

The Hard X-ray Spectral Evolution in X-ray Binaries, Active Galactic Nulcei and Ultraluminous X-ray Sources

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We explore the relationship between the hard X-ray photon index Γ and the Eddington ratio ($\xi = L_X(0.5 - 25 \text{ keV})/L_{\text{Edd}}$) in six X-ray binaries (XRBs) with well-constrained black hole masses and distances. We find that different XRBs follow different anti-correlations between Γ and ξ when ξ is less than a critical value, while they follow the same positive correlation when ξ is larger than the critical value. This anti-correlation and positive correlation are also found in low luminosity active galactic nuclei (LLAGNs) and luminous QSOs respectively. The anti-correlation and positive correlation of different XRBs roughly converge to the same point ($\log \xi = -2.1 \pm 0.2, \Gamma = 1.5 \pm 0.1$), which may correspond to the accretion mode transition, since that the anti-correlation and positive correlation between Γ and ξ are consistent with the prediction of advection dominated accretion flows (ADAFs) and standard disk/corona system respectively. We note that traditional low-hard state are divided into two parts by the cross point $\log \xi \sim -2.1$, i.e., *faint-hard state* in the anti-correlation part and *bright-hard state* in the positive correlation part. The accretion process in the *bright-hard state* may be still the *standard accretion disk* as that in the high/soft state, which is consistent with that both the cold disk component and broad Fe K emission line are observed in some bright-hard state of XRBs (e.g., GX 339-4, Miller et al. 2006). The ADAF is only important in the *faint-hard state* XRBs.

Motivated by the similarities of the state transition and timing properties of the ultraluminous X-ray sources (ULXs) to that of XRBs, we then constrain the black hole masses for seven luminous ULXs assuming that their X-ray spectral evolution is similar to that of XRBs (i.e., photon index is only depend on the Eddington ratio). We find that the BH masses of these seven ULXs are around $10^4 M_{\odot}$, which are typical intermediate-mass BHs (IMBHs). Our results are roughly consistent with the BH masses constrained from the model fitting with a multi-color disk and/or the timing properties (e.g., QPO and break frequency).

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1. Introduction

It is generally assumed that black hole (BH) X-ray binaries (XRBs), active galactic nuclei (AGNs) and other BH systems have a similar central engine, namely the central BH, the accretion flow and a relativistic jet (for reviews see Fender et al. 2007, and Körding et al. in this proceeding). The similarities are supported by recent two “fundamental planes” of the BH activity on all mass scales, which include $L_{\text{radio}} - L_{\text{Xray}} - M_{\text{BH}}$ (e.g., Merloni et al. 2003; Falcke et al. 2004) and $L_{\text{bol}} - M_{\text{BH}} - T_{\text{break}}$ (McHardy et al. 2006). The hardness-intensity diagram and pattern of radio loudness in XRBs and AGNs also support this unification scenario (e.g., Körding et al. 2006).

The low/hard state and high/soft state are two main states in XRBs. Typically, the X-ray spectrum in hard state can be described as a power law with a photon index $\Gamma = 1.5 - 2.1$, while the energy spectrum can be described with a thermal disk component and a power law with a photon index $\Gamma = 2.1 - 4.8$ in soft state (e.g., Remillard & McClintock 2006). The hard X-ray photon index is anti-correlated to the Eddington ratio in some low/hard state XRBs (e.g., Yamaoka et al. 2005) and a sample of low luminosity AGNs (LLAGNs, Gu & Cao 2008) when the Eddington ratio is less than a critical value. However, a positive correlation is found in XRBs with higher Eddington ratio (e.g., Kubota & Makishima 2004) and luminous QSOs (e.g., Shemmer et al. 2006).

Ultraluminous X-ray sources (ULXs) are pointlike, nonnuclear X-ray sources with X-ray luminosities between 10^{39} and 10^{41} ergs/s, well in excess of the Eddington limit for a stellar mass black hole. The true nature of ULXs is still unclear, especially their BH mass, and current models include two main alternatives: (1) “intermediate-mass BHs” (IMBHs) with mass $M_{\text{BH}} \simeq 10^2 - 10^5 M_{\odot}$ (e.g., Colbert et al. 1999); (2) stellar mass BHs (e.g., Mirabel & Rodriguez 1999).

2. Sample

Six XRBs observed by *Rossi X-ray Timing Explorer* (*RXTE*) are selected, which have well determined hard X-ray spectral slopes, BH masses and distances. The X-ray data of all XRBs were observed during the *decay* of the outburst, i.e., transition from soft to hard state. For comparison, 55 LLAGNs (27 LINERs + 28 Seyferts), 26 radio-quiet QSOs, and 8 luminous ULXs are also selected. These luminous ULXs have the 0.3-10 keV X-ray luminosities near or larger than 10^{40} erg/s, and have multiple (at least three epochs) high resolution *XMM-Newton* and/or *Chandra* observations (see Wu & Gu 2008 for more details and references therein).

3. Results and Discussion

3.1 The hard X-ray spectral evolution in XRBs and AGNs

We present the relation between the photon index, Γ , and the Eddington ratio, ξ , of the XRB sample in Figure 1a, where the photon index Γ is fitted in the 3-25 keV band. We define the Eddington ratio $\xi = L_X(0.5 - 25 \text{ keV})/L_{\text{Edd}}$, in which $L_X(0.5 - 25 \text{ keV})$ is extrapolated from the unabsorbed 3-25 keV band luminosity, since which was regarded as more represent the bolometric luminosity. It can be clearly seen that the X-ray photon index Γ is strongly correlated with the Eddington ratio ξ when $-2 \lesssim \log \xi \lesssim 0$. In the low Eddington ratio (e.g., $\log \xi \lesssim -2$) part, the anti-correlation is generally present, which actually has already been found in several occasions

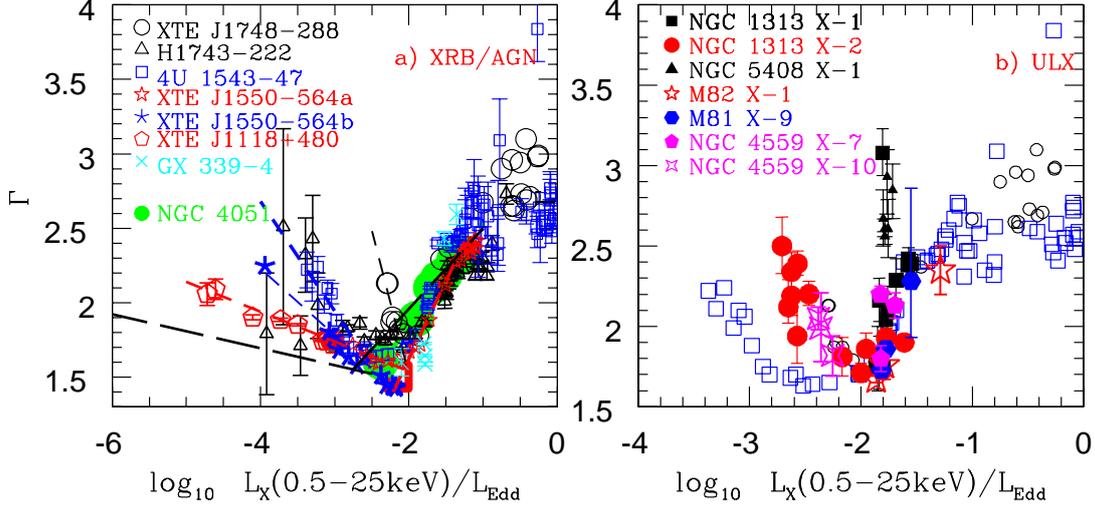


Figure 1: (a) The relation between the X-ray photon index and the Eddington ratio in XRBs and AGNs. The short dashed lines are the linear least-square fits of XRBs, and long-dashed lines are for LLAGNs (left) and QSOs (right) respectively. (b) The relation between the X-ray photon index and the Eddington ratio in ULXs. For comparison, two XRBs (XTE J1748-288 and 4U 1543-47) are also plotted.

(e.g., Yamaoka et al. 2005; Yuan et al. 2007). However, the most remarkable result in our work is that different sources follow the different anti-correlations (Fig. 1a). We fit the anti-correlation points with linear least-square method for each source. We also fit all data points at the positive correlation ($-2 \lesssim \log \xi \lesssim -1$) region as a whole with the same method (short dashed line in Fig. 1a). Therefore, for each source, we obtained the cross point between the positive and anti-correlation part. Although the anti-correlation varies from source to source, we find the cross points of all XRBs roughly converge to the same point with small scatter ($\log \xi = -2.1 \pm 0.2, \Gamma = 1.5 \pm 0.1$).

For comparison, we also plot the best fits to the relation between the photon index and the Eddington ratio in LLAGNs (long dashed-line in Fig. 1a, Gu & Cao 2008) and luminous QSOs (long dashed-line in Fig. 1a, Shemmer et al. 2006). We also include the Seyfert galaxy NGC 4051, which show strong X-ray spectrum and flux variation (green solid circles in Fig. 1a). We find that the photon index is anti-correlated to the Eddington ratio in LLAGNs, while a positive correlation is present in QSOs and NGC 4051. The anti-correlation in LLAGNs and the positive correlation in luminous AGNs cross at point ($\log \xi = -2.78, \Gamma = 1.61$), where the Eddington ratio ξ is several times less than that of XRBs, which is mainly caused by the different bolometric correction factor (see Wu & Gu 2008 for details). Therefore, it seems that the hard X-ray spectral evolution are also similar in XRBs and AGNs, which can be formulized as:

$$\Gamma = \kappa(\xi + 2.1_{-0.2}^{+0.7}) + 1.5_{-0.1}^{+0.1} \quad (3.1)$$

where κ is the slope and ξ is the Eddington ratio.

3.2 The possible accretion process and the so-called “hard state problem”

Both the UV/optical bumps observed in QSOs and the soft X-rays observed in high state XRBs can be naturally interpreted as blackbody emission from the standard accretion disk (Shakura &

Sunyaev 1976). ADAF is a hot, optically thin, geometrically thick accretion flow, which can successfully explain most features of the LLAGNs and low/hard-state XRBs (see Ho 2008; Narayan & McClintock 2008 for recent reviews). The qualitative behavior of the *anti-correlation* between the photon index and Eddington ratio is consistent with the predictions of the *ADAF* spectrum (e.g., Esin et al. 1997). The Comptonization of thermal synchrotron photons in the ADAF is the dominated cooling mechanism at low Eddington ratios. As the accretion rate increases, the optical depth of the ADAF also increases, increasing the Compton y -parameter, thereby leading to a harder X-ray spectrum. However, the *positive correlation* is consistent with the *standard disk-corona* model (e.g., Janiuk & Czerny 2000). As the accretion rate increases, both the fraction of accreting energy released to the corona and electron temperature decreases, the corona becomes weak and the *optical depth* decreases, reducing the y -parameter, and leading to a softer X-ray spectrum.

Recently, the observations of the cool disk component and the relativistic broad Fe K emission line in hard state of several XRBs (e.g., GX 339-4, Miller et al. 2006; Tomisic et al. 2008) have suggested that the standard disk may extend to the innermost stable circular orbit, which challenged the popular ADAF model in the hard state (so-called “*hard state problems*”, see a review of Tomsick et al. in this proceeding). It is interesting to note that the traditional hard state are divided into two parts, i.e., *bright hard state* and *faint hard state*, by the cross point ($\log \xi \sim -2.1 \pm 0.2$) of the anti-correlation and the positive correlation. The X-ray spectral evolution in the bright hard state is the same as that of high/soft state of XRBs and luminous QSOs. It implies that accretion process in this *bright-hard state* may be the *standard accretion disk*. It is consistent with the cool disk component and the relativistic broad Fe K emission line in the several bright hard state of XRBs (e.g., Miller et al. 2006). In contrast, the *ADAF model* becomes important in the *faint-hard state* of the XRBs with $\log \xi \lesssim -2.1$. If this is the case, the cross point may correspond to the accretion mode transition, which, however, is different from the popular idea that the disk transition occurs at $\Gamma = 2.1$.

3.3 The X-ray spectral evolution in ULXs and constraints on their BH masses

It is found that the X-ray photon index of NGC 1313 X-1 is positively correlated to the luminosity, while these two parameters are anti-correlated in NGC 1313 X-2 (Feng & Kaaret 2006), which are similar to that of XRBs/AGNs. This phenomenon has also been found in many other ULXs (e.g., Roberts et al. 2004). The similarity between XRBs, ULXs and AGNs implies that there may be similar physics behind the phenomena, which motivates us to explore the properties of ULXs utilizing the unification of ULXs and XRBs (and AGNs). Specifically, the BH masses of ULXs can be constrained if we assume that the BH accretion is scale-free and that their X-ray spectral evolution is only determined by the Eddington ratio. Assuming the spectral evolution can be described by Eq. 3.1, we thus calculate the BH masses of ULXs through the least-squares linear fit on the available data for each ULX. Our results show that all the BHs in these luminous ULXs are IMBHs of around $(4 - 30) \times 10^3 M_{\odot}$ (Table 1). We find that our estimated BH masses are consistent within a factor of two with that derived either using $v_{\text{break}} - M_{\text{BH}} - L_{\text{Bol}}$ relation for XRBs and AGNs (McHardy et al. 2006) or from the multi-color disk fittings (Miller et al. 2004) (see Table 1). These consistency may support the validity of our method, which further implies that the assumption of similarity between ULXs and XRBs is likely reasonable.

Table 1: BH mass of ULXs.

Source Name	Our BH mass	other BH mass ¹	Source Name	Our BH mass	other BH mass ²
M81 X-9	6.6×10^3	$5_{-2}^{+7} \times 10^3$	NGC 5408 X-1	$< 4.0 \times 10^3$	$2.5 \pm 1 \times 10^3$
M82 X-1	6.6×10^3	$5_{-2}^{+7} \times 10^3$	NGC 4559 X-7	1.4×10^4	7.6×10^3
NGC 1313 X-1	7.9×10^3	$4_{-1}^{+2} \times 10^3$	NGC 4559 X-10	2.7×10^4	...
NGC 1313 X-2	2.4×10^4	...			

(1)BH mass derived from the multicolor disk fittings; (2) BH mass derived from the timing properties in this work.

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