Probing clumpy stellar winds with a neutron star

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INTEGRAL tripled the number of super-giant high-mass X-ray binaries (sgHMXB) known in the Galaxy by revealing absorbed and fast transient (SFXT) systems. Quantitative constraints on the wind clumping of massive stars can be obtained from the study of the hard X-ray variability of SFXT. A large fraction of the hard X-ray emission is emitted in the form of flares with a typical duration of 3 ksec, frequency of 7 days and luminosity of 10^{36} erg/s. Such flares are most probably emitted by the interaction of a compact object orbiting at $\sim 10\ R_*$ with wind clumps ($10^{22\ldots23}$ g) representing a large fraction of the stellar mass-loss rate. The density ratio between the clumps and the inter-clump medium is $10^{2\ldots4}$. The parameters of the clumps and of the inter-clump medium, derived from the SFXT flaring behavior, are in good agreement with macro-clumping scenario and line-driven instability simulations. SFXT are likely to have larger orbital radius than classical sgHMXB.

1 Introduction

Indirect measures of the structure of massive-star winds are possible in X-ray binaries through the analysis of the interaction between the compact companion and the stellar wind. In this report we summarize the constraints obtained on wind clumping in HMXB using the hard X-ray variability observed by the IBIS/ISGRI instrument on board INTEGRAL (Winkler et al., 2003). Further details can be found in Walter and Zurita (2007) and Leyder et al. (2007).

Classical wind-fed, Roche-lobe underflow, super-giant HMXB (sgHMXB) are made of a compact object orbiting within a few (1.5 to 2.5) stellar radii from a super-giant companion. Recently INTE-GRAL almost tripled the number of sgHMXB systems known in the Galaxy and revealed a much more complex picture with two additional families of sources: (1) the highly-absorbed systems which have orbital and spin periods similar to those of classical sgHMXB but much higher absorbing column densities on average (Walter et al., 2006) and (2) the fast transient systems which are characterized by fast outbursts and by a very low quiescent luminosity (Sguera et al., 2006, Negueruela et al., 2007).

2 Sources and data analysis

Several sources have now been proposed as candidate super-giant fast X-ray transient based on their hard X-ray variability characteristics, and, for a subset of them, optical counterpart spectral type. Contrast-ing statements have however been made on specific sources for what concerns their persistent or transient nature. In the frame of the current study we have considered all SFXT candidates together with several persistent and absorbed super-giant HMXB for comparison. Among them, we specifically excluded known Be systems, sources detected only once by INTEGRAL, blended INTEGRAL sources, long period systems and the sgB[e] system IGR J16318−4848.

We analyzed the available INTEGRAL data for 12 candidate SFXT (table 1) that have large variability factors and compared them with the classical and absorbed sgHMXB systems that have a typical variability factor $\lesssim 20$. The sources of the sample are located along the galactic plane that has been heavily observed by INTEGRAL. All public data available until March 2007 are considered in this study. Individual ISGRI sky images have been produced for each INTEGRAL pointing in the energy band 22–50 keV. The detection of the sources of the sample is forced in each image and the source count rate extracted.

Source flares have been detected by requiring a minimum of 25 ksec of inactivity between them. Flare duration of the order of a single INTEGRAL pointing (2 ksec) have been observed in all sources (excepting IGR J16465−4507). Their typical duration is 3 ksec. Fewer longer (> 15 ksec) flares have also been detected but in most cases could be interpreted as a serie of shorter flares or a long activity period. They will not be discussed further here.

Table 1: List of SFXT candidates with quiescent flux $F_{\rm q}$, source observing elapsed time $T_{\rm obs}$ and flaring characteristics: maximum count rate $F_{\rm fl}$, number of flares $N_{\rm fl}$ and the average flare duration $t_{\rm fl}$.

Source	$F_{\rm q}$ ct/s	$F_{\rm fl}$ ct/s	$N_{\rm fl}$	$t_{\rm fl}$ ks	$T_{\rm obs}$ days
SFXT systems					
IGR J08408−4503	< 0.1	3.9	2	3.6	52.0
IGR J17544−2619	0.06	24	8	2.5	127.0
XTE J1739−302	0.08	28	12	4.2	126.4
SAX J1818.6−1703	0.18	45	11	2.9	76.9
IGR J16479−4514	0.2	19	38	3.6	67.0
AX J1841.0−0536	< 0.1	15	4	5.8	51.9
AX J1820.5−1434	< 0.1	5.3	4	3.9	59.4
Intermediate systems					
AX J1845.0−0433	0.2	6.2	6	4.0	55.2
IGR J16195−4945	0.2	4.8	6	2.2	71.8
IGR J16465−4507	0.1	6.9	3		66.7
IGR J16207−5129	0.4	9.2	11	4.3	73.7
XTE J1743−363	0.5	9.2	19	2.5	122.9

Table 1 lists the sources together with their quiescent count rate ($F_{\rm q}$), average flare count rate ($F_{\rm fl}$), number of flares ($N_{\rm fl}$), range of flare durations ($t_{\rm fl}$) and total source observing elapsed time ($T_{\rm obs}$). As the probability to detect a flare decreases when the source gets outside of the fully-coded field of view, the effective observing time for flare detection can be estimated as $0.6\,T_{\rm obs}$.

The sources have been separated in two categories. The SFXT include systems featuring hard X-ray variability by a factor $\gtrsim 100$. "Intermediate" systems are candidate SFXT with smaller variability factors that could be compared with those of classical systems. From the variability point of view, sources closer to the bottom of the table are more similar to classical sgHMXB.

3 Discussion

The distances to the SFXT systems has been evaluated (2–7 kpc) in a few cases. We will assume, for the rest of the discussion, a distance of 3 kpc. The average count rate observed during flares lies between 3 and 60 ct/s which translates to hard X-ray luminosities of $(0.2 - 4) \times 10^{36}$ erg/s. Such luminosities are not exceptional for sgHMXB but very significantly larger than the typical X-ray luminosity of single massive stars of 10^{30-33} erg/s at soft X-rays (Cassinelli et al., 1981).

As the sources are flaring at most once per day, their average hard X-ray luminosity is very low, reaching $(0.2 - 4) \times 10^{34}$ erg/s. It is therefore very unlikely that those systems have average orbital radius lower than 10^{13} cm i.e. $\sim 10\,R_*$. One expects orbital periods larger than 15 days and underflow Roche lobe systems (note that no orbital period has yet been derived in any of these systems).

Wind clumps

The interaction of a compact objet with a dense clump formed in the wind of a massive companion leads to increased accretion rate and hard X-ray emission.

The free-fall time from the accretion radius $R_a = 2 \times 10^{10}$ cm towards the compact object is of the order of $(2...3) \times 10^2$ sec. As the intrinsic angular momentum of the accreted gas is small (Illarionov and Beloborodov, 2001) the infall is mostly radial (down to the Compton radius) and proceeds at the Bondi-Hoyle accretion rate.

With a duration of $t_{\rm fl} = 2...10$ ksec, the observed short hard X-ray flares are significantly longer than the free-fall time. The flare duration is therefore very probably linked with the thickness of the clumps which, for a clump radial velocity $V_{\rm cl} = 10^8$ cm/s, is $h_{\rm cl} = V_{\rm cl} \times t_{\rm fl} \sim (2...10) \times 10^{11}$ cm.

The average hard X-ray luminosity resulting from an interaction between the compact object and the clump can be evaluated as $L_{\rm X} = \epsilon\, M_{\rm acc} c^2 / t_{\rm fl}$ (where $\epsilon \sim 0.1$) and the mass of a clump can then be estimated as $M_{\rm cl} = (R_{\rm cl}/R_{\rm a})^2\, M_{\rm acc} = (R_{\rm cl}/R_{\rm a})^2\, L_{\rm X}\, t_{\rm fl}/(\epsilon\, c^2)$ where $R_{\rm cl}$ is the radius of the clump perpendicular to the radial distance. In the case of a spherical clump, $M_{\rm cl} = \left(\frac{L_{\rm X}}{10^{36}\,{\rm erg/s}}\right)\left(\frac{t_{\rm fl}}{3\,{\rm ks}}\right)^3 7.5 \times 10^{21}$ g.

If $\dot{N}$ is the rate of clumps emitted by the star, the observed hard X-ray flare rate is given by $T^{-1} = \dot{N}(R_{\rm cl}^2/4R_{\rm orb}^2)$. The rate of mass-loss in the form of wind clumps can then be estimated as $\dot{M}_{\rm cl} = \left(\frac{10{\rm d}}{T}\frac{L_{\rm X}}{10^{36}{\rm erg/s}}\frac{t_{\rm fl}}{3{\rm ks}}\right)\left(\frac{R_{\rm orb}}{10^{13}{\rm cm}}\right)^2 3 \times 10^{-6}$ $M_\odot$/yr.

For a $\beta = 1$ velocity law and spherical clumps, the number of clumps located between $1.05R_*$ and $R_{\rm orb}$ can be evaluated as $N = \left(\frac{10\,{\rm d}}{T}\right)\left(\frac{3\,{\rm ks}}{t_{\rm fl}}\right)^2\left(\frac{R_{\rm orb}}{10^{13}\,{\rm cm}}\right)^3 3.8 \times 10^3$.

Assuming spherical clumps, the clump density at the orbital radius is $\rho_{\rm cl} = \left(\frac{L_{\rm X}}{10^{36}\,{\rm erg/s}}\right) 7 \times 10^{-14}$ g cm^{-3} and the corresponding homogeneous wind density is $\rho_h = \dot{M}_{\rm cl}/(4\pi R_{\rm orb}^2 V_{\rm cl}) = \left(\frac{10\,{\rm d}}{T}\frac{L_{\rm X}}{10^{36}\,{\rm erg/s}}\frac{t_{\rm fl}}{3\,{\rm ks}}\right) 1.5 \times 10^{-15}$ g cm^{-3}. The clump volume filling factor at the orbital radius is $f_{\rm V} = \frac{\rho_h}{\rho_{\rm cl}} = \left(\frac{10\,{\rm d}}{T}\frac{t_{\rm fl}}{3\,{\rm ks}}\right) 0.02$ and the corresponding porosity length is $h = \frac{R_{\rm cl}}{f_{\rm V}} = \left(\frac{T}{10\,{\rm d}}\right) 15 \times 10^{12}$ cm.

If the density of a clump decreases with radius as $r^{-2\beta}$ and its mass remains constant, the averaged homogeneous wind density within $R_{\rm obs}$ is

$\overline{\rho_h} = NM_{\mathrm{cl}}/(\frac{4}{3}\pi R_{\mathrm{orb}}^3) = \left(\frac{10\ \mathrm{d}}{T}\frac{L_{\mathrm{X}}}{10^{36}\ \mathrm{erg/s}}\frac{t_{\mathrm{fl}}}{3\ \mathrm{ks}}\right)\ 7\ \times$ 10^{-15} g cm^{-3} and the average clump volume filling factor and porosity length could be estimated as 0.1 and 3×10^{12} cm, respectively.

The variety of t_{fl}, T and F_{fl} that are observed probably reflects a range of clump parameters and orbital radii. Several of the average clump parameters estimated above, in particular the clump density, filling factor and porosity length do not depend on the orbital radius, which is unknown, and only slowly depend on the observed quantities.

These average parameters match the macro-clumping scenario of Oskinova et al. (2007) to reconcile clumping and mass-loss rates. The number of clumps derived above is also comparable to evaluations by Lepine and Moffat (1999), Oskinova et al. (2006). The volume filling factor, porosity length and the clump mass-loss rate are also similar to those derived by Bouret et al. (2005) from the study of ultraviolet and optical line profiles in two super-giant stars.

The column density through a clump can also be estimated as $N_H = \frac{M_{\mathrm{cl}}}{R_{\mathrm{cl}}^2 m_p} = \left(\frac{L_{\mathrm{X}}}{10^{36}\mathrm{erg/s}}\frac{t_{\mathrm{fl}}}{3\mathrm{ks}}\right)\ 5\ \times$ 10^{22}cm^{-2}. The clumps remain optically thin in the X-rays.

Inter-clump medium

The variation of the observed X-ray flux between flares and quiescence provides in principle a direct measure of the density constrast between the wind clumps and the inter-clump medium.

Density contrasts of $> 10^{2-4}$ and 15–50 have been observed in SFXT and "Intermediate" sources, respectively. The density contrast is larger in SFXT than in "Intermediate" and, of course, classical systems. Density contrasts are probably stronger when clumping is very effective.

Numerical simulations of the line driven instability (Runacres and Owocki, 2005) predict density contrasts as large as 10^{3-5} in the wind up to large radii. At a distance of 10 R_*, the simulated density can vary between 10^{-18} and 10^{-13} g cm^{-3} and the separation between the density peaks are of the order of R_*. These characteristics are comparable to the values we have derived.

What about classical sgHMXB ?

Classical sgHMXB are characterized by small orbital radii $R_{\mathrm{orb}} = (1.5-2.5)\ R_*$, and by flux variability of a factor $\lesssim 10$. Such variabilities were modelled in terms of wind inhomogeneities largely triggered by the hydrodynamic and photo-ionisation effects of the accreting object on the companion and inner stellar wind (Blondin et al., 1991, Blondin, 1994). At small orbital radii, the companion is close to fill its Roche lobe, which triggers tidal streams. In addition the X-ray source ionizes the wind acceleration zone, prevents wind acceleration and generates slower velocities, denser winds, larger accretion radius and finally larger X-ray luminosities. Whether or not the stellar wind is intrinsically clumpy at low radius, the effect of the compact object on the wind is expected to be important.

The main difference between SFXT and classical sgHMXB could therefore be their orbital radius (Leyder et al. (2007)). At very low orbital radius ($< 1.5\ R_*$) tidal accretion will take place through an accretion disk and the system will soon evolve to a common envelope stage. At low orbital radius ($\sim 2\ R_*$) the wind will be perturbed in any case and efficient wind accretion will lead to copious and persistent X-ray emission (10^{36-37} erg/s). At larger orbital radius ($\sim 10\ R_*$) and if the wind is clumpy, the SFXT behavior is expected as described above. If the wind clumps do not form for any reason, the average accretion rate will remain too low and the sources will remain mostly undetected by the current hard X-ray survey instruments.

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O. Reimer: What are the considered time scales if you invoke the TeV-emission connection of the integral absorbed binaries, when having clumps involved?

Walter: The protons are accelerated extremely rapidly in the magnetosphere gaps and are released as soon as the gyration radius exceeds the Alfvén radius. Those protons that will interact with the dense clump will generate TeV emission immediately. I therefore expect the TeV to be correlated with the X-ray light curve.

Cassinelli: So you have a clump of density 10^4 times the density of the wind that directly collides with the neutron star? Also the factor of 10^4 is not far from the $\mathrm{Ma}^2\,\rho_{\mathrm{wind}}$ from the driven wave model I have discussed here.

Walter: The density ratio seems to vary from source to source. However in some sources indeed the ratio reaches 10^4.

Moffat: Are you saying there is essentially only one clump size? Or do you see a distribution in clump masses, and if so, what kind of a distribution?

Walter: We are observing clumps with sizes between 10^{11} to 10^{12} cm, assuming spherical geometry. I cannot exclude smaller clouds that would not be massive enough to be considered within our current analysis.