Transition Luminosities of Galactic Black Hole Transients with Swift/XRT and NICER/XTI Observations

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Abstract

Galactic black hole transients (GBHTs) show distinct X-ray spectral states at different X-ray luminosities in their outbursts. The state transitions are considered to be associated with the change in the structure of the accretion flows, caused by the change in the mass accretion rate. A narrow distribution of transition luminosity in terms of the Eddington ratio has been found in previous studies of GBHTs based on RXTE/PCA 2–20 keV data (Macarone 2003; Vahdat et al.2019) and this Eddington ratio at the transitions is often used in recent studies with instruments covering softer energy bands, such as Swift/XRT and NICER/XTI, covering energies below 1 keV to 10 keV. However, the X-ray states characterized by the spectral parameters may have different definitions depending on the energy ranges adopted in the spectral analysis, leaving the question whether the distribution of transition luminosity obtained with RXTE remains the same when we use the instruments covering softer energy bands. In this work, we investigated the state transitions and the variations of luminosities of 8 outbursts of 7 GBHTs. Our results show that the bolometric luminosity of the power-law component is tightly constrained to 1% Eddington luminosity at index transition when the photon index of that component starts to decrease towards the hard state. This is consistent with the conclusions from the previous RXTE results (Vahdat et al. 2019; Kalemci et al. 2013). Moreover, our results suggest that the disk truncation starts after bolometric disk luminosity drops below 1% Eddington luminosity.

Source Selection

sources that were observed transitions by Swift /XRT or NICER/XTI are selected. 3 of them have the simultaneous RXTE observations Those marked with circles are employed in this study.

source	period	Swift/XRT	NICER/XTI	RXTE
GX339 – 4	2007. 04 – 2007. 06	○		○
H1743 – 322	2009. 05 – 2009. 07	○		○
	2013. 07 – 2013. 09	○		
XTE J1817 – 322	2006. 02 – 2006. 07	○		○
MAXI J1305 – 704	2012. 05 – 2012. 07	○		
MAXI J1820+070	2018. 02 – 2018. 11	○	△	
MAXI J1727 – 203	2018. 05 – 2018. 10	△	○	
MAXI J0637 – 043	2019. 10 – 2020. 03	△	○	

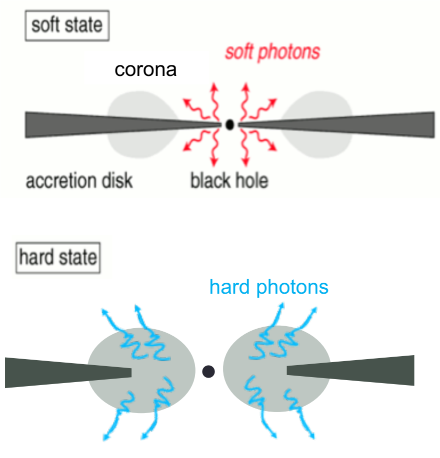
Source	Mass ($M_\odot$)	Dist. (kpc)	Inclination (°)	Binary period(h)	Binary[(a)] sep.	N_H (10^{22})	References[(b)]
GX 339–4	9.0 ± 1.4	8.4 ± 0.9	$< 60^*$	42.2	25	0.4	1, 2, 3, 4
H1743–322	8 ± 1.5	8.5 ± 0.8	$75 \pm 3^\ddagger$	...	...	1.6–2.3	5, 6, 7
XTE J1817–330	8 ± 1.5	8 ± 2	...	...	...	0.12	8
MAXI J1305–704	$8.9^{+1.6}_{-1.0}$	$7.5^{+1.8}_{-1.4}$	72^{+5*}_{-8}	9.46 ± 0.10	...	0.1–0.10	9,10
MAXI J1820+070	$8.48^{+0.79}_{-0.72}$	2.96 ± 0.33	$66 - 81^\dagger$	16.87 ± 0.07	...	$0.216^{+0.073}_{-0.065}$	11, 12, 13, 14
MAXI J1727–203	8 ± 1.5	8 ± 2	...	...	...	0.28	
MAXI J0637–430	8 ± 1.5	8 ± 2	64 ± 6	< 4	...	0.044–0.052	15, 16, 17

[(a)] Binary separation, in lightseconds.

[(b)] References: (1) Parker et al. [2016]; (2) Kong et al. [2000]; (3) Zdziarski et al. [1998]; (4) Gandhi et al. [2008]; (5) Steiner et al. [2012]; (6) Aneesha and Mandal [2020]; (7) Swartz et al. [2010]; (8) Rykoff et al. [2007]; (9) Mata Sánchez et al. [2021]; (10) Shidatsu et al. [2013]; (11) Torres et al. [2020]; (12) Espinasse et al. [2020]; (13) Atri et al. [2020]; (14) Patterson et al. [2018]; (15)Lazar et al. [2021], (16)Tetarenko et al. [2021]; (17) Jana et al. [2021]

X-ray Spectral Analysis

Model: Multicolor disk + Power-law



Diskbb: accretion disk consisting of multiple blackbody components

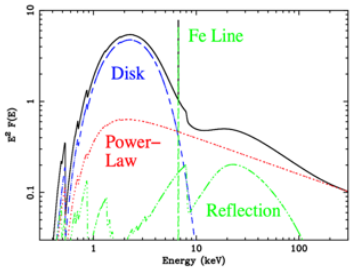
T_{in} (keV) : inner disk temperature

r_{in} (km) : Innemost disk radius

Power-law : simple photon power-law

Γ: Photon index

$A(E)= KE^{-\Gamma}$



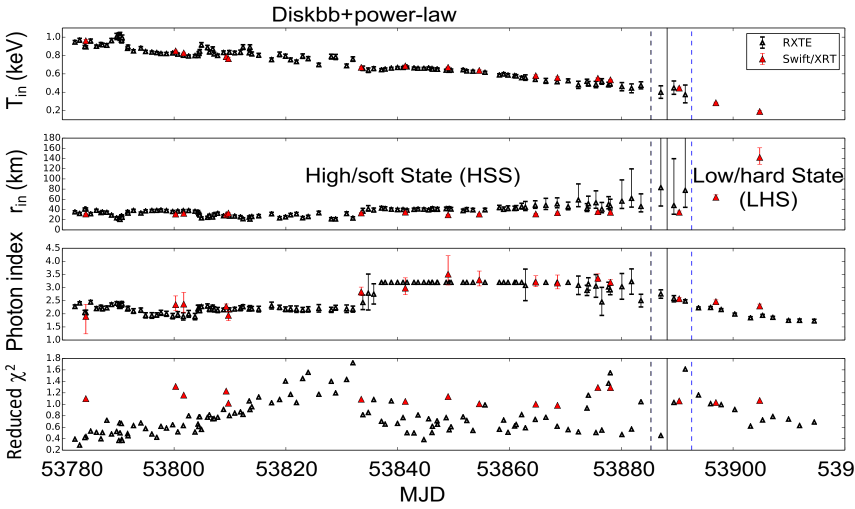
(Miller et al. 2007)

Soft State ⟶ Hard State:

T_{in} ↓ r_{in} ↑ Γ ↓

Example of Spectral Fittings: XTE J1817 – 330

Swift/XRT spectra (0.6 – 10 keV) & RXTE/PCA spectra (3 – 25 keV)



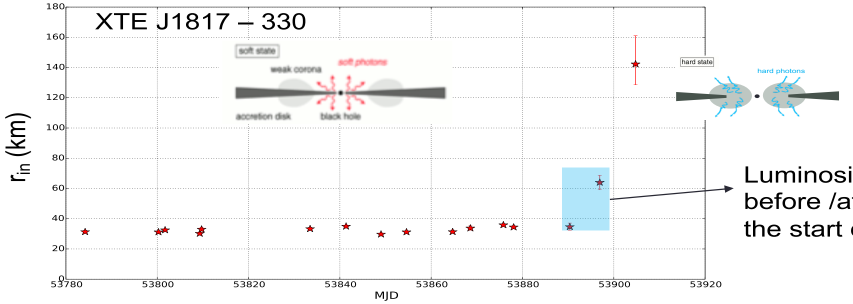
Summary 1

(1) The overall trends of spectral parameters are similar between RXTE and Swift/XRT data

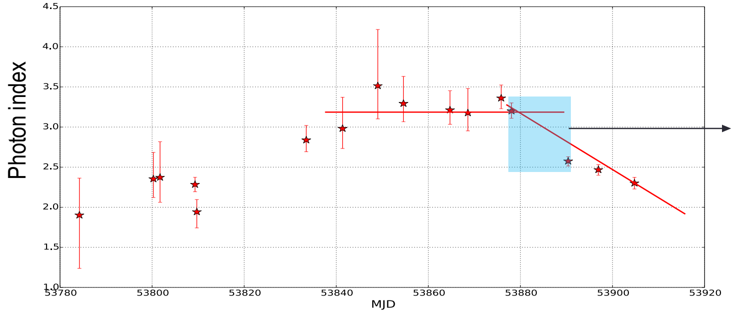
(2) The specific values may be different for simultaneous RXTE and Swift Spectra: e.g., photon index Γ is not the same in the LHS (Comptonized plasma is more complex than a single zone structure: inhomogeneous coronae)
Γ > 2.0 with XRT data is inconsistent with the typical value in LHS (RXTE definition)::specific threshold is not universal in X-ray state definition

Definitions of Transition Luminosities

To avoid the bias of applying state definitions concluded from RXTE observations in previous studies, we used two epoch to define the transition: disk recession and drop of photon index.



Luminosities
before /after
the start of disk recession

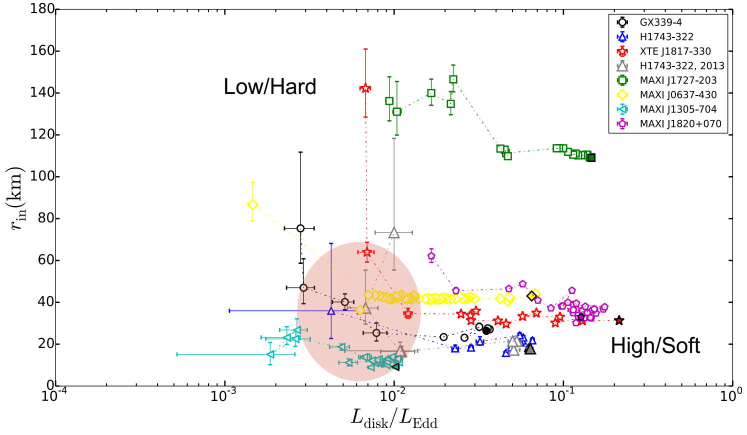


Luminosities
before /after
Index transition
(index starts to decrese)

Disk Luminosity Variations Near Disk Truncation

$$L = 4\pi D^2 F_{\rm bol} \qquad L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma_T} \cong 1.26\times 10^{38} \left(\frac{M}{M_\odot}\right) \text{ erg/s},$$

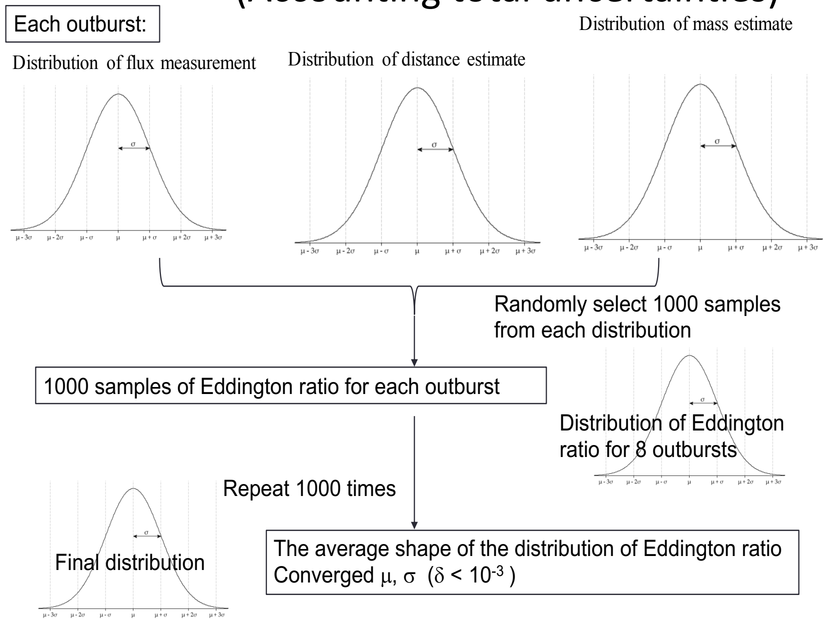
disk starts to recede ($L_{\rm disk} < 1\%\ L_{\rm edd}$)



This figure shows how the disk evolves along the disk luminosity varies, the filled star in the right side represents the start point. We can see that after the disk luminosity decreases to around 1%, though there are some outbursts deviate the "1% Eddington ratio", such as the MAXI J1727 – 203.

Monte Carlo Simulation (MCS) Applied to Luminosity Distributions (Accounting total uncertainties)

To quantify the transition luminosity distributions and to reduce the bias from a specific outburst, we performed a Monte Carlo simulation and accounted the total uncertainty of the Eddington ratio caused by the errors of flux calculation, source distance and black hole mass estimates. The black hole masses and distances are quoted from the table in "Source Selection", averaged values were adopted when lacking information (marked with blue in table). The averaged final distributions obtained after performing Monto Carlo simulation are converged and were fitted by gaussian curves.



Each outburst:

Distribution of flux measurement

Distribution of distance estimate

Distribution of mass estimate

Randomly select 1000 samples from each distribution

1000 samples of Eddington ratio for each outburst

Distribution of Eddington ratio for 8 outbursts

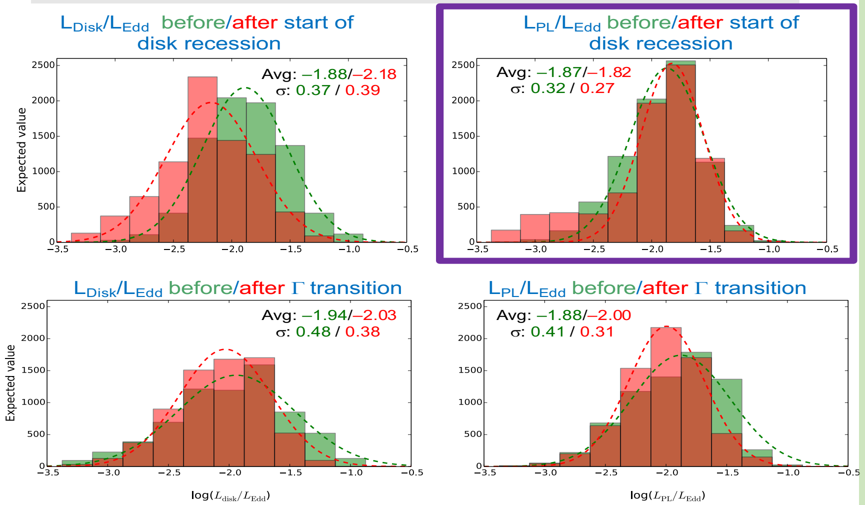
Repeat 1000 times

The average shape of the distribution of Eddington ratio Converged μ, σ ($\delta < 10^{-3}$)

Final distribution

Distributions of Transition Luminosities (MCS)

Bolometric correction: Disk flux: 0.01 – 200 keV
Power-law flux: $T_{\rm in}$ – 200 keV; 0.5 – 200 keV (no disk)


$L_{\rm Disk}/L_{\rm Edd}$ before/after start of disk recession

$L_{\rm PL}/L_{\rm Edd}$ before/after start of disk recession

$L_{\rm Disk}/L_{\rm Edd}$ before/after Γ transition

$L_{\rm PL}/L_{\rm Edd}$ before/after Γ transition

Summary 2

(1) Distinct decrease in $L_{\rm disk}$ when disk starts to recede ($L_{\rm disk} < 1\%\ L_{\rm edd}$)

(2) A narraow distribution of power-law Eddington ratio (HSS – LHS index transition)

Siwft/XRT, NICER :

$\text{Log}\ (L_{\rm pl}/L_{\rm edd}) = -2.00 \pm 0.31$

RXTE (Vahdat et al .2019):

$\text{Log}\ (L_{\rm pl}/L_{\rm edd}) = -1.70 \pm 0.21$

(3) The **narraowest distribution** of power-law Eddington ratio right after disk recession

Siwft/XRT, NICER:

$\text{Log}\ (L_{\rm pl}/L_{\rm edd}) = -1.82 \pm 0.27$

Important for constraining black hole mass with Swift/NICER data!