The broad band X-ray/hard X-ray spectra of accreting neutron stars

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ABSTRACT

I review the energy spectra of low mass X-ray binaries (LMXBs) containing weakly magnetized accreting neutron stars (NS), emphasizing the most recent broad band (0.1-200 keV) spectral and timing observations performed by Beppo-SAX and RXTE. Drawing on the similarities between black hole candidate (BHC) and NS accretion, I discuss the accretion geometry and emission processes of NS LMXBs.

INTRODUCTION

With Beppo-SAX and RXTE, for the first time since their discoveries about 40 years ago, LMXBs with NS primary have been observed with good sensitivities simultaneously from X-rays (\(\sim 0.1\) keV) to hard X-rays (up to \(\sim 200\) keV). These spectral observations have set unprecedented constraints on the emission processes of these systems. They have also shed some light on the accretion geometry in the immediate vicinity of the NS, and revealed many new similarities between BHC and NS accretion. At the same time, the RXTE fast timing observations, in particular through the discovery and follow-up studies of kilo-Hertz Quasi-Periodic Oscillations (kilo-Hz QPOs) have provided direct diagnostics of the innermost regions of the accretion disks (e.g. Van der Klis 2000). Thus, in the last few years, significant advances have been made on the study of the accretion flows around NS. In the next section, I will briefly summarize the state of the observations before the Beppo-SAX and RXTE era. Then, I will review the most recent broad band spectral observations of NS. I will then briefly present some results obtained from correlated spectral and fast timing studies. I will then discuss what we have recently learned from all these results when combined together.

THE PICTURE BEFORE BEPPO-SAX AND RXTE ERA

Prior to Beppo-SAX and RXTE, observations of LMXBs had been performed in X-rays with satellites such as EINSTEIN (e.g. Christian & Swank 1997), TENMA (Mitsuda et al. 1984, 1989), EXOSAT (e.g. White et al. 1986, White et al. 1988), GINGA (Mitsuda 1992), more recently with ASCA (e.g. Narita et al. 2001), and separately in hard X-rays with SIGMA (e.g. Barret & Vedrenne 1994, Churazov et al. 1997), BATSE (e.g. Harmon et al. 1996) and OSSE (e.g. Strickman et al. 1996).

The X-ray spectra of LMXBs were generally described as the sum of a soft and hard component and were interpreted in the framework of two models: the eastern model (also called the TENMA model, Mitsuda et al. 1984), and the western model (or EXOSAT model, White et al. 1988). The soft component of the TENMA model is a multi-color disk component approximating the emission from an optically thick geometrically thin accretion disk. The hard component is a weakly Comptonized blackbody component. Comptonization of seed photons emitted at the neutron star surface/boundary layer would take place in the inner parts of the accretion disks (Mitsuda et al. 1989). In the EXOSAT model, the soft component is a single temperature blackbody, attributed to an optically thick boundary layer, whereas the hard one represents unsaturated Comptonization taking place in the innermost regions of the accretion disks (White et al. 1988). In both models, the luminosity of the component associated with the boundary layer was systematically lower than the one attributed to the disk, contrary to theoretical expectations (Sunyaev & Shakura 1986).

X-rays/hard X-rays are defined as photons of energy below/above \(\sim 20 – 30\) keV.
Luminosity related spectral changes were observed by TENMA from the LMXB 4U1608-52 (Mitsuda et al. 1989). With decreasing luminosity, the degree of Comptonization increased, and the X-ray spectrum approached a power law shape. In the low/hard states, deviations from a simple power law, appearing as a broad absorption edge between 8 and 10 keV were first observed by GINGA from 4U1608-522 (Yoshida et al. 1993). These deviations could be interpreted as due to the reflection of the incident power law by a relatively cold medium (Mitsuda 1992). Line emission centered between 6.4 and 6.8 keV, with equivalent width of 70-130 eV and Full Width Half Maximum (FWHM) of \(\sim 1\) keV had also been reported (White et al. 1986, see however Mitsuda 1992).

In hard X-rays, the observations suffered dramatically from the lack of simultaneous X-ray coverage. At the end of the SIGMA/CGRO era, we knew that bright LMXBs (e.g. GX5-1) do not display significant hard X-ray emission, although a variable and low luminosity hard X-ray tail had been detected by OSSE from Sco X-1 (Strickman & Barret 2000). On the other hand, a few low luminosity LMXBs had been detected up to 100 keV (Barret & Vedrenne 1994, Churazov et al. 1997). Due to the limited statistics of the data (the first detection was only at the 5\(\sigma\) level!), the hard X-ray spectrum could be fitted by steep power laws (index around 2.5-3.0), or thermal Bremsstrahlung with temperatures around 50 keV, or by Comptonization models with electron temperatures around 30 keV (e.g. Churazov et al. 1997). It was soon hypothesized that the emission of a hard X-ray tail could be associated with a low luminosity state in X-rays, when the X-ray spectrum approaches a power law, and that the softness of the hard X-ray spectrum could be due to the presence of an undetected break or high energy cutoff (Barret & Vedrenne 1994, Churazov et al. 1997). This hypothesis was soon after confirmed by the detection by BATSE of 4U1608-522 quasi-simultaneously with GINGA during a low X-ray state (Zhang et al. 1996). Thermal and non-thermal models had then been proposed to account for the hard X-ray emission observed (for a review see Tavani & Barret 1997).

Over the last few years, significant advances have been possible thanks to the broad band spectral capabilities of Beppo-SAX and RXTE. Low energy coverage (below \(\sim 2\) keV) enables to resolve the soft (\(\sim 1\) keV) component of the spectra, simultaneous hard X-ray coverage is necessary to constrain the physical parameters of the hard component. In addition, a good overlap region between the X-ray and hard X-ray bands is required to extract the Compton reflection component. Good spectral resolution below \(\sim 10\) keV is then needed to resolve the associated emission line and absorption edge features. The broad band spectral capabilities of Beppo-SAX are illustrated in Frontera et al. (1998). RXTE is presented in Bradt, Swank & Rothschild (1993). In addition to providing broad band coverage, Beppo-SAX and RXTE are also very complementary satellites: Beppo-SAX has good spectral resolution in X-rays, good sensitivity in hard X-rays, and is perfectly suited for dedicated deep pointed observations for detailed spectral studies. On the other hand, RXTE with its large collecting area, high time resolution, and large telemetry rate is the instrument of choice for fast timing studies. Furthermore, with its flexibility of operations, it offers the unique capability of performing repeated observations over long periods of time, allowing to sample multiple spectral and timing states of the same source. The results presented later should nicely illustrate the unique capabilities of both satellites.

**BROAD BAND BEPPO-SAX AND RXTE OBSERVATIONS**

Following on the detection of hard X-ray tails from low luminosity LMXBs, Van Paradijs & Van der Klis (1994) showed, using the HEAO-1 A4 data that, in LMXBs there is a global anti-correlation between the X-ray luminosity and spectral hardness. Although the global trend is indeed real when considering the X-ray luminosity (the higher X-ray luminosity sources have on average softer spectra than lower luminosity sources), when considering broad band luminosity the separation between soft and hard spectra is not as clear. There are some sources with soft spectra and low luminosities, as well as some sources with hard spectra and relatively large luminosities. Furthermore, within a given source, it can be found that a softer spectrum does not always imply a larger luminosity (see Fig. right panel). Finally the luminosity is computed for a distance which is sometimes poorly constrained. For these reasons, in this paper, independently of the observed source luminosity, I define the spectral hardness as a measure of the fraction of flux radiated in the hard X-ray band. A soft spectrum is therefore a spectrum for which most (say larger than 80%) of

2In the past, due to the absence of broad band coverage, the word luminosity usually referred to the X-ray luminosity. In this paper, it refers to the broad band X-ray to hard X-ray luminosity.
Fig. 1. Spectral state changes observed by RXTE from the two variable LMXBs, KS1731-260 (left) and 4U1705-44 (middle) as observed by RXTE. The soft spectra are well fitted by the sum of a MCD and a CompTT whereas for the hard spectra they are well fitted by a BB/MCD and a cutoff power law (PCA and HEXTE spectra are combined). Right) Two PCA spectra taken by RXTE from 4U1705-44 during a spectral transition that occurred in February 1999. The hard spectrum corresponds to a broad band luminosity that is about twice the one associated with the soft spectrum, owing to the appearance of a relatively strong hard X-ray component (the 2.5-25.0 keV X-ray count rate differs by less than 2\% between the two observations, Barret & Olive, work in preparation). This illustrates that the X-ray count rate alone is not a great indicator of the spectral state.

the source flux is radiated below 20 keV. Based on this, I will review separately soft and hard spectra. Both soft and hard spectral states have been observed from a number of LMXBs characterized by large intensity variations. These spectral changes are sometimes very spectacular as shown in Fig. 1 for the two LMXBs KS1731-260 and 4U1705-44.

**Soft spectra**

Soft spectra have been observed over a range of luminosity going from $\sim 10^{37}$ ergs s$^{-1}$ to $\sim 10^{38}$ ergs s$^{-1}$ (e.g. GX3+1, $1.3 \times 10^{37}$ ergs s$^{-1}$ Oosterbroek et al. 2001, 4U1728-34, $1.8 \times 10^{37}$ ergs s$^{-1}$ Piraino et al. 2000, GX17+2, $1.0 - 1.2 \times 10^{38}$ ergs s$^{-1}$ Di Salvo et al. 2000). Soft spectra have been observed both from Z and Atoll sources. These spectra are always decomposed as the sum of a soft component and a Comptonized component (e.g. 4U1728-34, see Fig. 2). Despite its good sensitivity and spectral resolution at low energies, which resolves nicely the soft component, Beppo-SAX is not able to distinguish between a single temperature blackbody (BB) and a multi-color disk (MCD) blackbody model (e.g. Di Salvo et al. 2000b). BB temperatures of less than 1 keV are generally observed. For the MCD model the typical range for the color temperature is $\sim 0.5$ to 1.5 keV. In addition for the latter model, very small values of the projected inner disk radius $R_{\text{in}} \cos \theta$ are derived, typically a few kilometers (e.g. 2.8 km for GX3+1, Oosterbroek et al. 2001). Merloni et al. (2000) have shown however that the inner disk radius so measured underestimates the true inner disk radius (see also Gierliński et al. 1999 for a discussion about the importance of the assumed inner boundary conditions on the disk radius estimate). The observed value is therefore poorly constraining, as it must be corrected by a spectral hardening factor, which varies with the accretion rate and the fraction of energy dissipated outside the disk (Merloni et al. 2000). With these limitations in mind, when corrected for an invariant spectral hardening factor of 1.7, in the best case, a plausible value of the effective inner disk radius is obtained (e.g. $R_{\text{eff}} \sqrt{\cos \hat{i}} \sim 20$ km in 4U1728-34, Di Salvo et al. 2000a, $\hat{i}$ is the inclination angle).

For the Comptonized component, a temperature of a few keV and a relatively large optical depth of $\sim 5 - 15$ are observed (e.g. GX3+1, $kT_e=2.7$ keV, $\tau = 6.1$, Oosterbroek et al. 2001, GX17+2, $kT_e=3.0$ keV, $\tau \sim 10$, Di Salvo et al. 2000b, KS1731-260 $kT_e=2.7$ keV, $\tau \sim 12$, Barret et al. 2000). Using the CompTT model in XSPEC (Titarchuk 1994), it is in principle possible to determine the characteristic temperature of the seed photons for the Comptonization. Seed photon temperatures range from 0.3 to 1.5
Fig. 2. *Left*) A soft spectrum of Ser X-1 and *Middle*) 4U1728-34 as measured by Beppo-SAX (from Oosterbroek et al. 2001 and Di Salvo et al. 2000a). In both cases, the spectrum is the sum of a soft component (disk blackbody or blackbody) and a harder Comptonized component, plus a broad 6.4 keV and 6.7 keV line for Ser X-1 and 4U1728-34 respectively. An additional line at 1.7 keV is detected in 4U1728-34. *Right*) The 0.1-50 keV soft spectrum of 4U 1728-34 observed by BeppoSAX is shown together with the residuals in the entire band, in unit of standard deviations, when the best fit continuum is applied in the whole band except the 4-8 keV energy range. The inset shows the residuals of the MECS data rebinned to better display the profile of the observed Fe Kα feature (Piraino et al. 2000)

keV, i.e. in the same range of temperatures measured for the soft component (e.g. Oosterbroek et al. 2001, Di Salvo et al. 2000a).

The ratio between the fluxes of the soft (BB or MCD) and Comptonized components varies typically between 0.1 and 0.5, thus indicating that the soft component does not dominate the source luminosity. This has generally led to the interpretation that the soft component originates from an optically thick accretion disk, whereas the harder Comptonized component arises from a hot inner flow and/or a hot boundary layer with the seed photons coming from both the accretion disk and the NS surface (e.g. Di Salvo et al. 2000a, Barret et al. 2000). Obviously, this is a revisited version of the previously mentioned *eastern* model.

In addition to the above components, line features between 6.4 and 6.7 keV have been convincingly reported in a few NS soft spectra. One of the nicest example to date is provided by the Beppo-SAX observation of 4U1728-34 (Piraino et al. 2000, see Fig B, right). The line is broad (relativistic broadening ?) and interpreted as emission from highly ionized iron (Fe XXV to Fe XXXVI). As an iron line produced at the NS surface would be redshifted down to ~ 5 keV, it most likely arise from an irradiated accretion disk (e.g. Piraino et al. 2000). In that case, one would expect also a reflection component. The reflection component is however not expected to be intense, due to the softness of the primary spectrum, which means that photons should be photo-electrically absorbed and thermalized in the disk, rather than being Compton scattered. Yet, weak evidence for the presence of such a reflection component has been reported recently (Oosterbroek et al. 2000, Di Salvo et al. 2000a). In the case of 4U1728-34 (Fig. B, Middle), using the reflection model of Życki et al. (1998) in which the iron line is computed self-consistently with the reflection component, the observed line would require reflection from a moderately ionized disk ($\xi = 280$, Di Salvo et al. 2000a).

**Soft spectra and hard X-ray tails**

Departing from the extrapolation of the X-ray spectrum around 40-60 keV, a hard X-ray tail extending out to 100 keV or more has been detected with high significance in Cyg X-2 (Frontera et al. 1998), in GX17+2 (Di Salvo et al. 2000b, Fig. 3), in Sco X-1 by HEXTE (D’Amico et al. 2000) thus confirming the previous detections by OSSE (Strickman & Barret 2000), in GX349+2 (Di Salvo et al. 2001a), and from the somewhat peculiar Cir X-1 source (Iaria et al. 2000). In Sco X-1, the luminosity of the hard tail is less than 1% of the broad band source luminosity, whereas it reaches 8% in GX17+2. Due to the limited statistics, these hard tails have been fitted by simple power laws. The photon index measured by Beppo-SAX is 2.5
The spectrum shown in Fig. 3 shares clearly some similarities with those of high state BHCs, when the broad band spectrum is the sum of a so-called *ultrasoft* component and a hard X-ray tail (Grove et al. 1998). There are two noticeable differences however. First in NS, as we have shown above the X-ray spectrum is the sum of MCD/BB and a harder Comptonized component, whereas for BHC the X-ray spectrum can be generally modeled by a single component, approximated by a MCD (e.g. Tanaka & Lewin 1995). This difference makes the X-ray part of the spectrum of NS to look *harder* than the one for BHCs. Second, concerning the hard X-ray tail, in BHCs it is most of (if not all) the time present, whereas the available data suggest that it is much more variable in NS.

**Hard spectra**

Hard spectra have been observed for luminosities ranging from a few times $10^{36}$ ergs s$^{-1}$ up to $\sim 3 \times 10^{37}$ ergs s$^{-1}$. So far only Atoll sources (and more generally X-ray bursters) have been observed with hard spectra. For those spectra, about half of the source luminosity is radiated in hard X-rays. There are now about 20 NS LMXBs detected up to 100 keV (Barret et al. 2000). For all of them and within distance uncertainties, the hard X-ray luminosity never exceeds $\sim 1.5 \times 10^{37}$ ergs s$^{-1}$. This is unlike for BHCs for which the hard X-ray luminosity can largely exceed that value (Barret et al. 2000).

Like for soft spectra, broad band hard spectra are generally described by the sum of a soft component and a Comptonized component. The main difference between the two classes of spectra resides in the parameters of the Comptonizing component. The inferred optical depth of the Comptonizing cloud is now a few ($\sim 2-3$ for a spherical geometry), whereas the electron temperature is typically a few tens of keV, equivalent to an energy cutoff around 60-80 keV in the spectra (e.g. 1E1724-3045, $kT_e=27$ keV, $\tau=3.3$, Guainazzi et al. 1998).
Fig. 4. left) The unfolded spectra of 1E1724-3045 in Terzan 2 (Guainazzi et al. 1998) and right) SAXJ1810.8-2609 (Natalucci et al. 2000a). In both cases, the hard spectrum can be fitted by the sum of a soft component (either a BB or a MCD) and a hard Comptonized component (for SAXJ1810.8-2609 however, the hard X-ray component can also be fitted with a simple power law).

SAXJ1747.0-2853, $kT_e=33$ keV, $\tau=3.1$, Natalucci et al. 2000a, see Fig. 4). The above values are typical of NS LMXBs, and seem to be lower than the values observed from BHCs (e.g. $kT_e$ 100 keV for Cyg X-1, Di Salvo et al. 2001b, see also Natalucci 2001). The idea the electron temperature could be used as a criteria for distinguishing between BHC and NS has already been invoked (Tavani & Barret 1997, Zdziarski et al. 1998, Barret et al. 2000), and interpreted as the signature of the neutron star surface acting as a thermostat for the Comptonization region (e.g. Kluźniak 1993).

However, in a few cases so far, no clear energy cutoffs were observed in the hard X-ray spectrum (e.g. Aql X-1, Harmon et al. 1996). For 4U 0614+09 a lower limit of 220 keV on $kT_e$ was derived (Piran et al. 1999). These non attenuated power laws have photon index in the range 2.0-2.5 (see Fig. 5, left). They clearly share some similarities with those observed during the so-called power-law gamma-ray spectral state of BHCs as defined in Grove et al. (1998). The lack of high energy cutoffs may again be a signature of non-thermal Comptonization (Poutanen 1999 for a review).

As far as the soft component is concerned, it can be fitted either by a blackbody or a multi-color blackbody and contributes modestly to the source luminosity (e.g. 10% in SAXJ1747.0-2853, Natalucci et al. 2000b, 15-30% in 1E1724-3045, Barret et al. 2000). Sometimes the soft component is not detected (e.g. In’t Zand et al. 1999 for SAZJ1748.9-2021), this may be because it is absent, or too faint, or that the bulk of its emission is radiated below the observed energy range.

Below the continuum, a reflection component has been detected in a few cases (e.g. SAXJ1808-3658; Gierliński et al. 2001, GS1826-283, Barret et al. 2000, see Fig. 6). This reflection component is important as it can be used to probe the ionization state, element abundances and geometry of the accretion flow (e.g. Georges & Fabian 1991, Matt et al. 1991). In general it is found that the reflector is neutral/moderately ionized (e.g. Barret et al. 2000). Furthermore the magnitude of the reflected component ($R^2$) indicates that the reflecting medium subtends a small solid angle to the irradiating source. Consistent with the presence of reflection, a weak iron line has been detected (EqW~ 50 eV). These observed values are significantly lower than the ~ 130 eV and $R = 1$ of an isotropic X-ray source above a flat infinite slab (Georges & Fabian 1991). The most likely site for the reflection is the accretion disk. However, for 4U0614+09 for which no thermal cutoffs were observed in the hard X-ray tail, a stronger reflection component has been observed with R ranging from 1 to ~ 3. Such a large $R$ implies that the primary source is either partially obscured or anisotropic in the reflector frame. This might be expected if the power law results from non-thermal Comptonization on relativistic electrons (Piran et al. 1999). In addition, a correlation between the

$^3$Compton reflection is generally measured as a relative normalization ($R$) of the reflected component with respect to the irradiating component. If the irradiating source is isotropic and neither the primary nor the reflecting medium are obscured, then $R=\Omega/2\pi$, where $\Omega$ is the solid angle subtended by the reflector as viewed by the irradiating source.
Fig. 5. *left*) Beppo-SAX unfolded averaged spectra of 4U0614+09, for the October 19–20, 1998 observation together with a model consisting of a powerlaw, reflection, a blackbody, and a low energy Gaussian line all with absorption. The total model fit is shown as a solid line, the powerlaw as dotted line, the reflection component as a dot-dot-dashed line, the blackbody component as a dot-dashed line, and the Gaussian line as a dashed line. No clear high energy cutoff is observed in the hard X-ray tail. *Right*) Spectral parameters correlations. (a) Magnitude of reflection (as defined above) versus photon index. (b) Blackbody flux (erg cm$^{-2}$ s$^{-1}$) versus photon index (From Piraino et al. 2000).

CORRELATED TIMING AND SPECTRAL STUDIES
Kilo-Hz QPOs have now been detected from over 20 LMXBs (Van der Klis 2000). Without entering into the details of the QPO phenomenology, in most sources two kilo-Hz QPOs have been observed. Although the origin of the lower QPO is still debated, in most models, the higher QPO is associated with a Keplerian frequency at the inner edge of the accretion disk (Van der Klis 2000). Thus for a NS producing kilo-Hertz...
QPO, some new information can be gathered by relating the luminosity/spectral changes observed to changes of the QPO frequency.

On short time scales (a few hours to less than 1 day) there is a good correlation between the kilo-Hz QPO frequency and the X-ray count rate. On longer time scales, the correlation does not hold, and while the source span the same frequency range, its count rate can change by up to a factor of a few (e.g. Méndez et al. 1999, see Fig. 6, left). On the other hand, a much better correlation on all time scales exists between the kilo-Hz QPO frequency and the X-ray spectral shape, when measured as a position in the X-ray color-color diagram (Méndez et al. 1999, Fig. 6, right). Kilo-Hz QPOs correlate well with some other timing features (e.g. break frequency in the power density spectrum; e.g. Ford et al. 1997), all better correlating with the X-ray colors than with the X-ray flux. From X-ray burst studies, simultaneous optical/UV and X-ray observations, the sense of variation of \( \dot{M} \) on the color-color diagram has been determined. For instance, in Atoll source the \( \dot{M} \) should increase from the so-called Island state to the upper-banana state (see Fig. 6, e.g. Van der Klis 1994). This has led to the definition of an \( \dot{M} \) inferred from the position of the source on the color-color diagram. Kilo-Hz QPOs, like other timing features appear therefore to be set by this inferred \( \dot{M} \). If this inferred \( \dot{M} \) is the total mass accretion rate, then the lack of correlation between the X-ray flux and inferred \( \dot{M} \) needs to be explained. Several arguments have been put forward; e.g. a time variable beaming of the emission, or a redistribution of energy over an unobserved energy range, or the existence of significant time variable mass outflows to remove mass and kinetic energy (see e.g. Ford et al. 2000). Alternatively, following an idea developed in Fortner et al. (1989) (see also Lamb 1989), it has been suggested that the accretion flow could be decoupled in the form of a disk and radial flow, and that the inferred \( \dot{M} \) could be the accretion rate through the disk (e.g. Kaaret 2000, see discussion below). In that picture, the total (disk plus radial) mass accretion rate would determine the X-ray flux, which could in turn be decoupled from any other observed quantities, such as the frequency of the kilo-Hz QPOs.

When considering the components of the X-ray spectrum rather than X-ray colors, the correlation between kilo-Hz QPOs and spectral shape can be made very clear. Ford et al. (1998) have shown that there is a one to one correlation between the flux of the blackbody component of the X-ray spectrum and the QPO frequency (Fig. 6 left). No such correlation exists between the total X-ray flux and the QPO frequency. Similarly, when fitting the X-ray spectra of 4U0614+09 and 4U1608-52 with simple power laws, Kaaret et al. (1998) observed a correlation between the index of the power law and the QPO frequency, the larger the index, the higher the QPO frequency (Fig. 6 middle). Finally, Kaaret (2000) have shown that the strength of the reflection component (Fig. 6) also correlates with the QPO frequency (Fig. 6 right).

The mechanism to produce such a flow is the following: For sufficiently high luminosities, the radiation pressure from the disk drives some gas into a corona above the disk. Radiation drag causes the gas to lose its angular and vertical momentum and to fall radially toward the star (Fortner et al. 1989, Lamb 1989)

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**Fig. 7.** Left) Kilo-Hz QPO frequency versus flux of the blackbody spectral component (Ford et al. 1997). Middle) Photon index vs. QPO frequency on a log-log plot. The crosses indicate data for 4U 0614+09; the solid line is a power-law fit to the data for 4U 0614+09; the diamonds and the dashed line indicate the data and fit, respectively, for 4U 1608-52 (Kaaret et al. 1998). Right) Correlation between the strength of the reflection component and the QPO frequency in 4U0614+09 (Kaaret 2000)
DISCUSSION

The list of spectral similarities between BHC and NS accretion has grown considerably over the last few years. Some new similarities are illustrated in this paper: non-thermal power law tail, Compton reflection, soft X-ray spectrum and steep hard X-ray tail. These spectral similarities add to the long list of already known similarities of the timing properties of the two classes of accreting sources (Van der Klis 1994, see Wijnands 2001 for a recent review of timing properties of LMXBs). The similarities are especially striking in the hard spectral state of those sources, when they both display large amplitude band limited noise (flickering), and hard energy spectra. This implies that the timing and spectral properties of NS are weakly affected by the presence of a hard surface (and a boundary layer) or a small magnetosphere and that very similar accretion flows exist around BHC and NS.

Accretion geometry and emission processes

For BHC, the available spectral and timing data are consistent with two accretion geometries (see Done 2001 for an extensive discussion). The first one consists of a truncated optically thick geometrically thin accretion disk, beyond which the nature of the flow changes to form a hot inner disk region, most probably an advection dominated accretion flow (ADAF, Narayan 1997 for a review). The broad band spectrum of Cyg X-1, the low amplitude of reflection and relativistic smearing would be consistent with a truncation radius of the order of a few tens of $R_g$ ($R_g=2GM/c^2$) (Di Salvo et al. 2001b). Similarly, frequency resolved spectroscopy of Cyg X-1 yields an inner disk radius of $\sim 100 R_g$ in the hard state and less than $\sim 10 R_g$ in the soft spectral (high) state (Gilfanov et al. 2000). In that picture, the soft component of the spectrum comes from the truncated accretion disk, whereas the hard component arises through thermal Comptonization from the hot inner disk region. Conduction of heat between the hot inner flow and a cold disk leading to the evaporation of the disk has been proposed as a mechanism for the transition (Różańska & Czerny, 2000).

The alternative geometry is an accretion disk extending all the way to the last stable orbit, with the hard X-rays produced in active regions above the disk, most likely powered by magnetic reconnection (e.g. Haardt et al. 1994). To be reconciled with the spectral observations (mainly the weakness of the reflection and reprocessed component), the active regions should be expanding away from the disk with relativistic velocities (Beloborodov 1999), or the disk should be strongly photo-ionized (Ross et al. 1999, Nayakshin et al. 2000). Magnetic flares above a disk could account for the fast variability and the magnitude of the hard time lags observed in both BH and NS (e.g. Ford et al. 1999), while keeping the X-ray source small (Poutanen & Fabian 2000).

In NS, if one assumes that the disk terminates where the kilo-Hz QPO is produced, then the disk is truncated. Kilo-Hz QPO range typically from $\sim 300$ to $1300$ Hz which correspond to Keplerian orbital radius of 15 to 50 km. From both observational (Psaltis et al. 1999) and theoretical grounds (e.g. Stella et al. 2000), there is some evidence that those QPOs could be produced at even lower frequencies ($\sim 100$ Hz or less) for lower luminosity sources, in which case, this would push the inner disk radius much further out ($\sim 100$ km). So if one assume that the kilo-Hz QPOs are produced at the truncation radius between the cool disk and the hot inner disk region then the correlations described above (e.g. Fig. 4) can be naturally explained. This is because $R_{in}$ not only sets the QPO frequency, but determines also the spectral shape, as the accretion disk is the main source of cool photons for the Comptonization (Kaaret 2000). For instance, when $R_{in}$ decreases, the kilo-Hz QPO frequency increases, and the disk blackbody flux increases (Ford et al. 1997). At the same time, the spectrum steepens in response to an increased cooling flux from the disk (see Fig. 5, note that this will be true only if the spectrum in produced through thermal Comptonization). Simultaneously, the angle subtended by the truncated disk to the hot inner disk region increases, leading to an increase of the amplitude of the reflection component (Kaaret 2000). It has then been argued that, provided that the accretion takes place through two different channels (as discussed in Fortner et al. 1989), one being the disk, $R_{in}$ could be set by the accretion rate through the disk (Kaaret 2000). In this picture,

The profile of the Fe line associated with the reflection component could also be used to test the proposed picture. When the disk moves in, the combination of Doppler effects and gravity in the vicinity of the NS should lead to appreciable changes in the line profiles. Similarly, as shown by Nayakshin (2000) in the accretion disk model with an X-ray heated skin, the parameters of the Fe line and absorption features should also change when the spectrum changes; harder spectra are expected to produce no Fe lines and no edges, whereas softer spectra should yield stronger ionized absorption edges and highly ionized Fe lines. This clearly emphasizes the need for spectroscopic observations (e.g. with XMM-Newton and Chandra) of those systems.
the inner disk radius moves in when the accretion rate through the disk increases (e.g. Miller et al. 1998). Eventually, if the NS radius is smaller than the radius of the Innermost Stable Circular Orbit (ISCO at $R_{\text{ms}}$) predicted by General relativity, the disk should stop at the ISCO and the kilo-Hz QPO frequency should saturate. Evidence for such a saturation at $R_{\text{ms}}$ has been claimed for one source: 4U1820-303 (Zhang et al. 1998, Bloser et al. 2000). Although attractive, this scenario faces already some problems. First, it is unclear how systems with luminosities differing by up to 2 orders of magnitude with QPO in the same frequency range can keep the same accretion rate through the disk at very different total accretion rate (Ford et al. 2000). Furthermore, one would expect that at a constant kilo-Hz QPO frequency (i.e. fixed disk mass accretion rate), the strength of the QPO should decrease rapidly, when the X-ray count rate (tracing the total accretion rate) increases. Such a rapid decrease has not been observed (Méndez et al. 2001). To conclude, timing and spectral observations could be explained by a varying inner disk radius. However, the fundamental parameter or the combination of parameters that set the value of the inner disk radius has yet to be identified.

What is the nature of the hot inner accretion flow? Driven by the similarities with BHCs, despite the very different inner boundary conditions (a solid surface as opposed to an event horizon) in the hard spectral state, it has been hypothesized that the hot inner accretion flow could be an ADAF (Barret et al. 2000). For the ADAF to remain and for the hard spectra observed to be produced, the flow must settle down on the NS surface in the form of hot optically thin boundary layer (see computations in Narayan & Yi 1995, Yi et al. 1996). At higher luminosities, in response to a larger cooling flux from the disk (and possibly from a change in the nature of the boundary layer), the ADAF should collapse. Most of the emission could then come from the boundary layer between the NS and the disk (e.g. Popham & Sunyaev 2001, Inogamov & Sunyaev 1999). Although the similarities between BHC and NS point to a similar accretion geometry and emission processes, more theoretical work is needed to study the nature of the inner flow and the structure and properties of such a flow when it reaches the NS surface.

Non-thermal processes in NS

In the above discussion, it is implicitly assumed that the main emission mechanism is thermal Comptonization. However, recent observations have shown that NS, like BHC, may occasionally display non-thermal state with hard X-ray spectra extending up to $\sim 200$ keV with no observable cutoffs (see Fig. 3, for an early review of non-thermal models specific to NSs, see Tavani & Barret 1997). For BHCs, these spectral states are generally interpreted in the framework of two competing models. The first one is involving bulk motion Comptonization in a converging accretion flow (e.g. Titarchuk & Zanni 1998). This model is however unlikely to apply to bright NS, because the radiation pressure caused by the large mass accretion rate will prevent the flow from free-falling toward the NS surface (Laurent & Titarchuk 1999). The second model is the hybrid thermal/non thermal model, where a fraction of the accretion power goes in the acceleration of non thermal electrons for the Comptonization (Gierliński et al. 1999). For Sco X-1, a jet is directly and repeatedly observed with VLBA (e.g. Bradshaw et al. 1999) and the hard X-ray emission seems to correlate with periods of radio flaring (Strickman & Barret 2000). In addition, two other sources for which non thermal hard tails have been observed (Cyg X-2, GX17+2) are already known to be all relatively bright radio sources, likely generating radio-emitting outflows or jets (Fender & Hendry 2000). The fact that in general the radio emission is stronger on the the so-called horizontal branch (e.g. Fender 2001), when the hard X-ray tail was detected in GX17+2 (Di Salvo et al. 2000b) strongly suggests that the hard X-ray and radio emissions are related. Up-scattering of soft photons could therefore involve non-thermal electrons from a jet (Di Salvo et al. 2000b). Alternatively, synchrotron emission from the jet itself could be responsible for the variable hard X-ray tail observed (Markoff et al. 2000). Further simultaneous radio/hard X-ray observations are needed to test whether the emission of a non thermal hard X-ray tail is indeed associated with the formation of a jet both in low and high luminosity sources. This would imply that jet formation can occur in systems covering a broad range of accretion rates, and that the jet formation is more likely related to changes of the accretion flow structure rather than to a high accretion rate (Fender & Hendry 2000).

Boundary layer models

In the previous sections, the discussion draws on the similarities between BH and NS accretion. However, several models specific to NS accretion have been proposed. These models involve either a boundary layer
where a standard disk interacts with the NS surface (Inogamov & Sunyaev, 1999, and Popham & Sunyaev, 2001) or an accretion gap between a standard disk terminating at the ISCO and the NS surface (e.g. Kluźniak & Wagoner 1985).

If the accretion disk is not truncated and extends all the way to the NS surface or to the last stable orbit, significant energy release is expected to occur in the so-called boundary layer. Sibigatullin & Sunyaev (2000) have recently computed approximated formulas for the ratio of the boundary layer to the total luminosities for various NS equations of states, and for various spin frequencies of the NS. For plausible spin frequencies of the NS as inferred from kilo-Hz QPOs and burst oscillations, it is found that the luminosity of the boundary layer exceeds that of the disk by a large factor. In this framework, the hard component which dominates the source luminosity in NS could arise from such a boundary layer, whereas the soft component would originate from the accretion disk. Inogamov & Sunyaev (1999) have modeled the boundary layer as an accretion belt around the NS equator. The gas enters the spreading layer at nearly keplerian rotation velocity. The deceleration of the spreading matter occurs due to friction against the dense underlying layer. The energy release takes place on the NS surface in a latitudinal belt whose width rises with increasing luminosity. Such a spread layer could be the seat of very fast variability (1-2 kHz), and could therefore be responsible for the extra high frequency noise component seen only in the power density spectra of NS (Sunyaev & Revnivtsev 2000). Alternatively, Popham & Sunyaev (2001) have modeled the boundary layer as part of the accretion disk using the slim disk equations. In this model, the drop from the Keplerian to the stellar angular velocity takes places during the radial inflow of the gas, rather than during the spread of matter over the NS surface as in the above model. The energy is transported by viscosity from the outer parts of the boundary layer to the more slowly rotating inner parts, concentrating the energy release at the NS surface. In both models, in the low $\dot{M}$ regime, relatively hard spectra can be produced through thermal Comptonization of seed photons emitted by the denser parts of the boundary layer. On the other hand, at high $\dot{M}$ much softer spectra are predicted. Finally, the last model to be considered applies if the disk terminates at $R_{\text{ms}}$ and the NS radius is smaller than $R_{\text{ms}}$ (as allowed for some soft NS equations of state, Kluźniak & Wagoner 1985). Beyond $R_{\text{ms}}$ the matter will fall freely onto the surface of the NS. The size of the gap will also depend on the spin rate of the NS and the sense of rotation of the disk versus the NS (Sibigatullin & Sunyaev 2000). The kinetic energy of the fluid crossing the gap could be dissipated in the luminous equatorial belt around the NS equator. Self consistent computations of the stucture of the belt showed that it could produce hard X-rays for sufficiently low accretion rate, when the accretion gap is optically thin to electron scattering (Kluźniak & Wilson 1991, see also Hanawa 1991).

Clearly the above boundary layer models make predictions that are in qualitative agreement with the observations (e.g. hard X-ray emission in the low $\dot{M}$ regime, softer spectra at higher $\dot{M}$). Obviously, it is unclear how this class of models could account for the similarities between BH and NS accretion. Furthermore, as we have discussed above, in the hard spectral state, there is some evidence that the accretion disk may be truncated at large radii, with the nature and structure of the inner flow differing from that of a standard disk. How the properties of the inner flow will affect the properties of the boundary layer remains to be explored. On the other hand, the above models might be more applicable in the high accretion rate regime when the disk extends very close to the NS surface.

**CONCLUSIONS**

To conclude, in NS like in the case of BHC, in the hard spectral state, accretion could occur in the form of a truncated accretion disk and a hot inner flow. It is very tempting to relate the QPO frequency and spectral changes to a varying inner disk radius, the hard spectral state corresponding to the larger inner disk radius. However the parameter which makes the inner disk radius vary has yet to be identified. Similarly the nature of the hot inner flow is unknown. By analogy with BHCs, it could be an advection dominated accretion flow, settling on the NS surface in the form of a hot optically thin boundary layer. At higher accretion rate, the inner accretion flow would cool down and collapse, and as the disk would get closer to the NS, most of the emission could arise from a classical boundary layer. Like in BHCs, non thermal processes occur also in NS. The evidence is growing that mass outflows are also important in NS, and that the non thermal hard X-ray emission is related to periods of radio emission, and hence could be associated with the formation of a jet.
Broad band observations have been shown to be a powerful tool to study the accretion flows around compact objects. Similarly, when these observations are correlated with fast timing observations, very strong constraints can be derived. Significant progresses have been possible recently thanks to Beppo-SAX and RXTE. Soon, more progresses should be accomplished with INTEGRAL which will have both broad band coverage and higher sensitivity in hard X-rays, and later with a next generation X-ray timing satellite which should provide an order of magnitude improvement in sensitivity for timing studies together with enhanced broad band spectral capabilities (e.g. the proposed Experiment for X-ray Timing and Relativistic Astrophysics, Barret et al. 2001).

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