observations led to the detection of a new unexpected outburst starting on 2007, July 24, which reached roughly the same flux as during the February 2007 outburst (Paper III). Details of the *Swift/XRT* data analysis and spectral/timing results are reported in Paper II and Paper III. Here we concentrate on the shape of the X–ray lightcurve in order to understand the physical mechanism which produces the outbursts.

3. A new model for the outburst mechanism in SFXTs

The IGR J11215–5952 lightcurve observed during the February 2007 outburst represents the most complete set of observations of a SFXT outburst (Fig. 1, black curve). The first important result of these observations is that the whole outburst phase lasts longer than what previously thought, based on less sensitive instruments: a few days, instead of a few hours. Only the brightest part of the outburst is short (lasts less than 1 day) and would have been seen by the INTEGRAL instruments. Intense flaring activity is also present, both during the bright peak and the declining phase of the outburst, with each single flare lasting minutes or a few hours.

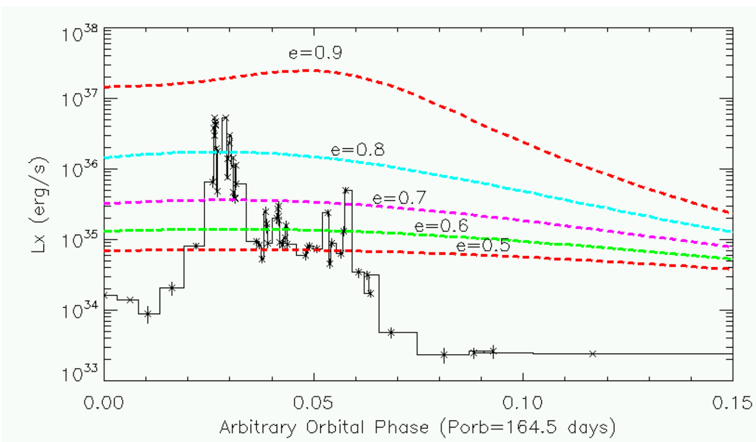

Figure 1. Comparison of the IGR J11215–5952 lightcurve observed with *Swift*/*XRT* during the February 2007 outburst, with the X–ray luminosity calculated from Bondi-Hoyle accretion from the spherically symmetric wind of the B1-type supergiant companion, for different binary system eccentricities. An orbital period of 164.5 days is assumed. The orbital phase is arbitrary. We assumed a beta-law for the supergiant wind, with an exponent β=1, a stellar mass of 39 $M_{\odot}$, a radius of 42 $R_{\odot}$, a wind terminal velocity of 1200 km s^{-1} and a wind mass loss of 3.7×10^{-6} $M_{\odot}$ yrs^{-1}.

It is natural to associate the clock responsible for the outbursts with the orbital periodicity of the binary system. Since IGR J11215–5952 displayed a new outburst after about a half of the 329 days period (Paper III; Romano et al. 2007c), it is possible that 164.5 days is indeed the real orbital period which escaped detection up to now. In both cases (P_{orb}=329 days or 164.5 days), the system is a wide binary where the blue supergiant does not fill its Roche lobe, and the system is very likely wind-fed. Applying the Bondi-Hoyle wind accretion scenario, where the neutron star accretes from the wind of the supergiant at different rates depending on the wind density and relative velocity along the orbit, and assuming reasonable parameters for the B-supergiant, we obtain that the observed X–ray lightcurve is always too narrow and steep to be explained with accretion from a spherically symmetric wind, even adopting extreme eccentricities for the binary system (see Fig. 1).

This result led us to suggest that the wind from the B supergiant is not spherically symmetric. The alternative viable explanation we propose for the sharpness of the observed X–ray lightcurve is that in IGR J11215–5952 the supergiant wind has a second component (besides the polar spherically symmetric one), in the form of an “equatorial disk”, inclined with respect to the orbital plane (see Fig. 2 for an artistic view of the geometry of the system). The short outburst is then produced when the neutron star crosses this equatorial wind component, denser and slower than the polar one. Deviations from spherical symmetry in hot massive star winds are also suggested by optical observations (e.g. Prinja 1990, Prinja et al. 2002) and the presence of equatorial disk components, denser and slower with respect to the polar wind, also results from simulations (ud-Doula et al. 2006).

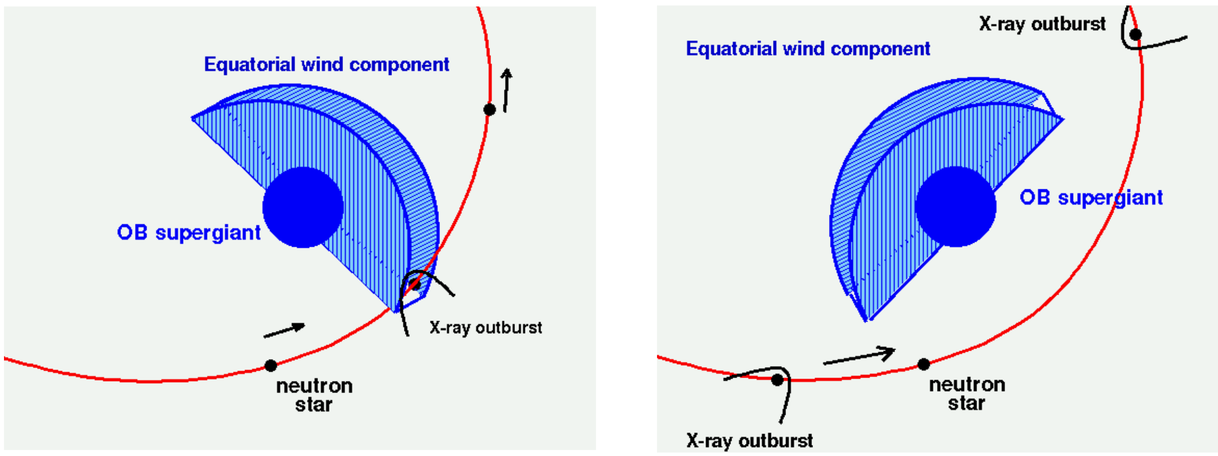

Figure 2. *Left panel:* sketch of the proposed geometry for the equatorial wind component and the outburst mechanism in IGR J11215–5952. *Right panel:* sketch of the proposed geometry for a SFXT in general (see text).

The thickness h of the densest part of this supergiant equatorial wind can be calculated from the duration of the brightest part of the outburst (which lasts less than 1 day, time needed for the neutron star to cross it) and the neutron star velocity, 100–200 km s^{-1}: $h \sim (0.8\text{–}1.7) \times \sin(\theta) \times 10^{12}$ cm, where θ is the inclination angle of the equatorial wind with respect to the orbital plane (with θ=90° if the disk is perpendicular to the orbital plane).

The model we are proposing can explain also the short flares from all the other SFXTs where a clear periodicity in the outbursts recurrence has not been found yet, if a different geometry of the equatorial wind component with respect to the orbital plane is assumed: in IGR J11215–5952, where the outbursts are equally spaced and occur with a fixed periodicity, the inclined equatorial disk wind component should intersect the neutron star at the periastron (or very close to it, see the left panel in Fig. 2) and can intersect the neutron star orbit once or twice depending both on the extension of the wind disk and on the orbital eccentricity. Instead, it is possible that in the other SFXTs the inclined disk wind intersects twice a wide and highly eccentric orbit, not at the periastron (see the right panel in Fig. 2), leading to a double periodicity (one shorter than the other) which has not been found yet *only* because of a lack of a continuous monitoring. This model can also explain the X–ray emission from the persistently accreting HMXBs, if we admit that in this case the neutron star is always moving inside the equatorial wind component which lies on the orbital plane.

In this framework, the sharp X–ray lightcurve observed from IGR J11215–5952 can be modelled with different wind parameters (for both polar and equatorial components) depending on the orbital period (164.5 days or 329 days) and the eccentricity of the binary. We assume a blue supergiant with a mass of 39 $M_{\odot}$ and radius of 42 $R_{\odot}$, and a polar wind component with a terminal velocity of 1800 km s^{-1}. The X–ray lightcurve observed with *Swift/XRT* is better reproduced assuming a "polar wind" mass loss rate of 5×10^{-6} $M_{\odot}$ yrs^{-1} (for a P_{orb} of 164.5 days and an eccentricity of 0.4) and 9×10^{-7} $M_{\odot}$ yrs^{-1} (for a P_{orb} of 329 days and a circular orbit, which is required by the fact that the two consecutive outbursts from IGR J11215–5952 reached roughly the same peak flux). The equatorial wind component should have a variable velocity ranging from 750 km s^{-1} to 1400 km s^{-1} (for P_{orb}=164.5 days), and from 850 km s^{-1} to 1600 km s^{-1} (for P_{orb}=329 days), and a density about 100 times higher than the polar wind component.

Note however that since the X–ray luminosity expected for the wind accretion is proportional to $\dot{M}_w {v_{rel}}^{-4}$ (where $\dot{M}_w$ is the wind mass loss rate, and v_{rel} is the relative velocity of the wind with respect to the neutron star), different combinations of wind density and velocity in the equatorial component can reproduce the X–ray lightcurve as well.

In conclusion, in our model we explain the short recurrent flares if the neutron star intersects an inclined equatorial wind component (once or twice) during its orbit. A different particular geometry and inclination of this equatorial wind with respect to the orbital plane can account for the whole phoenomenology of both SFXTs and persistently accreting HMXBs in general. Both the orbital eccentricity and no-coplanarity can be explained by a substantial supernova kick at birth. This could indicate that SFXTs are likely young systems, probably younger than persistent HMXBs.

Acknowledgments. Based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA member states and the USA (NASA). Based on observations with INTEGRAL, an ESA project with instruments and the science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA. We thank the *XMM–Newton*, *INTEGRAL*, and *Swift* teams for making these observations possible, in particular the duty scientists and science planners. PR thanks INAF-IASFMi for their kind hospitality. DG acknowledges the French Space Agency (CNES) for financial support. This work was supported by contract ASI/INAF I/023/05/0.

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