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Abstract. The INTEGRAL satellite has revealed a major population of supergiant High Mass X-ray Binaries in our Galaxy, revolutionizing our understanding of binary systems and their evolution. This population, constituted of a compact object orbiting around a massive and luminous supergiant star, exhibits unusual properties, either being extremely absorbed, or showing very short and intense flares. An intensive set of multi-wavelength observations has led us to reveal their nature, and to show that these systems are wind-fed accretors, closely related to massive star-forming regions. In this paper I describe the characteristics of these sources, showing that this newly revealed population is closely linked to the evolution of active and massive OB stars with a compact companion. The last section emphasizes the formation and evolution of such High Mass X-ray Binaries hosting a supergiant star.

THE γ-RAY SKY SEEN BY THE *INTEGRAL* SATELLITE

The *INTEGRAL* observatory is an ESA satellite launched on 17 October 2002 by a PROTON rocket on an excentric orbit. It is hosting 4 instruments: 2 γ-ray coded-mask telescopes –the imager IBIS and the spectro-imager SPI, observing in the range 10 keV-10 MeV, with a resolution of $12'$ and a field-of-view of $19°$– a coded-mask telescope JEM-X (3-100 keV), and an optical telescope (OMC).

The γ-ray sky seen by *INTEGRAL* is very rich, since 723 sources have been detected by *INTEGRAL*, reported in the 4th IBIS/ISGRI soft γ-ray catalogue, spanning nearly 7 years of observations in the 17-100 keV domain [1]. Among these sources, there are 185 X-ray binaries (representing 26% of the whole sample of sources detected by *INTEGRAL*, called "IGRs" in the following), 255 Active Galactic Nuclei (35%), 35 Cataclysmic Variables (5%), and $\sim$ 30 sources of other type (4%): 15 SuperNova Remnants, 4 Globular Clusters, 3 Soft γ-ray Repeaters, 2 γ-ray Burst, etc. 215 objects still remain unidentified (30%). X-ray binaries are separated in 95 Low Mass X-ray Binaries (LMXBs) and 90 High Mass X-ray Binaries (HMXBs), each category representing $\sim$ 13% of IGRs. Among identified HMXBs, there are 24 BeHMXBs (HMXBs hosting a Be companion star) and 19 sgHMXBs (HMXBs hosting a supergiant companion star), representing respectively 31% and 24% of HMXBs).

It is interesting to follow the evolution of the ratio between BeHMXBs and sgHMXBs. During the pre-*INTEGRAL* era, HMXBs were mostly BeHMXB systems. For instance, in the catalogue of 130 HMXBs by Liu et al. [2], there were 54 BeHMXBs and 7 sgHMXBs (respectively 42% and 5% of the total number of HMXBs). Then, the situation changed drastically with the first HMXBs identified by *INTEGRAL*: in the catalogue of 114 HMXBs (+128 in the Magellanic Clouds) of Liu et al. [3], there were 60% of BeHMXBs and 32% of sgHMXBs firmly identified. Therefore, while the ratio of BeHMXBs/HMXBs increased by a factor of 1.5 only, the sgHMXBs/HMXBs ratio increased by a factor of 6.

Let the *INTEGRAL* show go on!

The ISGRI detector on the IBIS imager has performed a detailed survey of the Galactic plane, discovering many new high energy celestial objects, most of which reported in Bird et al. [1][1]. The most important result of *INTEGRAL* to date is the discovery of many new high energy sources – concentrated in the Galactic plane, mainly towards tangential directions of Galactic arms, rich in star forming regions, – exhibiting common characteristics which previously had

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[1] See an up-to-date list at *http://irfu.cea.fr/Sap/IGR-Sources/*, maintained by J. Rodriguez and A. Bodaghee

rarely been seen (see e.g. Chaty and Filliatre 2005). Many of them are HMXBs hosting a neutron star (NS) orbiting around an OB companion, in most cases a supergiant star. Nearly all the *INTEGRAL* HMXBs for which both spin and orbital periods have been measured are located in the upper part of the Corbet diagramme [5] (see Figure 2). They are wind accretors, typical of sgHMXBs, and X-ray pulsars exhibiting longer pulsation periods and higher absorption (by a factor ~ 4) as compared to the average of previously known HMXBs [6]. They divide into two classes: some are very obscured, exhibiting a huge intrinsic and local extinction, –the most extreme example being the highly absorbed source IGR J16318-4848 [7]–, and the others are HMXBs hosting a supergiant star and exhibiting fast and transient outbursts – an unusual characteristic among HMXBs. These are therefore called Supergiant Fast X-ray Transients (SFXTs, Negueruela et al. 2006), with IGR J17544-2619 being their archetype [9].

Multi-wavelength observations of *INTEGRAL* sources

To better characterise this population, Chaty et al. [10] and Rahoui et al. [11] studied a sample of 21 IGRs belonging to both classes described above. Sources of this sample are X-ray pulsars, with high $P_{\rm spin}$ from 139 to 5880 s and P_{orb} ranging from 4 to 14 days. They are therefore wind accreting sgHMXBs, according to the Corbet diagramme (Figure 2). Multiwavelength observations were performed from 2004 to 2008 at the European Southern Observatory (ESO), using Target of Opportunity (ToO) and Visitor modes, in 3 domains: optical ($400 - 800$ nm) with EMMI, NIR ($1 - 2.5\ \mu$m) with SOFI, both instruments at the focus of the 3.5m New Technology Telescope (NTT) at La Silla, and mid-infrared (MIR, $5 - 20\ \mu$m) with the VISIR instrument on Melipal, the 8m Unit Telescope 3 (UT3) of the Very Large Telescope (VLT) at Paranal (Chile). They also used data from the GLIMPSE survey of *Spitzer*. With these observations they performed accurate astrometry, identification, photometry and spectroscopy, aiming at identifying IGR counterparts and the nature of the companion star, deriving their distance, and finally characterising the presence and temperature of their circumstellar medium, by fitting their spectral energy distribution (SED).

The main results of this study are that 15 of these IGRs are identified as HMXBs, and among them 12 HMXBs contain massive and luminous early-type companion stars. By combining optical, NIR and MIR photometry, and fitting their SEDs, Rahoui et al. [11] showed that (i) most of these sources exhibit an intrinsic absorption and (ii) three of them exhibit a MIR excess, which they suggest to be due to the presence of a cocoon of dust and/or cold gas enshrouding the whole binary system, with a temperature of $T_d \sim 1000$ K, extending on a radius of $R_d \sim 10\ R_\star$ (see Chaty and Rahoui 2006).

SUPERGIANT FAST X-RAY TRANSIENTS

General characteristics

SFXTs constitute a new class of ~ 12 sources identified among the recently discovered IGRs. They are HMXBs hosting NS orbiting around sgOB companion stars, exhibiting peculiar characteristics compared to "classical" HMXBs: rapid outbursts lasting only for hours, faint quiescent emission, and high energy spectra requiring a black hole (BH) or NS accretor. The flares rise in tens of minutes, last for ~ 1 hour, their frequency is ~ 7 days, and their luminosity L_x reaches $\sim 10^{36}$ erg s^{-1} at the outburst peak.

IGR J17544-2619, archetype of SFXTs

This bright recurrent transient X-ray source was discovered by *INTEGRAL* on 17 September 2003 [13]. *XMM-Newton* observations showed that it exhibits a very hard X-ray spectrum, and a relatively low intrinsic absorption ($N_{\rm H} \sim 2 \times 10^{22}$ cm^{-2}, González-Riestra et al. 2004). Its bursts last for hours, and inbetween bursts it exhibits long quiescent periods, which can reach more than 70 days. The X-ray behaviour is complex on long, mean and short-term timescales: rapid flares are detected by *INTEGRAL* on all these timescales, on pointed and 200s binned lightcurve (Zurita Heras & Chaty in prep.). The compact object is probably a NS [15]. Pellizza et al. [9] managed to get optical/NIR ToO observations only one day after the discovery of this source. They identified a likely counterpart inside the *XMM-Newton* error circle, confirmed by an accurate localization from *Chandra*. Spectroscopy showed that the companion star was a blue supergiant of spectral type O9Ib, with a mass of $25 - 28\ M_\odot$, a temperature of
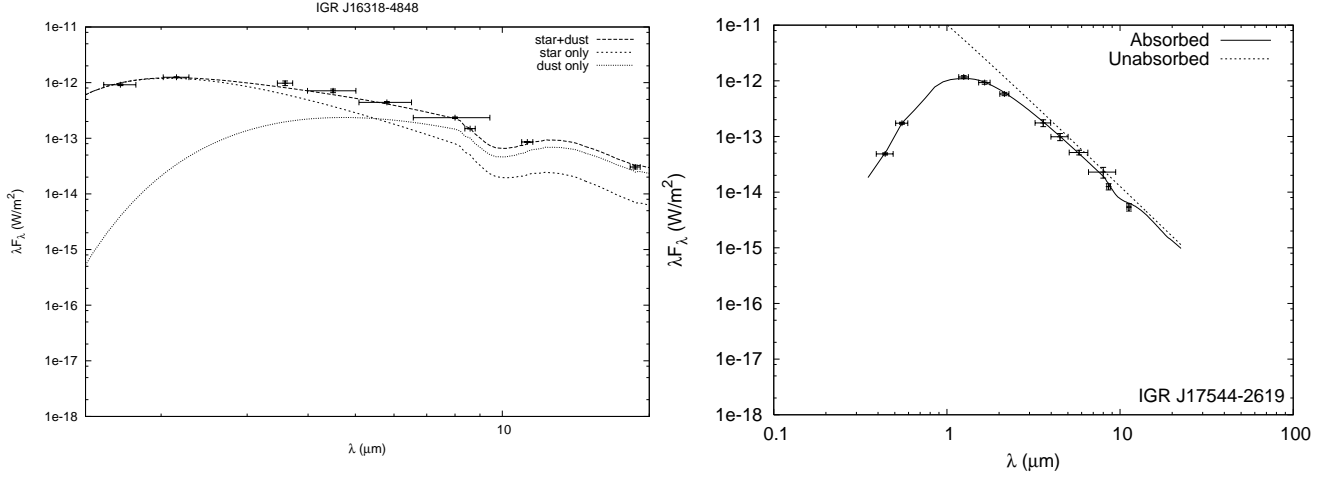
FIGURE 1. Optical to MIR SEDs of IGR J16318-4848 (left) and IGR J17544-2619 (right), including data from ESO/NTT, VISIR on VLT/UT3 and *Spitzer* [11]. IGR J16318-4848 exhibits a MIR excess, interpreted as the signature of a strong stellar outflow coming from the sgB[e] companion star [7]. On the other hand, IGR J17544-2619 is well fitted with only a stellar component corresponding to the O9Ib companion star spectral type [9].

$T \sim 31000$ K, and a stellar wind velocity of $265 \pm 20\ \mathrm{km\,s^{-1}}$ (which is faint for O stars): the system is therefore an HMXB [9]. Rahoui et al. [11] combined optical, NIR and MIR observations and showed that they could accurately fit the observations with a model of an O9Ib star, with a temperature $T_\star \sim 31000$ K and a radius $R_\star = 21.9\ R_\odot$. They derived an absorption $A_v = 6.1$ magnitudes and a distance $D = 3.6$ kpc. Therefore the source does not exhibit any MIR excess, and is well fitted by an unique stellar component (see Figure 1, right panel, Rahoui et al. 2008).

Classification of SFXTs

We can divide the SFXTs in two groups, according to the duration and frequency of their outbursts, and their $\frac{L_{\max}}{L_{\min}}$ ratio. The classical SFXTs exhibit a very low quiescence L_X and a high variability, while intermediate SFXTs exhibit a higher $< L_X >$, a lower $\frac{L_{\max}}{L_{\min}}$ and a smaller variability, with longer flares. SFXTs might appear like persistent sgHMXBs with $< L_X >$ below the canonical value of $\sim 10^{36}\ \mathrm{erg\,s^{-1}}$, and flares superimposed. But there might be some observational bias in these general characteristics, therefore the distinction between SFXTs and sgHMXBs is not well defined yet. While the typical hard X-ray variability factor (the ratio between deep quiescence and outburst flux) is less than 20 in classical/absorbed systems, it is higher than 100 in SFXTs (some sources can exhibit flares in a few minutes, like for instance XTE J1739-302 & IGR J17544-2619). The intermediate SFXTs exhibit smaller variability factors.

SFXT behaviour: clumpy wind accretion?

Such sharp rises exhibited by SFXTs are incompatible with the orbital motion of a compact object through a smooth medium (Negueruela et al. 2006, Smith et al. 2006, Sguera et al. 2005). Instead, flares must be created by the interaction of the accreting compact object with the dense clumpy stellar wind (representing a large fraction of stellar $\frac{dM}{dt}$). In this case, the flare frequency depends on the system geometry, and the quiescent emission is due to accretion onto the compact object of diluted inter-clump medium, explaining the very low quiescence level in classical SFXTs.

Macro-clumping scenario

Each SFXT outburst is due to the accretion of a single clump, assuming that the X-ray lightcurve is a direct tracer of the wind density distribution. The typical parameters in this scenario are: a compact object with large orbital radius: $10\,R_\star$, a clump size of a few tenths of $R_\star$, a clump mass of $10^{22-23}g$ (for $N_H = 10^{22-23}$ cm^{-2}), a mass loss rate of $10^{-(5-6)}\,M_\odot/yr$, a clump separation of order $R_\star$ at the orbital radius, and a volume filling factor: $0.02->0.1$. The flare to quiescent count rate ratio is directly related to the $\frac{clump}{inter-clump}$ density ratio, which ranges between 15-50 for intermediate SFXTs, and 10^{2-4} for "classical" SFXTs. A very high degree of porosity (macroclumping) is required to reproduce the observed outburst frequency in SFXTs, in good agreement with UV line profiles and line-driven instabilities at large radii (Oskinova et al. 2007; Runacres and Owocki 2005; Walter and Zurita Heras 2007).

SFXTs in the context of sgHMXBs

To explain the emission of SFXTs in the context of sgHMXBs, Negueruela et al. [21] and Walter and Zurita Heras [20] invoke the existence of two zones around the supergiant star, of high and low clump density respectively. This would naturally explain the smooth transition between sgHMXBs and SFXTs, and the existence of intermediate systems; the main difference between classical sgHMXBs and SFXTs being in this scenario the NS orbital radius. Indeed, a basic model of porous wind predicts a substantial change in the properties of the wind "seen by the NS" at a distance $r \sim 2\,R_\star$ (Negueruela et al. 2008), where we stop seeing persistent X-ray sources. There are 2-regimes: either the NS sees a large number of clumps, because it is embedded in a quasi-continuous wind; or the number density of clumps is so small that the NS is effectively orbiting in an empty space.

The observed division between sgHMXBs (persistent sgHMXBs and SFXTs) is therefore naturally explained by simple geometrical differences in the orbital configurations:

1. The obscured sgHMXBs (persistent and luminous systems) would have short and circular orbits lying inside the zone of stellar wind high clump density ($R_{orb} \sim 2\,R_\star$).
2. The intermediate SFXTs would have short orbits, circular or eccentric, and possible periodic outbursts, the NS being inside the narrow transition zone.
3. The classical SFXTs would have larger and eccentric orbital radius, the NS orbiting outside the high density zone.

IGR J18483-0311: an intermediate SFXT?

X-ray properties of this system were suggesting an SFXT nature [22], exhibiting however an unusual behaviour: its outbursts last for a few days (to compare to hours for classical SFXTs), and the ratio L_{max}/L_{min} only reaches $\sim 10^3$ (meaning that its quiescence is at a higher level than the ratio $\sim 10^4$ for classical SFXTs). Moreover, its orbital period P_{orb}=18.5d is low compared to classical SFXTs (with large/eccentric orbits). Finally, its orbital and spin periods (P_{spin}=21.05s) located it ambiguously inbetween Be and sgHMXBs in the Corbet Diagramme (see Figure 2). Rahoui and Chaty [23] identified the companion star of this system as a B0.5Ia supergiant, unambiguously showing that this system is an SFXT. Furthermore, they suggest that this system could be the first firmly identified intermediate SFXT, characterised by short, eccentric orbit (with an eccentricity e between 0.4 and 0.6), and long outbursts... An "intermediate" SFXT nature would explain the unusual characteristics of this source among "classical" SFXTs.

What is the origin of "misplaced" sgHMXBs?

As noted by Liu et al. [24], there are two "misplaced" SFXTs in the Corbet diagram: IGR J11215-5952 (a neutron star orbiting a B1 Ia star, Negueruela et al. 2005) and IGR J18483-0311, described in the previous paragraph (see Figure 2). According to Liu et al. [24], these 2 SFXTs can not have evolved from normal Main Sequence O-type stars, since they are not at the equilibrium spin period of sgHMXBs (see e.g. Waters and van Kerkwijk 1989). They must therefore be the descendants of BeHMXBs (i.e. hosting O-type emission line stars), after the NS has reached the equilibrium spin period [24].
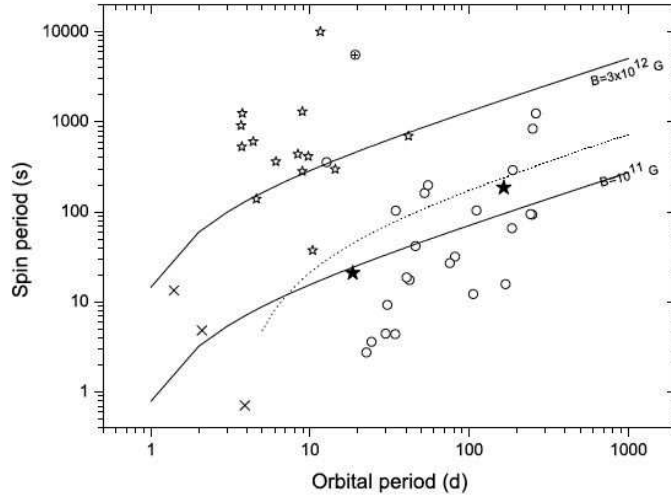
FIGURE 2. Corbet diagram, adapted and taken from Liu et al. [24], showing the relation between orbital and spin periods. The open circles are for Be/X-ray binaries and the open stars for wind-fed sgHMXBs. The two "misplaced" SFXTs –IGR J11215-5952 and IGR J18483-0311– are indicated by the filled stars. The solid lines stand for the theoretical equilibrium period for sgHMXBs, with magnetic field of 10^{11} and 3×10^{12} G, respectively. The dot line is the theoretical line with the parameters of B1 Ia supergiants (see Liu et al. 2010 for more details).

OBSCURED HMXBS

IGR J16318-4848, an extreme case

IGR J16318-4848 was the first source discovered by IBIS/ISGRI on *INTEGRAL* on 29 January 2003 [27], with a $2'$ uncertainty. *XMM-Newton* observations revealed a comptonised spectrum exhibiting an unusually high level of absorption: $N_{\mathrm{H}} \sim 1.84 \times 10^{24}$ cm^{-2} [28]. The accurate localisation by *XMM-Newton* allowed Filliatre and Chaty [7] to rapidly trigger ToO photometric and spectroscopic observations in optical/NIR, leading to the confirmation of the optical counterpart [29] and to the discovery of the NIR one [7]. The extremely bright NIR source (B $> 25.4 \pm 1$; I $= 16.05 \pm 0.54$, J $= 10.33 \pm 0.14$; H $= 8.33 \pm 0.10$ and Ks $= 7.20 \pm 0.05$ magnitudes) exhibits an unusually strong intrinsic absorption in the optical ($A_v = 17.4$ magnitudes), 100 times stronger than the interstellar absorption along the line of sight ($A_v = 11.4$ magnitudes), but still 100 times lower than the absorption in X-rays. This led Filliatre and Chaty [7] to suggest that the material absorbing in X-rays was concentrated around the compact object, while the material absorbing in optical/NIR was enshrouding the whole system. The NIR spectroscopy in the $0.95 - 2.5\,\mu$m domain allowed them to identify the nature of the companion star, by revealing an unusual spectrum, with many strong emission lines:

1. H, HeI (P-Cyg) lines: characteristic of dense/ionised wind at v $= 400$ km/s,
2. HeII lines: the signature of a highly excited region,
3. [FeII] lines: reminiscent of shock heated matter,
4. FeII lines: emanating from media of densities $> 10^5 - 10^6$ cm^{-3},
5. NaI lines: coming from cold/dense regions.

All these lines originate from a highly complex, stratified circumstellar environment of various densities and temperatures, suggesting the presence of an envelope and strong stellar outflow responsible for the absorption. Only luminous early-type stars such as sgB[e] show such extreme environments, and Filliatre and Chaty [7] concluded that IGR J16318-4848 was an unusual HMXB hosting a sgB[e] with characteristic luminosity of $10^6\,L_\odot$ and mass of $30\,M_\odot$, located at a distance between 1 and 6 kpc (see also Chaty and Filliatre 2005). This source would therefore be the second HMXB hosting a sgB[e] star, after CI Cam (see Clark et al. 1999).

The question of this huge absorption was still pending, and only MIR observations would allow to solve this question, and understand its origin. By combining optical, NIR and MIR observations, and fitting these observations

with a model of sgB[e] companion star, Rahoui et al. [11] showed that IGR J16318-4848 was exhibiting a MIR excess (see Figure 1, left panel), that they interpreted as due to the strong stellar outflow emanating from the sgB[e] companion star. They found that the companion star had a temperature of $T_\star = 22200$ K and radius $R_\star = 20.4\,R_\odot = 0.1$ a.u., consistent with a supergiant star, and an extra component of temperature T $= 1100$ K and radius R $= 11.9\,R_\star = 1$ a.u., with $A_v = 17.6$ magnitudes. Recent MIR spectroscopic observations with VISIR at the VLT showed that the source was exhibiting strong emission lines of H, He, Ne, PAH, Si, proving that the extra absorbing component was made of dust and cold gas.

By assuming a typical orbital period of 10 days and a mass of the companion star of 20 $M_\odot$, we obtain an orbital separation of 50 $R_\odot$, smaller than the extension of the extra component of dust/gas ($= 240\,R_\odot$), suggesting that this dense and absorbing circumstellar material envelope enshrouds the whole binary system, like a cocoon (see Figure 3, left panel). We point out that this source exhibits such extreme characteristics that it might not be fully representative of the other obscured sources.

THE GRAND UNIFICATION: DIFFERENT GEOMETRIES, DIFFERENT SCENARIOS

In view of the results described above, there seems to be a continuous trend, from classical and/or absorbed sgHMBs, to classical SFXTs. We outline in the following this trend.

"Classical" sgHMXBs: the NS is orbiting at a few stellar radii only from the star. The absorbed (or obscured) sgHMXBs (like IGR J16318-4848) are classical sgHMXBs hosting NS constantly orbiting inside a cocoon made of dust and/or cold gas, probably created by the companion star itself. These systems therefore exhibit a persistent X-ray emission. The cocoon, with an extension of $\sim 10\,R_\star = 1$ a.u., is enshrouding the whole binary system. The NS has a small and circular orbit (see Figure 3, left panel).

"Intermediate" SFXT systems: (such as IGR J18483-0311), the NS orbits on a small and circular/excentric orbit, and it is only when the NS is close enough to the supergiant star that accretion takes place, and that X-ray emission arises.

"Classical" SFXTs: (such as IGR J17544-2619), the NS orbits on a large and excentric orbit around the supergiant star, and exhibits some recurrent and short transient X-ray flares, while it comes close to the star, and accretes from clumps of matter coming from the wind of the supergiant. Because it is passing through more diluted medium, the $\frac{Lmax}{Lmin}$ ratio is higher for "classical" SFXTs than for "intermediate" SFXTs (see Figure 3, right panel).

Although this scenario seems to describe quite well the characteristics currently seen in sgHMXBs, we still need to identify the nature of many more sgHMXBs to confirm it, and in particular the orbital period and the dependance of the column density with the phase of the binary system.

Formation and evolution of sgHMXBs, link with population synthesis models

sgHMXBs revealed by *INTEGRAL* will allow us to better constrain and understand the formation and evolution of X-ray binary systems, by comparing them to numerical study of LMXB/HMXB population synthesis models. For instance, these new systems might represent a precursor stage of what is known as the "Common Envelope phase" in the evolution of LMXB/HMXB systems, when the orbit has shrunk so much that the neutron star begins to orbit inside the envelope of the supergiant star. In addition, many parameters do influence the various evolutions, from one system to another: differences in mass, size, orbital period, ages, rotation, magnetic field, accretion type, stellar endpoints, etc... Moreover, stellar and circumstellar properties also influence the evolution of high-energy binary systems, made of two massive components likely born in rich star forming regions.

In the very nice review on the formation and evolution of relativistic binaries written by van den Heuvel [31], the evolution of these supergiant INTEGRAL sources is mentioned. We can have an idea of the formation of these systems, since orbital periods of later evolutionary phases are linearly dependent of initial orbital periods. It is therefore possible to derive that the initial orbital periods of currently very wide O-supergiant INTEGRAL binaries could be as long as 100 days [31]. The systems having long orbital periods are expected to survive the Common Envelope phase. They may then either end as a close eccentric double neutron star, or in some cases, as a black hole-neutron star binary (van den Heuvel, priv. comm.).
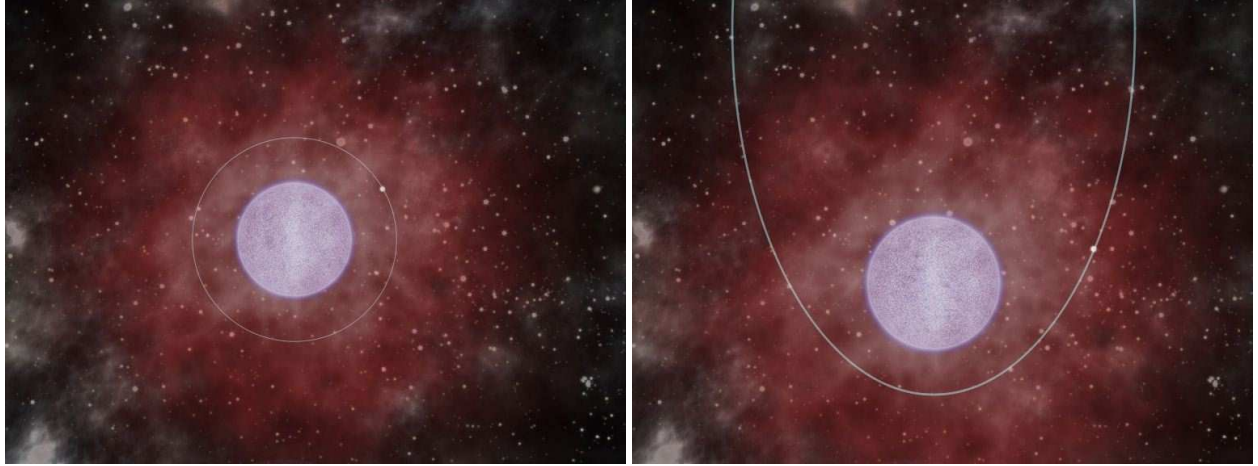
FIGURE 3. Scenarios illustrating two possible configurations of *INTEGRAL* sources: a NS orbiting a supergiant star on a circular orbit (left image); and on an eccentric orbit (right image), accreting from the clumpy stellar wind of the supergiant. The accretion of matter is persistent in the case of the obscured sources, as in the left image, where the compact object orbits inside the cocoon of dust enshrouding the whole system. On the other hand, the accretion is intermittent in the case of SFXTs, which might correspond to a compact object on an eccentric orbit, as in the right image. A 3D animation of these sources is available on the website: *http://www.aim.univ-paris7.fr/CHATY/Research/hidden.html*

No such system is known yet, however some of these systems might harbour a black hole as the compact object. Of course neutron stars are easier to detect through X-ray pulsations, but, as Carl Sagan already pointed it out, *absence of evidence is not evidence of absence...* We should look for black holes orbiting around supergiant companion stars in wind-accreting HMXBs, however this is only feasible through observational methods involving detection of extremely faint radial velocity displacement due to the high mass of the companion star, or through extremely accurate radio measurements that will be available in the future. On the other hand, massive stars lose so much matter during their evolution that they might always finish as neutron stars (see e.g. Maeder and Meynet 2008). If this is the case, then such systems hosting black holes might not form at all.

Finally, these sources are also useful to look for massive stellar "progenitors", for instance giving birth to coalescence of compact objects, through NS/NS or NS/BH collisions. They would then become prime candidate for gravitational wave emitters, or even to short/hard γ-ray bursts.

CONCLUSIONS AND PERSPECTIVES...

The *INTEGRAL* satellite has tripled the total number of Galactic sgHMXBs, constituted of a NS orbiting around a supergiant star. Most of these new sources are slow and absorbed X-ray pulsars, exhibiting a large N_H and long P_{spin} ($\sim$1ks). The influence of the local absorbing matter on periodic modulations is different for sgHMXBs or BeHMXBs, segregated in different parts of N_H-P_{orb} or N_H-P_{spin}. *INTEGRAL* revealed 2 new types of sources. First, the SFXTs, exhibiting short and strong X-ray flares, with a peak flux of 1 Crab during 1–100s, every $\sim$ 100 days. These flares can be explained by accretion through clumpy winds. Second, the obscured HMXBs are persistent X-ray sources composed of supergiant stellar companions exhibiting a strong intrinsic absorption and long P_{spin}. The NS is deeply embedded in the dense stellar wind, forming a dust cocoon enshrouding the whole binary system.

These results show the existence in our Galaxy of a dominant population of a previously rare class of high-energy binary systems: sgHMXBs, some of them exhibiting a high intrinsic absorption (Chaty et al. 2008; Rahoui et al. 2008). Studying this population will provide a better understanding of the formation and evolution of short-living HMXBs. Furthermore, stellar population models now have to take these objects into account, to assess a realistic number of high-energy binary systems in our Galaxy.

ACKNOWLEDGMENTS

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