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Hard X-ray emission from low mass X-ray binaries

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Abstract In this paper we review our current knowledge of the hard X-ray emission properties of old accreting neutron stars in low mass X-ray binaries, with particular attention to recent results obtained for the brightest sources of this class, the so-called Z sources. While less luminous low mass X-ray binaries often show quite hard spectra, sometimes extending up to energies $\gtrsim 100$ keV, the spectra of Z sources are always very soft, dominated by thermal components with characteristic temperatures $\sim 3-6$ keV. However, recent broad band observations revealed the presence of a weak hard (power-law) component that is sometimes present in the spectra of these sources. These observations have strengthened the analogies between the spectral behavior of low mass X-ray binaries hosting neutron stars and binary systems containing black hole candidates. The physical parameters regulating the presence of this hard component are unknown yet. The first parameter may be the mass accretion rate, as indicated by the general anticorrelation between the fraction luminosity in hard X-rays and mass accretion rate apparent over different sources spanning a large range of luminosities as well as individual sources undergoing state changes. However, a second, yet unknown, parameter is probably needed to explain all the phenomenology. The broad high energy coverage and good sensitivity of the INTEGRAL mission can represent an important step forward in the understanding of the origin and properties of high energy components in accreting X-ray binaries.

Key words: accretion, accretion disks — stars: neutron — X-rays: stars — X-rays: binaries — X-rays: general

1 INTRODUCTION

The most luminous Galactic X-ray sources are binary systems containing a compact object, such as a neutron star (NS) or a black hole candidate (BHC), accreting matter from a companion (usually main-sequence) star. Now we know more than 200 X-ray binaries. Binary systems that

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are classified as Low Mass X-ray Binaries (hereafter LMXB) consist of a low-mass star losing mass which is accreted, at least in part, onto a weakly magnetic NS or BH. LMXB containing NSs are usually divided into two classes: the so-called Z sources, with luminosities close to the Eddington luminosity, $L_{\rm Edd}$, and the Atoll sources, which usually have lower luminosities, $0.01 - 0.1\ L_{\rm Edd}$. The latter class encompasses mainly type I X-ray bursting sources. A group with intermediate properties is that of the four bright GX sources: GX 13+1, GX 3+1, GX 9+1 and GX 9+9.

This widely used classification relies upon a combination of the X-ray spectral properties of these sources, namely the pattern traced out by individual sources in an X-ray color-color diagram (CD), and their correlated timing properties (Hasinger & van der Klis 1989). The six known (Galactic) Z sources describe a Z-track in the CD on timescales of a few days, while the sources of the Atoll class trace out an Atoll-shaped track in the CD on a timescale of weeks. Considerable evidence has been found that the mass accretion rate of individual Z-sources (but not necessarily the X-ray luminosity) increases from the top left to the bottom right of the Z-pattern (e.g. Hasinger et al. 1990), i.e. along the so called horizontal, normal and flaring branches (hereafter HB, NB and FB, respectively). Similarly, in Atoll sources the accretion rate increases from the so-called island state to the upper banana branch. This conclusion was based on several indicators, such as the correlated behavior of optical and radio emission, and has been recently confirmed by the monotonic and continuous frequency increase of the kHz QPOs along the same path (see van der Klis 2000). However, while there is a general correlation between kHz QPO frequencies and position in the CD, the correlation between kHz QPO frequencies and the source X-ray flux (in the 2–50 keV energy range) is complex; a correlation is observed on short time scales (hours to days), but not on longer time scales. A possible explanation of this behavior is that most timing and spectral parameters are determined by the dynamical properties of the accretion disk, while the X-ray flux is determined by the total accretion rate, which may be different from the instantaneous accretion rate through the disk if, for instance, matter can flow radially close to the neutron star (see e.g. van der Klis 2001). The whole scenario is not clear yet; we will continue to use the widely adopted terminology of "inferred mass accretion rate" to indicate the position of the source in the CD, keeping in mind that, while this terminology might be correct for the short term (hours to a day), in the longer term there might not be an exact correspondence between instantaneous accretion rate and position in the CD.

The X-ray spectrum (in the classical X-ray range 1–10 keV) of LMXBs has been decomposed in terms of a blackbody spectrum, plus an additional component, either an unsaturated Comptonised spectrum (the "Western Model"; White et al. 1988), or a multi-color optically thick disk model (the "Eastern model"; Mitsuda et al. 1989). At high X-ray energies, a variable hard component dominating the spectrum of Sco X-1 above ~ 40 keV was detected as early as 1966 (Peterson & Jacobson 1966). In other occasions the hard tail in Sco X-1 was not found, perhaps owing to pronounced variations (e.g. Miyamoto & Matsuoka 1977, and references therein). Evidence for a hard component was also found in Cyg X-2 (Peterson 1973) and GX 349+2 (Greenhill et al. 1979). These results received relatively little attention, mostly because the lack of a broad band spectral coverage did not allow to say whether an extra component was indeed required to fit the hard spectrum of these sources (see e.g. Matt et al. 1990). Renewed interest in the hard X-ray emission properties of NS/LMXBs was motivated by the SIGMA/GRANAT discovery of a spectral component extending up to energies of $\sim 100 - 200$ keV in Terzan 2 (Barret et al. 1991), KS 1731-260 (Barret et al. 1992), SLX 1735-269 (Goldwurm et al. 1996) and Terzan 1 (Borrel et al. 1996). More recently, the presence of hard components in the X-ray spectra of LMXBs could be confirmed and studied thanks to the broad band capabilities of BeppoSAX and RXTE, sensitive in the energy range 0.1–200 keV and 2–220 keV, respectively.

2 HARD X-RAY EMISSION FROM ATOLL SOURCES

Recent broad band spectral analysis has shown that the spectral behavior of the less luminous ($< 10^{37}$ ergs/s) LMXBs, the so-called Atoll sources, is indeed more complex than previously thought. The spectrum of these sources often extends to substantially high energies (up to 150-200 keV in a few cases) and requires an extended power-law or unsaturated Comptonisation model. In some cases (e.g. 4U 1705–44) the energy flux above 20 keV can exceed 30% (Barret et al. 1996). The hard component can thus be very important in the energetics of emission from these sources. Hard X-ray components extending up to energies of several hundred keV have been revealed in about 20 NS/LMXBs of the Atoll class (see also Di Salvo & Stella 2003).

Similar to the case of accreting BHCs, these sources can be found in soft or hard states (see Barret et al. 2000). As first noted by van Paradijs & van der Klis 1994, there is a clear trend for the spectral hardness of these sources (and accreting X-ray sources in general) over the 13–25 and 40–80 keV energy ranges to be higher for lower X-ray luminosities. Therefore mass accretion rate appears to be the main parameter driving the spectral hardness of Atoll sources, both as a group and as individual sources. However, a recent study of 4U 1705–44 showed that the source underwent a soft to hard state transition while the 0.1–200 keV bolometric luminosity of the source decreased by a factor of ~ 3 from the soft to the hard state and increased by only a factor of ~ 1.2 in the opposite transition from the hard to the soft state (Fig. 1 right panel; Barret & Olive 2002). On other occasions the same source displayed hard and soft states which were found to differ by a much larger factor (up to one order of magnitude) in their luminosity (Fig. 1 left panel). Hence, although the mass accretion rate appears to be the main parameter driving the spectral hardness of these sources, there is evidence that at least on occasions an additional parameter controls the soft/hard spectral transitions. This might be generally true for this kind of systems. Indeed the existence of a second parameter was already proposed to explain the soft/hard spectral transitions observed in the BHC XTE J1550–564 (Homan et al. 2001).

In the hard state the spectrum of these sources is dominated by the power law-like component, with typical slopes of $\Gamma \sim 1.5 - 2.5$, which is followed by an exponential cutoff, the energy of which is often in between ~ 20 and many tens of keV (see e.g. Yoshida et al. 1993, Barret et al. 2000). It was originally thought that the electron temperature in the scattering cloud should be lower for NSs than for BHs in similar spectral states, in agreement with the expectation that an extra cooling should be present in the NSs because of the soft photons emitted by the surface. This seems indeed true for those systems in which a high energy cutoff has been observed, although some LMXBs in the hard state do not show any cutoff in their spectra up to ~ 100 keV (Barret et al. 1991, Harmon et al. 1996, Piraino et al. 1999). The hard spectrum of 4U 0614+091, for instance, can be modeled as thermal Comptonization of low-energy photons on electrons having a temperature greater than 220 keV or as a non-thermal power law (Piraino et al. 1999; see Fig. 2 left panel).

An emission line is usually present at ~ 6.4 keV, interpreted as fluorescence from iron in low ionization states. The probable origin of this line is reprocessed emission from the accretion disk surface illuminated by the primary Comptonized spectrum. In this case one would also expect the presence of a bump between 20 and 40 keV due to Compton reflection of the primary spectrum by the disk. Indeed this reflection bump has been observed in the spectra of some NSs, usually with reflection amplitudes (*i.e.* the solid angle $\Omega/2\pi$ subtended by the reflector as seen from the corona) lower than 0.3 (Barret et al. 2000, Piraino et al. 1999, Yoshida et al.

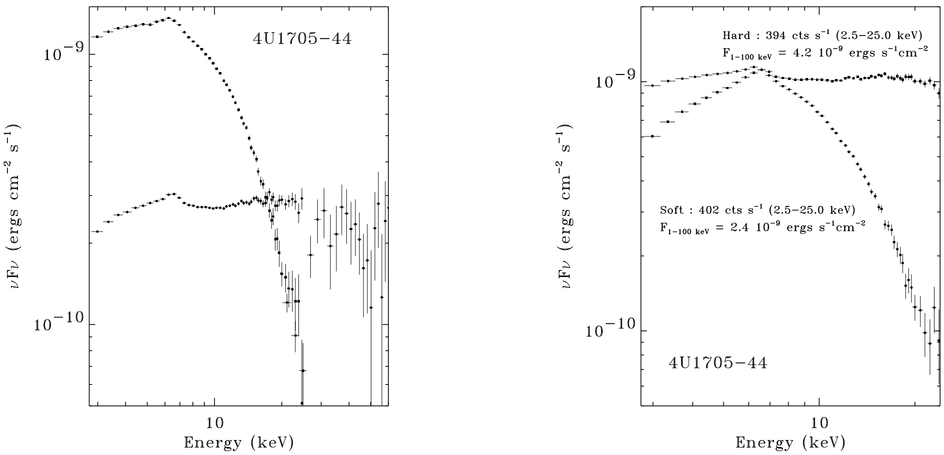

Fig. 1 *Left*) Typical soft and hard spectral states from the LMXB 4U 1705-44 as observed by RXTE (PCA and HEXTE spectra are combined). *Right*) PCA spectra taken by RXTE from 4U 1705-44 during a spectral transition that occurred in February 1999 (Barret & Olive 2002, see also Barret 2001). The broad band luminosity in the hard spectrum is about twice the one associated with the soft spectrum, because of the presence of a strong hard X-ray component. This illustrates that the X-ray flux alone is not a good indicator of the spectral state.

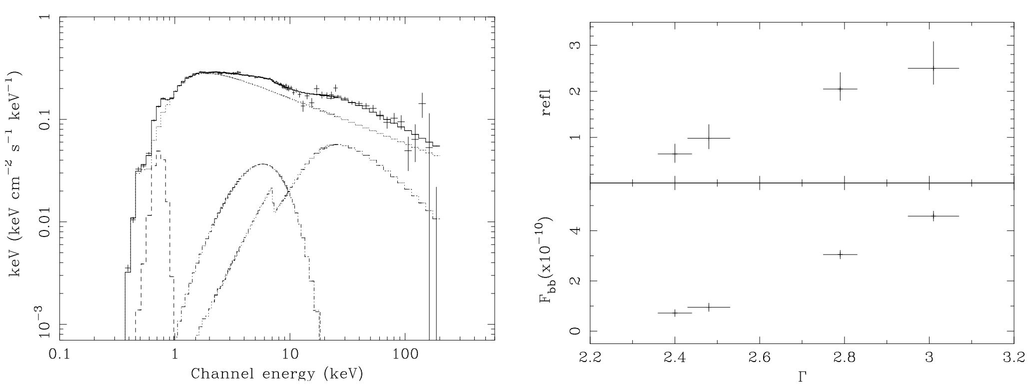

Fig. 2 *Left*) BeppoSAX unfolded spectrum of 4U 0614+091 together with a model consisting of (from low to high energies, respectively) a low-energy Gaussian line, a blackbody, a reflection component, and a power law. *Right*) Correlation between some spectral parameters in 4U 0614+091: (a) Magnitude of reflection versus photon index. (b) Blackbody flux (ergs cm^{-2} s^{-1}) versus photon index. From Piraino et al. (1999).

1993). In these cases a correlation has been observed between the photon index of the primary spectrum and the reflection amplitude of the reprocessed component, the same observed in Seyfert galaxies and Galactic BHCs (Zdziarski et al. 1999, Barret et al. 2000, Piraino et al. 1999; in Fig. 2 right panel the correlation between the reflection amplitude and the flux in the blackbody component with the photon index of the power-law component is shown for the case of the Atoll source 4U 0614+091). This similarity with the spectra of the BHCs suggests that the same emission mechanism and geometry operate in NSs. In this scenario the soft blackbody emission, at a temperature of 0.5–1 keV, comes from the accretion disk, and the Comptonized component originates in a hot and optically thin cloud (corona), probably placed between the NS and the accretion disk. A fraction of this component is reprocessed by the surface of the accretion disk, originating the reflection bump and the iron Kα line. The weakness of these components suggests that the reflector subtends a small solid angle ($\Omega/2\pi < 0.3$) as seen from the corona. This is possible if the disk is truncated and its inner part is absent, or if the inner accretion disk is highly ionized. In this geometry, a decrease of the inner radius of the disk causes an increase of the solid angle subtended by the reflector and a steepness of the power law. This could be responsible of the observed correlation between the photon index of the power law component and the reflection amplitude. Otherwise, a small reflection amplitude can be obtained in a plane-parallel geometry if the corona moves away from the disk at high speed ($\sim 0.3\,c$); this suppresses the amount of reflection by beaming the observed X-ray spectrum away from the disk (Beloborodov 1999).

3 HARD X-RAY EMISSION FROM Z SOURCES

The spectrum of the brightest LMXBs was usually observed to be very soft, with cutoff energies well below 10 keV. This is in agreement with the expectation that in a high-luminosity regime the presence of such numerous soft photons (due to the enhanced thermal disk contribution) could provide strong Compton cooling and result in softer spectra. However, recent broad band spectral analysis has shown that Z sources can also display hard, power-law shaped components, dominating their spectra above ~ 30 keV. The presence of a variable hard tail in Sco X–1, firstly observed in 1966, was recently confirmed by OSSE and RXTE observations (Strickman & Barret 2000, D'Amico et al. 2001). A hard tail was also detected in BeppoSAX data of GX 17+2 (Di Salvo et al. 2000), GX 349+2 (Di Salvo et al. 2001), the peculiar bright LMXB Cir X–1 (Iaria et al. 2001, recently confirmed by RXTE observations; Ding, Qu, & Li 2003), and Cyg X-2 (Di Salvo et al. 2002). In GX 5-1 a hard power-law component was detected in Ginga data, whose intensity decreased when the source moved from the NB to the FB, i.e., from lower to higher inferred mass accretion rates (Asai et al. 1994; note, however, that contamination from a nearby source could not be excluded in this case). The fact that a similar hard component has been observed in several Z sources indicates that this is probably a common feature of these sources. The hard components detected in bright (otherwise soft) LMXBs can be fitted by a power law, with photon index in the range 1.9–3.3, contributing up to 10% of the total source luminosity.

The presence of these components in Z sources seems, at least in some cases, to be related to the source state or its position in the CD. This was unambiguously shown for the first time by the BeppoSAX (0.1–200 keV energy range) observation of GX 17+2, where the hard tail was observed to vary systematically with the position of the source in the CD (Di Salvo et al. 2000). In particular, the hard component (a power-law with photon index of ~ 2.7) showed the strongest intensity in the upper HB (see the corresponding spectrum in Fig. 3). A factor of 20 decrease was observed moving from the HB to the NB, i.e. from low to high inferred mass accretion rate.

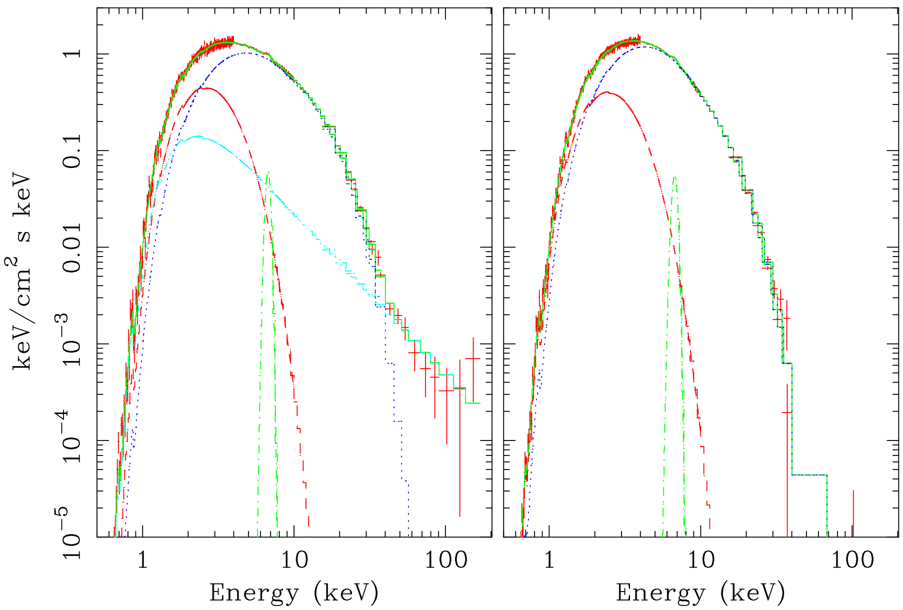

Fig. 3 Counts spectrum of GX 17+2 as observed by BeppoSAX when the source was in the upper HB (left panel) and in the lower NB (right panel), respectively, and the best fit model, shown in this figure as the solid line on top of the data. The individual model components are also shown. In particular, the hard power law, dominating the spectrum above 30 keV, is plotted as a dotted line (left panel).

In most of the cases the hard component becomes weaker for higher accretion rates. Yet, in the HEXTE observations of Sco X–1, a hard power-law tail was detected in 5 out of 16 observations, without any clear correlation with the position in the CD (D'Amico et al. 2001). Interestingly, Strickman & Barret (2000) report that the hard X-ray emission present in Sco X–1 data from OSSE may be correlated with periods of radio flaring. GX 349+2 may show a behavior that is similar to the one observed in Sco X–1. Although the source showed similar spectral states in two BeppoSAX observations performed in 2000 and 2001, respectively, the hard tail, that was significantly detected in 2000 (Di Salvo et al. 2001), was not observed in the more recent observations (Iaria et al. 2003), showing that the hard tail may be highly variable and probably not univocally related to the source position in the CD. Alternatively, the continuous flaring activity during the 2001 BeppoSAX observation might have quenched the hard X-ray emission. In this case the non-detection of the hard component during the 2001 BeppoSAX observation would in agreement with the paradigm that the hard emission is suppressed at the highest inferred mass accretion rates (see Iaria et al. 2003). Note that GX 349+2 is one of the Sco-like sources, which are thought to have a lower inclination than the other Z sources (referred to as Cyg-like sources; Kuulkers et al. 1994), and similarly to Sco X–1 (but not to GX 17+2), does spend a relatively short time in the HB (i.e. at the lowest inferred mass accretion rates). Note that RXTE data of Sco X–1 (D'Amico et al. 2001) and Cir X–1 (Ding, Qu, & Li 2003) suggest that the photon index of the power-law component might be correlated with the position in the CD, with the softest index corresponding to the lowest inferred mass accretion rates.

The behavior of Sco X–1 and GX 349+2 suggests again that there might be a second parameter, besides mass accretion rate or position of the source in the Z-track, regulating the presence of hard emission in these systems. This second parameter might be the truncation radius of the optically thick disc. However, what determines the radius at which the disc is truncated is not clear yet: this could be the mass accretion rate through the disk normalized by its own long-term average (as proposed by van der Klis 2001), but also magnetic fields, the fraction of power dissipated in a hot, optically thin, corona (see e.g. Chen 1995), or the formation/quenching of a jet could play a role.

These spectra of Z sources seem quite similar to the spectra of BHCs in some soft states. The latter are dominated by soft emission with characteristic temperatures of ∼1–2 keV, and display a hard power-law component with photon index ∼2–3, extending to several hundreds keV and contributing a few per cent of the total luminosity (see e.g. Grove et al. 1998). These considerations suggest that the hard tails in both BHCs and NSs originate from the same mechanism. This would imply that this mechanism does not depend on the presence (or absence) of an event horizon. As in BHCs, the hard tails observed in Z sources can be produced either in a thermal or non-thermal corona (e.g. Poutanen & Coppi 1998) or in a bulk motion of matter close to the NS (e.g. Titarchuk & Zannias 1998). Fast radial converging motions are unlikely to be dominant in the innermost region of the accretion flow in such high-luminosity systems, because of the strong radiation pressure emitted from near the NS surface, which would reduce the electron velocity in any radial inflow towards the compact object. For this reason the presence of a hard extended power-law component was considered by some authors (e.g. Titarchuk & Zannias 1998) as a signature for the presence of a BH in the system, i.e. a tool to discriminate between NS and BH X-ray binaries. However, power-law tails, dominating the spectra at high energy, can also be produced when the flows are mildly relativistic ($v/c \sim 0.1$) or when the velocity field does not converge (Psaltis 2001). Therefore outflows can be the origin of these components, with flatter power laws corresponding to higher optical depth of the scattering medium and/or higher bulk electrons velocities, in a way that is similar to thermal Comptonization (see Psaltis 2001).

In recent years radio emission is being recognised as a more and more ubiquitous property of X-ray binaries; most of the BHC, Z, and Atoll sources have been detected as radio sources (Fender & Hendry 2000). It seems that all BHCs in the low/hard state are observed to produce almost-continuous jets whose total power budget is likely to be a significant fraction ($\geq 20\%$) of the total accretion energy (Fender 2001). All the Z sources are detected as variable radio sources, with the highest radio fluxes associated with the HB, gradually decreasing when the source moves to the NB and to the FB (Penninx et al. 1988, Hasinger et al. 1990), and this radio emission is again probably due to jets (e.g. Fender & Hendry 2000). Recent multiwavelength studies of the ‘hybrid Atoll/Z source’ GX 13+1, one of the strongest radio sources among NS/LMXBs, indicate that, while there is no apparent relation between radio emission and X-ray count rate (in the 2-20 keV range), there is a clear correlation between radio emission and X-ray spectral hardness (or hard color), although with a lag of ~ 40 min (Homan et al. 2003). This time delay between changes in the X-ray spectral hardness and the radio brightness might be due to the time taken for material to travel along the jet if the hard X-ray and radio emission are produced relatively far from each other.

More in general, the radio emission from these objects, which probably arises in jets (Fender & Hendry 2000), is correlated with the hardness of the X-ray spectrum. This seems to be a fairly general behavior, holding for different kinds of accreting collapsed objects, BHCs, Z-sources, as well as Atoll sources (although only a few Atolls have been detected in radio so far, e.g. Fender 2001). Since the jet is thought to consist of a population of relativistic electrons streaming out from the core of the system, it may be that these synchrotron-emitting electrons observed at radio wavelengths are part of the population responsible for the Comptonisation producing the X-ray power-law (Fender et al. 1999) or, more radically, that the X-ray power-law is in fact high frequency optically-thin synchrotron emission directly from the jet (Markoff et al. 2001).

4 FINAL REMARKS

The results described above demonstrate that all these sources, both the BHC and NS X-ray binaries show important analogies in the hard X-ray component. In fact, the hard X-ray spectrum of Atoll sources is similar to the spectrum of Galactic BHCs in the hard state, while the hard tail in Z sources are similar to the hard power-law component detected in some soft states of BHCs. At a first analysis, these hard tails are not expected in NS sources, because of the presence of the NS surface that is a source of copious soft photons. This should result in a lower temperature of the surrounding corona (because of Compton cooling) and should reduce any bulk motion due to radial inflows towards the compact object, especially in such luminous and soft sources as Z sources. However, the observation of hard power-law components in NS systems seems to contradict this expectation. This requires a revision of the current models in order to explain the hard emission of both NSs and BHCs. As an example, the presence of outflows or jet emission can originate high velocity electrons responsible for the hard tails in both NSs and BHCs.

Other methods have been proposed to distinguish between NSs and HBs. In particular, Barret et al. (1996) proposed a luminosity criterion. They compared the 1–20 keV luminosity to the 20–200 keV luminosity for all BHCs (with mass function estimates indicating a mass of the compact object larger than 3 $M_{\odot}$) and all NSs of the Atoll class (the so-called X-ray bursters) detected up to at least 100 keV. They find a clear distinction in luminosity between the X-ray bursters, which lie in the so-called *X-ray burster box*, and the BHCs, which are found outside. However, the distinction between NSs and BHCs is no more clear when the Z sources, in which a hard tail has been detected, are included in the diagram (see Di Salvo et al. 2001). In terms of a fraction of the corresponding Eddington luminosity, BHCs and NSs have soft and hard luminosities in the same range. It seems that only the Eddington luminosity (that is higher for a BH because of its higher mass) is responsible of the distribution of BHCs and NSs in the luminosities' diagram observed by Barret et al. (1996).

There are still many questions that should be addressed on this issue. The most important of these is the origin (thermal or non thermal) of the hard components in Z sources, which can be deduced, e.g., by the observation (or absence) of an exponential cutoff in the power-law hard tail. Another important question to address is the correlation of the hard component intensity with the source state, as deduced from the CD, or other properties of the source such as the radio emission, which can give important information about the origin of these components, or the rapid X-ray variability. In fact there might exist a deep relationship between the presence of the hard X-ray component and QPOs. This is suggested by the fact that: the hard X-ray component of GX 17+2 is most pronounced in the source state(s) in which both the kHz and horizontal branch QPOs are detected and reach the highest rms amplitudes; both these rms amplitudes and the contribution from the hard X-ray component to the total spectrum increase dramatically with energy (e.g. Wijnands et al. 1997).

These considerations open many questions that have to be addressed by further studies of the broad band X-ray spectra of these sources. In this sense, the INTEGRAL mission, with its good sensitivity in the energy range between 30 and a few 100 keV, where most of the signal from the hard components is present, is expected to provide valuable information to address these questions.

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