

Supergiant Fast X-ray Transients: a review

Lara Sidoli* †

*INAF, Istituto di Astrofisica Spaziale e Fisica Cosmica,
Via E. Bassini 15, I-20133 Milano, Italy
E-mail: sidoli@iasf-milano.inaf.it*

Supergiant Fast X-ray Transients are a class of Galactic High Mass X-ray Binaries with supergiant companions. Their extreme transient X-ray flaring activity was unveiled thanks to INTEGRAL/IBIS observations. The SFXTs dynamic range, with X-ray luminosities from 10^{32} erg s⁻¹ to 10^{37} erg s⁻¹, and long time intervals of low X-ray emission, are puzzling, given that both their donor star properties and their orbital and spin periodicities seem very similar to those displayed by massive binaries with persistent X-ray emission. Clumpy supergiant winds, accretion barriers, orbital geometries and wind anisotropies are often invoked to explain their behavior, but still several open issues remain. A review of the main recent observational results will be outlined, together with a summary of the new scenarios proposed to explain their bright flaring X-ray activity. The main result of a long *Suzaku* observation of the SFXT IGR J16479–4514 with the shortest orbital period is also briefly summarized. The observation of the X-ray eclipse in this source allowed us to directly probe the supergiant wind density at the orbital separation, leading to the conclusion that it is too large to justify the low X-ray luminosity. A mechanism reducing the accretion rate onto the compact object is required.

*An INTEGRAL view of the high-energy sky (the first 10 years) - 9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch
15-19 October 2012
Bibliothèque Nationale de France, Paris, France*

*Speaker.

†Solicited talk

1. Supergiant Fast X-ray Transients

Supergiant Fast X-ray Transients (SFXTs) are one of the most spectacular discoveries obtained by the *INTEGRAL* satellite (Sguera et al. 2005, 2006; Negueruela et al. 2006). Their X-ray emission, characterized by short (typically lasting ~ 100 – $10,000$ s) bright X-ray flares, is produced by a compact object (mostly a neutron star, given that X-ray pulsations have been detected in about a half of the members of the class), transiently accreting matter directly from the strong wind of the blue supergiant companion (e.g. Chaty 2010), although the mechanism producing the transient X-ray emission is still an open issue. Indeed, it is difficult to explain why SFXTs, which seem to be massive binary systems similar to persistently accreting High Mass X-ray Binaries (HMXBs), display so different X-ray properties, showing extreme X-ray transient behavior (with X-ray intensity spanning from 2 to 5 order of magnitudes) instead of persistent X-rays. Although their brightest X-ray emission is concentrated into short flares, the SFXTs accretion phase can last a few days (Romano et al. 2007, Sidoli et al. 2009a, Rampy et al. 2009).

INTEGRAL observations, with the large field of view, good angular and spectral resolution, good sensitivity at hard X-rays, are particularly suited in discovering new members of the class (ten are now the known SFXTs, with several candidates with peculiar X-ray flaring emission but no optical identification), catching the brightest flares to study the long-term properties and source duty cycles (Ducci et al. 2010, Martínez-Núñez et al. 2010, Blay et al. 2012), and in discovering X-ray periodicities (Drave et al., 2011 and references therein), which are fundamental quantities to unveil the nature of these sources.

The first orbital periodicity in a SFXT was discovered with *INTEGRAL* from IGR J11215–5952 (Sidoli et al. 2006), which displays bright flaring episodes every ~ 165 days (Sidoli et al. 2007). Other SFXTs have shown X-ray modulations in *INTEGRAL* data, associated with their orbital periods (Bird et al. 2009, Clark et al. 2009, Drave et al. 2010, Zurita Heras & Chaty 2009). Long-term X-ray modulations have been discovered also by other missions, like *Swift*/BAT and *RXTE*/ASM (Corbet et al. 2006, Levine et al. 2006, Jain et al. 2009, La Parola et al. 2010), produced by orbital X-ray variability in eccentric and/or eclipsing binaries. X-ray pulsations have been discovered in a few SFXTs (Fig. 1), demonstrating the neutron star nature of the compact object. These periodicities can be plotted in a Corbet diagram of orbital period versus neutron star spin period (Fig. 1, updated to 2012, October), where SFXTs have been indicated by the large green circles around blue stars. While persistent HMXB pulsars with supergiant donors (marked by blue stars) mainly concentrate in a region of the diagram with orbital periods less than 15 days and spin periods around a few hundred seconds, SFXTs span across the whole diagram, also lying in regions in-between the wind-fed pulsars with supergiants (in blues) and the Be/X-ray transients (in red), or lying completely inside the region typical for Be/X-ray transients (the SFXT IGR J11215–5952).

A possibility is that SFXTs represent an evolutionary link between HMXBs with Be companions and with supergiant donors (Liu et al. 2011; Chaty et al. 2013 these proceedings). An alternative explanation is that, for SFXTs lying near the Be/XRBs region of this diagram, the physical mechanism driving the outbursts is similar to that producing the Be/XRBs outbursts: the presence of a denser and slower outflowing wind component (Sidoli et al. 2007) which triggers the outburst when the neutron star crosses it. This could explain the strictly periodic X-ray flares observed from the SFXT IGR J11215–5952 (Sidoli et al. 2006), as well as the three peaks observed in the orbital

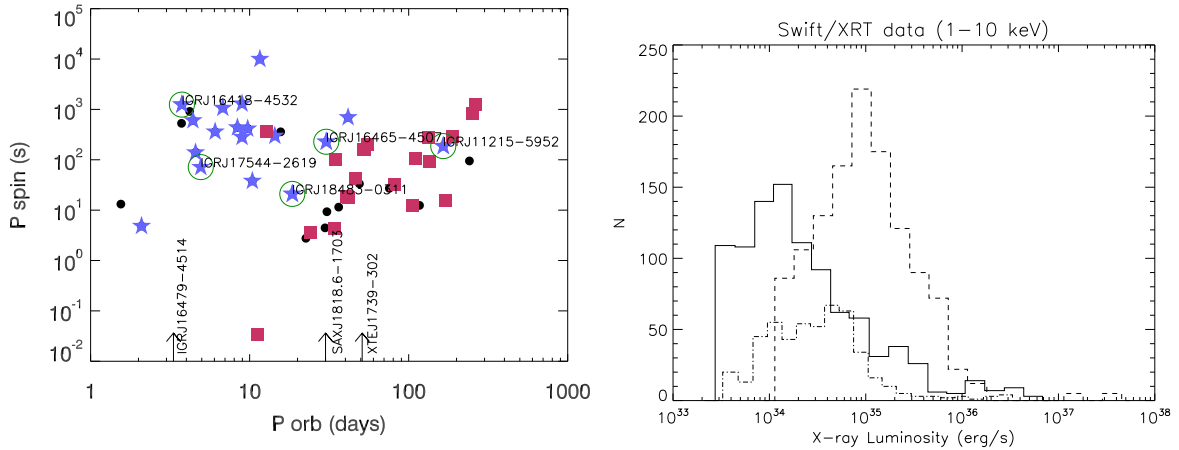


Figure 1: *Left panel:* High Mass X-ray Binary Pulsars located in our Galaxy as they appear in an updated version of the Corbet diagram. *Blue stars* indicate sources with supergiant companions, while the *red squares* the pulsars with Be donors (Liu et al., 2006). SFXTs are indicated by the *large circles* around blue stars. Arrows mark SFXTs where only the orbital period is known. *Right panel:* X-ray luminosity distribution calculated for three SFXTs (solid line, XTE J1739-302; dashed line, IGR J16479-4514; dashed-dotted line, IGR J17544-2619) from the 1-10 keV count rates observed by Swift/XRT (count rate distributions taken from Romano et al. 2010).

light curve of the prototypical SFXT XTE J1739-302 (Drave et al. 2010).

This is only one of the proposed explanation for the SFXTs behavior. Other possibilities are that the compact object accretes matter from an extremely inhomogeneous supergiant wind (e.g. in t Zand 2005; Oskina et al. 2012), or that the geometry of the SFXTs orbits are crucial in determining the probability for the injection of massive dense clumps by the neutron star along its orbit. In persistent systems the neutron star lies always inside the region where the outflowing clumps are more numerous, while in SFXTs with wider orbits it lies outside it (Negueruela et al. 2008). *XMM – Newton* observations of the spectral evolution of the iron line emission during a bright flare in one SFXT seems to be compatible with the accretion of a single dense wind clump (Bozzo et al. 2011).

A result of the *Swift/XRT* two years long campaign on three SFXTs (Romano et al. 2010) is the distribution of count rates in the 1-10 keV energy band. From these distributions, I derived the histogram of the X-ray luminosities (1–10 keV) shown in Fig. 1 (right panel; Pizzolato & Sidoli 2013), assuming a power law spectrum and the distance appropriate for each individual SFXT, as reported in Sidoli et al. (2008). Both the shape of the distributions and their average X-ray luminosity appear to be different in the three SFXTs. Compared with the luminosity distributions of persistently accreting HMXBs, where the dynamic range of the X-ray luminosity is limited to about 10 or 100 (only when considering the so called “off-states” and the rare “giant flares”, e.g. Kreykenbohm et al. 2008), the difference can be due completely to different properties of the accreting matter, that is HMXBs accrete from clumpy winds with a narrow mass distribution, while SFXTs from supergiant winds with a much wider clumps’ mass distribution (Pizzolato & Sidoli 2013).

Oskina et al. (2012) recently studied the clumped stellar winds in supergiant HMXBs. They performed hydrodynamical simulations and derived the implied X-ray variability, mainly due to

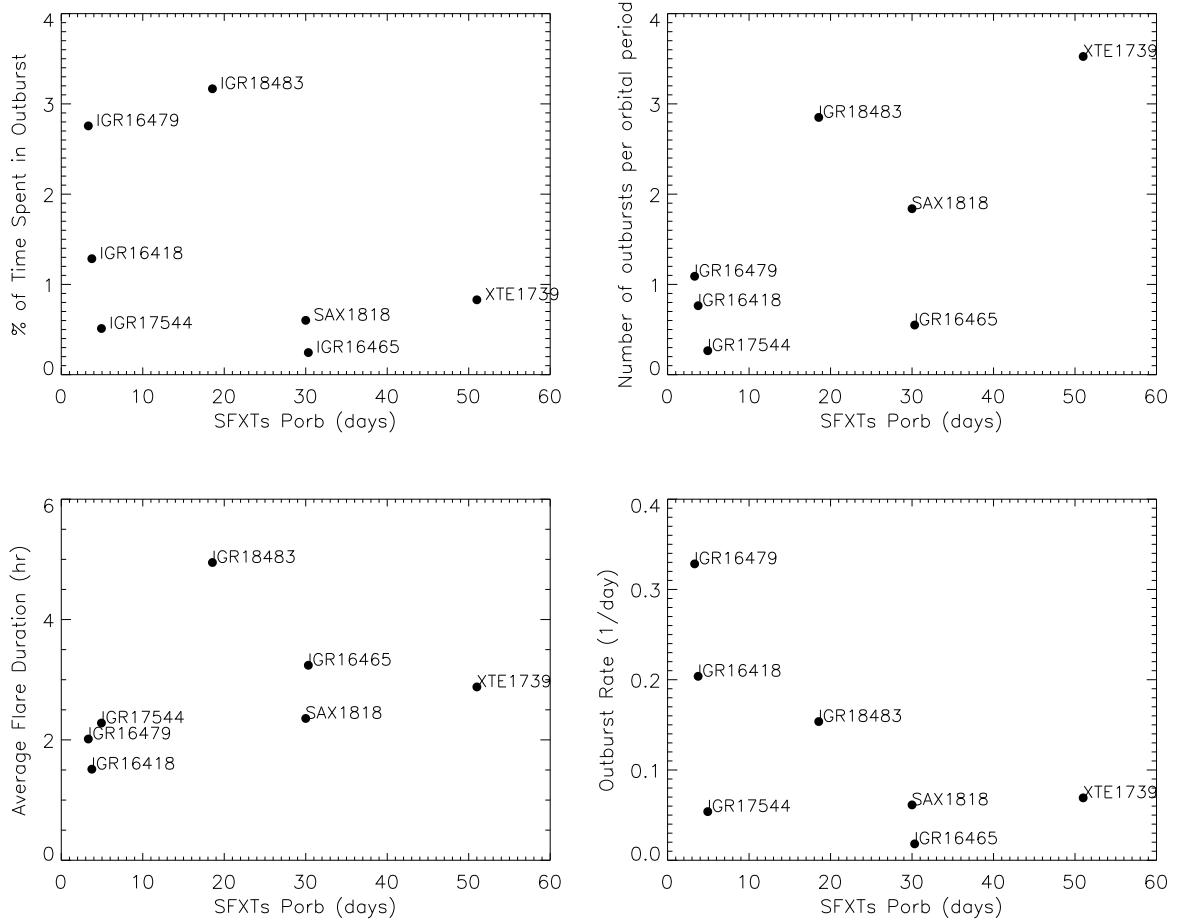


Figure 2: *INTEGRAL* archival data results for SFXTs with known orbital periods (IBIS data from Ducci, Sidoli & Paizis, 2010). Abbreviated source names are the following: IGR16479=IGRJ16479-4514, IGR16418=IGRJ16418-4532, IGR16465=IGRJ16465-4507, XTE1739=XTEJ1739-302, IGR17544=IGRJ17544-2619, IGR18483=IGRJ18483-0311, SAX1818=SAXJ1818.6-1703.

variability of the wind velocity, the role of which was poorly considered in previous works. The strong variability in both the density and the velocity in the structured wind translates (by means of Bondi-Hoyle-Lyttleton wind accretion) into an extreme X-ray variability up to eight orders of magnitude on short time-scales. This X-ray variability is too large and has never been observed in HMXBs (even in SFXTs). These authors suggested that the details of the accretion process reduce the variability resulting from the stellar wind velocity and density jumps. Viable possibilities is that clumps are destructed near the accreting neutron star, or that the density and velocity gradients are smoothed out in the accretion wake, or that a physical mechanism is at work in *damping* the variability.

Long-term properties of a sample of SFXTs, as observed with *INTEGRAL*/IBIS, are displayed in Fig. 2 versus the known orbital periods, and in Fig. 3 versus the spin periods (numbers have been calculated from data reported in Ducci et al. 2010): they are the percentage of time spent by SFXTs in bright flares, the number of outbursts in a single orbital period, the average duration of the flaring activity and the outburst rate. The trend for SFXTs with longer orbital periods is to show

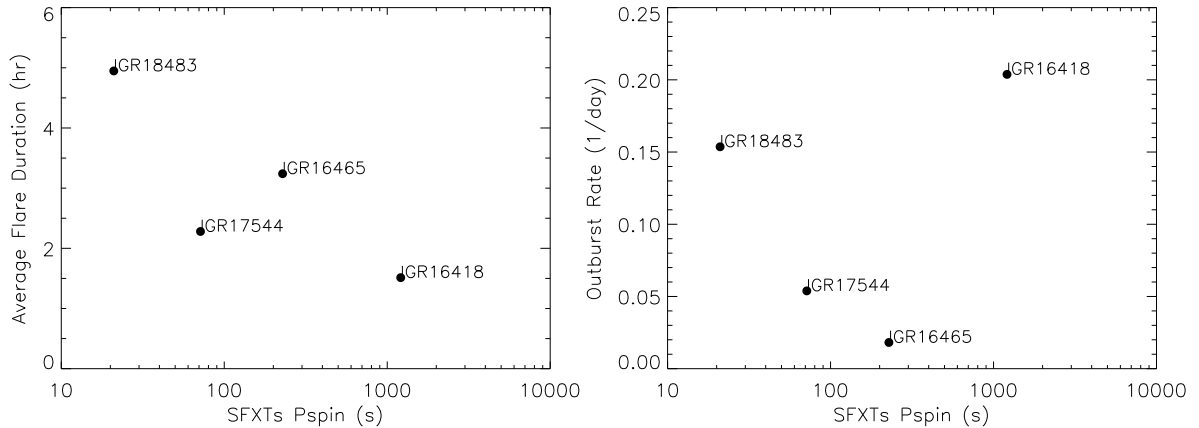


Figure 3: *INTEGRAL* archival data results for SFXTs with known spin periods (IBIS data are from Ducci, Sidoli & Paizis, 2010). Abbreviated source names are the same as in Fig. 2.

a lower outburst rate. This behavior agrees with the clumpy wind model (Negueruela et al. 2008). On the other hand, the SFXTs with the narrowest orbits can display very different outburst rates (with IGR J17544-2619 showing an outburst rate even lower than XTE J1739-302, but with very different orbital periods) demonstrating that the difference between persistently accreting HMXB pulsars and SFXTs *cannot* be explained *only* by different orbital geometries. Indeed, for example, the SFXTs IGR J16479-4514 and IGR J17544-2619 have orbital periods much shorter than the bulk of persistently accreting, wind-fed pulsars (see also Fig. 1).

Besides the structure of the supergiant companion and the orbital configuration, some authors considered a further possibility, that the compact object in SFXTs is slowly rotating (~ 1000 s) and that it undergoes a transition between the direct accretion regime and the onset of a centrifugal or a magnetic barrier (Grebenev and Sunyaev 2007, Bozzo et al. 2008). In this latter case, the neutron star in SFXTs should be a magnetar ($B \sim 10^{14} - 10^{15}$ G). These gated mechanisms, able to halt accretion rate most of the time, could explain the SFXTs with very short orbital periods where the compact object is always embedded within the dense and strong wind from the companion.

2. IGR J16479-4514: the SFXT with the shortest orbital period

In order to explore this possibility, to probe the X-ray and wind properties along a single orbit in a SFXT, we obtained a 250 ks long *Suzaku* observation of the member with the shortest orbital period, IGR J16479-4514 (Sidoli et al. 2013, in press; Sidoli et al. these proceedings for details). The XIS light curve (1–10 keV) observed in February 2012 is shown in Fig. 4, covering about 80% of the orbit ($P_{orb} = 3.32$ days). The low X-ray intensity at the beginning of the observation is consistent with being due to the eclipse by the companion. Outside the eclipse, the source is highly variable, with two faint flares lasting 10–15 ks. The first flare is interestingly located at an orbital phase similar to other bright flares observed in the past (Bozzo et al. 2009), suggestive of the presence of a phase-locked gas stream from the supergiant, or wind component, which triggers an enhanced accretion of matter onto the compact object. The average luminosity, assuming a dis-

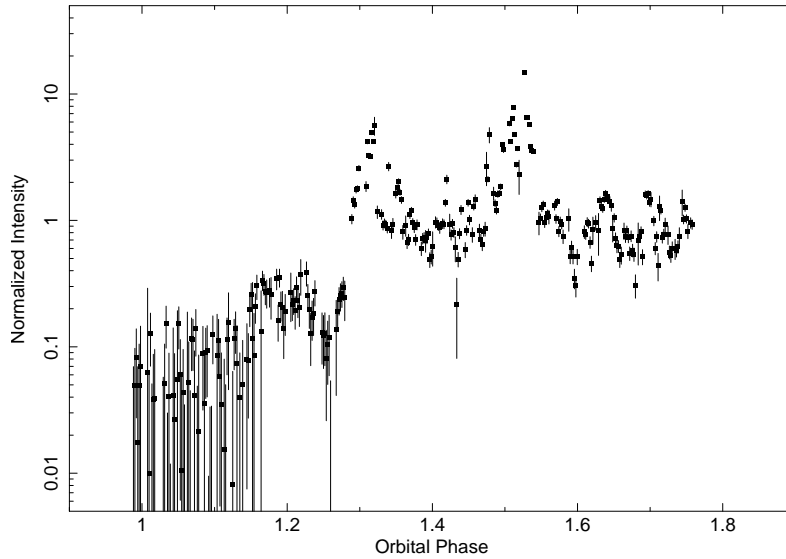


Figure 4: IGR J16479-4514 X-ray light curve observed by *Suzaku*/XIS (1–10 keV) in February 2012 (Sidoli et al. 2013), folded on the orbital period of 286792 s, assuming epoch 54547.05418 MJD.

tance of 2.8 kpc, is around 10^{34} erg s $^{-1}$. The 1–10 keV time selected spectra can be well fit with an absorbed power law together with a narrow Fe $K\alpha$ emission line at 6.4 keV. The intensity of the iron line is variable along the orbit and correlates with the X-ray emission above 7 keV (outside the eclipse). The resulting absorbing column density does not show evidence for variability, ($N_{\text{H}} \sim 10^{23}$ cm $^{-2}$, in excess of the interstellar value), except from during the X-ray eclipse, where it is significantly lower, consistent with the presence of Thomson scattering by electrons in the supergiant wind.

The main result of the *Suzaku* observation is that the scattered X-rays visible during the X-ray eclipse (compared with the uneclipsed emission), allowed us to determine the density of the donor wind at the orbital separation ($a = 2.2 \times 10^{12}$ cm for a companion with $M_{\text{opt}} = 35 M_{\odot}$) resulting in 7×10^{-14} g cm $^{-3}$. Assuming a spherical geometry for the outflowing supergiant wind, this density implies a ratio, \dot{M}_w / v_{∞} , between the wind mass loss rate and the wind terminal velocity, of 7×10^{-17} M_{\odot} /km. This ratio, assuming terminal velocities in the range from 500 to 3000 km s $^{-1}$, translates into an accretion luminosity of $L_X = 3 - 15 \times 10^{36}$ erg s $^{-1}$, which is two orders of magnitude higher than that observed. In conclusion, a physical mechanism should reduce the mass accretion rate. A viable possibility is the mediating role of a neutron star magnetospheric surface.

I have also reanalysed an archival *XMM-Newton* observation performed during the eclipse ingress, originally reported by Bozzo et al. (2008a). I show the *XMM* light curve in Fig. 5 (left panel) together with numbers and vertical lines displaying the time intervals for the temporal selected spectra. The results fitting the *XMM* spectra with an absorbed power law are displayed on the right panel, where again the large variability in the absorption is only due to the X-ray eclipse. Even with EPIC it is not possible to find any clear variability of the absorption (which would be expected in case of a clumpy wind), indicating a quite smooth nature for the IGR J16479–4514 supergiant wind, possibly because we are probing here the inner regions of the companion wind.

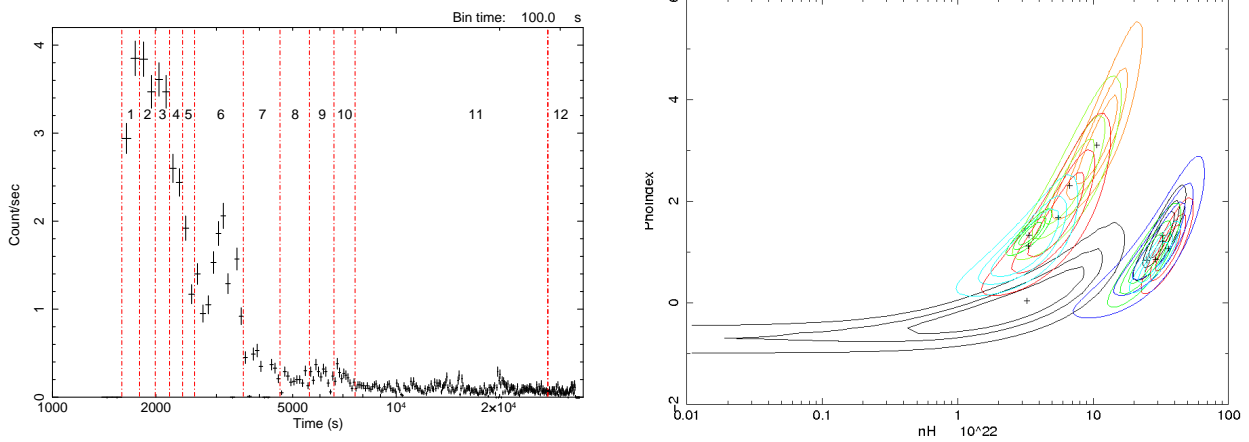


Figure 5: *Left panel:* XMM-Newton archival pn data of IGR J16479–4514, observed on 2008, March 21 (I have reanalysed obs. ID 0512180101, originally reported by Bozzo et al. 2008a). Numbers mark the time selected spectra during the X-ray eclipse ingress. *Right panel:* Confidence contour levels (68%, 90%, 99%) for the two parameters (photon index and absorbing column density) of the absorbed power law fitting the IGR J16479–4514 EPIC pn time selected spectra (confidence contours of spectra 1–6 are concentrated around $3 \times 10^{23} \text{ cm}^{-2}$, spectra 8–12 have contours around $6 \times 10^{22} \text{ cm}^{-2}$, while spectrum number “7” lies in between, with black contours).

In conclusion, in the SFXT IGR J16479–4514 the supergiant wind at the orbital separation is too dense to explain the low X-ray luminosity and quite smooth to explain the source flares.

Acknowledgments

I would like to thank the organizers for their kind invitation at the 9th INTEGRAL Workshop “An INTEGRAL view of the high-energy sky (the first 10 years)” held in Paris, on 15-19 October 2012, to celebrate the 10th anniversary of the launch. This work was supported in Italy by ASI-INAF contracts I/033/10/0 and I/009/10/0, and by the grant from PRIN-INAF 2009, “The transient X-ray sky: new classes of X-ray binaries containing neutron stars” (PI: L. Sidoli).

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