PROCEEDINGS OF SCIENCE

Evolution of the disc radii during outburst of X-ray binaries as infered from thermal emission.

Clément Cabanac[*]
University of Southampton
E-mail: c.cabanac@astro.soton.ac.uk

Rob Fender
University of Southampton
E-mail: r.fender@soton.ac.uk

Elmar Körding
University of Southampton
E-mail: elmar@phys.soton.ac.uk

Robert Dunn
University of Southampton
E-mail: r.j.dunn@phys.soton.ac.uk

Compact object displays drastic spectral and timing changing from the beginning to the end of an outburst, showing the different efficiencies of accretion processes. Black hole binaries hence exhibit schematically two different states in X-ray spectra: the first dominated by a thermal component and the second by a hard powerlaw shape like. Whereas the hard component is often attributed to the emission of a radiatively inefficient corona, the thermal component is interpreted as the emission of the optically thick accretion disc.
The commonly accepted picture suggests that the observed transition between hard and soft states is associated by a drop in the accretion efficiency of the thermal component by a recession of the internal disc radius in hard states. However, recent studies based on relativistically broadened iron line and the thermal component strength analysis would tend to show the presence of the disc in the vicinity of the horizon. By a reanalysis of archive spectra where thermal emission is present, we tracked the values of the disc radii during outbursts among several sources. Indeed, whereas a constant inner radius would imply that the disc luminosity should monotonically depends on the temperature, we show that this relationship seems to deviate at the lowest luminosities.

VII Microquasar Workshop: Microquasars and Beyond
September 1 - 5, 2008
Foca, Izmir, Turkey

[*]Speaker.

PoS(MQW7)009

1. Introduction

The powerful X-ray emission observed in X-ray binaries is now believed to come from the high efficiency of the accretion processes around compact object, i.e., a neutron star (NS) or a black hole (BH). During outbursts, BH binaries use to transit between the so-called "canonical states" which changes can be observed in X-ray spectra, radio and timing behaviour (see e.g. [9] for the classification, or also [1] for slightly different definitions).

Among them, the "soft state" is characterised by a strong soft component in its X-ray spectrum (typically peaking at $0.5-1$ keV) and usually interpreted as the emission from an optically thick accretion disc. On the contrary, the "hard state" exhibits a powerlaw shape usually extending up to a few hundred of keV. The nature of the medium emitting this component is still under debate and by analogy with the hard and optically thin emission of the sun, it was called a corona. A dichotomy can also be clearly identified between the hard state, where the timing variability and the radio emission are high, and the soft state, where the latter are far dimmer or unobservable.

Until recently, to explain those drastic changes, the accepted picture was involving changes in the geometry of the accretion flow (see the contribution of J. Tomsick in this volume for a review). Of particular importance is the the inner accretion disc radius value $R_{\rm in}$. Indeed, it determines the efficiency of the accretion process in the disc due to the increase of the gravitational potential in the vicinity of the BH. The transition from soft to hard states are usually interpreted as being partly caused by the increase of $R_{\rm in}$, from a few gravitational radii $R_{\rm g}$ to about hundreds, lowering the accretion efficiency from the optically thick disc.

However, a recent debate flared-up about the relevance of such picture. Some XMM spectra of GX 339-4 suggested that they could be compatible with a disc remaining close to the horizon of the black-hole, even in its hard state [11]. To measure the value of $R_{\rm in}$, both general relativity broadening iron line model and strength of the thermal component were used. Indeed considering this latter component, it is possible to evaluate the value of $R_{\rm in}$ by using a simple multicolour disc model. The disc luminosity $L_{\rm disc}$ will indeed be proportional to $R_{\rm in}^2 T_{\rm in}^4$, as the inner part of the disc dominate the optically thick emission.

The aim of our work is to perform an extensive analysis of this thermal component, involving several sources and observatories, either by reanalysing data, or taking the value given in the literature.

2. The data set

Our data set is chosen to probe the thermal component close or during the state transition and also in quiescence. As $T_{\rm in} \propto R_{\rm in}^{-3/4} \dot{M}_{\rm disc}^{1/4}$ with the multicolour disc model which is used in this whole study ($\dot{M}_{\rm disc}$ is the accretion rate flowing through the disc), a disc radius increase is better observed with instruments working at low energy, such as XMM, *Chandra* and *Swift*, but also past mission like Beppo-SAX, ASCA or EUVE.

This study is based on a sample of 6 black hole candidates: XTE J1118+480, GX339-4, GRO J1655-40, XTE J1817-330, SWIFT J1753.5-0127 and AO 620-00. For XTE J1118+480 2000 outburst, we first used the published results, where the disc geometry is mainly tracked by the UV spectra [3, 7]. Those data are consistent with a quite cold ($T_{\rm in} \sim 24$ eV) and recessed disc

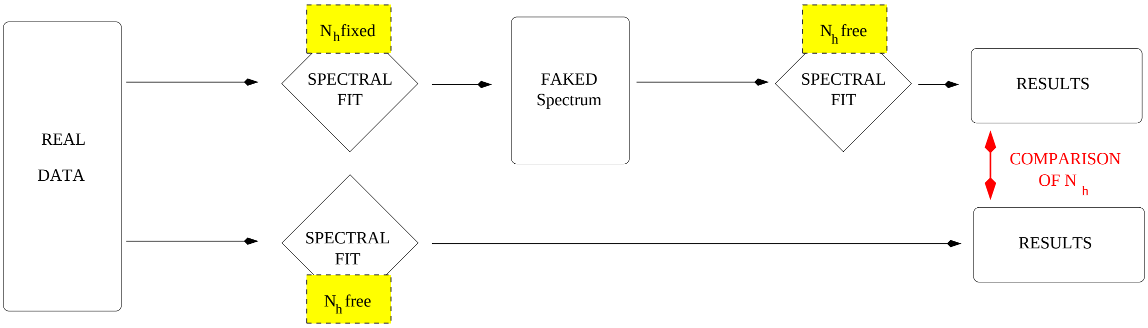

Figure 1: Schematic process we adopted to probe if the variation in the column density value observed is a systematic effect of data analysis or real. This comparison is called the *fff* method in the text.

($R_{\rm in} \sim 700 R_{\rm g}$ with $M = 8.5$ $M_\odot$ and $d = 1.7$ kpc). We also reanalysed Beppo-SAX spectra (LECS, MECS and PDS) of the same source observed during the same outburst. The thermal component is however consistent with a disc closer to the black hole horizon (though still recessed as $R_{\rm in} \sim 35 R_{\rm g}$) and hotter ($T_{\rm in} \sim 65$ eV). As this discrepancy is still unclear, we decided to keep both results. We also included the results coming from the quiescent observations of XTE J1118+480 and A0 620-00 [8].

A significant part of this study is based on *Swift*/XRT data, as about 110 GRO J1655-40, XTE J1817-330, GX 339-4 and SWIFT J1753.5-0127 spectra are analysed. The use of the latest response files allows us to fit the spectra between 0.3 and 10 keV in WT mode (and 0.5-10 keV for LrPD mode). In addition, three ASCA GX 339-4 (1994 and 1995 outbursts) spectra were included and also the XMM long study performed by [11]. We used XSPEC v12.3.1ao to fit the spectra with an absorbed (`wabs`) multicolour disc model (`diskbb`) and a powerlaw.

3. A varying absorption?

In spectral analysis, the evaluation of the thermal component strength (and hence the value of $R_{\rm in}$) may interfere with the absorption value and especially when $T_{\rm in}$ is lowering. For example, the effect of the absorption begin to be noticeable under 0.5 keV in a spectrum if $N_{\rm H} > 10^{21}$ cm^{-2}.

We therefore decided to examine in details the ability of *Swift*/XRT to disentangle this possible degeneracy by following the method summed-up in Fig. 1. Each spectrum is analysed following two ways. On the one hand, we simply fit it with the best model (a powerlaw and a multicolour disc when necessary), leaving the absorption free to vary. We then obtain fit parameter and among them a value of the absorption $N_{\rm H}$. On the other hand, we apply the *fff* method: we first fit the spectrum with a **f**ixed absorption, hence we obtain fit parameters. Then we **f**ake a spectrum with those fit parameters and fit this fake spectrum by allowing now the $N_{\rm H}$ to **f**reely vary. At the end we compare the values of $N_{\rm H}$ obtained with the real spectra, and the ones obtained with the *fff* method. In the hypothesis that variations of $N_{\rm H}$ were only due to the spectral analysis, one should therefore obtain the same values with both methods.

The evolution of the absorption as a function of the powerlaw photon index Γ obtained for XTE J1817-330 and SWIFT J1753.5 is displayed in Fig. 2 for both methods. It shows first that a trend can be noted for both sources. The higher Γ, the higher $N_{\rm H}$ in real spectra. Moreover, paying

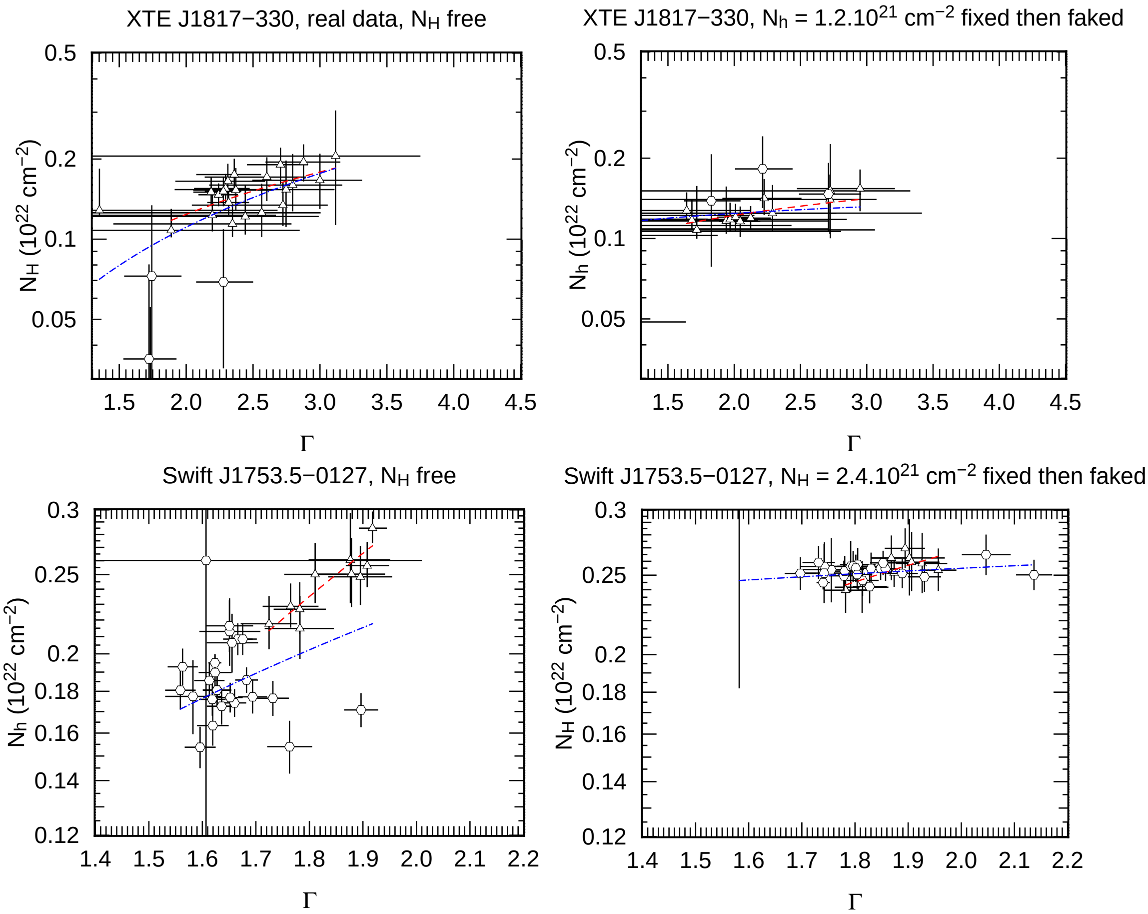

Figure 2: Column density variation during the Swift observation of XTE J1817-330 and SWIFT J1753.5-0127 when high energy component in real and faked data are fitted with a powerlaw model. The model is either a simple *wabs* ∗ *po* (⬠) or a *wabs* ∗ (*diskbb* + *po*) (△). Red dashed line shows the fit by a powerlaw of the △ and the dotted-dashed blue line is a fit of all acceptable points (△ and ⬠ when $\Gamma > 1$).

attention to the *fff* spectra (right column plots on Fig. 2), we note that this trend, though present, is quite less intense. This is confirmed by analysing the statistical errors on this correlation and also noticed in GX 339-4 and GRO J1655-40 *Swift*/XRT spectra (see [2] for further details).
We conclude that when analysing *Swift*/XRT spectra, one has to leave the absorption free to vary, as there seem to be a real variation of the absorption during the outburst.

4. The disc evolution in XTE J1817-330

Whereas for the previous study we included the maximum of spectra available, for the following, we only include the one where a thermal component is necessary (i.e., reduced $\chi^2 > 1.2$ with a single absorbed powerlaw and F-test probability $< 10^{-2}$ when adding a disc). According to the previous section, adopting a free $N_{\rm H}$ in the fitting process, we show that an absorbed powerlaw is sufficient to fit the data in the last three observations of the source (reduced χ^2 always under 1.1, see [2]), whereas [13], performing a similar analysis but fixing the value of $N_{\rm H}$, suggest that a disc component was required.

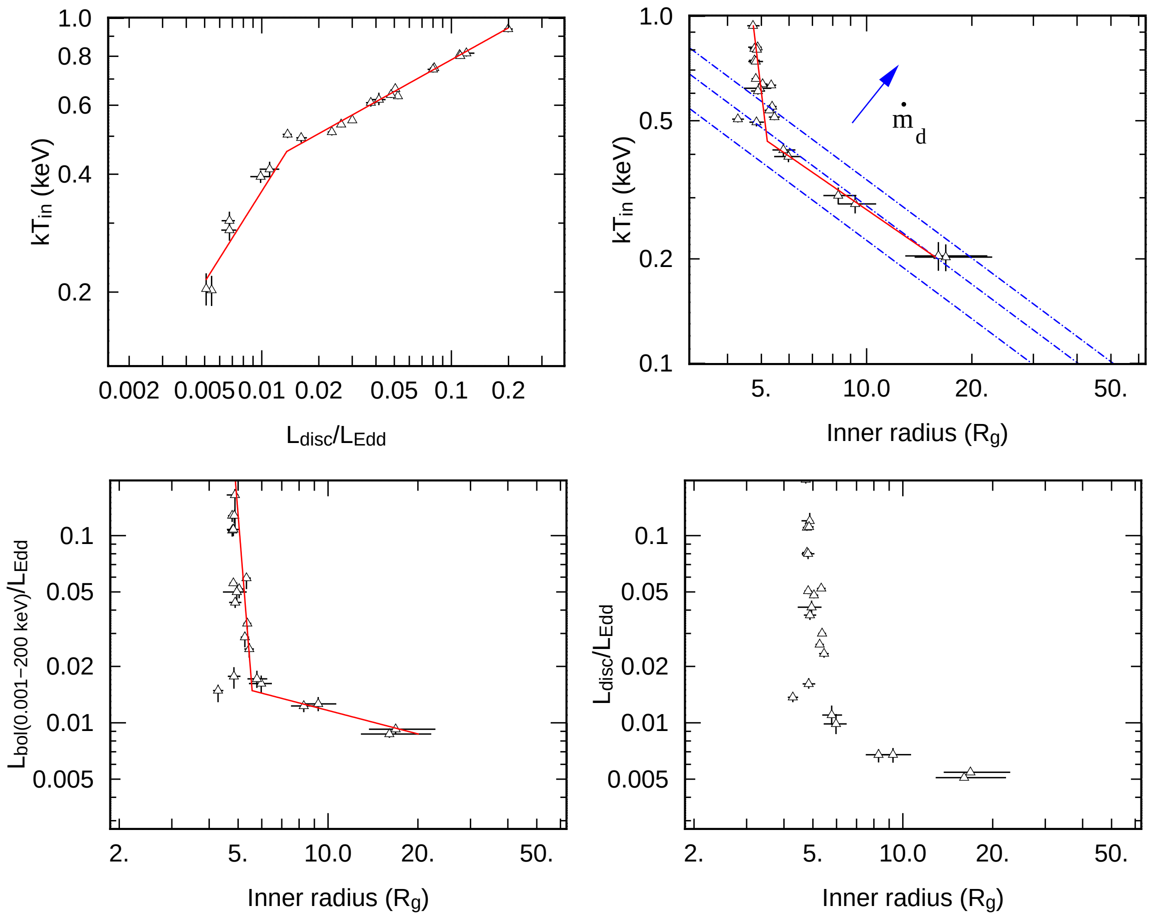

Figure 3: Variation of the disc properties during the decline of XTE J1817-330 when leaving the absorption free to vary. The $kT_{\rm in}$ vs $L_{\rm disc}/L_{\rm Edd}$, $kT_{\rm in}$ vs $R_{\rm in}/R_{\rm g}$ and $L_{\rm bol}/L_{\rm Edd}$ vs $R_{\rm in}/R_{\rm g}$ data sets have been fitted by a broken powerlaw (red solid broken lines). The blue dotted dashed lines plotted in the upper right panel are showing constant disc accretion rate $\dot{M}_{\rm d}$ profile. From upper right to lower left: $\dot{m}_{\rm d} = \dot{M}_{\rm d}/\dot{M}_{\rm Edd} = 0.01,\ 0.005,\ 0.002$ and the accretion efficiency at the Eddington luminosity $\eta_{\rm Edd} = 0.1$.

The results concerning the remaining spectra are however quite interesting regarding the evolution of $R_{\rm in}$, as shown in Fig. 3. When examining the evolution of $T_{\rm in}$ as a function of $L_{\rm disc}$, a drop can clearly be noted under $L_{\rm disc} < 0.015 L_{\rm Edd}$ (assuming $M = 6$ M$_\odot$ and $d = 6.3$ kpc). This has been tested by fitting the $T_{\rm in}$ vs $L_{\rm disc}$ relationship with either a simple powerlaw (spl) or a broken powerlaw (bknpl). The break is thus clearly necessary (red. $\chi^2_{\rm bknpl} = 1.15$ whereas $\chi^2_{\rm spl} = 4.96$). Moreover, over the break, the fit results are consistent with $L_{\rm disc} \propto T_{\rm in}^4$, which is expected for a constant inner radius, whereas it is not the case anymore under the break at $L_{\rm disc} \sim 0.014\ L_{\rm Edd}$.

The same analysis was performed with the bolometric and disc luminosities in function of the inferred radius, and it gives similar results: under $L_{\rm bol} \sim 0.015\ L_{\rm Edd}$, the data are consistent with a disc that begins to recess. This is consistent with the results obtained by [5], but using an irradiated disc model.

The analysis of the $T_{\rm in}$ as a function of $R_{\rm in}$ relationship gives another information. The begin-

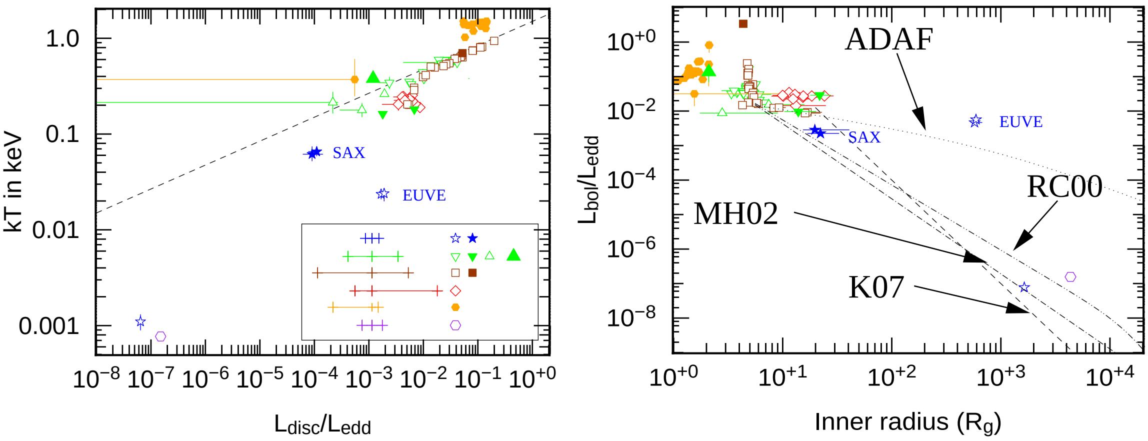

Figure 4: *Left panel*: $kT_{\rm in}$ versus $L_{\rm disc}/L_{\rm Edd}$. The black dashed correspond to $T_{\rm in} \propto (L_{\rm disc}/L_{\rm Edd})^{0.25}$. The impact of the orbital parameters (distance, mass and inclination angle) uncertainties on the disc luminosity is shown on the inset for each source. *Right panel*: $L_{\rm bol}/L_{\rm Edd}$ versus $R_{\rm in}$. Continuous curve refers to the accretion model or timing relationship used (see text). Parameters value used: ADAF $\alpha = 1.33 \times 10^{-2}$ and $\beta = 10^{-8}$. MH02 [10]: $\alpha = 0.3$ and $\beta = 0.11$. RC00 [12]: $\alpha = 3 \times 10^{-5}$ and $\beta = 0.11$. K07 refers to [6]. Color/symbol codes: GX 339-4 (▽: SWIFT data. ▼: [15]. △: ASCA data. ▲: [11]). GRO J1655-40 (●, SWIFT data). XTE J1817-330 (□: SWIFT data. ■: [14]). SWIFT J1753.5-0127 (◇, SWIFT data). XTE J1118+480 (★. open : EUVE data, [3, 7]. filled : SAX data). A0 620-00 (⬡).

ning of this disc recession seems indeed to occur at constant accretion rate in the disc $\dot{m}_{\rm d}$. It would mean that the observed drop in the disc luminosity at the beginning of this transition is only due to the disc recession, and not to the decrease of the accretion rate flowing through the disc.

5. Multi-sources analysis

We then include the other data set available to see how typical XTE J1817-330 behaviour was for BHB. It also allows a wide extension of the previous study as the bolometric luminosity $L_{\rm bol}$ is now probed from quiescence ($L_{\rm bol} \sim 10^{-7} L_{\rm Edd}$) to the highest states ($L_{\rm bol} \sim L_{\rm Edd}$). Figs. 4 and 5 show the results obtained with our whole data set.

The main result deals with the disc radius evolution as a function of the luminosity. Over $L_{\rm bol} > 10^{-2} L_{\rm Edd}$, the data are consistent with a constant radius, close to the ISCO. On the contrary, under this value, the $T_{\rm in}$ versus $L_{\rm disc}/L_{\rm Edd}$ relationship clearly deviates from the expected $T_{\rm in} \propto (L_{\rm disc}/L_{\rm Edd})^{0.25}$ in a constant $R_{\rm in}$ hypothesis.

By using the normalisation value of the multicolour disc to estimate the inner radius, we obtain the right plot of Fig 4. The disc radius values obtained are therefore consistent with a recessed disc when $L_{\rm bol} \lesssim 10^{-2} L_{\rm Edd}$. Moreover the left plot of Fig. 5 seems to confirm that the beginning of the disc recession takes place at constant $\dot{m}_{\rm d}$. However, the accretion rate in the disc in quiescence then drops by about 3 order of magnitude, suggesting that both a lowering accretion rate and the disc recession may contribute to the observed drop in luminosity.

We also attempt to plot the evolution of the sources in a Disc Fraction Luminosity Diagram (right plot of Fig. 5, see e.g. [4] and reference therein for the definition), which follows the contribution of each component (optically thin vs optically thin) during the outburst. The pattern drawn by XTE

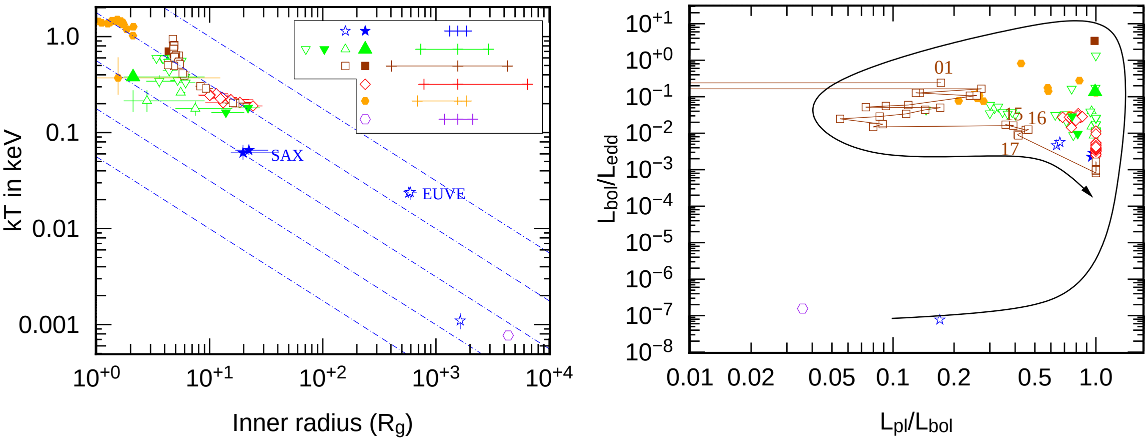

Figure 5: *Left panel*: T_{in} versus R_{in}. Blue dotted-dashed lines : $T_{in} \propto R_{in}^{-3/4}$ relationships obtained for a 8 $M_{\odot}$ BH accreting at constant $\dot{m}_d$ and an Eddington efficiency $\eta_{Edd} = 0.1$. From upper right to lower left $\dot{m}_d = 1, 10^{-2}, 10^{-4}, 10^{-6}, 10^{-8}$. *Right panel*: Disc Fraction Luminosity Diagram of the whole set of observations presented in this paper. The arrow represent the supposed path in the DFLD during an outburst, starting from quiescence. L_{pl} is the luminosity of the absorbed powerlaw component calculated between 0.05 and 200 keV. Color/symbol code is the same as in the figure 4.

J1817-330 is interesting as it follows part of the expected track of a BHB. From the softest state, when the bolometric flux decrease, the thermal component dominate the overall luminosity. Then, at about $L_{bol} \sim 10^{-2} L_{Edd}$, the optically thin component suddenly increase its contribution to the overall flux, at rather constant bolometric luminosity. However, we note that the disc contribution in quiescence is close to the one obtained in soft state. This is the reason why we suggest the possible evolution of a BHB in the DFLD on Fig. 5.

We then try to constrain accretion models with our data. Three models are used: the classic ADAF in its strong definition, and two models were evaporation by conduction of the inner part of the disc takes place [10, 12]. In all those models, the driving parameters are the classical viscosity parameter α and the magnetisation $\beta = P_{gas}/(P_{mag} + P_{gas})$. They all predict a certain L_{bol} vs R_{in} relationship according to the values of both parameters. We tried reasonable combinations of (α, β) values that could link both the quiescent points and the last observation where the disc is not recessed (i.e., $L_{bol} \sim 10^{-2}$ L_{Edd} and $R_{in} \sim 6$ R_g). It appears first that the strong ADAF model does not allow to fit those two ends with a single viscosity parameter value, and second that a high magnetisation is necessary for both other models (see caption of Fig. 4). However, the value of $\alpha \sim 3 \times 10^{-5}$ required for [12] model seems quite low compared to the one required with [10] $(\alpha \sim 0.3)$.

At the end we compared our data to the expected behaviour derived from the variability plane found by [6] for accreting compact objects, that links the typical frequency observed in the power spectra (ν_l), the BH mass (M) and the total accretion rate (in Eddington units) $\dot{m}$:

$$\left(\frac{\nu_l}{Hz}\right)\left(\frac{M}{10M_{\odot}}\right) \propto (\dot{m})\,. \tag{5.1}$$

If the frequency ν_l comes from Keplerian motion at R_{in}, and in the inefficient regime where $L_{bol} \propto \dot{m}^2$, we then expect that:

$$\frac{L_{bol}}{L_{Edd}} \propto \left(\frac{R_{in}}{R_g}\right)^{-3}. \quad (5.2)$$

The previous relationship is then overplotted on the right panel of Fig. 4, the normalisation being adjusted to fit the data at lowest luminosities of XTE J1817-330. We can see that this relationship is then also consistent with the data in quiescence.

6. Discussions

In this study we have been focusing on the evolution of the optically thick disc geometry as inferred from the thermal component. As the normalisation of this component can be affected by the absorption in the line of sight, we studied the possible changes of this value during state evolution. We showed with *Swift*/XRT data that a possible trend could be noticed and hence that the N_H should be thawed during the fitting process.

We then demonstrated, first on the striking example of XTE J1817-330, then on the comparison with other sources, that the evolution was compatible with a disc recessing when $L_{bol} < 10^{-2} L_{Edd}$. The L_{bol} vs R_{in} data points obtained are also consistent with models where evaporation of the inner part of the disc takes place, with a high magnetisation. The radius evolution is also consistent with the expected relationship derived from the timing behaviour in X-ray binaries.

We note however that our conclusions can be affected by several effects. First, the simple multicolour disc model used in this study can be, under certain circumstances, unphysical. However, these drawbacks are significant when the comptonised component is dominating the spectrum and always lead to an apparent decrease of R_{in}, whenever even if it remains constant in reality. Modelling of such irradiated disc has been performed on XTE J1817-330, showing that the disc recession is even emphasised when the comptonised flux dominates [5]. A reanalysis of our data set in this framework is showing the same trend.
On the contrary, the addition of a reflection component on the disc could also explain part of the soft X-ray emission (by reprocessing part of the hard emission), decreasing the disc intensity and hence the inner radius inferred from the fits by a multicolour disc.

References

[1] T. Belloni, *High-energy spectra from black-hole candidates*, Nuclear Physics B Proceedings Supplements **132**, 337–345 (2004) [arXiv:astro-ph/0309028].

[2] C. Cabanac, R. P. Fender, R. J. H. Dunn, and E. G. Körding, *On the variation of black hole accretion disc radii as a function of state and accretion rate*, submitted to MNRAS (2009).

[3] S. Chaty, C. A. Haswell, J. Malzac, R. I. Hynes, C. R. Shrader, and W. Cui, *Multiwavelength observations revealing the evolution of the outburst of the black hole XTE J1118+480*, MNRAS **346**, 689–703 (2003) [arXiv:astro-ph/0309047].

[4] R. J. H. Dunn, R. P. Fender, E. G. Körding, C. Cabanac, and T. Belloni, *Studying the X-ray hysteresis in GX 339-4: the disc and iron line over one decade*, MNRAS **387**, 545–563 (2008) [0804.0148].

[5] M. Gierliński, C. Done, and K. Page, *X-ray irradiation in XTE J1817-330 and the inner radius of the truncated disc in the hard state*, MNRAS **388**, 753–760 (2008) [0803.0496].

[6] E. G. Körding, S. Migliari, R. Fender, T. Belloni, C. Knigge, and I. McHardy, *The variability plane of accreting compact objects*, MNRAS **380**, 301–310 (2007) [0706.2959].

[7] J. E. McClintock, C. A. Haswell, M. R. Garcia, J. J. Drake, R. I. Hynes, H. L. Marshall, M. P. Muno, S. Chaty, P. M. Garnavich, P. J. Groot, W. H. G. Lewin, C. W. Mauche, J. M. Miller, G. G. Pooley, C. R. Shrader, and S. D. Vrtilek, *Complete and Simultaneous Spectral Observations of the Black Hole X-Ray Nova XTE J1118+480*, ApJ **555**, 477–482 (2001) [arXiv:astro-ph/0103051].

[8] J. E. McClintock, R. Narayan, M. R. Garcia, J. A. Orosz, R. A. Remillard, and S. S. Murray, *Multiwavelength Spectrum of the Black Hole XTE J1118+480 in Quiescence*, ApJ **593**, 435–451 (2003) [arXiv:astro-ph/0304535].

[9] J. E. McClintock and R. A. Remillard, *Black Hole Binaries* (2003) [arXiv:astro-ph/0306213].

[10] F. Meyer and E. Meyer-Hofmeister, *The effect of disk magnetic fields on the truncation of geometrically thin disks in AGN*, A&A **392**, L5–L8 (2002) [arXiv:astro-ph/0207573].

[11] J. M. Miller, J. Homan, D. Steeghs, M. Rupen, R. W. Hunstead, R. Wijnands, P. A. Charles, and A. C. Fabian, *A Long, Hard Look at the Low/Hard State in Accreting Black Holes*, ApJ **653**, 525–535 (2006) [arXiv:astro-ph/0602633].

[12] A. Różańska and B. Czerny, *Vertical structure of the accreting two-temperature corona and the transition to an ADAF*, A&A **360**, 1170–1186 (2000).

[13] E. S. Rykoff, J. M. Miller, D. Steeghs, and M. A. P. Torres, *Swift Observations of the Cooling Accretion Disk of XTE J1817-330*, ApJ **666**, 1129–1139 (2007) [arXiv:astro-ph/0703497].

[14] G. Sala, J. Greiner, M. Ajello, E. Bottacini, and F. Haberl, *XMM-Newton and INTEGRAL observations of the black hole candidate XTE J1817-330*, A&A **473**, 561–568 (2007) [0707.4155].

[15] J. A. Tomsick, E. Kalemci, P. Kaaret, S. Markoff, S. Corbel, S. Migliari, R. Fender, C. D. Bailyn, and M. M. Buxton, *Broadband X-Ray Spectra of GX 339-4, and the Geometry of Accreting Black Holes in the Hard State*, ApJ **680**, 593–601 (2008) [0802.3357].

PoS(MQW7)009