Discovery of photon index saturation in the black hole binaries

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Abstract. We present a study of the correlations between spectral, timing properties and mass accretion rate observed in X-rays from the eight Galactic Black Hole (BH) binaries during the transition between hard and soft states. We analyze all transition episodes from X-ray sources observed with Rossi X-ray Timing Explorer (*RXTE*). We show that broad-band energy spectra of Galactic sources during all these spectral states can be adequately presented by Bulk Motion Comptonization (BMC) model. We also present observable correlations between the index and the normalization of the disk "seed" component. The use of "seed" disk normalization, which is presumably proportional to mass accretion rate in the disk, is crucial to establish the index saturation effect during the transition to the soft state. We discovered the photon index saturation of the hard spectral components at values of 2.1-3. We present a physical model which explains the index-seed photon normalization correlations. We argue that the index saturation effect of the hard component (BMC1) is due to the soft photon Comptonization in the converging inflow close to BH. We apply our scaling technique to determine BH masses and distances for Cygnus X-1, GX 339-4, 4U 1543-47, XTE J1550-564, XTE J1650-500, H 1743-322 and XTE J1859-226. Good agreement of our results for sources with known values of BH masses and distance provides an independent verification for our scaling technique.

Keywords: accretion, accretion disks—black hole physics—stars:individual (GRS 1915+105):radiation mechanisms: non-thermal—physical data and processes
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INTRODUCTION

The study of the characteristic changes in spectral and variability properties of X-ray binaries is proved to be a valuable source of information on the physics governing the accretion processes and on the fundamental parameters of black holes (BHs).

The simultaneous study of the spectral and timing evolution of a BH source during a state transition has been a subject of many investigations [see references in a review by [37]]. [10], hereafter FB04, introduced a classification of the spectral states in GRS 1915 +105 and studied the spectral state evolution. Using X-ray colors (hardness ratio) they introduced three spectral states. State A: in which the strong blackbody-like (BB) component of color temperature $\gtrsim 1$ keV dominates in the overall spectrum and little time variability is detected. State B: similar to state A but substantial red-noise variability on scales > 1 s occurs in this state. State C: the spectra are harder than those in states A and B. Photon indices of the power-law components vary from 1.8 to 2.5. White-red noise (WRN) variability on scales > 1 s takes place in this state.

Furthermore FB04 discussed the connection between states A, B, C observed in GRS 1915 with the three "canonical" states in black hole candidates (BHCs) also identified by their timing and spectral properties.

At a low luminosity state the energy spectrum is dominated by a hard Comptonization component combined (convolved) with a weak thermal component. The spectrum of this low (luminosity) hard state (LHS) is presumably a result of Comptonization (upscattering) of soft photons, originated in a relatively weak accretion disk, off electrons of the hot ambient plasma [see e.g. [45]].

Variability in LHS is high (fractional root-mean-square variability is up to 40%) and presented by a flat-top broken power law (white-red noise) shape, accompanied by quasi-periodic oscillations (QPOs) in the range of 0.01-30 Hz, observed as narrow peaks in the power density spectrum (PDS). In high soft state (HSS) a photon spectrum is characterized by a prominent thermal component which is probably a signature of a strong emission coming from a geometrically thin accretion disk. A weak power-law component is also present at the level of not more than 20% of the total source flux. In the HSS the flat-top variability ceases, QPOs disappear and PDS acquires a pure power-law shape. The total variability in HSS is usually about 5% fractional rms. The intermediate state (IS) is a transitional state between LHS and HSS. Note in addition to LHS, IS and HSS sometimes very soft state (VSS) is observed in which the BB component is dominant and the power-law component is either very weak or absent at all. The bolometric luminosity in VSS is a factor of 2-3 lower than that in HSS.

In particular, FB04 concluded that probably all three states A, B, C of GRS 1915+105 are instances of something similar to the HSS/IS observed in other BHC systems, associated to the high accretion rate value for this source, although during the hardest intervals LHS might be sometimes reached. We come to the similar conclusions analyzing spectral and timing data from GRS 1915+105 obtained by *RXTE* (see below).

Close correlations of nearly periodic variability [quasi-periodic oscillations (QPO)] observed during low-hard and intermediate states with the photon index of the Comptonization spectral component have been reported in multiple state transitions observed from accreting BHs [see [60], [44], [43], [42], hereafter V03, ST06, ST07 ST09 respectively]. The ubiquitous nature of these correlations suggests that the underlying physical processes which lead to the observed variability properties are closely tied to the corona; furthermore, they vary in a well defined manner as the source makes a transition between spectral states. The fact that the same correlations are seen in many sources, which vary widely in both luminosity (presumably with mass accretion rate) and state, suggests that the physical conditions controlling the index and the low frequency QPOs are characteristics of these sources. Moreover, they may be an universal property of all accreting compact systems, including neutron sources too [see [48], hereafter TF04, and [54]].

When a BH is in LHS, radio emission is also detected and a jet is either seen or inferred [11]. Several models are successful in reproducing the energy spectrum from the radio domain to the hard X-rays [see e.g. [23], [59], [7], [24] and [8]]. The multiplicity of models that can fit well the time average spectrum of galactic BHs indicates that this alone is not enough to distinguish the most realistic one among them. X-ray timing features can be the key features to finally finding the common physical connection between the corona, the accretion disk and the jet radio emission in BHs.

There is a big debate in the literature on the origin of quasiperiodic oscillation (QPO) frequencies [see e.g. [37]] and its connection with the radio emission. [30] reported on correlation between radio luminosity and X-ray timing features in X-ray binaries containing a number of low magnetic field neutron stars and one black hole GX 339-4. They showed that in the low-hard state (LHS) radio luminosity is correlated with the low frequency QPO (LFQPO). Note ST09 demonstrate that in LHS of Galactic BHs LFQPO changes by order of magnitude, from 0.2 to 2 Hz whereas the photon index has almost the same value of 1.5. Below we show that in GRS 1915+105 the photon index monotonically increases with LFQPO and disk mass accretion rate, although the radio luminosity does not correlate with LFQPO and X-ray luminosity in the whole range of spectral states, from low-hard to high-soft through intermediate states. Recently [14] suggested a model which explains how the QPO phenomenon is related to an appearance of radio flares (jets). In Titarchuk & Seifina (2009), hereafter TS09, we present details of our observational study of the QPO connection with the X-ray and radio flaring activity in GRS 1915+105.

In LHS and IS which we consider in our study, only a small part of the disk emission component is seen directly. The energy spectrum is dominated by a Comptonization component presented by a power law. To calculate the total normalization of the “seed” disk blackbody component we model the spectrum with a Generic Comptonization model [BMC XSPEC model, see details in [51]] which consistently convolves a disk blackbody with a Green function of the Compton Corona to produce the Comptonization component. We argue that the disk emission normalization calculated using this approach produces a more accurate correlation with respect to the correlation with the direct disk component which was obtained using the additive model, multicolor disk plus power law [see e.g. [26]].

This review is a continuation of the study of index-QPO and index-seed photon normalization correlations in BH sources started in ST07 and it continues in ST09 and TS09.

We present a study of the index-seed photon normalization (disk flux) correlation observed from a number of X-ray sources when they evolve from LHS to HSS. We analyze more than 20 transition episodes from 9 BH sources observed with *Rossi X-ray Timing Explorer* (*RXTE*). Our scaling technique for BH mass determination uses a correlation between spectral index and quasi-periodic oscillation (QPO) frequency. In addition, we use a correlation between index and the normalization of the disk "seed" component to cross-check the BH mass determination and estimate the distance to the source. While the index-QPO correlations for two given sources contain information on the ratio of the BH masses in those sources, the index-normalization correlations depend on the ratio of the BH masses and the distance square ratio. In fact, the index-normalization correlation also discloses the index-mass accretion rate saturation effect given that the normalization of disk "seed" photon supply is proportional to the disk mass accretion rate.

We present arguments that this observationally established index saturation effect is a signature of the bulk motion (converging) flow onto black hole which was early predicted by the dynamical Comptonization theory. We use GRO J1655-40 as a primary reference source for which the BH mass, distance and inclination angle are evaluated by dynamical measurements with unprecedented precision among other Galactic BH sources. We apply our scaling technique to determine BH masses and distances for Cygnus X-1, GX 339-4, 4U 1543-47, XTE J1550-564, XTE J1650-500, H 1743-322 and XTE J1859-226. Good agreement of our results for sources with known values of BH masses and distance provides an independent verification for our scaling technique. Also we have analyzed a broader sample of state transitions from GRS 1915+105 and we found a diverse phenomenology for index evolution through a transition. We also discuss and interpret the results of our observational study. Specifically we consider the effect of the bulk motion Comptonization in the inner part of the accretion flow on the index evolution during a state transition. Also we show that the index saturation effect is a direct consequence of the existence of this inner bulk motion region and, therefore, can be considered as an observational signature of the converging flow (black hole).

SPECTRAL ANALYSIS

The broad-band source spectra were modeled in XSPEC with an additive model consisting of *two BMC*: a BMC with high energy cut-off (*BMC1* component) and *BMC2* component: $wabs*(bmc+bmc*highecut)$. We also use a multiplicative *wabs* model to take into account of an absorption by neutral material. The *wabs* model parameter is an equivalent hydrogen column N_H. Systematic error of 1% has been applied to the analyzed X-ray spectra.

The *BMC* model describes the outgoing spectrum as a convolution of the input "seed" blackbody-like spectrum, whose normalization is N_{bmc} and color temperature is kT, with the Comptonization Green's function. Similarly to the ordinary *bbody* XSPEC model, the normalization N_{bmc} is a ratio of the source (disk) luminosity to the square of the distance

$$N_{bmc} = \left(\frac{L}{10^{39}\mathrm{erg/s}}\right)\left(\frac{10\,\mathrm{kpc}}{d}\right)^2. \qquad (1)$$

The resulting spectrum is characterized by the parameter $\log(A)$ related to the Comptonized fraction f as $f = A/(1+A)$ and a spectral index $\alpha = \Gamma - 1$. There are several advantages of using the BMC model with respect to other common approaches used in studies of X-ray spectra of accreting compact objects, i.e. sum of blackbody/multi-color-disk and power-law/thermal Comptonization. First, the BMC, by the nature of the model, is applicable to the general case where there is an energy gain through not only thermal Comptonization but also via dynamic (bulk) motion Comptonization [see 44, for details]. Second, with respect to the phenomenological *powerlaw* model, the BMC spectral shape has an appropriate low energy curvature, which is essential for a correct representation of the lower energy part of spectrum. Our experience with *powerlaw* components shows that the model fit with this component is often inconsistent with the N_H column values and produces an unphysical component "conspiracy" with the *highecut* part. Specifically, when a multiplicative component *highecut* is combined with BMC, the cutoff energies E_{cut} are in the expected range of 20∼30 keV, while in a combination with *powerlaw*, E_{cut} often goes below 10 keV, resulting in unreasonably low values for photon index. As a result, the implementation of the phenomenological *powerlaw* model makes much harder, or even impossible to correctly identify the spectral state of the source, which is an imminent task for our study. Third, and even a more important property of the BMC model, it calculates consistently the normalization of the original "seed" component, which is expected to be a correct mass accretion rate indicator. Note the Comptonized fraction is properly evaluated by the BMC model.

We consider a scenario related to our spectral model (see Fig. 1) where the Compton cloud along with converging flow are located in the innermost part of the source and the Keplerian disk is extended from the Compton cloud (CC) to the optical companion (see e.g. TF04). An iron K_α-line (*laor*) component [16] was included in our model spectrum. To summarize the spectral model parameters are the equivalent hydrogen absorption column density N_H; spectral indices α_1, α_2 (photon index $\Gamma = \alpha + 1$); color temperatures of the blackbody-like photon spectra kT_1, kT_2; $\log(A_1)$, $\log(A_2)$ related to the Comptonized fractions f_1, f_2 [$f = A/(1+A)$]; normalizations of the blackbody-like components N_{bmc1}, N_{bmc2} for the *BMC1* and *BMC2* components of the resulting spectrum, respectively.

When the parameter $\log(A) \gg 1$ we fix $\log(A) = 2$ because the Comptonized fraction $f = A/(1+A) \to 1$ and

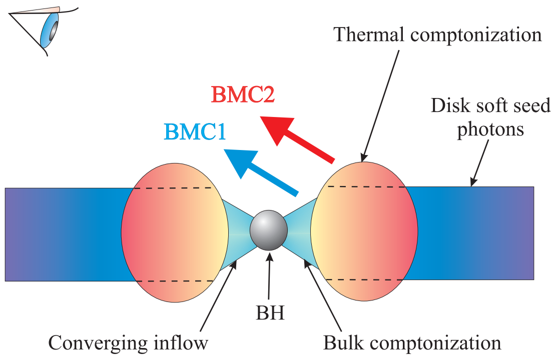

Figure 1. Schematic view of the proposed geometry for thermal and bulk Comptonization regions in the source hosting a BH with PL-like emission at high energies. The thermal plus bulk Comptonization spectrum (thermal plus bulk *BMC1*) arises in the innermost part of the transition layer (TL), where the disk BB-like seed photons are (thermally and dynamically) Comptonized by the in-falling material. Whereas the thermal Comptonization spectrum (thermal *BMC2*) originates in the outer part of the TL region.

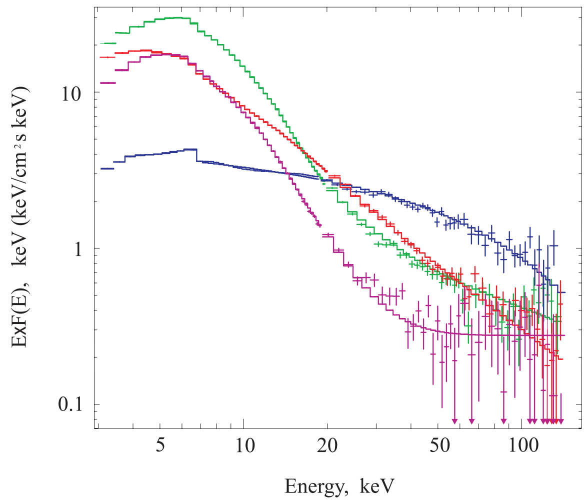

Figure 2. Four representative EF_E spectral diagrams during LHS, IS, HSS and VSS spectral states of GRS 1915+105. Data are taken from *RXTE* observations 20402-01-11-00 (*blue*, LHS), 91701-01-33-00 (*red*, IS), 91701-01-11-00 (*green*, HSS) and 91701-01-19-00 (*purple*, VSS).

variation of A does not improve the fit quality any more.

During LHS the BMC2 component is often very low or barely detectable or undetectable at all. This observational fact is in agreement with scenario of BH spectral state transition (TF04). During LHS the spectrum is characterized by a strong hard power-law component. In other words the energy spectrum is dominated by a Comptonized component seen as a power-law hard emission in energy range from ~ 10 to ~ 70 keV while the disk emission remains weak (LHS, IS), because only a small fraction of the disk emission component $(1-f)$ is directly seen

OBSERVATIONAL RESULTS

Evolution of spectral properties during state transitions

Observations of Galactic BH X-ray binaries reveal diverse spectral and dynamic phenomenologies. The evolution of a BH binary is usually described in terms of spectral states. There are several flavors of BH state definitions in literature, which slightly differ in BH state definitions and terminology [see, for example 37, 2, 3, 12]. To distinguish different states, the properties observed in the energy spectrum and Fourier power density spectrum (PDS) are utilized. As we have already emphasized in the introduction section we use, in our study, the general state classification for four major BH states: *low-hard* (LHS), *intermediate* (IS), *high-soft* (HSS) and *very soft* state (VSS).

The general picture of LHS-IS-HSS transition is illustrated in Figure 2, for the case of GRS 1915+105, where we bring together spectra of LHS, IS, HSS and VSS to demonstrate the source spectral evolution from low-hard to soft states. We should emphasize different shapes of the spectra for the different spectral states. In the LHS spectrum the Comptonization component is dominant and the blackbody (BB) component is barely seen in 3-150 keV energy range. The IS and HSS spectra are characterized by a strong soft BB component and a power law extended up to 150 keV. In VSS the soft BB component is dominant and the power-law component is relatively weak with respect of this in IS and HSS.

As seen from Fig. 3 the start of this rise transition coincides with active phase of X-rays, and of radio emissions which exceed 10 ASM counts/s and 50 mJy levels respectively in the 1997 rise transition. Around MJD 50580 day the source reaches the HSS (when $\Gamma_1 \sim 3$). Then a long HSS period from MJD 50580 to 50700, when Γ_1 stays almost the same, is followed by the state transition to IS during which Γ_1 decreases to 2.5.

We also find that the photon index of X-ray spectrum is tightly correlated with the quasi-periodic oscillations (QPO) frequency (see e.g. Fig. 5 and more examples of index-QPO correlations in ST09) which can be considered as a strong argument that QPOs and X-ray Comptonization spectrum emerge from the same geometrical configuration (Compton cloud). However the flux density S_{15GHz} and QPO frequency are not correlated with each other when the source changes its spectral states

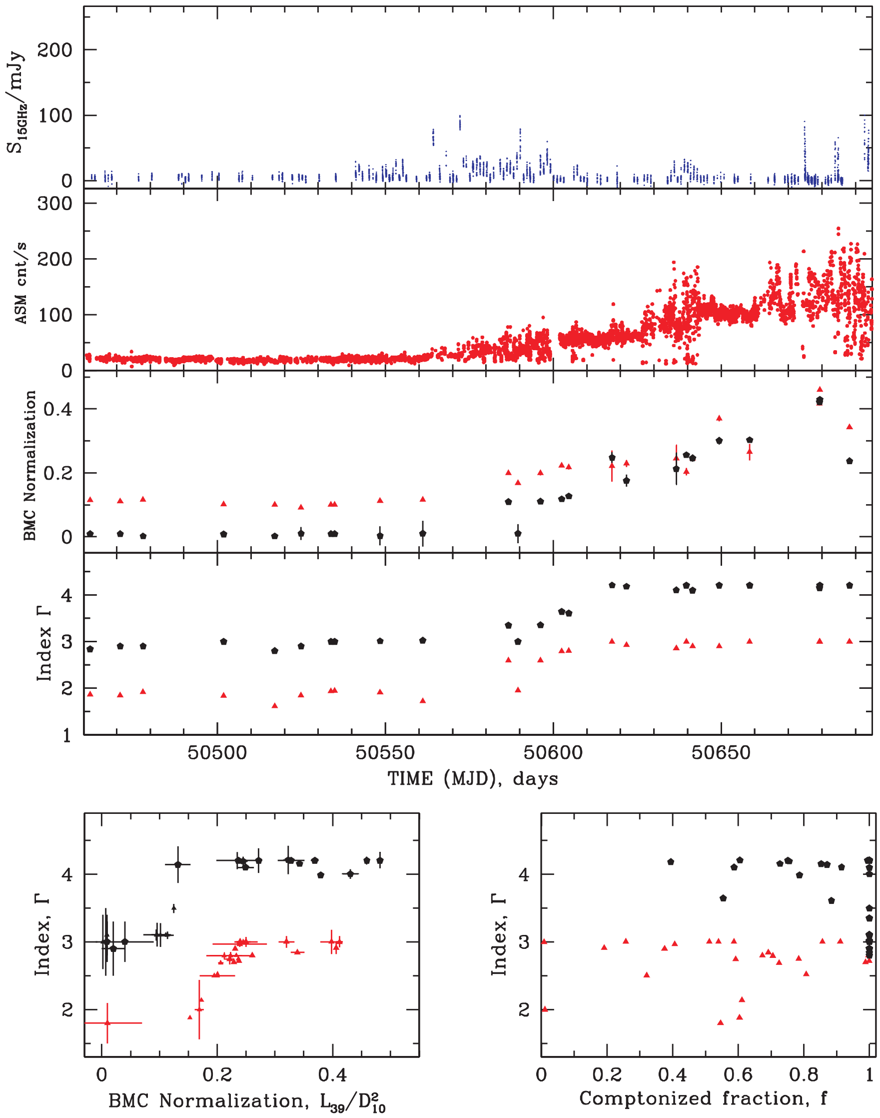

Figure 3. *From Top to Bottom:* Evolutions of the flux density S_{15GHz} at 15 GHz (Ryle Telescope), *RXTE*/ASM count rate, BMC normalization and photon index Γ in the beginning of the 1997 rise transition of GRS 1915+105 (MJD 50460-50700). Red/black points (*for two last panels*) correspond to hard/soft components with Γ_1 and Γ_2, respectively. *Bottom:* Spectral index Γ plotted versus BMC normalization (*left*) and Comptonized fraction (*right*) for this transition. Here the red triangles/black circles correspond to hard/soft components with Γ_1 and Γ_2, correspondingly. Note that in most cases the normalization of the hard BMC component (*BMC*1) is higher than that of the soft component (*BMC*2) (see red points vs black points in BMC normalization-time panel).

(see the case of GRS 1915+105 in TS09).

INTERPRETATION AND DISCUSSION OF OBSERVATIONAL RESULTS

Before to proceed with the interpretation of the observations let us to briefly summarize them as follows: i. The spectral data of BH sources are well fit by two (soft and hard) BMC components for most of analyzed IS and HSS spectra while LHS spectra essentially require only one BMC component, the soft BMC component is very weak (see panel S1 in Fig. 4). ii. The Green's function indices of each of these components rise and saturate with an increase of the BMC normalization (disk flux). iii. We also find a tight positive correlation of QPO frequencies with the index and consequently that with the disk flux (see Figs. 4-5). iv. We also do not find any correlation between X-ray and radio fluxes and X-ray power-law index (see TS09).

Index-QPO and index-$\dot{m}$ correlations. Index saturation

We confirm the index-QPO correlation in GRS 1915+105 previously found by V03 and ST07. This correlation was indeed predicted by [49], hereafter TLM98, who argued that the transition layer [Compton cloud (CC)] formed between the Keplerian disk and the central object (NS or BH), contracts and becomes cooler when the disk mass accretion rate $\dot{m}$ increases. The observational effect of the CC contraction were later demonstrated by ST06, TSA07, TS08 and [32] in Cyg X-1 and XTE J1650-500 respectively. As a result of the transition layer (TL) contraction the QPO low frequency ν_L, which is presumably the TL's normal mode oscillation frequency, increases with $\dot{m}$ given that ν_L is inversely proportional to the TL size. On the other hand the index monotonically increases when the TL (CC) cools down. TF04 provided the details of the index-QPO correlation model where they pointed out that this correlation is a natural consequence of the spectral state transition.

In this Paper we have demonstrated the index correlation with ν_L along with the index saturation vs the BMC normalization N_{bmc} (Eq. 1) for the Comptonized components of the X-ray spectra of BH binaries (see Figs. 4-5). Below we show that N_{bmc} is actually proportional to mass accretion rate in the disk. Namely the disk flux L (as a source of soft photons for Comptonization, see e.g. Fig. 1 for the geometry of soft photon illumination of Comptonized region) can be represented as

$$L = \frac{GM_{bh}\dot{M}}{R_*} = \eta(r_*)\dot{m}_d L_{\rm Ed}. \quad (2)$$

Here $R_* = r_* R_{\rm S}$ is an effective radius where the main energy release takes place in the disk, $R_{\rm S} = 2GM/c^2$ is the Schwarzschild radius, $\eta = 1/(2r_*)$, $\dot{m}_d = \dot{M}_d/\dot{M}_{crit}$ is dimensionless mass accretion rate in units of the critical mass accretion rate $\dot{M}_{crit} = L_{\rm Ed}/c^2$ and $L_{\rm Ed}$ is the Eddington luminosity.

On the other hand

$$L_{\rm Ed} = \frac{4\pi GMm_p c}{\sigma_{\rm T}} \quad (3)$$

i.e. $L_{Ed} \propto M$ and thus using Eqs. (2-3) we obtain that

$$L \propto \eta(r_*)\dot{m}_d m. \quad (4)$$

In HSS when the inner disk radius R_* reaches its lowest value $R_* \gtrsim 3R_{\rm S}$, the efficiency of the gravitational energy release $\eta(r_*)$ reaches its highest value and thus the disk flux increases only when the disk mass accretion rate increases (see Eq. 4). Given that BMC normalization N_{bmc} is proportional to $\dot{m}_d$ in HSS the observational effect of the index saturation with N_{bmc} is translated to the index saturation with $\dot{m}_d$.

First we interpret the index saturation related to the hard Comptonization component (*BMC1*). We suggest that this BMC1 component of the emergent spectrum is presumably originated in the converging flow onto a compact object, in our case to the BH (see Fig. 1). In fact, in HSS the plasma temperature of the accretion flow is comparable with the color temperature of the disk photons (see TF04). Thus, in order to explain the high energy tail observed in HSS of BH sources, one should assume either an unknown source of high energy non-thermal electrons [see e.g. [6]] or consider effects of energy transfer from the converging flow electrons to the photons emitted from the innermost part of the accretion flow.

Optical depth of the converging flow τ is proportional to $\dot{m}_d$ if one assumes that disk accretion flow continuously goes to the converging flow and there are no other components in the accretion flow [see e.g. a model of two component accretion flow by [5], hereafter CT95]. This effect of the index saturation vs optical depth of the bulk flow (BM) τ was first predicted by [56] and then it was subsequently reproduced in Monte-Carlo simulations by [17], hereafter LT99.

It is worth noting that the index saturation effect is an intrinsic property of the bulk motion onto a BH given that the spectral index $\alpha = \Gamma - 1$ is a reciprocal of the Comptonization parameter Y [see this proof in ST09 and [4]] which saturates when the BM optical depth,

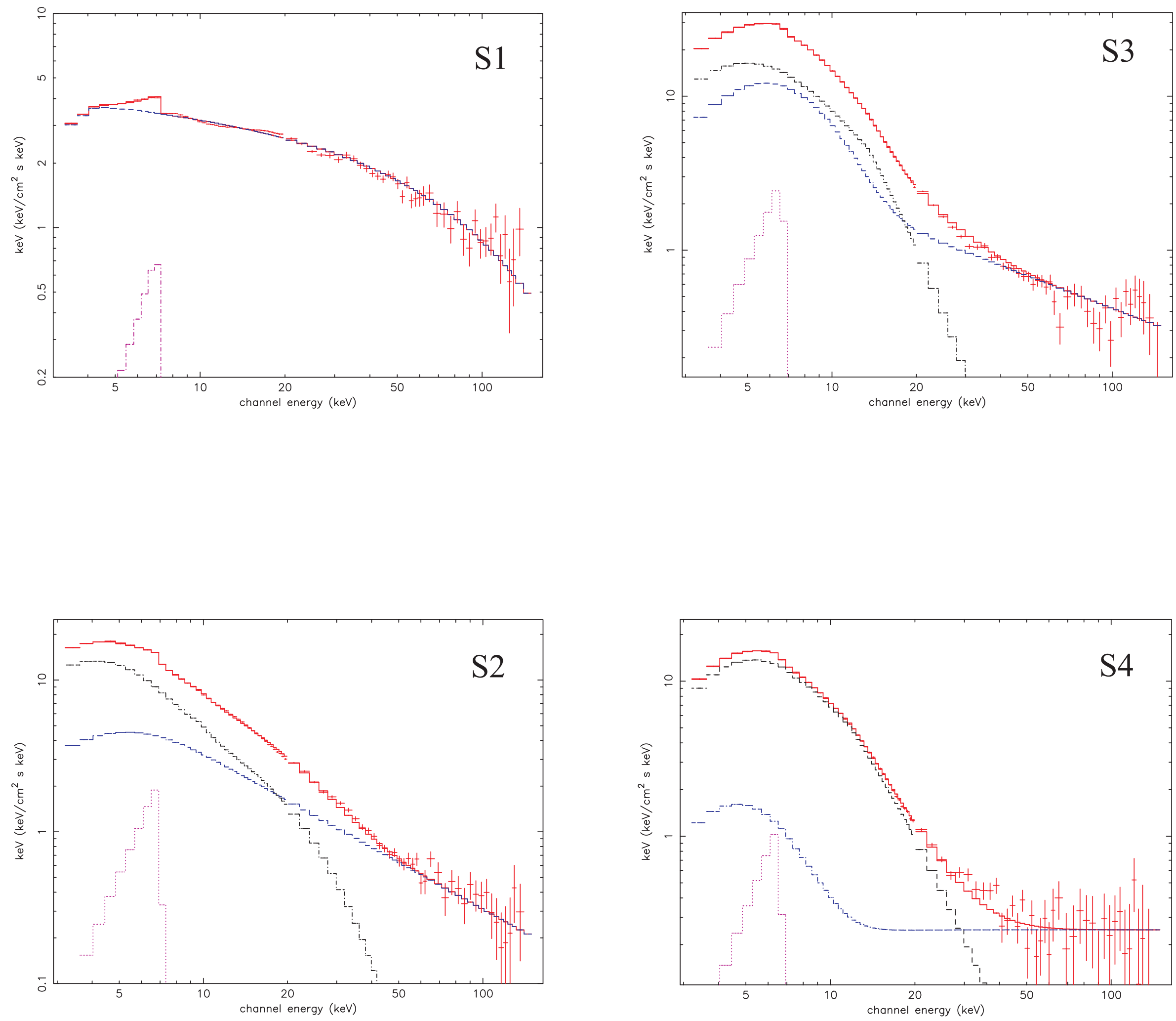

Figure 4. Evolution of spectum shape of GRS 1915+105 during LHS, IS, HSS and VSS spectral states. Data are taken from *RXTE* observations 20402-01-11-00 (*S1*, $\Gamma_1 = 1.8$, LHS), 91701-01-33-00 (*S2*, $\Gamma_1 = 2.9$, $\Gamma_2 = 3.7$, IS), 91701-01-11-00 (*S3*, $\Gamma_1 = 2.7$, $\Gamma_2 = 4.1$, HSS) and 91701-01-19-00 (*S4*, $\Gamma_2 = 4.2$, VSS). Here data are denoted by red points, the spectral model presented with components are shown by blue, black and dashed purple lines for *BMC1*, *BMC2* and *laor* components respectively.

or $\dot{M}$, increases. In fact, the Y-parameter is a product of the average photon energy exchange per scattering η and the mean number of photon scattering N_{sc}, i.e. $Y = \eta N_{sc}$. For the thermal Comptonization case, $Y \sim (4kT/m_ec^2)\tau^2$ given that in this case $\eta = 4kT/m_ec^2$ and $N_{sc} \sim \tau^2$ for $\tau \gg 1$ [see e.g. 40] and, thus, the thermal Comptonization spectral index is

$$\alpha \sim [(4kT/m_ec^2)\tau^2]^{-1}. \quad (5)$$

In the case of converging flow, the preferable direction for upscattered photons is the direction of bulk motion onto the BH, i.e along the radius. Note that the fractional photon energy change is

$$\Delta E/E = (1-\mu_1 V_R/c)/(1-\mu_2 V_R/c).$$

where μ_1 and μ_2 are the cosines of the angles between the direction of the electron velocity $\mathbf{n} = \mathbf{V}_R/V_R$ and direction of incoming and outcoming (scattered) photons respectively.

The number of scatterings of the up-Comptonized photons N_{sc} can be estimated as a ratio of the radial characteristic size of the converging flow L and the free path l in the direction of motion, namely $N_{sc} \propto L/l = \tau$ given that $\Delta E/E$ has a maximum at $\mu_2 = 1$ for given μ_1 and V_R. On the other hand the efficiency per scattering for bulk motion flow $\eta \propto 1/\tau$ when $\tau \gg 1$ [[19], hereafter LT07] hence for bulk motion Comptonization, the Y-parameter does not depend on τ for high values of τ or dimensionless mass accretion rate $\dot{m}$. Thus one can conclude that *the Comptonization parameter $Y = \eta N_{sc}$ and hence the energy index $\alpha = Y^{-1}$ saturate to a constant value when optical depth (or mass accretion rate) of the BM flow increases*.

However the index saturation value is determined by the plasma temperature during a transition [see LT99]. The plasma temperature strongly depends on the mass accretion rate in the bulk motion region $\dot{M}_{bm}$ and its illumination by the disk photons L (see TLM98 and TF04). For higher $\dot{M}_{bm}$ and L the plasma temperature is lower. The level of the index saturation decreases when the plasma temperature in the bulk motion increases (TF04). Thus the index saturation levels can be different from source to source depending on the strength of the disk. Looking at Figure 4 one can also notice that the index Γ_1 starts its saturation at different values of BMC normalization ($\propto \dot{m}_d$) for different types of active episodes. In fact, the index should saturate with mass accretion rate in the converging flow $\dot{m}_{bm}$ which is a sum of the disk mass accretion rate $\dot{m}_d$ and that in sub-Keplerian flow (CT95). Hence one can argue that this lower value of $\dot{m}_d$ at which the index saturates can be a sign of the presence of extra (sub-Keplerian) component in the accretion flow onto BH, for example in the case of GRS 1915+105.

[18], hereafter LT09, study the index-$\dot{m}$ correlation and also a modification of the disk blackbody spectrum due to Comptonization in the optically thick CC, which is formed due to accumulation of accretion matter in the TL. They indeed explain the saturations of the indices of the soft and hard components of the resulting spectrum. Specifically LT09 show that gravitational energy of the accretion flow is released in the optically thick and relatively cold TL when mass accretion rate $\dot{m}_d$ is higher than 1. The level of the index saturation depends on the radial velocity in the transition layer (TL). LT09 also show that the observable saturation index of the soft BMC component $\Gamma_2 \sim 4.2$ can be reproduced in their Monte Carlo simulations for values of the TL radial velocity $\gtrsim 0.05$ c.

CONCLUSIONS

We concentrate our efforts on the study of the correlation between the spectral index and the accretion disk luminosity. We argue that the shape of the correlation pattern can contain the direct BH signature. Namely, we show both observationally and theoretically that the index saturates with mass accretion rate which is a signature of a converging flow. This index saturation effect can exist only in BH sources. Also this correlation pattern carries the most direct information on the BH mass and the distance to the source (see ST09).

We compiled the state transition data from 8 BH candidate sources. collected with the *RXTE* mission. We examined the correlation between the photon index of the Comptonized spectral component, its normalization and the QPO frequency.

The spectral data of these BH sources are well fitted by two BMC components for most of analyzed IS and HSS spectra (see e.g. Figs. 2-5) while LHS spectra essentially require only one BMC component.

A remarkable result of our study is that the index - normalization (mass accretion rate) correlation seen in these BH candidate sources is predicted by the theory of the converging flow. We demonstrate that a strong index saturation vs disk flux seen in the index-disk flux correlation (see e.g. Fig. 4-5) is an observational signature of the presence of the converging flow, which should only exist the BH sources. In other words, *this index saturation effect provides a robust observational evidence for the presence of black hole in these sources*.

We also find a tight positive correlation of QPO frequencies with the index and consequently that with the disk flux.

Also our comprehensive analysis of X-ray and radio emissions in GRS 1915+105 shows that QPOs are seen independently of radio activity of the source during the spectral transition from low-hard to high-soft state. Specifically these QPO features have been detected at any level of the radio flux and even when the radio emission is at the noise level. We also do not find any correlation between X-ray and radio fluxes and X-ray power-law index. (see TS09). However, we establish a strong correlation between equivalent width of iron line and radio flux in binary GRS 1915+105 (see TS09).

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