Boundary layer emission and Z-track in the color-color diagram of luminous LMXBs

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ABSTRACT

Aims. We explore the accretion disk and boundary layer emission in bright neutron star LMXBs and their dependence on the mass accretion rate.

Methods. Fourier-frequency resolved spectroscopy of the archival RXTE data.

Results. We demonstrate that Fourier-frequency resolved spectra of atoll and Z- sources are identical, despite significant difference in their average spectra and luminosity (by a factor of $\sim 10^{20}$). This result fits in the picture we suggested earlier, namely that the $f \gtrsim 1$ Hz variability in luminous LMXBs is primarily due to variations of the boundary layer luminosity. In this picture the frequency resolved spectrum equals the boundary layer spectrum, which therefore can be straightforwardly determined from the data. The obtained so boundary layer spectrum is well approximated by the saturated Comptonization model, its high energy cut-off follows $kT \approx 2.4$ keV black body. Its independence on the global mass accretion rate lends support to the theoretical suggestion by Inogamov&Sunyaev (1999) that the boundary layer is radiation pressure supported. With this assumption we constrain the gravity on the neutron star surface and its mass and radius. Equipped with the knowledge of the boundary layer spectrum we attempt to relate the motion along the Z-track to changes of physically meaningful parameters. Our results suggest that the contribution of the boundary layer to the observed emission decreases along the Z-track from conventional $\sim 50\%$ on the horizontal branch to a rather small number on the normal branch. This decrease can be caused, for example, by obscuration of the boundary layer by the geometrically thick accretion disk at $\dot{M} \sim \dot{M}_{\text{Edd}}$. Alternatively, this can indicate significant change of the structure of the accretion flow at $\dot{M} \sim \dot{M}_{\text{Edd}}$ and disappearance of the boundary layer as a distinct region of the significant energy release associated with the neutron star surface.

Key words. accretion, accretion disks – instabilities – stars:binaries:general – stars:neutron – X-rays:general – X-rays:binaries

1. Introduction

Accreting neutron stars in low mass X-ray binaries (LMXB) are among the most luminous compact X-ray sources in the Galaxy. At least several of them have luminosities exceeding $\sim$ few $\times 10^{38}$ erg/s and presumably accrete matter at the level close to the critical Eddington accretion rate. Early observations of these sources (e.g. Toor \textit{et al.} 1970) revealed rather soft X-ray spectra, indicating that their X-ray emission is predominantly formed in the optically thick media. Similar to accreting black holes, at lower X-ray luminosities (lower mass accretion rates), $L_x \lesssim 5 \times 10^{36}$ erg/s, neutron stars undergo a transition to the hard spectral state (e.g. barrel 2001). The energy spectra in this state point at the neutron star surface and settle onto its surface. For the typical neutron star spin frequency ($\lesssim 500 - 700$Hz) comparable amounts of energy are released in these two regions (Sunyaev & Shakura 1986; Sibgatullin & Sunyaev 2000). This picture is based on rather obvious qualitative expectations as well as more sophisticated theoretical considerations and numerical modeling (Sunyaev & Shakura 1986; Khuzin 1988; Inogamov & Sunyaev 1999; Sibgatullin & Sunyaev 2000). It has been receiving, however, little direct observational confirmation. Due to similarity of the spectra of the accretion disk and boundary layer the total spectrum has a smooth curved shape, which is difficult to decompose into separate spectral components (Mitsuda \textit{et al.} 1984; White \textit{et al.} 1988; Di Salvo \textit{et al.} 2001; Done \textit{et al.} 2002).
This made application of physically motivated spectral models to the description of observed spectra of luminous neutron stars difficult, in spite of very significant increase in the sensitivity of X-ray instruments. A possible solution was suggested by early results of Mitsuda et al. (1984), which demonstrated the potential of using the combined spectral and variability information.

Recently, Gilfanov, Revnivtsev & Molkov (2003) analyzed spectral variability in luminous LMXBs and showed that in these sources aperiodic and quasi periodic variations of the luminosity and variability in luminous LMXBs and showed spectral and variability information. which demonstrated the potential of using the combined spectral and variability information.

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In this paper, we further explore the behavior of the boundary layer and the accretion disk emission in a number of bright neutron star LMXBs (both Z and atoll sources) and qualitatively describe their evolution with change of mass accretion rate. Our study will be based on the results of Gilfanov, Revnivtsev & Molkov (2003), namely, that the shape of the boundary layer spectrum is adequately represented by the frequency resolved spectrum (energy spectrum of the variable part of the emission) at the Fourier frequencies above $f \gtrsim 1$ Hz. We will concentrate on neutron star LMXBs in the soft/high spectral state with luminosities $L_X \gtrsim 0.5 - 1 \times 10^{37}$ erg/s. Sources in this state have very important property – their frequency resolved energy spectra do not depend on Fourier frequency. It is this property which allows us to decompose the averaged energy spectrum of the sources into two components. In high spectral state the variability is significantly more complicated (see e.g. Revnivtsev et al. 1999, 2000) and we leave it for other studies.

### 2. Data

For our study we used data of RXTE observatory (Bradt et al. 1993), which combines large collecting area with high time resolution. We have studied all Z-sources except for GX349+2 which during the majority of RXTE observations was on the “flaring” branch of its color-color diagram, supposedly corresponding to super-Eddington mass accretion rates (Hasinger & van der Klis 1989). The behavior of sources at such high accretion rates is more complex and is beyond the scope of this paper. The remaining five Z sources are: Cyg X-2, GX340+0, Sco X-1, GX 5-1 and GX 17+2. For these sources we have excluded the time intervals corresponding to the “flaring” branch of their color-color diagram. The atoll sources were represented in our sample by 4U1608-52 and 4U1820-30 in their soft/high spectral state, showing high rapid flux variability.

For the data reduction we used standard programs of package HEASOFT 5.3 in accordance to the RXTE Guest Observer Facility recommendations. We have corrected the obtained energy spectra for the deadtime and the pile up effects (http://heawww.gsfc.nasa.gov/docs/xray/xte/pca/). All subsequent spectral approximations included interstellar absorption which was fixed at values: $N_H = 6 \times 10^{22}$ cm$^{-2}$ for GX 340+0 (Maras et al. 2004), $0.2 \times 10^{22}$ cm$^{-2}$ for Cyg X-2 (Kuulkers et al. 1997), $0.2 \times 10^{22}$ cm$^{-2}$ for Sco X-1 (Kahn, Seward, & Chlebowski 1984), $1.0 \times 10^{22}$ cm$^{-2}$ for GX 17+2 (Langmeier, Hasinger, & Truemper 1990), $3.0 \times 10^{22}$ cm$^{-2}$ for GX 5-1 (Asai et al. 1994), $1.0 \times 10^{22}$ cm$^{-2}$ for 4U1608-52 (Penninx et al. 1994) and $0.2 \times 10^{22}$ cm$^{-2}$ for 4U1820-30 (Haberl et al. 1987). The luminosities of all Z sources are approximately $2 \times 10^{38}$ erg s$^{-1}$, for 4U1608-52 and 4U1820-30 approximately $10^{37}$ erg s$^{-1}$.

The color-color diagrams (CCD) of these sources are presented in Fig.1. For construction of the CCDs we have used energy channels 2.0-4.0 keV, 4.0-6.0 keV, 6.0-10.0 keV and 10.0-15.0 keV. The hard and soft colors are ratio of energy fluxes of sources in abovementioned energy bands. Energy fluxes were computed from spectra averaged over 128 sec intervals. All fluxes were corrected for absorption.

### 3. Spectrum of the boundary layer

The frequency resolved spectra (the energy spectrum of the variable part of the emission, Revnivtsev et al. 1999) computed at the frequencies $f \gtrsim 1$ Hz are shown for five sources from our sample in Fig.2. For Z sources we used only data on the horizontal branch of the CCD where the amplitude of variability at these frequencies is maximal. For Sco X-1 and GX 5-1 the RXTE achive does not contain high time resolution data for the horizontal branch with sufficient number of energy channels. The frequency resolved spectrum of 4U1608-52 was taken from Gilfanov, Revnivtsev & Molkov (2003). For plotting purposes, the normalizations of all spectra were adjusted to match that of GX340+0.

Similarity of the spectra shown in Fig.2 is remarkable, considering significant difference in the average spectra and a factor of $\sim 10 - 20$ spread in the luminosity between atoll and Z-sources ($\sim 0.1M_{\text{Edd}}$ and $\sim M_{\text{Edd}}$ correspondingly). This behavior fits in the picture proposed by Gilfanov, Revnivtsev & Molkov (2003). As summarized in the Introduction, they showed, in particular, that the frequency resolved spectra at these frequencies equal the spectrum of the boundary layer emission.
The shape of the frequency resolved (≈ boundary layer) spectrum can be adequately described by the saturated Comptonization. For the sake of comparison with other results and for convenient parametrization of the BL spectrum we used the Comptonization model of Titarchuk (1994). The best fit parameters of the model fitted in the 3-20 keV range simultaneously to all five spectra shown in the Fig 2 are: temperature of seed photons $kT_s = 1.5 \pm 0.1$, temperature of electrons $kT_e = 3.3 \pm 0.4$ and the optical depth $\tau = 5 \pm 1$ for slab geometry. The best fit model is shown by the thick dotted line on Fig 2. The temperature of the black body spectrum describing the shape of the cutoff in the observed spectrum at energies $> 13$ keV is $kT_{bb} = 2.4 \pm 0.1$ keV (thin dashed line on Fig 2).

It would be interesting to follow up on the results of Gilfanov, Revnivtsev & Molokov (2003) and to consider the evolution of the boundary spectrum along the Z track from the horizontal to normal branch. Unfortunately, apart from GX340+0, already considered in their paper, the variability level on the normal branch of color-color diagram for other Z-sources is insufficient to obtain frequency resolved spectra with reasonable signal-to-noise ratio.

The independence of the spectrum of the boundary layer on the luminosity lends support to the theoretical predictions by Inogamov & Sunyaev (1999) that the boundary layer is radiation pressure supported. It means that in the upper layers of the BL only the radiation pressure counteracts the gravitational force. Therefore we can say that every unit area of the BL should emit Eddington surface flux. At smaller mass accretion rates ($\dot{M} \sim 0.1 \dot{M}_{\text{Edd}}$) the BL occupies only a part of the NS surface, giving rise to moderate total X-ray luminosities ($L_x \sim 10^{37}$ erg s$^{-1}$). If mass accretion rate increases the total BL luminosity approaches the Eddington limit for the NS $L_{\text{Edd}} \sim 2 \times 10^{38}$ erg s$^{-1}$ ($1.4M_\odot)^{-1}$. In this picture, the parameters of the BL emission can be used to determine the value of the Eddington flux limit on the surface of the neutron star. As the Eddington flux limit is uniquely determined by the neutron star surface gravity and the atmospheric chemical composition, the neutron star mass and radius can be constrained.

If the boundary layer emitted true black body emission, the radiation flux of the unit area was determined only by its temperature. Therefore the observed shape of the BL spectrum, in particular the best fit black body spectrum, can be adequately described by the saturated Comptonization. For the sake of comparison with other results and for convenient parametrization of the BL spectrum we used the Comptonization model of Titarchuk (1994). The best fit parameters of the model fitted in the 3-20 keV range simultaneously to all five spectra shown in the Fig 2 are: temperature of seed photons $kT_s = 1.5 \pm 0.1$, temperature of electrons $kT_e = 3.3 \pm 0.4$ and the optical depth $\tau = 5 \pm 1$ for slab geometry. The best fit model is shown by the thick dotted line on Fig 2. The temperature of the black body spectrum describing the shape of the cutoff in the observed spectrum at energies $> 13$ keV is $kT_{bb} = 2.4 \pm 0.1$ keV (thin dashed line on Fig 2).
body temperature, could be used to determine the value of the Eddington flux limit on the neutron star surface. This approach has been utilized in the context of the Eddington limited X-ray bursts (e.g. Goldman 1979; Marshall 1982; Lewin, van Paradijs, & Taam 1993). Typical values of the hardening factor are about $\sim 1.7$. We used this result in order to make simple estimates of the gravity on the neutron star surface and to constrain its mass and radius. In these calculations we assumed the color temperature of the boundary layer surface and regarded it as $T_{\text{eff}}=10^4\text{K}$.

In reality, scatterings are important in the atmospheric chemical abundances between sources. In particular, we did not find statistically significant differences caused by variations in the atmospheric chemical abundances between sources. In particular, we did not find statistically significant differences caused by variations in the atmospheric chemical abundances between sources. In particular, we did not find statistically significant differences caused by variations in the atmospheric chemical abundances between sources.

Finally we note that the similarity of the spectral shape of the BL spectrum in different sources (Fig 2) indicates that they have close values of the mass and radius, in particular, that there is no significant difference in the surface gravity between atoll and Z-sources. It also shows that there are no significant differences caused by variations in the atmospheric chemical abundances between sources. In particular, we did not find statistically significant differences caused by variations in the atmospheric chemical abundances between sources.

5. Evolution along Z-track

In order to study the behavior of Z-sources in the color-color diagram we consider their spectra integrated over 128-sec time intervals. These spectra are fitted with a simple model consisting of two components, representing contributions of the boundary layer and the accretion disk. Also included in the model was the gaussian line at the energy 6.4 keV. It is not energetically important but significantly improves quality of the fit. The line parameters will not be considered here. The shape of the boundary layer spectrum was approximated by compact model with the best fit parameters obtained in the section 3. For the accretion disk spectrum we adopt the multicolor disk blackbody (Shakura & Sunyaev 1973; Mitsuda et al. 1984) ( diskbb model in XSPEC fitting package).

Quality of the spectral fits is uniformly good on the horizontal and normal branches of the Z-track in the color-color diagram, with the reduced $\chi^2$ never exceeding $\sim 1.3$ for 41 degrees of freedom. Relative deviations of the model from the data never exceed approximately one percent. This is illustrated by Fig 4 showing two spectra of Cyg X-2, at the beginning of the horizontal branch and at the end of the normal branch.
The model is obviously oversimplified. Firstly, it relies on the assumption about the shape of the boundary layer spectrum. This seems to have been established rather well for the horizontal branch and for the upper part of the normal branch. For the latter, it has been shown for GX340+0 only, for other sources the signal-to-noise ratio being insufficient. On the lower part of the normal branch the variability level and, consequently the signal-to-noise ratio of the frequency resolved spectra, are too low to conduct a similar study for any of the sources in our sample. Secondly, we chose the diskbb model to represent the spectrum of the accretion disk. Although the model involves several well known simplifying assumptions it has been shown to approximately reproduce the shape of the spectrum of the geometrically thin, optically thick accretion disk (Merloni, Fabian & Ross, 2000). The best fit color temperature obtained in this model can be related with certain accuracy to the maximum disk temperature. Therefore with this model we should be able to separate the disk and boundary layer components and to estimate their respective fluxes, as well as the characteristic temperature in the inner disk. Keeping in mind the limitations of the spectral model we will attempt to relate the motion of a source along the Z-track to the changes in the values of the physically meaningful parameters. The most important difference of our approach from similar studies undertaken previously is in a priori knowledge of the shape of the boundary layer spectrum.

5.1. Accretion disk

The relation between the accretion disk temperature and its flux for all five Z-sources is shown in Fig.5 (we emphasize that plotted along the x-axis is the disk flux, as opposite to the total flux). For three of them (GX 5-1, Cyg X-2 and GX 340+0) the disk temperature on the horizontal branch approximately follows the $T \propto F_{\text{disk}}^{1/4}$ law, which is to be expected for a standard accretion disk. For Sco X-1 and GX17+2 the temperature increases with the disk flux faster than the $T \propto F_{\text{disk}}^{1/4}$ law. For all sources the monotonic relation between the disk temperature and the disk flux breaks down on the normal branch and further along the Z-track the temperature either remains constant or decreases with the disk flux.

The significant deviation from $T \propto F_{\text{disk}}^{1/4}$ law near the transition from the horizontal to the normal branch indicates that the simple accretion disk model in the form represented by xspec’s diskbb becomes inapplicable. The exact reason for this is not clear. It may happen due to rather small modifications to the model, e.g. violation of the assumption that the effect of Comptonization can be represented by the single value of the spectral hardening factor, constant over the extend of the inner disk as well as along the Z-track in the color-color diagram. Alternatively, this
the predictions of the simple disk theory for $H/R$ color hardening factors are similar, see section 4) we find similar in the disk and in the boundary layer (i.e. the isation disk the gravitational force near the neutron star (Shakura & Sunyaev 1973). For geometrically thin accretion disk its height is determined by the equality of the radiation pressure and the gravitational force (see e.g. the radiation pressure supported accretion disk. This would point at the significant modification of the structure and geometry of the accretion disk. This would point at the significant modification of the structure and geometry of the accretion flow near the transition from the horizontal to the normal branch, presumably corresponding to $M \sim M_{\text{Edd}}$.

Knowledge of the boundary layer and the accretion disk spectra allows one to (crudely) estimate the scale-height of the disk $H/R$ in the region of the main energy release. Indeed, for the radiation pressure supported accretion disk its height is determined by the equality of the radiation pressure and the gravitational force (see e.g. Shakura & Sunyaev 1973). For geometrically thin accretion disk the gravitational force near the neutron star is $\sim R/H$ times smaller than on the neutron star surface. Assuming that the radiation transfer conditions are similar in the disk and in the boundary layer (i.e. the color hardening factors are similar, see section 4) we find $H/R \sim (T_{\text{disk}}/T_{\text{BL}})^4 \sim 0.1 - 0.2$ which is comparable with the predictions of the simple disk theory for $M \sim M_{\text{Edd}}$ (Shakura & Sunyaev 1973 1976). On the other hand, this estimate can be considered as a crude consistency check for the obtained values of the boundary layer and disk temperatures.

5.2. Boundary layer

The dependences of the BL contribution to the total X-ray emission on the position on the Z-track are plotted in Fig.6. The coordinate along the Z-track was defined to be $z = 0$ and $z = 2$ effectively constrains the boundary layer contribution on the normal branch (Fig.6). As the variability at $f \gtrsim 1$ Hz is primarily associated with the boundary layer emission, the decrease of the boundary layer fraction along the Z-track also explains well-known decrease of the level of aperiodic and quasi-periodic variability.

Statistical uncertainties in the values of the BL fraction are small and can be accounted for by the dispersion of the points in Fig. More important are the systematic ones associated with the imprecise knowledge of the shape of the BL spectrum and its possible variations along the Z-track. In order to probe the amplitude of these uncertainties on the horizontal branch we explored the range of $1\sigma$ errors of the parameters of the comptt model obtained in the section 3. The associated change of the boundary layer fraction did not exceed $\approx 0.05 - 0.07$ in the units of Fig. As for the normal branch, there is some difference between the frequency resolved spectra of GX340+0 on the horizontal and normal branch, the latter being better described by the Wien spectrum with $kT = 2.4$ keV than by the spectrum of saturated Comptonization (cf. thick and thin dashed lines in Fig.2). This difference could be related to weak dependence of the boundary layer spectrum on the global mass accretion rate (Gilfanov, Revnivtsev & Molko 2003). Substitution of the comptt model by the blackbody or Wien spectrum with $kT = 2.4$ keV, decreases the boundary layer fraction by $\approx 0.1$. As it is clear from these numbers, systematic uncertainties might change the Fig.6 in details but does not affect the general trend in a significant way.

The Fig.4 and 6 suggest that the boundary layer fraction decreases along the Z-track and it is smaller on the normal branch that on the horizontal branch. As demonstrated above, this conclusion is rather robust, as long as the assumption regarding the constancy of the boundary layer spectrum is approximately correct. Even if the diskbb model is not applicable on the normal branch any more, the $\sim 5$-fold decrease of the $E \gtrsim 15$ keV flux between $S_z = 0$ and $S_z = 2$ effectively constrains the boundary layer contribution on the normal branch (Fig.6). As the variability at $f \gtrsim 1$ Hz is primarily associated with the boundary layer emission, the decrease of the boundary layer fraction along the Z-track also explains well-known decrease of the level of aperiodic and quasi-periodic variability.

Although no complete physical interpretation of the observed behavior can be offered, we mention several possibilities. One of these is that the general structure of the accretion flow does not change significantly and $\sim 50\%$ of the energy is always released on, or very close to the neutron star surface. The apparent decrease of the boundary layer fraction on the normal branch is a result of its geometrical obscuration by, for example, the geometrically thickened accretion disk. An alternative possibility is that at high values of the mass accretion rate $M \sim M_{\text{Edd}}$ a significant modification of the accretion flow structure might occur and its division into two geometrically distinct parts – boundary layer and accretion disk, might become inapplicable. Namely, due to non-negligible pressure effects the deceleration of the orbital motion of the accreting matter from Keplerian frequency to the neutron star spin frequency would take place in a geometrically extended region with the radial extend of $\Delta R \sim R_{\text{NS}}$. In this case, the observed decrease of the boundary layer fraction could re-

**Fig. 6.** Dependence of the boundary layer contribution to the total X-ray emission of Z sources as a faction of the position on their Z-diagrams
reflect actual decrease of the fraction of the energy released on the neutron star surface with the rest of the energy being released in the extended transition region. Finally, it is also possible that the apparent decrease of the boundary layer fraction as well as the peculiar behavior of the accretion disk temperature (Fig.5) is the consequence of the complete break down of the model on the normal branch of the color-color diagram.

Sco X-1 and GX17+2 appear to have higher boundary layer fraction at the end of the normal branch than other three sources. Another indication of the possibly higher contribution of the BL emission at $S_z \sim 2$ in Sco X-1 and GX17+2 is that they typically show stronger fast variability at the normal and flaring branch than Cyg X-2, GX340+0 and GX5-1 (cf. Sco X-1-like and Cyg X-2-like sources, Hasinger & van der Klis 1989; Kuulkers et al. 1994; Jonker et al. 2006; Piraino, Santangelo, & Kuarett 2002; Homan et al. 2002). The observed difference can be caused, for example, by different inclination angles in these systems, as indicated by optical data (Fomalont, Geldzahler, & Bradshaw 2001; Steeghs & Casares 2002; Crampton & Cowley 1978; Orosz & Kuulkers 1998; Kuulkers et al. 1994). It should be mentioned though, that the appearance of the Fig.5 is a direct consequence of the definition of the $S_z$ coordinate, in particular the definition of the $S_z = 2$ reference point as the turning point from the normal to the flaring branch. If, for example, the BL fraction would be plotted against the hard color, all five sources will be almost indistinguishable.

5.3. Shape of Z-diagram

Motivated by these results we use the two-component spectral model introduced in the beginning of this section to explain behavior of the Z-sources on the color-color diagram. Unlike before, for the accretion disk spectral component we adopt here the general relativistic accretion disk model by Ebisawa et al. (1991) (the \textit{grad} model in the XSPEC fitting package) which explicitly includes dependence on the mass accretion rate. The mass of the compact object and binary system inclination were fixed at $M_{NS} = 1.4M_\odot$ and $i = 60^\circ$. Using this two-component spectral model we can calculate the position in the color-color diagram as a function of the mass accretion rate and the boundary layer fraction. This simple model is an attempt to understand general tendencies of the Z-diagram, rather than to construct its precise quantitative description. In particular, the fact is ignored, that the relation between the accretion disk temperature and its flux is more complex than predicted by the standard model of the geometrically thin disk (Fig.5).

The results are presented in Fig.5. The two dashed curves in the figure show the evolution of spectral colors with the increase of the mass accretion rate of the disk component for two different values of the boundary layer fraction. The upper curve assumes the BL-to-disk flux ratio of 0.8, in the lower curve the BL fraction equals zero. On each curve positions where the mass accretion rate equals $\dot{M} = 0.5, 1, 2, 3, 4 \times 10^{18}$ g/s are marked. The colors of sources assuming a rapid change of the BL contribution from $F_{BL}/F_{disk} = 0.8$ to zero approximately at $\dot{M} = 2 \times 10^{18}$ g/s is shown by thick solid line.

The general shape of the Z-track can be reproduced in the model as a result of variation of two parameters – the mass accretion rate and BL fraction. The mass accretion rate increases along the Z-track. The Z-shape of the track is defined by the variation of the BL fraction, which decreases along the normal branch from the value of $\sim 50\%$ expected in the “standard” theories to a small number of the order of $\sim$zero at the end of the normal branch.

Quantitatively, the exact value of the $\dot{M}$, corresponding to the transition from the horizontal to the normal branch depends on the disk model (\textit{grad}) parameters – the binary system inclination, the mass of the neutron star and the spectral hardening factor. For our choice of parameters, it equals $\dot{M} \sim 2 \cdot 10^{18}$ g/sec, i.e. is of the order of the Eddington critical value for a $1.4M_\odot$ neutron star, when we can expect that the structure of the inner accretion flow can start to change. It is interesting to note that similar conclusions (decrease of the observable NS emission due to possible inflation of the inner disk) were obtained from studies of simultaneous observations of Z-sources in radio, optical UV and X-ray ranges (e.g. Hasinger et al. 1990; Vrtilek et al. 1996).

The location of the horizontal branch on the color-color diagram depends on the boundary layer fraction at smaller $\dot{M}$. Theoretically, it could be used to determine the latter from observations which would be of great help for the theory. In particular, our spectral model suggests $F_{BL}/F_{AD} \sim 0.8$. In practice, however, the direct comparison of this number with theoretical predictions for the energy release in the disk and boundary layer is complicated, because the observed flux ratio $F_{BL}/F_{disk}$ is modified by geometrical factors and anisotropy of the AD and BL emission diagrams.

6. Summary

Using the archival data of RXTE observations of several bright LMXBs we study the boundary layer emission and the structure of the accretion flow in this sources. Our sample includes 2 atoll sources in the soft spectral state and 5 (all but one) Z-sources. Their luminosities range from $\sim 10^{37}$ erg/s (atoll sources) to $\sim 2 \cdot 10^{38}$ erg/s (Z-sources). Our results are summarized below.

- We construct Fourier-frequency resolved spectra (energy spectra of variable emission) at $f \gtrsim 1 - 5$ Hz for five sources, which data combines sufficient timing and spectral resolution. Within the statistical uncertainties all the spectra have the same shape (Fig.5). This is a remarkable result as the average spectra of the atoll and Z-sources differ significantly and their...
Fig. 7. The color-color diagram of 5 Z-sources. Overlayed on the data are the tracks predicted by the model (section 5.3). The thick two dashed lines show evolution of the colors with change of the accretion rate in the disk for two different values of the BL fraction: 44% (upper) and zero (lower). The values of the mass accretion rates $\dot{M}$ of the disk component are marked in units of $10^{18}$ g/s. The thick solid line shows the Z track with transition mass accretion rate $2 \times 10^{18}$ g/s.

The contributions of the boundary layer component to the observed emission decreases along the Z-track from the conventional value of $\sim 50\%$ on the horizontal branch to a rather small number at the end of the normal branch. The main difference of our approach from previous attempts is in the apriori knowledge of the shape of the boundary layer spectrum. This allowed us to avoid ambiguity of the spectral decomposition into boundary layer and disk components which was one of the major problems in previous studies.

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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, AdSpR, 28, 307
Bhattacharyya, S., Bhattacharya, D., Thampan, A. 2001, MNRAS, 325, 989
Bradtshaw C. F., Geldzahler B. J., Fomalont E. B., 2003, ApJ, 592, 486
Brdt, H., Rotshild, R., Swank, J. 1993, Astron. Astrophys. Suppl. Ser. 97, 355
Crampton D., Cowley A. P., 1976, ApJ, 207, L171
Dieter, S., Vaughan, B., Kuulkers, E. et al. 2000, A&A, 353, 203
Di Salvo, T., Robba, N., Iaria, R. et al. 2001, ApJ, 554, 49
Done, C., Zycki, P. T. & Smith, D. A. 2002, MNRAS, 331, 453
Ebisawa, K., Mitsuda, K. & Hanawa, T. 1991, ApJ, 367, 213
Fomalont E. B., Geldzahler B. J., Bradshaw C. F., 2001, ApJ, 558, 283
Gilfanov, M., Churazov, E., Revnivtsev, M. 2000, MNRAS, 316, 923
Gilfanov, M., Revnivtsev, M., & Molkov, S. 2003, A&A, 410, 217
Gilfanov, M., Areffiev V. 2005, submitted to MNRAS, astro-ph/0501215
Goldman I., 1979, A&A, 78, L15
Grebeniev, S. & Sunyaev, R. 2002, Astronomy Letters, 28, 150
Haberl F., Stella L., White N. E., Gottwald M., Priedhorsky W. C., 1987, ApJ, 314, 266
Hasinger, G., van der Klis, M. 1989, A&A, 225, 79
Hasinger G., van der Klis M., Ebisawa K., Dotani T., Mitsuda K., 1990, A&A, 235, 131
Homan J., van der Klis M., Jonker P. G. et al. 2002, ApJ, 568, 878
Iaria R., di Salvo T., Robba N. R., Burderi L., Lavagetto G., Stella L., Frontera F., van der Klis M., 2004, NuPhS, 132, 608
