THE HARD X-RAY TAILS IN NEUTRON STAR LOW-MASS X-RAY BINARIES: \textit{BeppoSAX} OBSERVATIONS AND POSSIBLE THEORETICAL EXPLANATION OF THE CASE OF GX 17+2

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ABSTRACT

We report results of a new spectral analysis of two \textit{BeppoSAX} observations of the Z source GX 17+2. In one of the observations, the source exhibited a power-law—like hard (>30 keV) X-ray tail, which was described in a previous work with a hybrid Comptonization model. Recent high-energy observations with \textit{INTEGRAL} of a sample of low-mass X-ray binaries including both Z and atoll classes have shown that dynamical (bulk) Comptonization of soft photons is a possible alternative mechanism for producing hard X-ray tails in such systems. We start from the \textit{INTEGRAL} results and exploit the broadband capability of \textit{BeppoSAX} to better investigate the physical processes at work. We use GX 17+2 as a representative case. Moreover, we suggest that weakening (or disappearance) of the hard X-ray tail can be explained by increasing radiation pressure that originates at the surface of the neutron star (NS). As a result, the high radiation pressure stops the bulk inflow, and consequently, this radiation feedback from the NS surface leads to quenching of the dynamical (bulk) Comptonization.

Subject headings: accretion, accretion disks — stars: individual (GX 17+2) — stars: neutron — X-rays: binaries

Online material: color figure

1. INTRODUCTION

One of the most interesting features of high-energy X-ray astronomy since the era of \textit{BeppoSAX} and the \textit{Rossi X-Ray Timing Explorer} is the observation of transient power-law—like emission above 30 keV in low-mass X-ray binaries (LMXBs) hosting a weakly magnetized neutron star (NS). This component, which appears over the persistent continuum composed of thermal Comptonization plus soft blackbody-like emission, up to now has been observed in the six X-ray sources belonging to the so-called Z class (GX 17+2 [Di Salvo et al. 2000, hereafter DS00; Farinelli et al. 2005, hereafter F05]; GX 349+2 [Di Salvo et al. 2001]; GX 340+0 [Lavagetto et al. 2004]; Sco X-1 [D’Amico et al. 2001]; GX 5–1 [Asai et al. 1994; Paizis et al. 2005]; Cyg X-2 [Frontera et al. 1998; Di Salvo et al. 2002]), in the peculiar source Cir X-1 (Iaria et al. 2001, 2002), and, very recently, by the \textit{International Gamma-Ray Astrophysics Laboratory} (\textit{INTEGRAL}) (Paizis et al. 2006, hereafter P06) in the source GX 13+1. It is worth noting that although GX 13+1 is classified as an atoll source by Hasinger & van der Klis (1989), it in fact shows spectral properties similar to those of Z sources.

The hard X-ray emission seems to be correlated with lower $M$ and radio-loud states (see, e.g., Penninx et al. 1988 for Sco X-1 and GX 17+2), but its physical origin is still a matter of debate. The thermal Comptonization of soft photons in very high temperature plasma does not seem to apply, because it is very difficult to explain where and how such a hot plasma could be present in a source in which a spectral signature of low-temperature ($\sim$3–5 keV) plasma is definitely observed (see, e.g., the review by Di Salvo & Stella 2002).

The first attempt to describe the hard X-ray tail in terms of some physically self-consistent model was performed by F05, who fitted the \textit{BeppoSAX} broadband spectrum of GX 17+2 using a hybrid Comptonization model (Coppi 1999) plus a soft blackbody (BB) component. The presence or absence of the hard tail was explained by decreasing the power (supplied by some unspecified mechanism) injected to accelerate some fraction of electrons over a Maxwellian energy distribution.

Titarchuk et al. (1998, hereafter TLM98) showed that the Keplerian disk flow should adjust to the sub-Keplerian rotation of the central object, be it NS or black hole (BH). For a given viscosity in the disk, the location of the adjustment radius $R_{\text{adj}}$ depends only on the mass accretion rate. Thus, in the transition layer between $R_{\text{NS}}$ and $R_{\text{adj}}$ the rotational velocity is sub-Keplerian. Moreover, L. Titarchuk & R. Farinelli (2007, in preparation [hereafter TF07]) calculate the radial velocity $v_R$ in the transition layer and find that $v_R$ is very close to the sound speed $v_S$ in the zone between $R_{\text{adj}}$ and some radius $R_{\text{in}}$ below which the accretion onto the NS occurs almost as a free-fall modified by NS radiation pressure.

Thus, TF07 unambiguously show that the bulk inflow must be considered a fundamental process in accretion onto such compact objects. Titarchuk et al. (1996, hereafter TMK96) studied the effect of the bulk motion Comptonization (BMC) of soft photons by energetic electrons in a converging flow onto a NS. They found that the BMC emergent spectrum has a specific hard tail that may be able to explain the hard X-ray emission in NS sources.

It is worthwhile to emphasize that this BMC process was not considered by F05 as a possible mechanism to produce the observed hard tails in X-ray spectra from NS sources. However, P06 analyzed high-energy (>20 keV) observations of NS systems performed by \textit{INTEGRAL}, and they confirmed that BMC indeed can explain this hard X-ray emission. P06 supported this spectral evolution picture of NS sources using a sample of 12 bright LMXBs hosting a NS. Their sample comprises the six Galactic Z sources and six atoll sources, four of which are bright GX bulge sources and two of which (H1750–440 and H1608–55) are weaker in the 2–10 keV range.

Comparing their results with those obtained by Falanga et al. (2006) from GX 354–0 (=4U 1728–34), P06 identified four...
main spectral states for NS LMXBs (see their Fig. 4): low/hard state (GX 354–0), hard-power-law (PL) state (H1750–440 and H1608–55), intermediate state (e.g., GX 5–1), and very soft state (e.g., GX 3+1). Above 20 keV, the low/hard spectra are described by thermal Comptonization (TC) with plasma temperature $kT_e \sim 30$ keV and optical depth $\tau \sim 1$; the hard/PL spectra, as suggested by the name, show simple PL-like emission; the intermediate-state spectra are characterized by the presence of a TC component with spectral parameters similar to those of the soft state plus additional PL-like emission (above $\sim 30$ keV); and the soft-state spectra are described by a single TC component with low $kT_e$ and high $\tau$.

We reiterate that P06 used high-energy (>20 keV) $\text{INTEGRAL}$ observations of these NS sources, so they could not reveal the soft BB component observed in NS LMXBs (see review by Barret 2001). Using broadband data, the intermediate states of NSs (e.g., GX 17+2 and Cyg X-2), similar to the high/soft states of black hole candidates (BHCs), clearly show the presence of a soft BB-like component plus PL emission at high energies, but with an additional TC feature that is absent in BHC spectra. This is because the presence of a solid surface leads to a further channel of emission. Thus, this similarity of spectral appearance between NSs and BHCs suggests a similarity in the physical processes occurring in these two classes of systems.

In this work, using the excellent broadband observing capability of BeppoSAX (Boella et al. 1997), we present the 0.4–120 keV energy spectrum of the Z source GX 17+2 in order to shed light on the source geometry. We find that the BMC model really can explain the origin of the high-energy emission in NS LMXBs.

2. THE BULK COMPTONIZATION MODEL

The TC theory, along with dynamical (bulk motion) Comptonization, was first suggested by Blandford & Payne (1981, hereafter BP81) and further developed in detail by Titarchuk et al. (1997, hereafter TMK97). BP81 derived the Fokker-Planck diffusion equation using the subrelativistic kinetic equation (see eq. [15] of BP81 and eq. [14] of TMK97). The relative efficiency of the TC effect with respect to BMC is expressed as

$$\frac{\langle \Delta E_{th} \rangle}{\langle \Delta E_{ph} \rangle} < \frac{1}{\delta}$$

(1)

(see TMK97), where $\langle \Delta E_{th} \rangle$ and $\langle \Delta E_{ph} \rangle$ represent the average photon energy change due to TC and BMC, respectively. The $\delta$-parameter is defined as

$$\delta \equiv (1 - l)^{1/2}/(n\Theta) = 51.1(1 - l)^{1/2} T_{10}^{-1} m^{-1}$$

(2)

(see TMK96 and TMK97), where $\Theta \equiv kT_e/m_c^2$ is a dimensionless plasma temperature and $T_{10} \equiv kT_e/(10$ keV), while $l \equiv L/L_{Edd}$ and $n \equiv M/M_{Edd}$ are the dimensionless luminosity emitted by the NS and the mass accretion rate calculated in Eddington units ($M_{Edd} = L_{Edd}/c^2$), respectively. When $\delta = 0$, the diffusion equation of TMK97 (their eq. [14]) reduces to the TC diffusion equation (see, e.g., Titarchuk 1994). For our purposes, it is sufficient just to point out that the photon occupation number of the emergent spectrum can be expressed as

$$F(x) = \sum_{k=1}^{\infty} \int_{0}^{\infty} I_k(x, \omega) s(\omega) d\omega = \sum_{k=1}^{\infty} I_k(x, \omega) * s(\omega),$$

(3)

We refer to Table 1 for the best-fit parameters of the multicomponent model.

### Table 1: Best-Fit Parameters of the Multicomponent Model

| Parameter | Observation 1 | Observation 2 |
|-----------|---------------|---------------|
| $N_{th}$ (10$^{22}$ cm$^{-2}$) | $1.93^{+0.07}_{-0.06}$ | $1.89^{+0.06}_{-0.05}$ |
| BMC: | | |
| $kT_{th}$ (keV) | $1.33^{+0.04}_{-0.03}$ | $1.31^{+0.04}_{-0.03}$ |
| $\log A$ | $0.73^{+0.29}_{-0.53}$ | | |
| $\alpha$ | $2.64^{+0.19}_{-0.26}$ | $2.64^{+0.0}$ |
| ComptT: | | |
| $kT_e$ (keV) | $3.32^{+0.07}_{-0.06}$ | $3.11^{+0.07}_{-0.08}$ |
| $c_{bb} (keV)$ | $12.5^{+0.2}_{-0.3}$ | $13.1^{+0.2}_{-0.3}$ |
| Gaussian: | | |
| $E_1 (keV)$ | $6.69^{+0.05}_{-0.05}$ | $6.72^{+0.08}_{-0.08}$ |
| $\sigma_1$(keV) | $0.21^{+0.01}_{-0.01}$ | $0.24^{+0.01}_{-0.01}$ |
| $I_{bb}$ | $5.8^{+1.1}_{-1.0}$ | $5.1^{+1.6}_{-1.3}$ |
| $E_{bb} (eV)$ | $38.1^{+35.8}$ | |
| $F_{bb}/F_{tot}$ | | $0.16$ |
| $E_{bb}$ | $1.46$ | $1.47$ |
| $\chi^2/dof$ | $154/145$ | $185/141$ |

Note.— For a vaib(mtc+compt+gaussian) model. Errors are computed at the 90% confidence level for a single parameter.

- Fixed value.
- Total photons in the line in units of 10$^{-3}$ cm$^{-2}$ s$^{-1}$.
- Extrapolated in the energy range 0.1–200 keV.
- In units of 10$^{39}$ ergs s$^{-1}$, assuming a distance of 7.5 kpc (Penninx et al. 1988).

where $x \equiv E/kT_e$, $x_0 \equiv E/kT_{bb}$, $kT_e$ and $kT_{bb}$ are the temperatures of plasma and seed photons, respectively, and the asterisk denotes the convolution operator.

TMK97 showed that $I_I(x, \omega) \propto x^{-\alpha}$ for $k = 1$ and $x \geq x_0$ up to a rollover energy on the order of $E_c \approx m_c^2/c^2$, while $I_i(x, \omega) \propto \delta(x - x_0)$ for $k \geq 2$, so that $I_i + s \propto \int_{x_0}^{\infty} \delta(x - x_0) s(x) dx \approx s(x)$. In other words, only the first term ($k = 1$) in the series of equation (3) significantly contributes to the upscattering (Comptonization) part of the emergent spectrum. The terms related to $k \geq 2$ represent the photons that escape the plasma cloud with insignificant energy change (see also Fig. 3 of TMK97), and thus they retain the shape of the original seed-photon spectrum.

The relative importance of the Comptonization term $I_i + s$ with respect to that of the seed photons depends on their spatial distribution within the cloud (see Fig. 4 of TMK97). In the BMC model for XSPEC developed by TMK97, the seed-photon spectrum $s(x)$ of equation (3) is assumed to be BB-like, while the relative importance of the efficiently upscattered photons, the term $I_i + s$ of the series (eq. [3]) with respect to the direct BB component, is expressed using a weighting factor $A/(A + 1)$; in fact, the XSPEC BMC model reports log $A$. Thus, the analytical formula (reverting back from $x$ to $E$) for the total spectrum is

$$F(E) = \frac{C_N}{A + 1} (BB + IA_{A} BB).$$

(4)

The free parameters for XSPEC are the temperature of the seed photons $kT_{bb}$, the spectral index $\alpha$ of the term $I_i$, the logarithm of the weighting factor $log A$, and the normalization $C_N$. The spectral index $\alpha$ is related to the efficiency of the Comptonization processes (both thermal and bulk). At higher $\alpha$-values, the Comptonization efficiency is less and thus the system is closer to thermal equilibrium, so that the emergent spectrum has a BB-like shape. The weighting factor $A$ is chosen in such a way that for $A \rightarrow 0$ the model reduces to the standard BB model in XSPEC.

3. RESULTS

Using XSPEC version 11.3, we performed a spectral analysis of a set of two BeppoSAX observations of the Z source GX 17+2
performed in 1997 (on April 3 and 21, respectively). A detailed description of the data processing and analysis can be found in F05; here we just point out that in both cases the source was in the horizontal branch (HB) of its color-intensity diagram (HID). During the first observation, the source stayed in a clustered region of the HB, whereas in the second it evolved along the branch, from right to left (see Fig. 2 of F05). The HB region of the second observation was divided into three parts, for which separate spectral analyses were carried out. Given that there was only a very slight variation of the spectral parameters in these regions, F05 reported their results in terms of the time-averaged spectrum.

In the first observation, F05 found a systematic excess in the residuals above 30 keV by fitting the persistent continuum with a photoelectrically absorbed BB ("wabs" in XSPEC) plus the TC model of Titarchuk (1994; "compTT" in XSPEC). This excess was phenomenologically described by a PL with photon index $\Gamma \sim 2.8$. DS00 obtained the same $\Gamma$-value for a different set of BeppoSAX observations, when the source was in the left part of the HB.

Given that the output shape of the physical BMC spectral model consists of a direct (non-upsctattered) BB-like component along with a PL shape at high energies, our new fitting model is comppTT plus BMC plus a Gaussian emission line around 6.7 keV,
which was previously observed by both DS00 and F05. By varying all the model parameters, we find that the data can be represented by two solutions in the framework of the same model. One solution is with \( kT_{bb} < kT_w \) (case A), and the other is with \( kT_{bb} > kT_w \) (case B). We remind the reader that \( kT_{bb} \) and \( kT_w \) are the seed-photon temperatures for the BMC and compTT models, respectively.

We note that this dichotomy was already reported by F05 for the BB plus compTT model. In both cases we obtain \( \chi^2/\text{dof} = 151/144 \). This implies that we cannot statistically distinguish between these two solutions. In case A, we find \( kT_{bb} = 0.62 \pm 0.02 \) keV, \( kT_w = 1.14 \pm 0.05 \) keV, \( A = 0.05 \approx -0.66 \), and \( \alpha = 2.1^{+0.3}_{-0.5} \), while for case B the best-fit parameter values are reported in Table 1 (see the second column). It is worth noting that both the compTT and Gaussian best-fit parameters are almost the same within the error bars for these two solutions.

In the second observation, the source was detected (signal-to-noise ratio \( > 3 \)) up to 50 keV. A simple BB plus compTT plus Gaussian model provides \( \chi^2/\text{dof} = 192/142 \) and \( \chi^2/\text{dof} = 197/142 \) for case A (\( kT_{bb} < kT_w \)) and case B (\( kT_{bb} > kT_w \)), respectively. As already discussed in F05, these nonexcellent \( \chi^2 \)-values can be attributed to the averaging of different (even though very close each other) spectral states. Indeed, no systematic deviations are observed in the residuals, and the last point in the power density spectrum (40 \( \pm 10 \) keV) is at a level \( \approx 2.5 \) \( \sigma \) above the model. As a consequence, the BMC parameters \( \alpha \) and \( \log \Lambda \) remain largely undetermined if they are left free in the fit. We thus fixed \( \alpha \) to 2.1 and 2.6 for cases A and B, respectively. In both cases the fit quality only improved slightly, the corresponding \( \chi^2/\text{dof} \) decreasing to a value of 187/140.

A comparison between the two observations shows that the major change is related to \( \log \Lambda \), the value of which decreases from \( \approx -0.73 \) in the first observation to about \( \approx -0.33 \) in the second. This is consistent with the fact that the PL-like emission was significantly detected only in the first observation (see Table 1).

Below, we present a physical reason why the best-fit parameters of case B are more preferable than those of case A. In Figure 1 (top), we present the deconvolved \( E\Phi(E) \) spectra of the two observations for case B to illustrate this effect of the transient hard X-ray emission.

4. DISCUSSION AND CONCLUSIONS

In this paper we show the results of a new X-ray spectral analysis, using BeppoSAX XMM broadband data, of the Z source GX 17+2 during two states in which a PL-like hard X-ray tail was present and absent, respectively. We describe this hard tail in the framework of Comptonization of soft BB-like seed photons in the converging flow onto the NS.

Comparison of our best-fit parameters with those reported by P06 reveals some significant differences: Restricting the energy band to above 20 keV allows one to see only the thermal (BB- or Wien-like) bump plus the additional PL-like X-ray tail in the spectrum (see, e.g., Fig. 5 of P06). This thermal bump, lacking low-energy information, is interpreted by BMC as the direct seed-photon component, namely, the component consisting of the photons subjected to insignificant energy change when they scatter in the ambient medium. This is confirmed by the fact that the color temperature \( kT_{bb} \) of this component, \( \approx 2.7 \) keV (see Table 2 of P06), is not far from the electron temperature of compTT found here (\( \approx 3.3 \) keV; see Table 1).

However, using broadband data, it is possible to see additional direct seed thermal emission located at lower energies, which thermal Comptonized part dominates in the 20–40 keV region (see Fig. 1, top). One unavoidable consequence of these considerations is also the different values of the illumination factor \( A \) (or \( \log A \)).

The broadband analysis allows us to elaborate a more detailed picture of the source properties. As shown in \( \S 3 \), we can identify two regions of seed-photon temperatures, in which the temperature values differ from each other by a factor of about 2. In case A, the hotter (\( \approx 1.2 \) keV) photons are a source for thermal Comptonization, while the cooler ones (\( \approx 0.6 \) keV) are upscattered to form the PL emission at high energies. In case B, the opposite situation occurs. Given that we cannot statistically distinguish one model from the other, as they yield the same \( \chi^2 \)-value, only considerations based on the physical characteristics of the emitting regions can help us to discriminate between them.

Several theoretical studies (e.g., TLM98; Popham & Sunyaev 2001, hereafter PS01) have shown that when the geometrically thin accretion disk approaches the NS, the difference in the angular velocity of the disk and the more slowly spinning, accreting star gives rise to a transition region, usually called the boundary layer (BL, by PS01) or transition layer (TL, in TLM98). PS01 argue that when \( M \) increases, the BL extends radially [reaching (2–3)\( R_N \)], significantly increasing its contribution to the total emitted luminosity (even to 70%). Moreover, PS01 show that inside the BL the plasma properties (e.g., temperature, density, pressure, radial velocity) are not constant but vary as a function of distance from the NS surface.

TF07 demonstrate that in the TL, the radial velocity profile as a function of radius is almost constant from the adjustment radius \( R_{ad} \) (defined as the outer TL radius) to some lower radius \( R_{ff} \) where the constant-velocity flow is followed by the free-fall accretion flow, which is affected by radiation pressure (see also \( \S 1 \)). TF07 obtain this radial velocity profile as a solution of the radial momentum equation (see eq. [5] of PS01), for which they use a solution of the angular momentum equation found by TLM98 (see also Titarchuk & Osherovich 1999). The free-fall region of the TL is likely the place where the BMC spectrum is formed.

The free-fall region is the innermost part of the TL, and consequently the seed photons subjected to BMC mainly come from the NS surface. The temperature of the NS photons, \( kT_{bb} \), is higher than that of the disk soft photons, \( kT_w \), because the effective area of the NS surface, \( \approx 3R_S \) (\( R_S \) is the Schwarzschild radius), is more compact than that of the Keplerian disk (\( \approx (10–15)R_S \); see Shrader & Titarchuk 1999). This is a physical (not statistical) reason why we choose, among the two solutions, the one for which \( kT_{bb} > kT_w \). In the bottom panel of Figure 1, we provide a schematic view of the possible source accretion geometry.

Conservation of energy provides a free-fall radial velocity given by

\[
\nu_{ff} = c[(1 - F/F_{Edd})(R_S/R)]^{1/2}, \tag{5}
\]

where \( F \) is the local flux and

\[
F_{Edd} = \frac{GMc^3n_i\bar{nu}}{R^2\sigma_T n_e} \tag{6}
\]

is the local Eddington flux. In equation (6), \( \sigma_T \) is the Thomson cross section, \( M \) is the NS mass, \( c \) is the speed of light, and \( n_i \) and \( \bar{n}_i \) are the ion density number and molecular weight, respectively, while \( n_e \) is the electron density.

It follows from equations (2) and (5) that \( \nu_{ff} \propto \delta \). When the local flux approaches the local Eddington flux, the factor \( (1 - F/F_{Edd})^{1/2} \) goes to zero, and consequently \( \nu_{ff} \) goes to zero too. Thus, the effect of the disappearance of the BMC hard tail (\( \delta \rightarrow 0 \)) can
be naturally explained as a result of feedback from the NS surface when the NS emergent (local) radiation flux is very close to Eddington.

In Table 1, one can see that while the total flux remains almost the same, the contribution of the seed BB component (suggested to come from the NS) increases from the first observation ($F_{bb}/F_{tot} = 0.16$) to the second ($F_{bb}/F_{tot} = 0.21$). Given that the BB flux is proportional to the total $M$, we can conclude that $M$ is a quantity that regulates the appearance and disappearance of the BMC hard tail in X-ray spectra from NS LMXBs.

If a firm surface is absent, as in BHs, then for a given electron temperature of the converging bulk flow, the index $\Gamma$ decreases with $M$ to some value and then saturates because of the effect of photon trapping in the converging flow (for more details, see Titarchuk & Zannias 1998). But in the NS case, as we explain above, there is feedback from the NS surface when $M$ is very high. The high radiation flux that emerges from the NS surface quenches the bulk free-fall flow. However, we may not exclude the possibility that the hard tail, instead of disappearing, just decreases its intensity, going below the instrumental detection threshold, because of a lower fraction of seed (NS) photons intercepted by the converging flow (a geometric effect). The amount of weakly upscattered seed photons leaving the flow depends on their spatial distribution within the flow itself (TMK97). The BB-like direct component is stronger for a more uniform spatial distribution of seed photons than that mainly concentrated at the bottom.

The changes of the observed contributions coming from the BB-like and the PL component may equally be provided by either a change of the seed-photon spatial distribution (a more uniform distribution would decrease the amount of efficiently upscattered photons—a spatial effect) or by a lower subtended angle of the flow as seen from the NS (geometric effect).

Another important point of our discussion concerns the apparent mass accretion rate $M$. Very often, changes in $M$ in a given source are inferred by measuring changes of its apparent luminosity, using the relation $M = F_x 4\pi D^2/(hc^2)$. However, this approach may lead to controversy. In fact, Di Salvo et al. (2002) and DS00 observed the hard X-ray tail in Cyg X-2 and GX 17+2 when the sources were in the HB of their HIDs. The apparent 0.1–100 keV luminosity $L_{app}$ evolves during the source’s motion along the Z track from the HB to the normal branch (NB). $L_{app}$ increases in Cyg X-2 and decreases in GX 17+2 with $S_z$ (where the length parameter $S_z$ along the Z track increases from HB to NB).

Moreover, the NS sources belonging to the high-luminosity atoll class, GX 3+1, GX 9+1, and GX 9+5, have stable X-ray spectra very close to those of $Z$ sources, but up to now, no evidence of PL-like hard X-ray emission has been provided for them. This is in contrast to what is expected, given that, despite their spectral similarity, these sources are less luminous than $Z$ sources. In addition, our data analysis shows that the hard X-ray behavior changes at the same apparent luminosity level (see Table 1). All these observable quantities show that mapping changes in $M$, either for one source or among different sources, must be treated very carefully.

Thus, we can suggest that the NS surface feedback on the BMC tail is not sensitive to the absolute (disk plus TL) $M$-value but mostly depends on the local radiation flux related to the $M_{TL}$ impinging on the converging flow. This value may significantly differ from the simple $L/(4\pi R^2)$ estimate (see also PS01).

From the results of the multicomponent fit, we are also able to map the energy budget of the system. We reveal that a fraction of the low-temperature (0.55 keV) BB radiation in the total flux, which is presumably the disk’s contribution to the total flux $F_{disk}/F_{tot}$, is only $\sim 34\%$. The larger fraction of the gravitational energy of the accreting material, $\sim 66\%$, is released in the transition layer and at the NS surface. We infer $F_{disk}/F_{tot}$ using a fraction of the TC component ($comp_{TT}$) in the total flux $F_{comp}/F_{tot} \sim 78\%$ and a value of the Compton enhancement factor $E_{comp} \sim 2.3$. Note that the values of $F_{comp}/F_{tot}$ and $E_{comp}$ are almost the same for the two observations. We remind the reader that $E_{comp}$ is defined as the ratio of the flux of the Comptonized emerging spectrum $F_{comp}$ with respect to the soft photon injected flux $F_{soft}$ (see Sunyaev & Titarchuk 1980). We calculate $E_{comp}$ using the compTT model. In other words, the model flux with the best-fit compTT parameters gives us $F_{comp}$, whereas the model flux with the best-fit $kT_{\nu}$, $kT_e$, normalization, and very small optical depth $\tau$ provides us $F_{soft}$.

We want also to emphasize that our preference to explain the transient hard X-ray tails in NS LMXBs in the framework of the BMC phenomenon is not related to the fact that this model better describes the data statistically. The hybrid Comptonization model by Coppi (1999), first used by F05 to explain the GX 17+2 BeppoSAX broadband spectrum, was statistically acceptable too.

The main reason for our choice is that the BMC process is related just to the dynamics of the accretion flow, based on the exact solution of dynamical equations, and does not require any particular tuning or any particular energetic configuration of the Comptonizing plasma (e.g., a thermal plus nonthermal distribution). We thus cannot a priori exclude that nonthermal electron distributions are present in such a system (for instance, in possible emitting jets), but the key point is that they are not required in order to explain our data. In BH sources, the BMC phenomena are likely even more prominent than in NSs (because of the absence of a solid surface and, thus, the absence of strong radiation feedback on the accreting flow), and their effect can well explain the transition from hard/low to high/soft states in these systems.

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REFERENCES

Asai, K., Dotani, T., Mitsuda, K., Nagase, F., Kamado, Y., Kuulkers, E., & Breedon, L. M. 1994, PASJ, 46, 479
Barret, D. 2001, Adv. Space Res., 28, 307
Blandford, R. D., & Payne, D. G. 1981, MNRAS, 194, 1033 (BP81)
Boella, G., Butler, R. C., Perola, G. C., Piro, L., Scarsi, L., & Bleeker, J. A. M. 1997, A&AS, 122, 299
Coppi, P. S. 1999, in ASP Conf. Ser. 161, High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson (San Francisco: ASP), 375
D’Amico, F., Heindl, W. A., Rothschild, R. E., & Gruber, D. E. 2001, ApJ, 547, L147
Di Salvo, T., Robba, N. R., Iaria, R., Stella, L., Burderi, L., & Israel, G. L. 2001, ApJ, 554, 49
Di Salvo, T., & Stella, L. 2002, in The Gamma Ray Universe, ed. A. Goldwurm, D. Neumann, & J. Trân Tranh Vắn (Hanoi: The¿ Gio´i), 67
D’Amico, F., Heindl, W. A., Rothschild, R. E., & Gruber, D. E. 2001, ApJ, 547, L147
Falanga, M., Goetz, D., Goldoni, P., Farinelli, R., Goldwurm, A., Mereghetti, S., Bazzano, A., & Stella, L. 2006, A&A, 458, 21
Farinelli, R., Frontera, F., Zdziarski, A. A., Stella, L., Zhang, S. N., van der Klis, M., Masetti, N., & Amati, L. 2005, A&A, 434, 25 (F05)

Given that the average number of scatterings for photons is proportional to $\tau^2$, it is sufficient to set $\tau \ll 1$ in compTT and obtain $F_{soft}$.

...
Frontera, F., et al. 1998, Nucl. Phys. B. Proc. Suppl., 69, 286
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Iaria, R., Burderi, L., Di Salvo, T., La Barbera, A., & Robba, N. R. 2001, ApJ, 547, 412
Iaria, R., Di Salvo, T., & Robba, N. R., & Burderi, L. 2002, ApJ, 567, 503
Lavagetto, G., Iaria, R., Di Salvo, T., Burderi, L., Robba, N. R., Frontera, F., & Stella, L. 2004, Nucl. Phys. B. Proc. Suppl., 132, 616
Paizis, A., Ebisawa, K., Tikkanen, T., Rodriguez, J., Chenevez, J., Kuulkers, E., Vilhu, O., & Courvoisier, T. J.-L. 2005, A&A, 443, 599
Paizis, A., et al. 2006, A&A, 459, 187 (P06)
Penninx, W., Lewin, W. H. G., Zijlstra, A. A., Mitsuda, K., & van Paradijs, J. 1988, Nature, 336, 146
Popham, R., & Sunyaev, R. 2001, ApJ, 547, 355 (PS01)
Shrader, C. R., & Titarchuk, L. G. 1999, ApJ, 521, L121
Sunyaev, R. A., & Titarchuk, L. 1980, A&A, 86, 121
Titarchuk, L. 1994, ApJ, 434, 570
Titarchuk, L., Lapidus, I., & Muslimov, A. 1998, ApJ, 499, 315 (TLM98)
Titarchuk, L., Mastichiadis, A., & Kylafis, N. D. 1996, A&AS, 120(3), 171 (TMK96)
———. 1997, ApJ, 487, 834 (TMK97)
Titarchuk, L., & Osherovich, V. 1999, ApJ, 518, L95
Titarchuk, L., & Zannias, T. 1988, ApJ, 493, 863