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ACCRETION-JET MODEL FOR THE HARD X-ray $\Gamma - L_X$ CORRELATION IN BLACK HOLE X-ray BINARIES

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ABSTRACT

In this work, we study the correlation between the photon index (Γ) of the X-ray spectrum and the $2 - 10$ keV X-ray luminosity (L_X) for black hole X-ray binaries (BHBs). The BHB sample is mainly from the quiescent, hard and intermediate states, with values of L_X ranging from $\sim 10^{30.5}$ to $10^{37.5}\,\mathrm{erg\,s^{-1}}$. We find that the photon index Γ is positively or negatively correlated with the X-ray luminosity L_X, for L_X above or below a critical value, $\sim 10^{36.5}\,\mathrm{erg\,s^{-1}}$. This result is consistent with previous works. Moreover, when $L_X \leq \sim 10^{33}\,\mathrm{erg\,s^{-1}}$, we found that the photon index is roughly independent of the X-ray luminosity. We interpret the above correlations in the framework of a coupled hot accretion flow – jet model. Besides, we also find that in the moderate-luminosity region, different sources may have different anti-correlation slopes, and we argue this diversity is caused by the different value of δ, which describes the fraction of turbulent dissipation that directly heats electrons.

Key words: accretion, accretion disks, binaries, X-rays

1. INTRODUCTION

The spectral and timing properties of X-ray radiation can provide important clues on the geometry of accretion disks and/or radiative properties of the central engines of black hole X-ray binaries (BHBs). We usually describe the observed BHB X-ray spectrum with a power-law form $N(E) \propto E^{-\Gamma}$, where $N(E)$ is the photon number density and Γ is the photon index.

The photon index Γ is observed to be tightly correlated with the X-ray luminosity L_X, and different correlations are observed. For example, through observations of two BHBs (XTE J1118+480 and XTE J1550-564), Yuan et al. (2007) found that there is a positive (negative) $\Gamma - L_X$ correlation when the 1-100keV X-ray luminosity is above (below) $\sim 2\%$ $L_{\rm Edd}$ ($L_{\rm Edd} = 1.26 \times 10^{38} [M/M_\odot]\,\mathrm{erg\,s^{-1}}$). Later, using a large sample of BHBs, Wu & Gu (2008) investigated the relationship between Γ and the Eddington ratio ($L_{0.5-25\ \rm keV}/L_{\rm Edd}$), and found a similar V-shaped $\Gamma - L_X$ correlation. However, when the BHBs are in the quiescent state, i.e., for the extremely low-luminosity region, Plotkin, Gallo & Jonker (2013) found Γ plateaus to a constant value $\Gamma \sim 2.1$, and it may be independent of L_X. The above correlations are important for us to understand the black hole radiative processes and accretion physics.

In this paper, we try to understand the range of observational $\Gamma - L_X$ correlations under the coupled hot accretion flow – jet model (cf. Yuan, Cui & Narayan 2005), a model which has been successfully applied to the hard/quiescent states of BHBs and low-luminosity AGNs. This work is organized as follows. First, we compile a sample of BHBs which is larger than all previous ones, and show the $\Gamma - L_X$ correlation results in §2. Then, in §3 & §4, we describe our model and present the results of our theoretical calculations. Finally, a brief summary and discussion are given in §5.

2. DATA AND CORRELATION

We collect from the literature data for when the sources are in the quiescent, hard, and intermediate states, and our final BHBs sample includes 195 observational data points. We show the $\Gamma - L_X$ correlation results in Fig. 1. We can see that L_X ranges from from $\sim 10^{30.5}$ to $\sim 10^{37.5}\,\mathrm{erg\,s^{-1}}$ and the photon indices Γ of the BHBs are mainly in the range of $1.5 - 2.5$.

Roughly, depending on the value of L_X, we can see from Fig. 1 that the correlation can be divided into three branches: 1) $L_X \geq 10^{36.5}\,\mathrm{erg\,s^{-1}}$; 2) $10^{33} \leq L_X \leq$

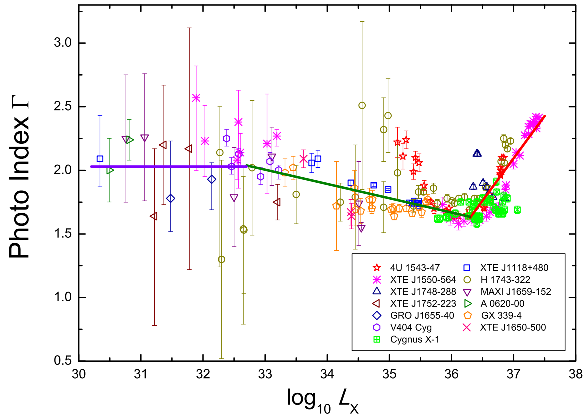

Figure 1. The X-ray photon index Γ versus the 2-10 keV X-ray luminosity L_X for BHBs. The solid lines represent the $\Gamma - L_X$ fitting results for three branches. See text for details.

$10^{36.5}\,\mathrm{erg\,s^{-1}}$; 3) $L_X \le 10^{33}\,\mathrm{erg\,s^{-1}}$. To obtain the correlations between Γ and $\log_{10} L_X$, we adopt the weighted least-χ^2 linear fitting method, and the results are as follows:

For the luminous part ($L_X \ge 10^{36.5}\,\mathrm{erg\,s^{-1}}$), Γ is positively correlated with L_X,

$$\Gamma = (0.66 \pm 0.01)\ \log_{10} L_X - (22.59 \pm 0.25). \quad (1)$$

For the moderate-luminosity regime ($\sim 10^{33} \le L_X \le 10^{36.5}\,\mathrm{erg\,s^{-1}}$), an anti-correlation between Γ and L_X is observed, with the form

$$\Gamma = (-0.11 \pm 0.01)\ \log_{10} L_X + (5.63 \pm 0.017). \quad (2)$$

We note that the above V-shaped $\Gamma - L_X$ correlation is consistent with previous works (e.g. Yuan et al. 2007; Wu & Gu 2008).

Finally, for the extremely low-luminosity region ($L_X \le 10^{33}\,\mathrm{erg\,s^{-1}}$), we find that Γ has nearly no dependence on L_X (also see Plotkin, Gallo & Jonker 2013). Therefore, we utilize an averaged value of Γ to fit this branch,

$$\langle\Gamma\rangle \approx 2.03 \pm 0.03. \quad (3)$$

3. THE THEORITICAL MODEl

The above correlations provide good constraints on theoretical models. In our work, we study whether the coupled hot accretion flow-jet model can interpret the observed $\Gamma - L_X$ correlations. The accretion-jet model includes three distinctive components, i.e., a standard thin disk which is truncated at radius $R_{\rm tr}$, a hot accretion flow within this radius, and a relativistic jet.

The hot accretion flow will dominate the hard X-ray radiation of BHBs when the accretion rate ($\dot{M}$) is high. However, decreasing $\dot{M}$, the X-ray emission from the jet decreases slower than that from the hot accretion flow. Therefore, the X-ray emission will be dominated by the the jet when the X-ray luminosity is below a critical value $L_{\rm crit}$ (e.g. Yuan & Cui 2005; Xie, Yang & Ma 2014).

In the following part of this section, we will introduce the hot accretion flows and the jet components briefly.

3.1. Hot Accretion Flow

The hot accretion flow is the advection-dominated accretion flow (ADAF)/the luminous hot accretion flow (LHAF) when the mass accretion rate is below/above a critical value, $\dot{M}_{\rm crit,ADAF}$ (Yuan 2001; Xie & Yuan 2012).

For ADAF, the viscous heating energy is mainly stored in the flow and advected inwards. With increasing $\dot{M}$, advection cooling becomes less dominant, and finally when $\dot{M} > \dot{M}_{\rm crit,ADAF}$, the flow will enter into the LHAF region. Yuan (2001) showed that hot accretion flows are permitted if $\dot{M}$ is less than the critical accretion rate $\dot{M}_{\rm crit,LHAF}$, and in this regime, we label the hot accretion flow as Type I LHAF. However, when the accretion rate is higher than $\dot{M}_{\rm crit,LHAF}$, radiative cooling become so strong that some cold dense clumps may be formed in the hot phase (Yuan 2003). We call this a two-phase model or Type II LHAF.

In the hot accretion flow, the main parameters are: viscous parameter α, magnetization parameter β (the ratio of the gas to the magnetic pressure, $P_{\rm gas}/P_{\rm mag}$), wind parameter s [$\dot{M}(r) \propto r^s$], and the electron heating parameter δ, which describes the fraction of the turbulent dissipation that directly heats electrons.

3.2. Jet

Detailed information about the jet model can be found in Yuan, Cui & Narayan (2005). The jet model adopted in this work is based on the internal shock scenario. A fraction of the material in the accretion flow is assumed to be transferred to the vertical direction to form a jet, which has a conical geometry with half-opening angle $\theta_j = 0.1$, and bulk Lorentz factor $\Gamma_{jet} = 1.2$ (or equivalently the bulk velocity is 0.6 c). In the jet, shells with different velocities likely collide with each other. The result is that a small fraction of the electrons in the jet will be accelerated into a power-law energy distribution with an index $p_{\rm e}$. Since the radiative cooling timescale of the high-energy electrons is typically much shorter than the dynamical timescale, the steady distribution of those most energetic electrons will become $p_{\rm e} + 1$. Two other parameters that describe the fractions of the shock energy that go into power-law electrons and the magnetic fields are ϵ_e and ϵ_B, respectively.

3.3. Underlying Physics of the $\Gamma - L_X$ Correlation

Before presenting the results of the theoretical calculations, we would like to explain the underlying physics of the $\Gamma - L_X$ correlation. In hot accretion flows, the main X-ray radiation process is usually Compton scattering. We make use of Compton y-parameter [$y = 4(\theta_e + 4\theta_e^2)(\tau + \tau^2)$] to characterize the spectral properties, where $\theta_e = kT_e/m_e c^2$ is the electron temperature and τ is the optical depth. A larger value of y means the X-ray spectrum is harder (Γ is smaller), and vise versa. For different values of $\dot{M}$, there are different dominant

X-ray radiation mechanisms in the coupled accretion – jet model, and the underlying physics for interpretation of the three branches (cf. Fig. 1.) is as follows:

(1) For the bright X-ray luminosity part, the dominant X-ray radiation is produced by two-phase (Type II LHAF) accretion flow. In this model, with the increase of $\dot{M}$, τ will also increase. However, due to the very strong radiative cooling, the electron temperature ($T_{\rm e}$) decreases dramatically. As a result, the value of y reduces (Γ becomes larger). Therefore, we have a positive $\Gamma - {\rm L_X}$ correlation in the two-phase model, as observed in the sample of luminous BHBs.

(2) For the moderate X-ray luminosity part, the X-rays are dominated by Compton scattering of synchrotron radiation in ADAF or Type I LHAF. With the decrease of $\dot{M}$, the optical depth is reduced ($\tau \propto \dot{M}$). Since $T_{\rm e}$ is only weakly anti-correlated with $\dot{M}$ ($T_e \propto \dot{M}^{-1/14}$), the value of y will be also decrease, and thus the photon index Γ increases. This means that we will have a negative $\Gamma - {\rm L_X}$ correlation underlying ADAF and Type I LHAF (also see the similar anti-correlation results in Esin et al. 1997).

(3) For the extremely low X-ray luminosity part, Yuan & Cui (2005) predicts that the X-ray radiation in the accretion – jet model is dominated by the synchrotron radiation of the jet. As we mentioned in §3.2, the steady distribution of the nonthermal electrons is $p_{\rm e}+1$, and according to synchrotron radiation theory, we have

$$\Gamma = 1 + (p_{\rm e} + 1 - 1)/2 = 1 + p_{\rm e}/2. \quad (4)$$

That means, given the value of $p_{\rm e}$, the jet model predicts a constant value of Γ, which has no dependence of the X-ray luminosity, as observed in quiescent BHBs sources.

4. THEORETICAL CALCULATION RESULTS

4.1. General Results

In our theoretical calculations, we set the black hole mass of the BHBs to be $10 M_\odot$, and our calculation results are presented in Fig. 2. We can see that the accretion-jet model explains the observational data reasonably well.

Detailed information about the theoretical modeling parameters is as follows. First, for the hot accretion flows, we set the viscous parameter $\alpha = 0.3$, magnetization parameter $\beta = 9$, wind parameter $s = 0.3$ throughout this paper. We treat the electron heating parameter δ as a free parameter, since there is no consensus about the value of δ at present, but work so far suggests that δ is mainly in the range of $0.1 \sim 0.5$ (Yuan & Narayan 2014). Specifically, for ADAF and Type I LHAF models, we adopt two different δ values ($\delta = 0.1$ & 0.5) to make the theoretical calculations; for the two-phase accretion flow, we only choose $\delta = 0.5$. Then, for the jet model, we set $\epsilon_B = 0.02$ and $\epsilon_e = 0.2$. According to the results of relativistic shock acceleration, we set $p_e = 2.2$. A further parameter is the mass loss rate into the jet ($\dot{M}_{\rm jet}$), which can be determined by the method given in Yuan & Cui (2005).

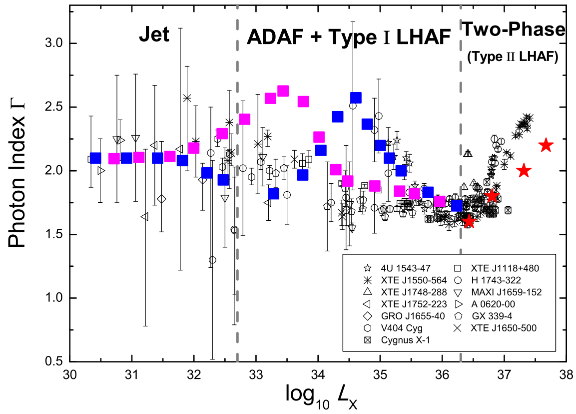

Figure 2. The theoretical calculation results under the framework of accretion-jet model for the BHBs. The detailed theoretical modeling parameters are as follows: $\alpha = 0.3$, $s = 0.3$, $\beta = 9$, and $p_{\rm e} = 2.2$. The values of δ are different for different symbols: for the red stars, $\delta = 0.5$; for the blue and pink solid squares, $\delta = 0.5$ & 0.1, respectively. The text words ("Jet", "ADAF+Type I LHAF", "Two-phase") label on the top of the figure stand for different dominant contributors of X-ray radiation in the three regimes (cf. §2), which are separated by the two vertical gray-dashed lines.

As we described in §3.3, in the moderate-luminosity regime, there should be a negative $\Gamma - {\rm L_X}$ correlation predicted by the ADAF+Type I LHAF model. From Fig. 2, in the range of $\sim 10^{34.5} \le {\rm L_X} \le 10^{36.5}\,{\rm erg\,s^{-1}}$, we see this anti-correlation is consistent with the detailed calculation results. However, when the X-ray luminosity varies from $10^{34.5}$ down to $10^{33}\,{\rm erg\,s^{-1}}$, the theoretical calculation results show that a "bump" or a positive $\Gamma - {\rm L_X}$ correlation seems to exist. The reason for such a "bump" is as following: at such low $\dot{M}$, the scattering optical depth of the accretion flow becomes very low. Thus, the resulting spectrum of Compton scattering is not a power-law form, but a curve with scattering bumps. The positive correlation part corresponds to the rise of the bump. Since the quality of BHBs data sample is this regime is not so high, further investigation and observations are highly desirable.

4.2. The Correlation of Individual BHBs

From Fig. 1, another interesting aspect is that the $\Gamma - {\rm L_X}$ correlations seem very diverse, especially in the moderate luminosity regime. We think this may be due to some physical parameters of accretion flow being different for different BHBs. Through quantitative calculations, we identify that one such parameter, among others, is the electron heating parameter δ.

We show the correlation results for two BHBs (4U 1543-47 & XTE J1118+480) in Fig. 3, with the X-ray luminosity ${\rm L_X}$ ranging from $10^{34.4}$ to $10^{36.5}\,{\rm erg\,s^{-1}}$. The pink-dashed line and the blue-solid line show the calculated results under the framework of the accretion-jet model, with $\delta = 0.1$ & 0.5, respectively. We can see from the figure that for a larger value of δ, the $\Gamma - {\rm L_X}$ correlation slope becomes steeper.

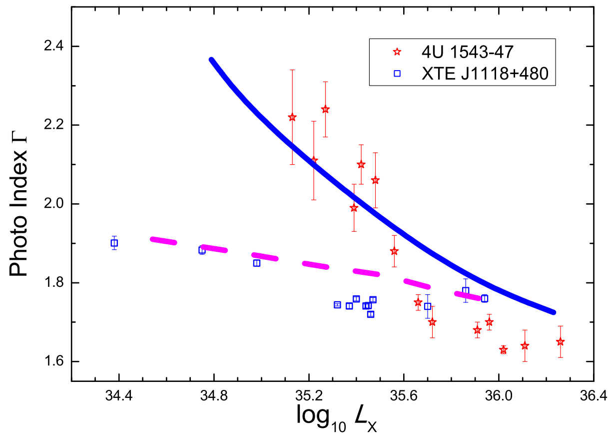

Figure 3. The $\Gamma - L_X$ correlation for 4U 1543-47 & XTE J1118+480 in the X-ray luminosity over $10^{34.4} \leq L_X \leq 10^{36.5}\,\mathrm{erg\,s^{-1}}$. The blue-solid line and the pink-dashed line are the calculational results for $\delta = 0.5$ and 0.1, respectively.

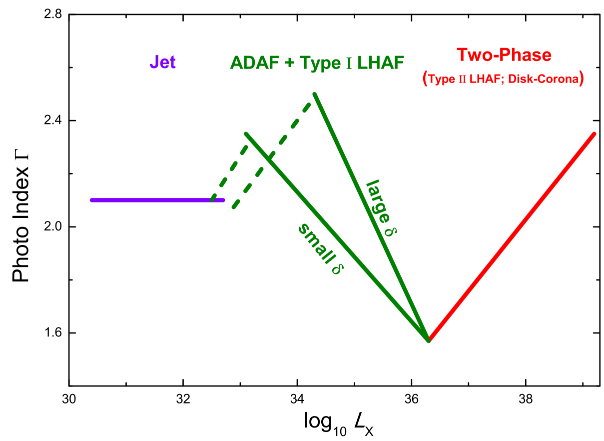

Figure 4. The schematic diagram of the 2-10 keV X-ray $\Gamma - L_X$ correlations.

We can understand the dependence between the $\Gamma - L_X$ correlation slope and δ in the following ways. First, when L_X is around $10^{36.5}\,\mathrm{erg\,s^{-1}}$, the accretion flow is Type I LHAF. We know that the radiative efficiency of Type I LHAF is not sensitive to δ (Xie & Yuan 2012), which implies that the value of Γ is very similar for different BHBs with different value of δ. Second, when L_X is around $\sim 10^{33.4}\,\mathrm{erg\,s^{-1}}$, i.e., in the relatively low-luminosity region, the accretion flow is ADAF. Because the radiative efficiency of ADAF is very sensitive to δ (Xie & Yuan 2012), for a given L_X, systems with larger δ require a smaller $\dot{M}$, which in turn results in a softer spectrum, since τ is small. From the theoretical modeling results, we argue that the δ value in XTE J1118+480 is smaller than that in 4U 1543-47.

5. SUMMARY AND DISCUSSION

In this work, we investigate the relationship between Γ and L_X, using the largest sample of BHBs to date. The value of L_X varies from $\sim 10^{30}$ to $\sim 10^{38}\,\mathrm{erg\,s^{-1}}$ (cf. Fig. 1). We explain the $\Gamma - L_X$ correlation through the coupled hot accretion flow – jet model. Our main results are shown schematically in the diagram of Fig. 4.

According to the X-ray luminosity, the observed $\Gamma - L_X$ correlations can be divided into three branches. Specifically, for the extremely low, moderate and high luminosity regions, the correlation slopes between Γ and L_X are ~ 0, negative, and positive, respectively. We argue these three $\Gamma - L_X$ correlations are caused mainly by different dominant X-ray radiation mechanisms in the accretion – jet model; detailed theoretical explanations can be found in §3. Another important issue is that, in the mid-luminosity regime, different sources seems to have different $\Gamma - L_X$ correlation slopes. We interpret such behavior via the model parameter, δ, and the result is shown in Fig. 3.

Finally, from Fig. 1, we find that there is a turning point around $L_X \sim 10^{36.5}\,\mathrm{erg\,s^{-1}}$. What is the physical origin of this turning point? In the coupled hot accretion – jet model, below/over this point, different accretion modes (Type I LHAF/the two-phase accretion flow) are at play. In addition, the turning point obtained from theoretical calculational results and the observed value are also very consistent with each otherl (see Fig. 2), which supports our theoretical model.

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