INTEGRAL review of HMXBs: SFXTs

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Abstract

This paper reviews the INTEGRAL discovery of Supergiant Fast X-Ray Transients (SFXTs) and in general the properties of the High Mass X-ray Binaries (HMXBs) observed in the 8 years in orbit.

In fact, INTEGRAL has discovered a new class of strongly absorbed X-ray binaries during its initial observation of the Galaxy Center and Plane. The prototype is IGR J16318-4848, associated with a sgB[e] star. This discovery was mainly due to the INTEGRAL unique capability to monitor the galactic center and bulge area for long periods at an unprecedented sensitivity level (<0.2 mCrab) in the soft gamma-ray range (15 keV-10MeV) if compared with other wide-field instruments. To date most of the members of this new class of HMXB has been discovered with INTEGRAL. More than half of these sources have supergiant companions and a substantial fraction are slow (∼100-1000s) X-ray pulsars. They are embedded in dense environments and the emission is so heavily absorbed that these sources were not detected/identified before with soft X-ray instruments.

Among the class of HMXB INTEGRAL has discovered a puzzling new sub class of transient sources: the Supergiant Fast X-ray Transients (SFXTs). They show short X and soft gamma-ray outbursts typically lasting from a fraction of an hour to a few hours. The total number of these sources is already comparable to that of persistent supergiant X-ray binaries: what is the different physical process active in the two cases? The nature of their short outbursts, in a few cases recurrent, is still not clear. The more plausible explanation is connected with clumps in the stellar wind accretion, eventually generated at some distance from the giant star by magnetic field.

Key words: new source class — fast transient — high energy sky

1. INTRODUCTION

The INTEGRAL satellite (Winkler et al. 2003), launched in October 2002, through its hard X-ray imager, IBIS characterized with large field of view (Ubertini et al. 2003), good sensitivity and combined with a deep exposure of the Galactic Plane, discovered a new class of fast X-ray transients. These sources are characterized by a significant X-ray luminosity (reaching a few 10^{36} erg s^{-1}) only during short (a few hours) sporadic and hard X-ray flares (Ubertini et al., 2005, 2006, Sguera et al. 2005, 2006, Sidoli et al. 2006). Their refined X-ray position allowed to identify the optical counterparts with blue supergiant companions (e.g. Masetti et al. 2006, Negueruela et al. 2006b, Nespoli et al. 2008). These two main characterizing properties (the unusually short transient X-ray emission together with the association with blue supergiant companions) suggested that these sources define a new class of HMXBs, later named Supergiant Fast X-ray Transients (SFXTs). Indeed, before these discoveries, HMXBs with blue supergiant companions were observed to display only persistent X-ray emission with values in the range 10^{36} - 10^{38} erg s^{-1}. Their rapid X-ray variability implies that they are difficult to discover, but SFXTs may be a large (and probably dominant) population of HMXBs, completely changing our current view of massive star evolution and fate, and chemical enrichment of the Galaxy. Other important properties of the SFXTs are X-ray spectral properties reminiscent of accreting X-ray pulsars (Lutovinov et al., 2005; Walter et al., 2006) and a high dynamic range, spanning 3 to 5 orders of magnitudes, from a quiescent emission at 10^{32} erg s^{-1} (characterized by a very soft spectrum, likely thermal) up to a peak emission in outburst of 10^{36} - 10^{37} erg s^{-1}. *They are a challenge to theory and could reveal a previously unrecognized type of accretion, completely changing our present view and comprehension of X-ray binaries hosting neutron stars. They would have missed without the INTEGRAL instrument capability, monitoring of the Galactic Plane and long deep exposure along the 8 years of observations.*

2. Survey

Along the 8 years of observations both through Core Programme and Open Programme, INTEGRAL and in particular the IBIS instrument, has been detecting new hard X-ray source besides monitoring the old known ones. So far 4 different IBIS catalogues have been produced using the same method even if refined for last version. The 4^{th} IBIS catalog (Bird et al., 2010), performed with 70 Ms exposure starting from February 2003 up to April 2008, has in fact made use of new developed tool to take into account sources appearing only for short period of time leading to the detection of about 100 objects that would not have been reported otherwise, and hence to a total of 723 hard X-ray sources. Source variability has been searched for at revolution level (about 200 ksec) and at observation level adding together sequence of similar pointing and then also optimized according with source detection time scale. This allow to increase the detection significance for each of the variable sources neglecting period of quiescence. Looking at the result of this 4^{th} IBIS survey of the sky we note, to our surprise, about 50 % of these sources are IGR ones, i.e. source detected for the first time at X-ray with INTEGRAL. A large fraction of these source still remains unidentified though we started since the release of the first catalog in 2004 (Bird et al., 2004), together with other teams, a long term programme of follow up at X-ray, optical and infrared to determine the sources nature. In deed the percentage of unknown sources was almost constant for the first 3 catalog (about 22%) and increased to 29% in the fourth one. Of these IGRs sources 10% are HMXB (both transient and persistent types) while 70% of the new IGRs identified with HMXB host a supergiant donor.

In Figure 1 left panel we show the evolution of source types with each catalogue. The increasing number for extragalactic sources reflects the sky exposure and the different observation programme. In fact going from the early time of the INTEGRAL operative life with regular scans of the Galactic Plane and Centre leading to the discovery of many new galactic object to the Open time Key Programme with long time coverage for high latitude sky the number of AGNs increase from about 30 to 250. In panel on the right we show the percentages of different type of source in cat 4 and the faction of identified in optical/NIR observation campaigns. The IBIS surveys and the BAT/Swift ones somehow complement each other as Swift offer a larger field of view and a different pointing strategy that allow a more uniform sky coverage providing a list of more than 1000 sources 60% of which are extragalactic ones (Cusumano et al., 2010).

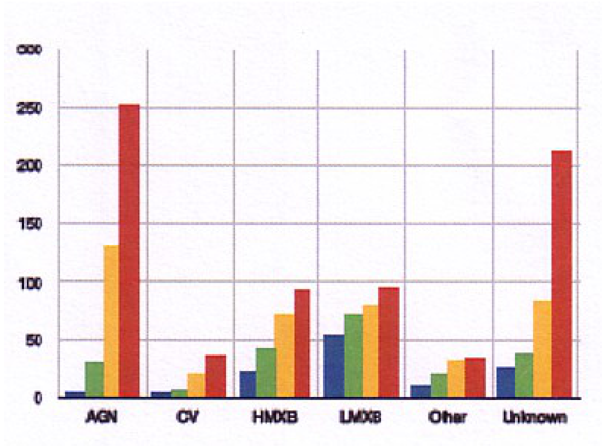

Fig. 1. Evolution of the source type with each catalogue.

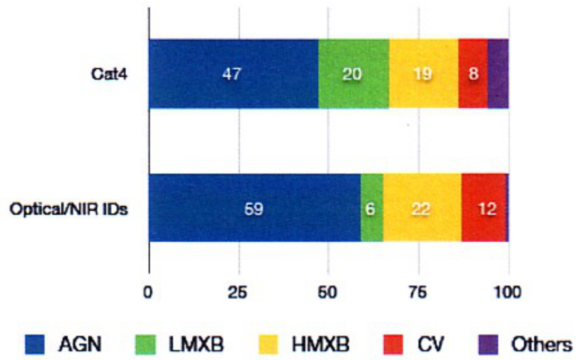

Fig. 2. Percentage of different type of sources in cat 4 (top) and the percentage of different source classes discovered in optical/NIR observation campaigns.

We want to outline the increased number of HMXB from the beginning of the INTEGRAL observation so that at the moment the number of detection are comparable to the one in LMXB (about 90 each). This is in fact due to the large number of identifications trough follow up programme first with X-ray telescope as Chandra, XMM and XRT/Swift leading to 21 Be binaries plus 17 more HMXB, quite often obscured. This indeed could be the main reason besides their intrinsic variability why they have been uncovered by previous observations at lower energies. The new discovered HMXBs show in fact an averaged N_H values that is of the order of 5.7 x 10^{22} cm $^{-2}$ while the rest are characterized by a value of 1.9 x 10^{22} cm $^{-2}$ (Bodaghee et al, Maxi workshop, December 2010). The highly absorbed sources are confined close to the tangent of the galactic spiral arms (see e.g Lutovinov 2008). Part of these new sources represent a third new class of HMXB being transients and associated to blu supergiant companion: the Supergiant Fast X-ray Transients (SFXT) characterized by luminosity of the order of 10^{32}-10^{36}, on-time of the order of hours/days and off time of weeks/months. The prototype of the obscured source is IGRJ16318-4848, with a value for N_H of 2 x 10^{24} cm $^{-2}$ while the prototype for SFXTs is the know source XTE J1739-302, discovered as transient with RXTE in 1997, (Smith et al., 1998), and then reported as belonging to this new class by Sguera et al., 2005 as showed in Figure 3 where the source is detected in 3 different pointings for a total time of 2 hours (from Sguera et al., 2005)

3. Observation status

As of December 2010, ten firm SFXTs have been reported in the literature plus the same number of candidates, i.e. unidentified X-ray sources with a temporal and spectral behaviour strongly resembling that of firm SFXTs. Numerically speaking, this is a huge achievement if we take into account that i) SFXTs hunting is not an easy task because of their very short active periods, thus the best way to discover them is the combination of a large field of view X-ray instrument and regular/frequent scans of the Galactic Plane ii) up to very few years ago we did not know about their existence.

From an observational point of view, the main defining properties of SFXTs are the following. They are composed by a blue supergiant star as companion donor and usually by a neutron star as compact object. Their X-ray emission is remarkably transient, reaching peakluminosities of 10^{36} - 10^{37} erg s^{-1} for typical dynamic ranges of 10^3 - 10^4. Their outburst activity is characterized by a typical duration of a few hours (as observed by INTEGRAL above 20 keV) and broad band X-ray spectra (0.3–60 keV) very similar to those of accreting neutron star in HMXB systems, i.e. hard power law below 10 keV and cutoff at 10–30 keV. INTEGRAL is particularly suited to detect the bright flares and not the much weaker persistent emission outside the outburst activity. To this aim, more sensitive X-ray instruments in the 0.2–10 keV energy band allow a proper investigation. The true X-ray quiescence (i.e. no accretion onto the compact object) was rarely observed, being characterized by luminosities values (or upper limits) of 10^{32}erg s^{-1} and very soft-thermal spectrum (in't Zand 2005). Conversely, Swift/XRT monitorings unveiled that SFXTs spent the majority of the time during a low level X-ray emission (10^{33} - 10^{34} erg s^{-1}) characterized by a hard spectrum, and high flux variability (Sidoli et al. 2008), strongly suggesting that accretion of material is still at work although at much lower rate than that during the outbursts. In addition, recent XMM and Suzaku observations (Sidoli et al. 2010, Bozzo et al. 2010) caught a few SFXTs during their lowest X-ray level ($\sim10^{32}$ erg s^{-1}) characterized by short-faint flares (for a dynamic range up to $\sim$10) and a double component X-ray spectrum, i.e. soft thermal plasma with kT$\sim$0.3 keV plus a hard power law. The duty cycles od SFXTs are small(Romano et al. 2011), typically in the range 3% - 5% as inferred from Swift/XRT monitorings, while they are even smaller in the INTEGRAL energy band.

Interestingly, besides the common characteristics reported above, the population of SFXTs display several important differences especially regarding to key observables such as the spin and orbital periods. There is a growing evidence that spin periods cover a large range from $\sim$5 s to a few hundred seconds (Bamba et al. 2001; Swank et al. 2007; Lutovinov et al. 2005) and that their orbits can be narrower than in persistent HMXBs (3.3 days, IGRJ16479-4514; Jain et al. 2009) or very wide and highly eccentric (IGRJ 11215–5952, P_{orb}=165 days, Sidoli et al. 2006, Sidoli et al. 2007; e>0.5, Lorenzo et al. 2010). These observational facts also seem to point to a different origin and evolutionary path of the members of the same class. For SFXTs where both spin and orbital periods are known (see Figure 4), at least two of them (IGRJ 11215–5952, IGR J18483–0311) lie in the typical region of the Corbet diagram (spin versus orbital period) for Be X–ray transients. Moreover, they are the only two members, to date, showing periodicly recurrent outbursts (Sidoli et al. 2006; Levine et al. 2006, Sguera et al. 2007). This led some authors to suggest that some SFXTs actually descend from Oe/Be X–ray transients (Liu et al. 2010, Chaty 2010). On the other hand, this hyphothesis seems to be unlikely in the case of the donor star HD 306414 in IGRJ 11215–5952, because of its high mass (Ducci et al. 2010). A larger sample of SFXTs with known orbital and spin periods is necessary to better understand possible evolutionary links.

4. Models to explain the SFXTs behavior

The main mechanism responsible for the extreme flux variability in SFXTs is still debated, despite the large amount of available observational data consisting of both long deep exposures on single well studied sources and long-term monitoring campaigns. The link between these transient sources and persistent HMXBs hosting similar donor stars is a mystery as well.

Besides the main defining properties of the class (blue supergiant companions and short transient flaring ac-

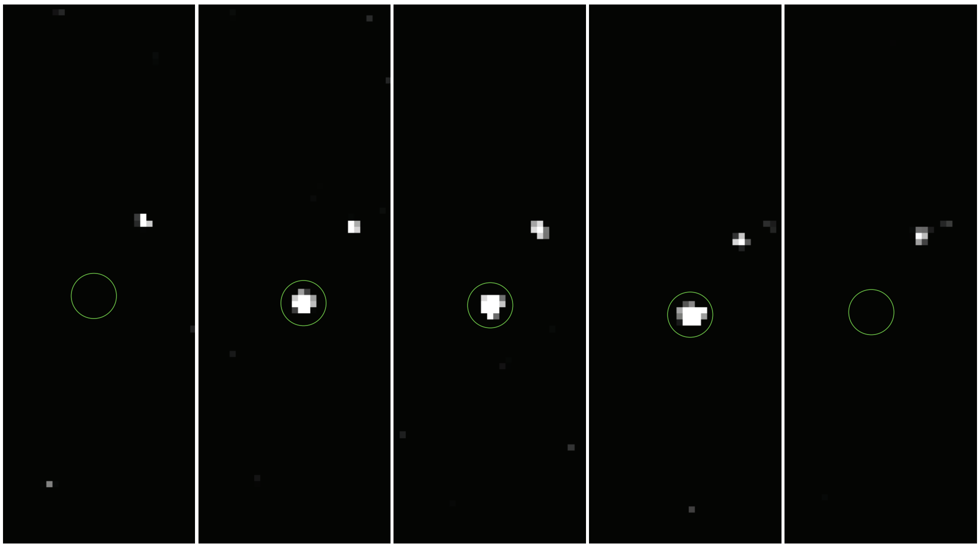

Fig. 3. IBIS/ISGRI Science Window (ScW) image sequence (20–30 keV) of a fast X-ray outburst of XTE J1739−302 (encircled).

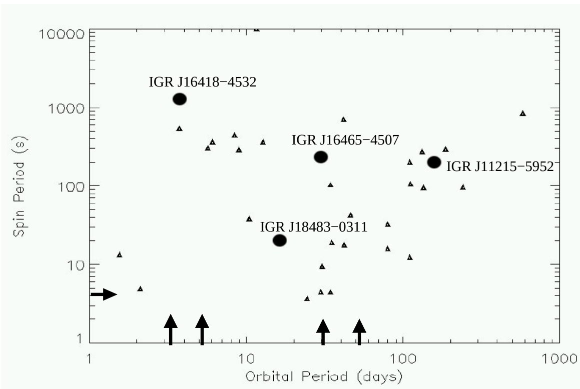

Fig. 4. Corbet diagram for the known HMXBs (triangles) and for the firm or candidate SFXTs (big black dots). Other four (one) SFXTs with known orbital periods (spin periods), but unknown spin periods (orbital periods) are marked by mean of arrows on the x axis (y axis).

tivity with a high dynamic range), SFXTs display very different key observables, like for example the spin and orbital periods. A possibility is that different mechanisms could be at work in different members of the same class.

The different mechanisms proposed to explain SFXTs are based on the assumption that these binaries are composed of neutron stars directly accreting from the wind of their blue supergiant companions. This implies that the accretion luminosity L_X depends on the supergiant mass loss rate, $\dot{M}_w$, and on the relative velocity, v_{rel}, of the neutron star and the wind, with L_X being proportional to $\dot{M}_w {v_{rel}}^{-4}$ (Waters et al. 1989). Large density and/or velocity wind contrasts (like those present in non-homogeneous clumpy winds) are able to drive large variability in the X–ray luminosity, and thus very large dynamic ranges. The sudden accretion of wind clumps onto the neutron star was one of the first hyphothesis proposed to explain the bright X–ray flaring activity in SFXTs (in't Zand 2005). In this framework, since donor stars in SFXTs and persistent HMXBs hosting blue supergiants are similar (same spectral type), another parameter should be at work to explain the different X–ray behaviors. A possibility is different orbital periods: narrower and (almost) circular orbits in the case of persistent X–ray sources versus wider (and/or more eccentric) orbits in SFXTs (Negueruela et al. 2006, 2008).

Anisotropic supergiant winds have been originally proposed to explain the periodic outbursts observed from the SFXT IGR J11215–5952 (Sidoli et al. 2007). In this case the short SFXTs outbursts can be triggered by the passage of the neutron star inside a second wind component, in the form of an equatorial wind (or any other preferential plane for the outflow), denser and slower than the polar spherical wind, inclined with respect to the orbital plane of the system. Depending on the geometry of this second dense wind component with respect to the orbital plane, also persistent HMXBs could be accounted for (if this wind component lies on the orbital plane) and other sources with different X–ray periodicities (as in the case of the SFXTs prototype XTEJ1739-302, where the folded lightcurve shows three peaks, which can be explained within the Sidoli et al. 2007 model; see Drave et al. 2010 for details).

Another possibility is that in SFXTs the accretion is

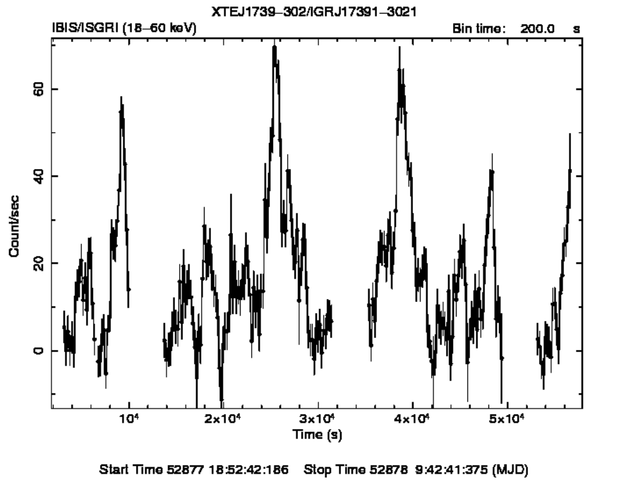

Fig. 5. XTEJ1739-302 light curve observed with INTEGRAL during an outburst.

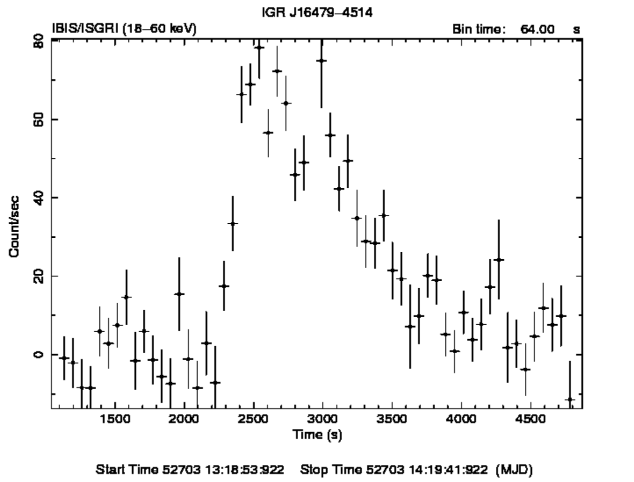

Fig. 6. IGRJ16479-4514 light curve of a bright flare observed with INTEGRAL. The flare shape can be well fitted with a FRED profile with an exponential decay time of 890±60 s.

halted for most of the time by the presence of a centrifugal or a magnetic barrier (Grebenev & Sunyaev 2007; Bozzo et al. 2008). Bozzo et al. (2008) have demonstrated that large X–ray luminosity swings (∼10,000 or more) can be produced by modest variability in the wind density and/or velocity (clumpy wind) if the neutron star is a magnetar (B$\sim10^{14}$–10^{15} G) rotating very slowly (P_{spin} ∼1000 s). This hyphothesis can possibly explain SFXTs where the orbital period is similar to persistent HMXBs (e.g. IGR J16479–4514). In these cases the neutron star always orbit within the strong supergiant wind, and it would produce a high persistent X–ray luminosity if gated mechanisms were not at work. On the other hand, magnetars have not yet been found in binary systems.

More recently, further investigations of the structure of the clumpy wind have been carried out, in particular its role in the accretion process, trying to modify the Bondi-Hoyle accretion (Ducci et al. 2009). In this model, different X–ray behaviors emerge depending on the relative size of the accretion radius and of the radius of the accreting clumps (see also Karino 2010).

Other modifications of the clumpy wind model have been suggested studying the shape of the X–ray lightcurves in some SFXTs observed with INTEGRAL. Indeed, sometimes (1)-a quasi-periodic multi-peaked flaring activity (see Figure 5), or (2)-bright flares with a fast rise and exponential decay (FRED; Figure 6) have been observed, opposite to more typical SFXTs flares, with complex and structured shapes (Ducci et al. 2010). Ducci et al. (2010) suggested that quasi periodic flares observed in some SFXTs (Figure 5) can be produced by the formation of transient accretion disks, thanks to the mass and angular momentum capture from the supergiant wind. This can happen if the wind velocity is reduced with respect to an isolated supergiant, by the ionization effect produced in SFXTs with short orbital periods.

Moreover, FRED flare profiles sometimes observed in IGRJ16479–4514 (see Figure 6) have been proposed by Ducci et al. (2010) to be the signature of a magnetospheric instability mechanism, interestingly indicating that the compact object in IGRJ16479–4514 is a neutron star.

5. Conclusion

The INTEGRAL mission provides to the international scientific community outstanding observations of the soft gamma-ray sky. Its unprecedented large FOV (∼1000□°), arc-minute position source location accuracy and fast timing capability is ideal for deep observations in complex region like the Galaxy Centre and Plane. Among other successful investigations, INTEGRAL has discovered a new class of high variable sources, named Supergiant Fast X-Ray Transient (SFXT) thought to be mainly NSs accreting winds from a Supergiant star. The robust follow-up programme of the newly detected sources in X-Ray, IR and optical waveband has confirmed the Supergiant nature of the companion star.
It is still to be fully understood the mechanism supporting the fast variability (∼hour or less) hypothesised to be due to winds clumps.

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References

Bamba, A. et al. 2001, PASJ, 53, 1179
Bird A.J. et al., ApJS, 186,1, 2010
Bird A.J. et al., ApJ, ,607,L33. 2004
Bozzo, E. et al. 2008, ApJ, 683, 1031
Bozzo, E. et al. 2010, A&A, 519, 6
Chaty, S. 2010, Proc. of the Conference on "Binary Star Evolution: Mass Loss, Accretion, and Mergers", Mykonos 2010, arXiv1008.2718
Cusumano G. et al., A&A, 524,64
Drave, S., et al. 2010, MNRAS, 409, 1220
Ducci, L., et al. 2009, MNRAS, 398, 2152
Ducci, L., et al. 2010, MNRAS, 408, 1540
in't Zand, J.J.M., 2005, A&A, 441, L1
Jain, C. et al. 2009, MNRAS, 397, L11
Karino, S. 2010, A&A, 523, 90
Levine, A. M. et al. 2006, The Astronomer's Telegram, 940
Liu, Q., et al. 2010, Science in China G: Physics and Astronomy, 53, 130
Lorenzo, J., et al. 2010, ASPC, 422, 259L
Lutovinov A. et al. 2005, A&A ,444,821
Lutovinov A. et al. ESA SP-622, 241, 2008
Masetti N. et al. 2006, A&A, 459, 21
Negueruela, I. et al. 2006, ApJ, 638, 982
Negueruela, I. et al. 2008, AIPC, 1010, 252
Nespoli E. et al. 2008, et al.,A&A, 486,911
Romano, P., et al., 2011, MNRAS, 410, 1825
Sguera V. et al. 2005, A&A, 444, 221
Sguera V. et al. 2006, ApJ, 646, 452
Sguera, V. et al. 2007 A&A, 467, 249
Sidoli, L. et al. 2006 A&A., 450, L9
Sidoli, L. et al. 2007 A&A., 476, 1307
Sidoli, L. et al. 2008 ApJ, 687, 1230
Sidoli L. et al. 2010 MNRAS, 409, 611
Smith et al., ApJL, 501,L101, 1998
Swank, J.H. et al. 2007, The Astronomer's Telegram, 999
Ubertini P. 2005 (15 August), "Populations of high-energy sources in galaxies" IAU Symposium 230, Dublin, Ireland
Ubertini P. et al.2006 (12 May), "The INTEGRAL Gamma-Ray Sky after 1000 days in orbit"Proceedings of the International Astronomical Union(2006), 1, 315-323 Cambridge University Press, Available on CJO
Ubertini, P., et al., A&A, 411, L131, 2003
Waters, R. 1989, L.B.F.M. et al. 1989, A&A, 223, 207
Walter, R. et al. 2006, A&A, 453, 133
Winkler, C., et al., A&A, 411, L1, 2003