High Energy Radiation from Neutron Star Binaries

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This paper surveys our current knowledge of the hard X-ray emission properties of old accreting neutron stars in low mass X-ray binaries. Hard X-ray components extending up to energies of a few hundred keV have been clearly detected in sources of both the Atoll and Z classes. The presence and characteristics of these hard components are discussed in relation to source properties and state. An overall anticorrelation between the fraction luminosity in hard X-rays and mass accretion rate is apparent over different sources spanning a large range of luminosities as well as individual source undergoing state changes. Evidence for a second, yet unknown, parameter controlling the hard X-ray emission is emerging. We draw a parallel with the spectral properties of X-ray binaries hosting a stellar mass accreting black hole, and conclude that, at a merely phenomenological level, there appears to be a close analogy between the spectral properties of black hole candidates in their high and intermediate states and Z-sources. We briefly mention models that have been proposed for the hard X-ray emission of neutron star low mass X-ray binaries and comment on perspectives in the INTEGRAL era.

1 Introduction

A variable hard component dominating the spectrum of Sco X-1 above $\sim 40$ keV was detected as early as 1966 (Peterson & Jacobsen 1966; see also Riegler et al. 1970; Agrawal et al. 1971; Haymes et al. 1971). 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; Soong & Rothschild 1983; Jain et al. 1984; Ubertini et al. 1992). 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, probably because the nature of Sco X-1-like and bright galactic bulge X-ray sources remained not understood or, at least, controversial until late seventies. On the contrary, that Cyg X-1 hosts an accreting black hole candidate, BHC, had become clear as early as 1972 (Bolton 1972; Webster & Murdin 1972). The conspicuous hard X-ray emission of this source (see e.g. Tanaka & Lewin 1995, and references therein) was therefore considered the prototypical "hard spectrum" of an accreting black hole and provided much of the observational basis for model development. Optically thick, geometrically thin accretion disk models that were developed in those years proved inadequate to explain the hard power-law like spectrum of Cyg X-1, that extended without a break up to $\sim 80 - 100$ keV in the hard state and was (likely) detected up to energies of $\sim 1$ MeV in soft/intermediate states (e.g. Liang & Nolan 1984). Standard accretion disk models were thus modified to include the presence of a hot inner disk region or corona, where unsaturated thermal Comptonisation of soft photons from the optically
thick disk up to energies of many tens or hundreds keV takes place (Eardley, Lightman, & Shapiro 1975; Eardley & Lightman 1976; Galeev, Rosner & Vaiana 1979).

Renewed interest in the hard X-ray emission properties of neutron star low mass X-ray binaries 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). Unlike Sco X-1 (and similar sources), the sources above have relatively low luminosity ($\sim 10^{36} - 10^{37}$ ergs/s) and emit type I X-ray bursts; moreover some of them are transients.

2 Neutron star low mass X-ray binary basics

Low mass X-ray binaries, LMXBs, contain neutron stars that have been spun up to periods of a few milliseconds by accretion torques (see e.g. van der Klis 2000; Strohmayer 2001). The fastest spin periods inferred so far are $\geq 1.5$ ms, i.e. longer than the mass shedding limit for virtually any equation of state. Direct evidence for the presence of a magnetosphere has so far been found in SAX J1808.4–3658, XTE J1751–305 and XTE J0929–314, the only three LMXBs displaying coherent pulsations in their quiescent emission (spin periods of 2.5, 2.3 and 5.4 ms, respectively, Wijnands, & van der Klis 1998; Markwardt et al. 2002; Galloway et al. 2002). The neutron star magnetic field is estimated to be $\sim 10^8 - 10^9$ G in these sources; other LMXBs which do not show coherent pulsations and have comparable (or higher) luminosities likely have comparable (or lower) magnetic field strengths.

The modern classification of LMXBs relies upon the branching displayed by individual sources in the X-ray color-color diagram assembled by using the sources’ count rate over a "classical" X-ray energy range (typically 2-20 keV). This classification has proven very successful in relating the spectral and time variability properties (Hasinger & van der Klis 1989; for reviews see van der Klis 1995, 2000; for recent work see Muno, Remillard, & Chakrabarty 2002; Gierlinski & Done 2002; Barret & Olive 2002) depending on the pattern described by each source in the X-ray color-color diagram. It comprises a Z-class (source luminosities close to the Eddington luminosity, $L_{\text{Edd}}$) and an Atoll-class (luminosities of $\sim 0.01 - 0.1 L_{\text{Edd}}$). Most Atolls emit Type-I X-ray bursts, i.e. thermonuclear flashes in the layers of freshly accreted material onto the neutron star surface; only two Z-sources are (somewhat peculiar) X-ray bursters. Considerable evidence has been found that the mass accretion rate (but not necessarily the X-ray luminosity) of individual Z-sources 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 to the top of the upper-banana branch.

Attempts at decomposing the X-ray spectra of Z sources in terms of two (or more) components have adopted different approaches and the origin of the spectral components is still debated (e.g. Mitsuda et al. 1984; White et al. 1986; 1988; Psaltis, Lamb, & Miller 1995). Over the classical X-ray range, two main models were discussed and applied. In the western model the spectrum is decomposed in the sum of an unsaturated Comptonised spectrum, supposedly produced in an inner disk corona, plus a blackbody originating from close to the neutron star surface or the boundary layer between the disk and the neutron star (White et al. 1986; White, Stella & Parmar 1988); in the eastern model the spectrum consists of the sum of an optically thick multi-temperature disk model (locally emitting like a pure blackbody) plus a blackbody again originating from the neutron star or the boundary layers (Mitsuda et al. 1984; Mitsuda et al. 1989).

Both decompositions proved adequate for fitting the $\sim 1 - 20$ keV spectra of Z-sources (see, however, Hasinger et al. 1990: analyzing Ginga data of Cyg X-2, they found that the western model was systematically below the high energy data in a few spectra in the FB; in those cases
the eastern model gave better fits). Typical temperatures for the blackbody component are in \( \sim 1 - 2.5 \text{ keV} \) range in the western and eastern model. The fraction of \( 1 - 20 \text{ keV} \) luminosity in the blackbody component is \( \leq 20\% \) in most cases. This value is substantially lower than that expected from boundary layers emission (\( \geq 50\% \) unless the neutron star rotates very close to mass shedding limit).

Concerning Atoll sources, the eastern model could not adequately fit the spectra of some of the lower luminosity sources, where the spectrum extended without any evidence for a break up to highest measured energies (White, Stella & Parmar 1988). In essence, this is due to the fact that given the local blackbody emissivity of the multitemperature disk model, the spectrum consist of a power law with photon index \( \Gamma = -2/3 \) up to an exponential cutoff corresponding to the temperature of the innermost (and hottest) disk region. Therefore the eastern model was modified in order to include the effects of the Comptonisation of the \( \sim 2 \text{ keV} \) blackbody coming from the neutron star (Mitsuda et al. 1989). In the unsaturated Comptonised component of the western model, the power law slope and cutoff energy are essentially determined by the Thomson depth and electron temperature of Comptonising region. These parameters can vary over a wide enough range to fit the \( \sim 1 - 20 \text{ keV} \) spectra of the harder Atoll sources as well. Moreover, we note that in some Atoll sources the additional blackbody component is not required within either of the spectral decompositions.

Attempts at ascribing spectral variations along the Z or Atoll pattern to variations of a single spectral component gave inconclusive results (see e.g. Hasinger et al. 1990; Hoshi & Mitsuda 1991; Schulz & Wijers 1993; Asai et al. 1994, and references therein). Similarly, constructing a parallel between the spectral components of Z and Atoll sources proved difficult, especially for the eastern model (Mitsuda et al. 1989). By contrast, the timing properties of LMXBs, as inferred from different power spectrum components such as QPOs, noise components etc., show a great deal of continuity along the different branches of each source and also a remarkable similarity across Z and Atoll sources (Wijnands & van der Klis 1999; Psaltis, Belloni, & van der Klis 1999; van der Klis 2000; Belloni, Psaltis & van der Klis 2002).

3 Hard X-ray spectral components in Atoll sources

Hard X-ray components extending up to energies of several hundred keV have been revealed in about 20 neutron star LMXBs of the Atoll class (some recent observations of hard X-ray spectra from low-luminosity LMXBs are reported in Table 1). In these systems the power law-like component, with typical slopes of \( \Gamma \sim 1.5 - 2.5 \), is followed by an exponential cutoff, the energy of which is often in between \( \sim 20 \) and many tens of keV. This component is interpreted in terms of unsaturated thermal Comptonisation. There are instances in which no evidence for a cutoff is found up to \( \sim 100 - 200 \text{ keV} \). This is the so called "hard state" of Atoll sources. There are sources that appear to spend most of the time in this state (e.g. 4U 0614+091, Ford et al. 1996, Piraino et al. 1999, and references therein). In others a gradual transition from the soft to the hard state has been observed in response to a decrease of the source X-ray luminosity and/or the source drifting from the banana branch to the island state (see Fig. 1, left panel). This transition is often modelled in terms of a gradual decrease of the electron temperature of the Comptonising region.

A reflection component in the characteristic shape of a broad bump centered around energies of a few tens of keV, sometimes together with a Fe K-shell line and edge, was detected in the hard state of some Atoll sources (e.g. Yoshida et al. 1993; Piraino et al. 1999; Barret et al. 2000). This component is believed to originate from reflection of the optically thick disk regions. Usually the reflection amplitudes (i.e. the solid angle \( \Omega/2\pi \) subtended by the reflector as seen from the hot inner corona are lower than 0.3. A correlation has been claimed between the photon index of the primary spectrum and the reflection amplitude of the reprocessed component (Zdziarski
| Source                  | Luminosity (10^{37} ergs/cm²/s) | Photon index | kT_e (keV) | E_{max} (keV) | Ref. |
|------------------------|---------------------------------|--------------|------------|--------------|------|
| 4U 0614+09             | 0.5–2.9 (0.1–200 keV)           | 2.3–2.4      | > 150      | 200          |      |
| 4U 1608–52             | 0.3–1 (2–60 keV)                | 1.7–2.2      | 30–60      | 200          |      |
| 4U 1705–44             | ~1.5 (1–20 keV)                 | 1.5          | ~ 25       | 20           |      |
| Ter 2 (X 1724-308)     | ~2 (0.1–100 keV)                | 1.6–1.9      | 30–90      | 200          |      |
| MXB 1728–34 (GX 354-0) | ~0.7 (35–200 keV)               | 3.0 ± 0.2    | –          | 200          |      |
| KS 1731–260            | ~1 (35–150 keV)                 | 2.9 ± 0.8    | –          | 150          |      |
| Ter 1 (X 1732-304)     | (4.0 ± 0.8) × 10^{-2} (40–75 keV) | 3.2 ± 0.7 | 20–60      | 170          |      |
| SLX 1735–269           | ~1.3 (1–20 keV)                 | 2–3          | 30–50      | 200          |      |
| SAX J1747.0–2853       | ~0.26 (2–10 keV)                | 1.6–2        | 30–70      | 200          |      |
| SAX J1748.9–2021       | ~1.2 (0.1–200 keV)              | 1.44 ± 0.5   | 20–50      | 100          |      |
| SAX J1808.4–3658       | ~0.38 (2–200 keV)               | 1.82 ± 0.04  | 180^{+120} | 200          |      |
| SAX J1810.8–2609       | ~0.12 (1–200 keV)               | 1.96 ± 0.04  | –          | 200          |      |
| 4U 1820–30             | 2.3–2.6 (2–50 keV)              | 2.05 ± 0.05  | ~ 20       | 50           |      |
| GS 1826–238            | ~0.88 (1–20 keV)                | ~ 1.7        | ~ 90       | 150          |      |
| X 1850–087             | ~0.13 (1–37 keV)                | ~ 2.3        | –          | 37           |      |
| 4U 1915–05             | ~0.6 (2–50 keV)                 | 1.8–1.95     | > 100      | 200          |      |
| Aql X-1                | ~0.2 (1–100 keV)                | 2.2–2.6      | –          | 150          |      |

Luminosity is the source luminosity calculated in the energy range specified in brackets; kT_e is the inferred electron temperature in the hot Comptonizing corona; E_{max} is the maximum energy at which the source was observed.

et al. 1999; Piraino et al. 1999; Barret et al. 2000), similar to that reported for BHCs and Seyfert galaxies.

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 luminosity. 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. Yet there is evidence that at least on occasions an additional parameter controls the soft/hard spectral transitions. This is especially apparent from a recent study of 4U 1705–44, in which 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 another occasion 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). It has been suggested that the second parameter regulating the spectral state transitions 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 to explain the “parallel tracks” observed in the kHz QPO frequencies vs. X-ray flux diagram), but also magnetic fields or the formation of jets could play a role.

4 Hard X-ray components in Z-sources

Recent broad band studies have shown that many Z-sources display variable hard, power-law shaped components, dominating their spectra above ~ 30 keV. As mentioned in the introduction,
Figure 1: Left) 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 Barr et 2001). The broadband 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 count rate alone is not a good indicator of the spectral state.

hard tails in Z-source spectra were occasionally detected in the past. The first detection was in the spectrum of Sco X–1; beside the main X–ray component (equivalent bremsstrahlung temperature of $\sim 4$ keV) Peterson & Jacobson (1966) found a hard component dominating the spectrum above 40 keV. The latter component was observed to vary by as much as a factor of 3. More recently the presence of a variable hard tail in Sco X–1 was confirmed by OSSE and RXTE observations (Strickman & Barret 2000; D’Amico et al. 2001).

Much progress in the study of the spectrum of Z-source and other high luminosity LMXBs has been recently achieved through BeppoSAX observations: a hard X-ray tail was found in the Z-sources GX 17+2 (Di Salvo et al. 2000), GX 349+2 (Di Salvo et al. 2001) and Cyg X-2 (Frontera et al. 1998; Di Salvo et al. 2002), as well as the peculiar bright LMXB Cir X–1 (Iaria et al. 2001, 2002) and during type II bursts from the Rapid Burster (Masetti et al. 2000). 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.

This hard component can be fitted by a power law, with photon index in the range 1.9–3.3, contributing up to 10% of the source bolometric luminosity. The parameters of these components, as deduced from recent X-ray observations, are reported in Table 2. The presence of the hard component in Z sources is in some cases 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 (Di Salvo et al. 2000, see Fig. 2), where the hard tail was observed to vary systematically with the position of the source in the CD. In particular the hard component (a power-law with photon index of $\sim 2.7$) showed the strongest intensity in the HB of its CD (see the corresponding spectrum in Fig. 2); a factor of $\sim 20$ decrease was observed when the source moved from the HB to the NB, i.e. from low to high inferred mass accretion rate. In a Ginga (1.5–37 keV energy range) observation of GX 5–1 a hard excess was detected. This could be fitted by a power law with photon index 1.8, the intensity of which decreased
Table 2: Recent observations of hard X-ray components in bright LMXBs.

| Source     | Spectral state | Luminosity (10^{38} ergs/cm^2/s) | Hard Luminosity (10^{36} ergs/cm^2/s) | Photon index | E_{\text{max}} (keV) | Ref. |
|------------|----------------|-----------------------------------|---------------------------------------|--------------|-----------------------|-----|
| GX 17+2   | HB             | 1.2                               | 2.0                                   | 2.7 ± 0.3    | 200                   |     |
| GX 349+2  | NB/FB          | 0.49                              | 0.5                                   | 1.9 ± 0.4    | 200                   |     |
| Cyg X-2   | HB             | 0.89 – 1.1                        | 0.8 – 0.9                             | 1.8 – 2.1    | 200                   |     |
| Sco X-1^b| NB             | –                                 | 0.9 – 1.4                             | 1.7 – 2.4    | 200                   |     |
|            | FB             | –                                 | 0.5 – 1.1                             | -1 – 0.1     | 200                   |     |
| GX 5-1^a  | NB             | ~ 3                               | ~ 10                                  | 1.8 (fixed)  | 37                    |     |
| Cir X-1   | NB/FB          | 1.4                               | 0.16                                  | 3.3 ± 0.8    | 200                   |     |
| Unknown   |                | 0.97                              | 0.27                                  | 3.0 ± 0.4    | 200                   |     |

Spectral in which the hard component was significantly detected: HB, Horizontal Branch, NB, Normal Branch, FB, Flaring Branch; Luminosity is the (absorbed) luminosity in the 0.1–200 keV energy range; Hard luminosity is the luminosity in the power-law component in the 20–200 keV energy range; E_{\text{max}} is the maximum energy at which a source was detected.

^a In this case a contribution from a nearby contaminating source could not be excluded.

^b The 2–20 keV luminosity of Sco X–1 was (2.1 – 3.2) × 10^{38} ergs/cm^2/s.

Figure 2: Left) BeppoSAX photon spectrum of GX 17+2 in the HB. The solid line represents the best fit model; individual model components are also shown. The hard power law, dominating the spectrum above 30 keV, is plotted as a dotted line. Right) 20-200 keV versus 1-20 keV luminosities of black hole binaries (open symbols, from Barret et al. 2000) and neutron star type-Z binaries (filled symbols, from Di Salvo et al. 2001). The so-called X-ray burster box is plotted as a solid line. Its boundaries are defined as in Barret et al. (2000).

from the NB to the FB (again from low to high mass accretion rate, Asai et al. 1994). The hard component detected in BeppoSAX data of GX 349+2 (Di Salvo et al. 2001) is among the hardest detected in bright LMXBs. Its photon index was of ~ 1.9, with no evidence of a high energy cutoff (up to ~ 100 keV). Cir X–1, thought to be a peculiar Z source (Shirey et al. 1999), was observed by BeppoSAX in the orbital phase interval 0.11–0.16, i.e. close to periastron. The state of the source was identified with the NB/FB (Iaria et al. 2001). Also in this case a hard tail was detected in the non-flaring spectrum, with a fairly steep power law slope of ~ 3.3. Cir
X–1 was also observed by BeppoSAX at orbital phases 0.61–0.63, i.e. close to apoastron. Again a hard tail, with photon index $\sim 3$, was required to fit its spectrum above 20 keV (Iaria et al. 2002).

In most of these cases the hard component becomes weaker for higher accretion rates (note that the contribution of the hard component to the total X-ray flux is different in different sources). Yet, in recent 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). The behavior of Sco X–1 again suggests that there might be a second parameter, besides mass accretion rate, regulating the presence of hard emission in these systems. Interestingly, Strickman & Barret (2000) suggest that the hard X-ray emission present in Sco X–1 data from OSSE may be correlated with periods of radio flaring.

5 Comparison with Black Hole Binaries

The hard X-ray spectra of Atoll sources in their hard (island) state are reminiscent of those of BHCs in their low state, LS. In both cases the hard component is well represented by a power-law spectrum that extends to many tens of keV; at higher energy an exponential cutoff sets in. Yet there are some notable differences. Firstly, the power-law slopes of the hard state Atolls are somewhat steeper than those of LS BHCs (Barret & Vedrenne 1994). More crucially, in the transition to the soft (banana) state, i.e. higher accretion rates, the cutoff energy of Atoll sources decreases markedly; this behaviour is not observed in BHCs when these move from the LS to the intermediate state, IS, or very high state, VHS (where a steep power law appears at high energies without evidences of a high energy cutoff).

On the other hand, the spectra of Z sources are quite similar to the spectra of BHCs in their soft states. At soft X-ray energies the latter, in fact, are dominated by soft emission with characteristic temperatures of $\sim 1–2$ keV, both in their IS and HS (this is to be contrasted with the characteristic temperatures of $3–4$ keV, plus an additional softer blackbody-like component in Z-sources).

As already mentioned, a hard spectral component is apparent in the IS/VHS of BHCs, which can be modelled with a power-law with photon index $\sim 2–3$, extending up to many hundred keV and showing no clear evidence for a high energy cutoff (see e.g. Grove et al. 1998). This component is very variable and usually contributes a few per cent of the total luminosity. This clearly parallels the characteristics of most Z-sources, which display a variable hard X-ray component in their HB and NB. At a purely phenomenological level, this is a clear indication that the presence of such a high energy tail in an otherwise soft spectrum cannot be considered a signature of black hole accretion. For the higher mass accretion rates of Z-sources (their FB) and in BHCs in the HS the intensity of the hard X-ray component is much reduced, often below detectability. Unlike BHCs, however, Z-sources have not yet shown transitions to a “low state” dominated by a power-law like spectral component extending up to high energies.

We note that even though mass accretion rate variations appear to be the main cause of the spectral transitions of BHCs, there is considerable evidence that a second, yet unknown, parameter can give rise to these transitions. The existence of a second parameter was indeed proposed to explain the soft/hard spectral transitions observed in the BHCs XTE J1550–564 (Homan et al. 2001) and GS2000+25 (Tanaka 1989).

The similarity between BHCs and Z-sources is also apparent from the “luminosity diagram”, in which the 1–20 keV luminosity is plotted versus the 20–200 keV luminosity. Barret et al. (1996) observed that all (low-luminosity) neutron star systems of the Atoll class in which a hard component had been detected lie in what they called the “X-ray burster box”, while all black hole systems lie outside. By plotting the X-ray luminosities of the Z-sources GX 17+2 (Di Salvo et al. 2000), Cir X–1 (Iaria et al. 2001), and GX 349+2 (Di Salvo et al. 2001a) in the same
diagram it is apparent that these sources lie in the region where BHCs lie, outside the X-ray burster box (see Fig. 2 right panel).

It appears, however, that only black hole candidates have a 20–200 keV luminosity $\geq 1.5 \times 10^{37}$ erg/s; this might be related to the higher Eddington luminosity that characterizes BHCs. These similarities might indicate that the hard tails in both black holes and neutron stars originate from the same mechanism. This would imply that this mechanism does not require the presence of an event horizon.

There might exist a relationship between the presence of the hard X-ray component and QPOs. Di Matteo & Psaltis (1999) found an interesting correlation between the QPO frequency and the slope of the power-law energy spectra in BHCs: the photon index increases with increasing the QPO frequency (see also Kaaret et al. 1998 for a similar correlation in Atoll sources). If the QPO frequency is related to the size of the innermost (optically thick, geometrically thin) disk region, which changes (mainly) in response to accretion rate variations (as indeed envisaged in a number of QPO models; see van der Klis 2000 for a review), then this correlation might simply reflect variations of the Comptonization parameter $y$ in response to variations of the innermost disk radius. In the case of Z sources, relatively poor statistics in the hard X-ray components prevented a study of the hard tail slope as the source moves from the HB to the NB, i.e., the path along which the QPO frequency increases. Yet the data are consistent with the hypothesis of a correlation between hard X-ray emission and QPO frequencies. This is suggested by the fact that: (1) the hard X-ray component of GX 17+2 is most pronounced over the source state(s) in which both the kilohertz and HB QPOs are detected and reach the highest rms amplitudes and (2) both the contribution from the hard X-ray component to the total spectrum and the rms amplitude of the QPOs increase dramatically with energy (e.g. van der Klis 2000).

Especially interesting is the possible relationship between hard X-ray and radio emission. All the Z sources are detected as variable radio sources. In the case of Sco X–1, the brightest radio source among neutron star LMXBs, recent VLBI observations have shown that the radio source consists of a variable core and two radio lobes which form close to the core and move outward at relativistic speeds, $\sim 0.45 c$ on average (Fomalont et al. 2001a, 2001b). Usually the highest radio fluxes are associated with the HB. The radio emission weakens in the NB, and is not detected any longer in the FB (e.g. Hjellming & Han 1995, and references therein). Therefore, the radio emission from these objects, which probably arises in the jets (Fender & Hendry 2000), is anticorrelated with the inferred mass accretion rate. This seems to be a fairly general behaviour, holding for different kinds of accreting collapsed objects, BHCs, Z-source, as well as Atoll sources (although only a few Atolls have been detected in radio so far, e.g. Fender 2001).

Since the hard X-ray emission component from these sources is, in general, more pronounced for lower mass accretion rates, it has been proposed that non-thermal, high energy electrons, responsible for the hard tails observed in Z sources, might be accelerated in the jets (Di Salvo et al. 2000, Iaria et al. 2001a; see also Fender 2001).

6 Models

In this section we briefly summarize the main features of some of the models proposed for the hard X-ray emission of neutron star LMXBs (for more details and references see Barret 2001). The analogy between the hard X-ray spectral components of neutron star LMXBs and BHCs suggests a similar emission mechanism and geometry in all these systems. The hard spectrum in neutron star systems (at least in those cases in which a thermal cutoff has been observed) can be explained as thermal Comptonisation of soft photons in a hot region (corona), perhaps placed between the neutron star and the accretion disk. This is similar to models proposed for
BHCs in their LS.

In some cases, however, a high energy cutoff is not observed up to energies of $\sim 100$ keV or higher, which would imply extremely high electron temperatures. In the case of Z sources these high temperatures would be difficult to explain considering that the most of the source emission sources is very soft. As in the case of black hole candidates in the IS, the hard tails observed in Z sources can be produced either in a hybrid thermal/non-thermal corona (i.e. a corona in which a fraction of the energy can be injected in form of electrons with a non-thermal velocity distribution, Poutanen & Coppi 1998) or in a bulk motion of matter close to the neutron star (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 neutron star surface. 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 depths in the scattering medium and/or higher bulk electrons velocities, in a way that is similar to thermal Comptonization.

An alternative possibility is that the hard X-ray component originates from the Comptonisation of seed photons by high-velocity electrons of a jet (e.g. Di Salvo et al. 2000), or via optically thin synchrotron emission directly by the jet (Markoff, Falcke, & Fender 2001).

7 Perspectives in the INTEGRAL era

Despite a considerable progress in recent years, the study of the hard X-ray emission properties from neutron star LMXB is still in its infancy. Luminosity plots of the kind shown in Fig. 2 (right panel) is about as much as current observations can afford for a few tens of sources of this class. Hard X-ray color-color diagrams are still to come; the analogy with the color-color diagrams assembled from data in the classical X-ray band suggests that new interesting information will be derived from them. This will soon be made possible by INTEGRAL observations of a number of neutron star LMXBs.

INTEGRAL holds also the potential to address key issues such as: (a) 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; (b) the correlation of the hard X-ray component with a variety of other source properties, such as source X-ray state, radio activity, X-ray line emission, QPOs frequencies etc. Coordinated observing programs exploiting the characteristics of INTEGRAL, as well as those of facilities such as Chandra, XMM and ground based optical and radio observatories will be especially relevant in this respect.

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