



# A Study on the Hysteresis Effect and Spectral Evolution in the Mini-Outbursts of Black Hole X-Ray Binary XTE J1550-564

Ai-Jun Dong<sup>1,2,3\*</sup>, Chang Liu<sup>2,3</sup>, Kang Ge<sup>2,3</sup>, Xiang Liu<sup>1</sup>, Qi-Jun Zhi<sup>2,3</sup> and Zi-Yi You<sup>2</sup>

<sup>1</sup> Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi, China, <sup>2</sup> School of Physics and Electronic Science, Guizhou Normal University, Guiyang, China, <sup>3</sup> Guizhou Provincial Key Laboratory of Radio Astronomy and Data Processing, Guizhou Normal University, Guiyang, China

## OPEN ACCESS

### Edited by:

Jianfu Zhang,  
Xiangtan University, China

### Reviewed by:

Fu-Guo Xie,  
Chinese Academy of Sciences, China  
Dahai Yan,  
Chinese Academy of Sciences, China

### \*Correspondence:

Ai-Jun Dong  
ajdong@163.com

### Specialty section:

This article was submitted to  
High-Energy and Astroparticle  
Physics,  
a section of the journal  
Frontiers in Astronomy and Space  
Sciences

**Received:** 10 January 2021

**Accepted:** 26 February 2021

**Published:** 16 June 2021

### Citation:

Dong A-J, Liu C, Ge K, Liu X, Zhi Q-J  
and You Z-Y (2021) A Study on the  
Hysteresis Effect and Spectral  
Evolution in the Mini-Outbursts of  
Black Hole X-Ray Binary XTE  
J1550-564.  
*Front. Astron. Space Sci.* 8:651661.  
doi: 10.3389/fspas.2021.651661

One normal outburst and three mini-outbursts have been detected by Rossi X-ray Timing Explorer satellite after 2000 in the well-known black hole X-ray binary XTE J1550-564. In this work, we explore the hysteresis effect of the four outbursts, which is a phenomenon that a similar spectral state transition occurs at different luminosity in an outburst of black hole X-ray binary. A q-like track was found in the hardness-intensity diagram of the normal outburst in 2000 but not in the three mini-outbursts that only occur in the Low/Hard state. The results demonstrate that the hysteresis effect is not apparent in the three mini-outbursts and the X-ray spectra are harder than that of the normal outburst at the same photon count rate. Furthermore, the results of the correlation analysis show that the  $\Gamma - F_{2-10\text{keV}}$  correlation of mini-outburst maintain negative in the Low/Hard state with the harder spectra than that of the normal outburst at the same X-ray flux. The X-ray spectral evolution can be well-explained by the state-transition model from the Shakura–Sunyaev disk to the advection-dominated accretion flow, which implies that the three mini-outbursts of XTE J1550-564 might originate from a smaller discrete accretion event.

**Keywords:** accretion, accretion discs, stars: black holes, X-ray binaries, X-rays: individual: XTE J1550-564

## 1. INTRODUCTION

The most of known black hole (BH) X-ray binaries (XRBs) are transients. They often spend most of their time in the quiescent state at a low flux level. After a long quiescent state, XRBs occasionally undergo an outburst, which is usually seemed triggered by hydrogen ionization instability (see reviews, e.g., Lasota, 2001). Basing on the spectral and timing properties of XRBs, several spectral states can be identified during one outburst (see reviews, e.g., McClintock and Remillard, 2006; Zhang, 2013). A typical outburst usually begin in the Low/Hard state (LHs), of which the X-ray spectra are dominated by a power law component with a photon index  $1.5 \leq \Gamma \leq 2.0$ . At the peak and the initial decay stage, XRBs will enter the High/Soft state (HSs), where the X-ray emissions are dominated by a thermal component and a weak power-law tail with a photon index  $\Gamma \geq 2.0$ . With the decay of X-ray luminosity, XRBs will return to the LHs. The intermediate state (IMs) often corresponds to the transition between LHs and HSs, when the power law and thermal component are of comparable significance. The physical origins of X-ray emissions in this state are very complex and unclear.

The correlation between X-ray photon index ( $\Gamma$ ) and X-ray flux ( $F_X$ ) has been widely studied in XRBs over the past 10 years (e.g., Wu and Gu, 2008; Gu and Cao, 2009; Gao et al., 2011a; Emmanoulopoulos et al., 2012; Trichas et al., 2013; Cao et al., 2014; Dong et al., 2014; Allen et al., 2015; Dong and Wu, 2015; Yang et al., 2015; Liu et al., 2019) and proven that XRBs show a positive and negative  $\Gamma - F_X$  correlation when the bolometric luminosity is much higher or lower than a critical value ( $L_{\text{bol,c}} \sim 10^{-2}L_{\text{Edd}}$ ), respectively. Wu and Gu (2008) argued that the transition between the positive and negative correlation of  $\Gamma - F_X$  are regulated by a radiatively efficient accretion mode [e.g., Shakura-Sunyaev disk (SSD)-corona, the luminous hot accretion flow (LHAF)] and a radiatively inefficient accretion mode [e.g., advection-dominated accretion flow (ADAF)], respectively. The detail theory analysis on SSD-corona and ADAF also supports the transition of accretion mode (e.g., Cao, 2009; Yuan et al., 2009; Qiao and Liu, 2013; Cao et al., 2014).

The hardness-intensity diagram (HID) is a powerful tool in describing the state transition and accretion-disc evolution of XRBs, where the thermal disk component and the non-thermal power law component evolved strongly during one outburst (e.g., Coriat et al., 2011; Fender and Belloni, 2012; Steiner et al., 2016). For a typical outburst, XRBs usually show a counter-clockwise q-like track in the HID. On the right of side of the HID, XRBs are in the LHs. On the left of the HID, XRBs are in the HSs. The top and bottom of the HID is correlated with the state transition between the LHs and the HSs. Because the hard-to-soft transition luminosity is higher than soft-to-hard transition luminosity, the HID often shows a q-like pattern, which is usually called as a hysteresis effect (see reviews in Fender and Belloni, 2012). The unusual outbursts have been found where XRBs are either still in the LHs or transition into the IMs before return to the LHs or quiescent state (e.g., Capitanio et al., 2009; Del Santo et al., 2016), which are often called a mini-outburst. In recent years, more and more mini-outbursts have been observed in several BH XRBs (e.g., GRS 1739-278, GX339-4, H1743-322, Swift J1753.5-0127, V404 Cyg, Capitanio et al., 2009; Munoz-Darias et al., 2016; Plotkin et al., 2017; Yan and Yu, 2017; Garcia et al., 2019; Xie et al., 2020), neutron star (NS) XRBs (e.g., XTE J1701-407 Degenaar et al., 2011), and even WZ sge type dwarf novae (DN) (e.g., Kato et al., 2004). However, the nature of mini-outburst is still unclear. It is quite a challenge to explain the mini-outburst using the accretion disk instability model (Lasota, 2001). Other models, such as a smaller discrete accretion event (e.g., Sturmer et al., 2005), the irradiation of the companion (e.g., Hameury et al., 2000), and the enhanced viscosity (e.g., Osaki et al., 2001), are usually invoked to explain the physical properties of the mini-outburst.

The BH XRB XTE J1550-564 was first discovered by All-Sky Monitor (ASM) on board the Rossi X-ray Timing Explorer (RXTE) during its 1998–1999 outburst (Smith, 1998). The BH mass and distance is  $M_{\text{BH}} = 9.4 M_{\odot}$  (Sturmer et al., 2005) and  $D_L = 4.4$  kpc (Orosz et al., 2011), respectively. The source has been observed by RXTE to be in outburst five times, where two normal outbursts in 1998–1999 and 2000 (e.g., Smith, 1998; Miller et al., 2001), three mini-outbursts in 2001, 2002, and 2003 (Tomsick et al., 2001; Belloni

et al., 2002; Sturmer et al., 2005; Chaty et al., 2011). It is noted that the outburst in 2002 is considered as a mini-outburst, because the RXTE ASM observations cover the data in the rise and decay phase and the peak luminosity is about one order magnitude less than the normal outburst in 2000 (see Figure 1 in Curran and Chaty, 2013).

The main purpose of this work is to explore the physical mechanism of the mini-outburst by comparing the X-ray spectral evolution and the hysteresis effect between the normal outburst and the mini-outburst of XTE J1550-564. Due to the complexity and irregularity of the outburst in 1998–1999, we only analyze four outbursts of XTE J1550-564 after 2000. The reminder of the paper is organized as follows: we briefly describe the data reduction and analysis in section 2. The main results are shown in section 3, which will be concluded and discussed in section 4.

## 2. DATA REDUCTION AND ANALYSIS

BH XRB XTE J1550-564 has monitored three mini-outbursts (2001, 2002, and 2003) by proportional counter array (PCA) on board the RXTE satellite after a normal outburst in 2000. In this work, we analyze the PCA data and produce the X-ray colors and the X-ray spectra by following the below steps.

We first extract the photon count rate and color from the PCA Standard 2 data after estimation of background. The hardness ratio (HR) is defined as  $\text{HR} = C/A$ , where A and C are the net count rates in 3–5 keV and 5–12 keV band, respectively. The X-ray spectra are extracted from PCA Standard 2 data, which have an intrinsic time resolution of 16 s. We only use the data from PCU2 in this work, since the PCU2 is the best calibrated detector out of five PCUs (e.g., Cao et al., 2014). The X-ray data are reduced and analyzed with standard RXTE software with Heasoft V6.25, following the standard extraction procedure described in RXTE cookbook. First, we extract the good time intervals (GTI) with the ftool *maketime*. Second, the background is generated using the ftool *pcabackest* and the latest PCA background model (faint or bright) are chosen according to brightness level. Third, the X-ray spectra and background spectra are generated with the ftool *saextract*, and the response matrices are generated using the ftool *pcarsp*.

The X-ray spectra are fitted with XSPEC V12.10.1. In order to investigate the spectra evolution of XTE J1550-564, only channels 4-52, corresponding to 3–25 keV energy band, are adopted and a systematic error of 0.5% in each channel is added in each spectral fitting. As the main purpose of spectral analysis is to obtain the unabsorbed X-ray flux and X-ray spectral index, the model as simple as possible is adopted. We chose a power-law component (*pow*) and an absorption component (*phabs*) as a starting model, where the hydrogen column density is freezed as  $N_{\text{H}} = 0.32 \times 10^{22} \text{cm}^{-2}$  (Orosz et al., 2002). A Gaussian emission line (*gau*) and a multi-temperature disk component (*diskbb*) will be added on condition that a fitting result is not satisfying enough (e.g.,  $\chi^2 \geq 1.40$ ). The ftool *Ftest* will be used to give a criterion whether a new component is needed to improve the fitting results substantially or not.

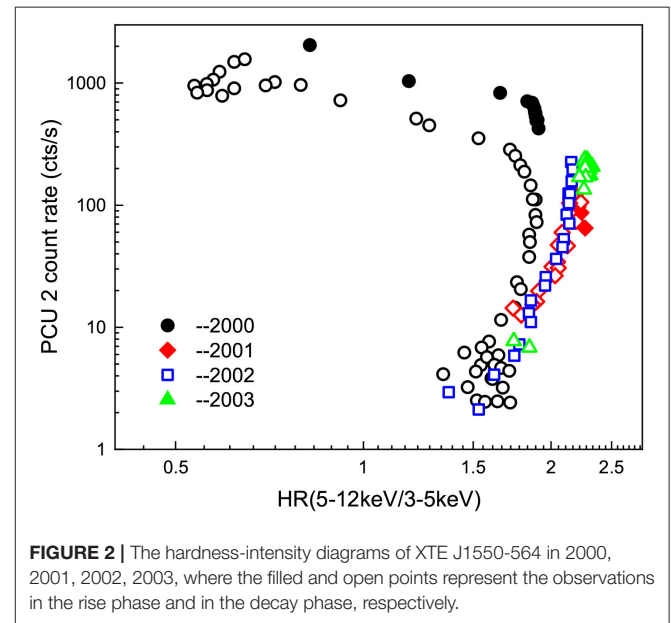
### 3. RESULTS

In **Figure 1**, we present the RXTE/PCA light curve of XTE J1550-564 on MJD = 51600–51280. It can be found from this figure that XTE J1550-564 has undergone one normal outburst and three mini-outbursts, where there are some observations on the rise phase in 2000, 2001, and 2003, but only observations on the decay phase in 2002. The peak luminosity of the mini-outbursts is more or less similar and about one order magnitude less than the normal outburst.

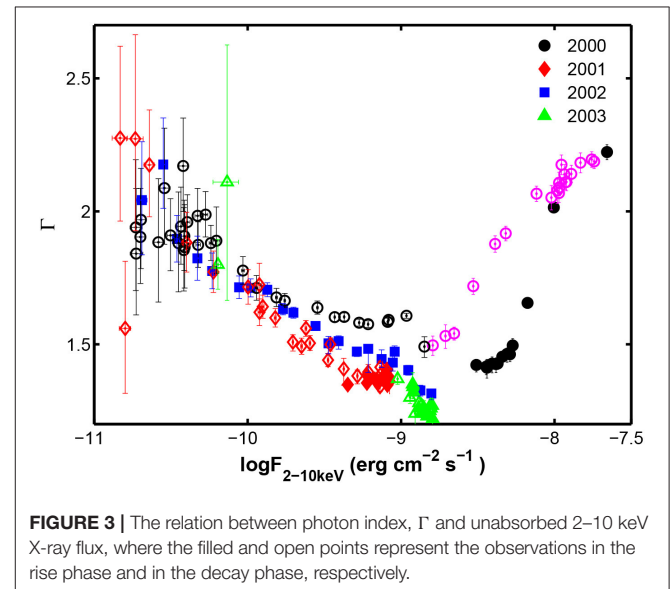
**Figure 2** shows the HIDs of XTE J1550-564 for one normal outburst and three mini-outbursts. The count rate and hardness ratio are produced from the standard products of RXTE. It can be found that the HIDs of the mini-outbursts have a quite difference with the normal outburst. For the normal outburst in 2000, the HID well follows a q-like track, and goes through a whole state transition with LHs–IMs–HSS–IMs–LHs. However, the HIDs of the three mini-outbursts all lie on the right of q-like track along with LHs, where the hardness ratios are very similar, but hardness ratios are much smaller than the normal outburst at the same photon count rate. The normal outburst and the mini-outbursts show a similar value of hardness ratio when the photon count rate less than  $\sim 20\text{cts}^{-1}$ , corresponding X-ray luminosity  $L_{0.1-200\text{keV}} \sim 2 \times 10^{-4} L_{\text{Edd}}$ .

We present the correlation of  $\Gamma - F_{2-10\text{keV}}$  for one normal outburst and three mini-outburst of XTE J1550-564 in **Figure 3**. The main results can be summarized as follows: (1) The three mini-outbursts show a more or less similarity, where the three mini-outbursts on the decay phase show a similar negative  $\Gamma - F_{2-10\text{keV}}$  correlation, and the  $\Gamma - F_{2-10\text{keV}}$  correlation in the rise phase is on the extension of the decay phase. (2) In the rise phase, the  $\Gamma - F_{2-10\text{keV}}$  correlation of the normal outburst shows an

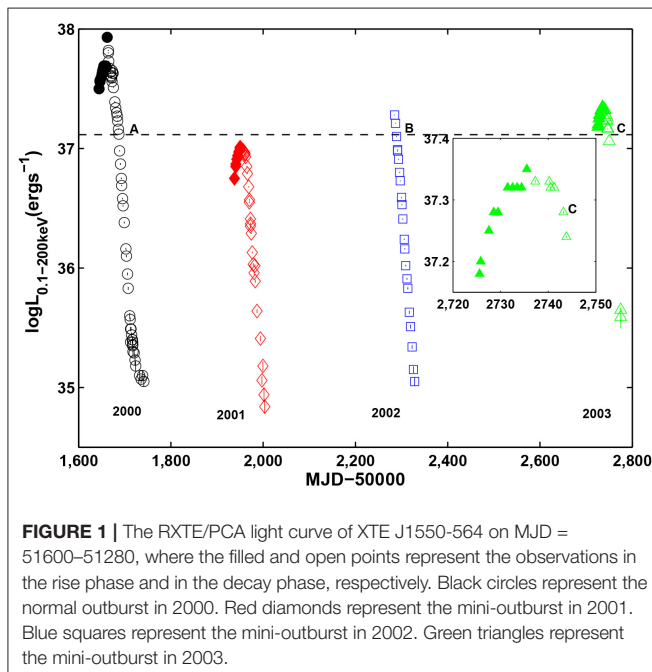
positive correlation when  $F_{2-10\text{keV}} \geq 10^{-8.5}\text{ergs}^{-1}$ . Due to the lack of observational data, no conclusion can be made that the correlation of  $\Gamma - F_{2-10\text{keV}}$  on the rise phase is on the extension



**FIGURE 2** | The hardness-intensity diagrams of XTE J1550-564 in 2000, 2001, 2002, 2003, where the filled and open points represent the observations in the rise phase and in the decay phase, respectively.



**FIGURE 3** | The relation between photon index,  $\Gamma$  and unabsorbed 2–10 keV X-ray flux, where the filled and open points represent the observations in the rise phase and in the decay phase, respectively.



**FIGURE 1** | The RXTE/PCA light curve of XTE J1550-564 on MJD = 51600–51280, where the filled and open points represent the observations in the rise phase and in the decay phase, respectively. Black circles represent the normal outburst in 2000. Red diamonds represent the mini-outburst in 2001. Blue squares represent the mini-outburst in 2002. Green triangles represent the mini-outburst in 2003.

**TABLE 1** | The best-fit parameters for A, B, and C point in **Figure 1**.

	A (50135-01-06-00)	B (60428-01-03-00)	C (80135-01-05-00)
Model	$pha(diskbb + gau + pow)$	$pha(gau + pow)$	$pha(gau + pow)$
$N_{\text{H}}$	$0.32 \times 10^{22}\text{cm}^{-2}$	$0.32 \times 10^{22}\text{cm}^{-2}$	$0.32 \times 10^{22}\text{cm}^{-2}$
$T_{\text{in}}$	$0.91^{+0.63}_{-0.47}$		
lineE	$5.90^{+0.91}_{-2.7}$	$5.02^{+0.38}_{-0.45}$	$4.60^{+0.88}_{-1.83}$
Sigma	$1.60^{+1.11}_{-0.85}$	$1.43^{+0.32}_{-0.28}$	$1.77^{+1.01}_{-0.63}$
PhoIndex	$1.49^{+0.04}_{-0.05}$	$1.40^{+0.02}_{-0.02}$	$1.35^{+0.04}_{-0.05}$
$\chi^2/\text{d.o.f}$	0.53/41	0.87/43	0.69/43

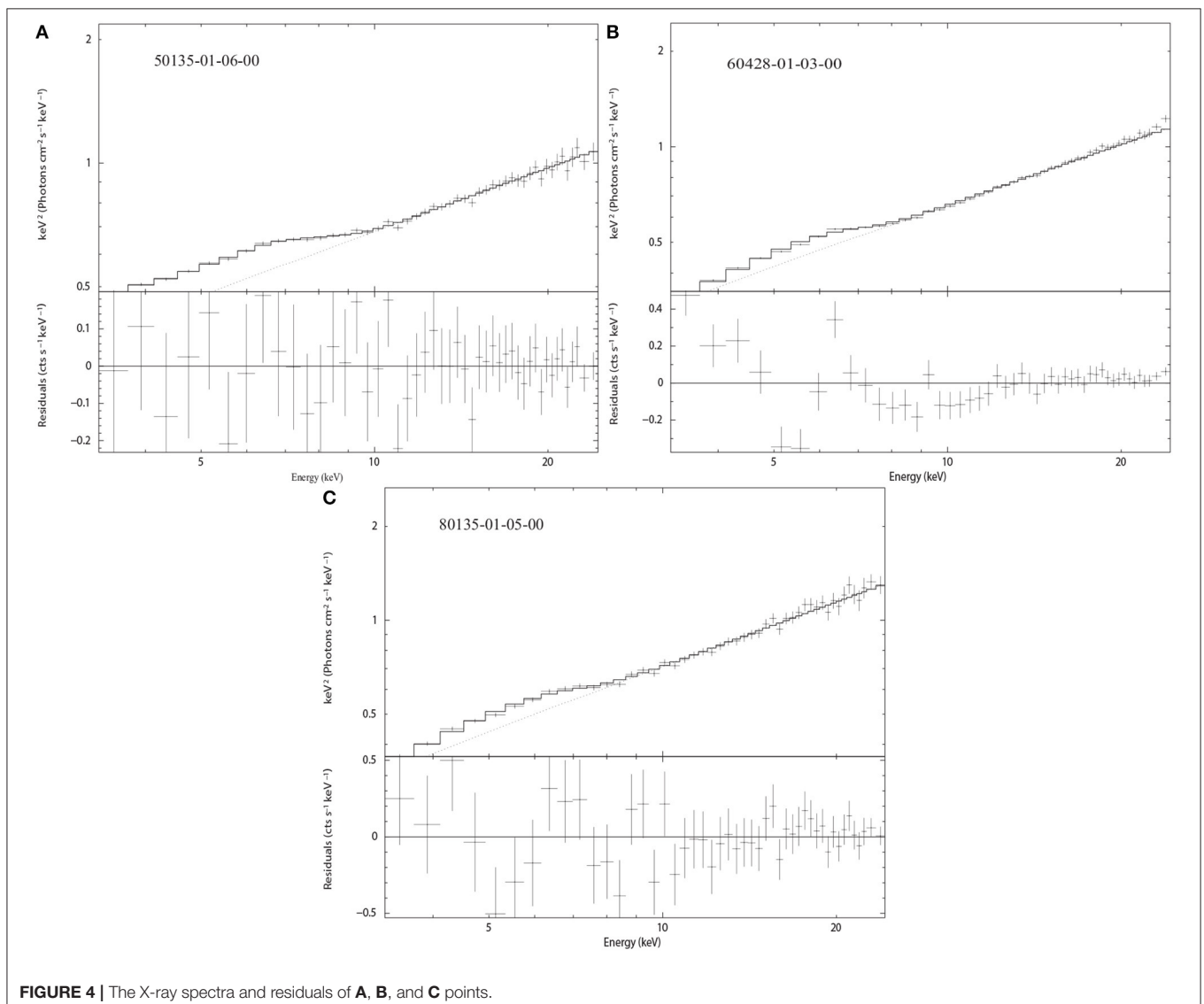
of the decay phase. (3) In the decay phase, the  $\Gamma - F_{2-10\text{keV}}$  correlation of the normal outburst shows a transition from a negative to positive correlation at a critical value  $F_{2-10\text{keV}} \sim 10^{-8.8} \text{ergs}^{-1}$ , corresponding to  $L_{0.1-200\text{keV}} \sim 1.2\%L_{\text{Edd}}$ . (4) In the decay phase, the photon index of the mini-outbursts is much smaller than the normal outburst at the same X-ray flux.

## 4. CONCLUSION AND DISCUSSION

We analyze the hysteresis effect and the evolution of X-ray photon index along X-ray flux of BH XRB XTE J1550-564 for one normal outburst and three mini-outbursts after 2000. The main results are summarized as follows. (1) A q-like HID is found in the normal outburst in 2000, but not in the other three mini-outbursts. (2) The  $\Gamma - F_{2-10\text{keV}}$  correlation of the mini-outbursts in the rise phase is on the extension of the decay phase. (3) The

mini-outbursts show a harder X-ray spectrum than the normal outburst at the same X-ray flux.

The hysteresis effect of XRBs has been studied widely, where the state transition is clearly demonstrated in the HID. Recently, more and more mini-outbursts have been studied, where the peak luminosity is about one to two order lower than the normal outburst, and the HID lies on the lower right along with the hard state (see Figure 7 in Yan and Yu, 2017). We first present the HID of XTE J1550-564 basing the PCA observation on board the RXTE satellite and find that the HID in normal outburst shows a q-like track, which is agreed with the normal outburst in other XRBs. In order to study the physical mechanism of the mini-outburst, we furthermore analyze the HID of the three mini-outbursts of XTE J1550-564 in 2001, 2002, and 2003. The peak luminosities are about one order lower than the normal outburst in 2000 with the hardness ratio  $\text{HR}(5 - 12\text{keV}/3 - 5\text{keV}) \sim 1.40 - 2.20$ , which predicts the three mini-outbursts are still in



**FIGURE 4** | The X-ray spectra and residuals of **A**, **B**, and **C** points.

the LHs. The HIDs of the three mini-outbursts all lie on the right of the normal outburst in 2000 and follow a similar track. The results demonstrate that the mini-outbursts have a similar physical properties and their X-ray spectra are much harder than the normal outburst at the same photon count.

The correlation of  $\Gamma - F_X$  has been studied extensively, where the negative and positive correlation are found when the bolometric luminosities are smaller and larger than 1–10% Eddington luminosity, respectively (e.g., Wu and Gu, 2008; Gao et al., 2011b; Emmanoulopoulos et al., 2012; Cao et al., 2014; Yang et al., 2015; Liu et al., 2019). Using the PCA observations on board RXTE satellite, we explore the correlation of  $\Gamma - F_X$  for three mini-outbursts and one normal outburst of XTE J1550-564. The three mini-outbursts show a similar negative correlation, and the correlation in the rise phase is still on the extension of the decay phase. The  $\Gamma - F_X$  correlation of the normal outburst in the decay phase shows a transition from positive to negative with the X-ray luminosity decreasing, in which the critical bolometric luminosity  $L_{\text{bol,c}} \sim 1.2\%L_{\text{Edd}}$ , estimated from X-ray luminosity at 0.1–200 keV energy band. The results agree with the former works (e.g., Dong et al., 2014). However, due to the lack of observational data during the rise phase, we cannot judge whether the  $\Gamma - F_X$  correlation in the rise phase is on the extension of the decay phase or not. The X-ray spectra of the mini-outbursts can be well-fitted by a single power law (*pow*) or a power law + Gaussian line (*pow + gau*) with  $\Gamma \sim 1.30 - 2.30$ , which consist of the state transition from LHs to quiescent state. Comparing with the normal outburst, the photon index of the mini-outburst is smaller in the range of  $F_{2-10\text{keV}} \sim 10^{-8.80} - 10^{-10.0} \text{ergs}^{-1}$ , corresponding to the bolometric luminosity  $L_{\text{bol}} \sim (1 \times 10^{-2} - 2 \times 10^{-4})L_{\text{Edd}}$ , which suggest that the X-ray spectra of mini-outbursts are harder than the normal outburst at the same X-ray flux.

The physical mechanism of  $\Gamma - F_X$  correlation is still unclear. A possible explanation is the transition from SSD-corona to ADAF accretion model (e.g., Wang et al., 2004; Yuan et al., 2007; Gu and Cao, 2009; Sobolewska and Papadakis, 2009; Emmanoulopoulos et al., 2012; Plotkin et al., 2013; Yang et al., 2015). To our knowledge, the X-ray photon index is regulated by electron temperature  $T_e$  and optical depth  $\tau$  of the ADAF (Liu et al., 2019). The ADAF model predict that as the accretion rate faded from an LHs into a quiescent state, the optical depth for comptonization decreases and thereby leading to a softer X-ray spectra (Qiao and Liu, 2013). As accretion rate increases, the hot plasma in the ADAF are cooled into a SSD and thereby leading to a softer X-ray spectrum (Cao, 2009). Therefore, the X-ray spectra of the normal outburst might exist a disc component nearby the transition from positive to negative  $\Gamma - F_X$  correlation during the decay phase. On the contrary, there is not a disc component in the X-ray spectra of mini-outburst, the lower accretion rate of which does not make the hot the hot plasma in the ADAF cool into an SSD. The X-ray emissions of the whole mini-outburst are all from the ADAF. Therefore, the mini-outbursts follow a similar  $\Gamma - F_X$  correlation and present the harder X-ray spectra at the same X-ray flux. In order to investigate the above conclusions, we analyze the X-ray spectra for the initial observational data (A point) on the negative  $\Gamma - F_X$  correlation in the normal

outburst and the observational data (B and C point) at the same X-ray flux in the mini-outbursts (see **Figure 1**). For the A point, the model *pha(pow)* are first adopted and a reduced chi-square  $\chi^2/\text{d.o.f} = 2.36/46$  are obtained. Furthermore, we add the *gau* component to fit the X-ray spectra and obtain a reduced chi-square  $\chi^2/\text{d.o.f} = 1.91/43$ , which is not yet a good enough fitting result. Therefore, the *diskbb* component are added to improve the fitting and we obtain a reduced chi-square  $\chi^2/\text{d.o.f} = 0.53/41$ . At the same way, we analyze the X-ray spectra of B point and C point and the main results are summarized as follows: (1) for the B point, the reduced chi-square  $\chi^2/\text{d.o.f} = 6.04/46$  for the model *pha(pow)* and  $\chi^2/\text{d.o.f} = 0.87/43$  for the model *pha(gau + pow)*, respectively; (2) for the C point, the reduced chi-square  $\chi^2/\text{d.o.f} = 1.76/46$  for the model *pha(pow)* and  $\chi^2/\text{d.o.f} = 0.69/43$  for the model *pha(gau + pow)*, respectively. Basing on the *ftool Ftest*, the model *pha(diskbb + gau + pow)* for the A point, *pha(gau + pow)* for the B point and C point are adopted in this work, respectively. The best fitting results are presented in **Table 1** and **Figure 4**, which predict that there is a disc component in the X-ray spectrum of A point, but not in points B and C. Alternatively, the negative  $\Gamma - F_X$  of the mini-outbursts can also be explained by a luminous hot accretion flow. For the mini-outburst with a lower accretion rate, the viscosity parameter is very small (e.g.,  $\alpha \sim 0.01$ , Xie and Yuan, 2016). With the accretion rate decaying, the electron density and the magnetic strength increases, which can result in the increasing of synchrotron absorption depth in luminous hot accretion flow and thereby leading to softer X-ray spectra (e.g., Yang et al., 2015; Xie and Yuan, 2016; Xie et al., 2020). We will obtain a negative  $\Gamma - F_X$  correlation. How then are these mini-outbursts produced? A possible explanation is a smaller discrete accretion event, where a lower mass accretion rate cannot cool the hot plasma in ADAF into an SSD (Sturmer et al., 2005). However, the transition from a ADAF to an SSD on the decay stage is caused by some other physical reasons (e.g., evaporation, magnetic field, inclination effect). A further detailed spectral and timing analysis is needed to investigate the nature of the mini-outburst.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found at: <https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl>.

## AUTHOR CONTRIBUTIONS

A-JD was responsible for the ideas and writing of the paper. CL and KG were responsible for data analysis. XL was responsible for the data curation and theory analysis. Q-JZ was responsible for theory analysis. All authors contributed to the article and approved the submitted version.

## FUNDING

This work was supported by National Key R&D Program of China (2018YFA0404602), NSFC (U1831120 and U1731238),

the Science and Technology Foundation of Guizhou province ([2017]7349, [2019]1241, [2016]4008, [2017]5726-37, and KY(2020)003), and the Excellent Post-doctoral Foundation of XinJiang and YJSCXJH ([2020]096).

## REFERENCES

- Allen, J. L., Linares, M., Homan, J., and Chakrabarty, D. (2015). Spectral softening between outburst and quiescence in the neutron star low-mass X-ray binary sax j1750.8-2900. *Astrophys. J.* 801, 10–22. doi: 10.1088/0004-637X/801/1/10
- Belloni, T., Colombo, A. P., Homan, J., Campana, S., and van der Klis, M. (2002). A low/hard state outburst of XTE J1550-564. *Astron. Astrophys.* 390, 199–204. doi: 10.1051/0004-6361:20020703
- Cao, X. (2009). An accretion disc-corona model for X-ray spectra of active galactic nuclei. *Mon. Not. RAS* 394, 207–213. doi: 10.1111/j.1365-2966.2008.14347.x
- Cao, X. F., Wu, Q., and Dong, A. J. (2014). Different X-ray spectral evolution for black hole x-ray binaries in dual tracks of radio-X-ray correlation. *Astrophys. J.* 788, 52–60. doi: 10.1088/0004-637X/788/1/52
- Capitanio, F., Belloni, T., Del Santo, M., and Ubertini, P. (2009). A failed outburst of H1743-322. *Astrophys. J.* 398, 1194–1200. doi: 10.1111/j.1365-2966.2009.15196.x
- Chaty, S., Dubus, G., and Raichoor, A. (2011). Near-infrared jet emission in the microquasar XTE J1550-564. *Astron. Astrophys.* 529, 3–10. doi: 10.1051/0004-6361/201015589
- Coriat, M., Corbel, S., Prat, L., Miller-Jones, J. C. A., Cseh, D., Tzioumis, A. K., et al. (2011). Radiatively efficient accreting black holes in the hard state: the case study of H1743-322. *Mon. Not. RAS* 414, 677–690. doi: 10.1111/j.1365-2966.2011.18433.x
- Curran, P. A., and Chaty, S. (2013). Near-infrared and optical observations of the failed outbursts of black hole binary XTE J1550-564. *Astron. Astrophys.* 557, 45–53. doi: 10.1051/0004-6361/201321865
- Degenar, N., Wijnands, R., Altamirano, D., Cackett, E., Linares, M., Homan, J., et al. (2011). X-ray re-brightening detected from the neutron star transient XTE J1701-407. *The Astronomer's Telegram*, 3654.
- Del Santo, M., Belloni, T. M., Tomsick, J. A., Sbarufatti, B., Cadolle Bel, M., Casella, P., et al. (2016). Spectral and timing evolution of the bright failed outburst of the transient black hole Swift J174510.8–262411. *Mon. Not. RAS* 456, 3585–3595. doi: 10.1093/mnras/stv2901
- Dong, A. J., and Wu, Q. (2015). Revisit the Fundamental Plane of black hole activity from sub-Eddington to quiescent state. *Mon. Not. RAS* 453, 3447–3454. doi: 10.1093/mnras/stv1801
- Dong, A. J., Wu, Q., and Cao, X. F. (2014). A new fundamental plane for radiatively efficient black-hole sources. *Astrophys. J. Lett.* 787, 20–25. doi: 10.1088/2041-8205/787/2/L20
- Emmanoulopoulos, D., Papadakis, I. E., McHardy, I. M., Arevalo, P., Calvelo, D. E., and Uttley, P. (2012). The 'harder when brighter' X-ray behaviour of the low-luminosity active galactic nucleus NGC 7213. *Mon. Not. RAS* 422, 1327–1334. doi: 10.1111/j.1365-2966.2012.12136.x
- Fender, R., and Belloni, T. (2012). Stellar-mass black holes and ultraluminous X-ray sources. *Science* 337, 540–544. doi: 10.1126/science.1221790
- Gao, Z. F., Peng, Q. H., Wang, N., Chou, C. K., and Huo, W. S. (2011a). The Landau level-superfluid modified factor and the overall soft X/ $\gamma$ -ray efficiency coefficient of a magnetar. *Astrophys. Space Sci.* 336, 427–439. doi: 10.1007/s10509-011-0791-x
- Gao, Z. F., Wang, N., Yuan, J. P., Jiang, L., Song, D. L., and Qiao, E. L. (2011b). Evolution of superhigh magnetic fields of magnetars. *Astrophys. Space Sci.* 333, 427–435. doi: 10.1007/s10509-011-0664-3
- García, J. A., Tomsick, J. A., Sridhar, N., Grinberg, V., Connors, R. M. T., Wang, J., et al. (2019). The 2017 failed outburst of GX 339-4: relativistic x-ray reflection near the black hole revealed by NuSTAR and swift spectroscopy. *Astrophys. J.* 885, 48–58. doi: 10.3847/1538-4357/ab384f
- Gu, M., and Cao, X. (2009). The anticorrelation between the hard X-ray photon index and the Eddington ratio in low-luminosity active galactic nuclei. *Mon. Not. RAS* 399, 349–356. doi: 10.1111/j.1365-2966.2009.15277.x
- Hameury, J. M., Lasota, J. P., and Warner, B. (2000). The zoo of dwarf novae: illumination, evaporation and disc radius variation. *Mon. Not. RAS*, 353, 244–252.
- Kato, T., Nogami, D., Matsumoto, K., and Baba, H. (2004). Super humps and repetitive rebrightenings of the WZ Sge-Type Dwarf Nova, EG Cancri. *Publ. ASJ.* 56, S109–S123. doi: 10.1093/pasj/56.sp1.S109
- Lasota, J. P. (2001). The disc instability model of dwarf novae and low-mass X-ray binary transients. *New A Rev.* 45, 449–508. doi: 10.1016/S1387-6473(01)00112-9
- Liu, H., Dong, A., Weng, S., and Wu, Q. (2019). Evolution of the hard X-ray photon index in black-hole X-ray binaries: hints for accretion physics. *Mon. Not. RAS* 487, 5335–5345. doi: 10.1093/mnras/stz1622
- McClintock, J. E., and Remillard, R. A. (2006). "Black hole binaries," in *Compact Stellar X-ray Sources*, eds W. Lewin, and M. van der Klis (Cambridge: Cambridge University Press), 157–215.
- Miller, J. M., Wijnands, R., Homan, J., Belloni, T., Pooley, D., Corbel, S., et al. (2001). High-frequency quasi-periodic oscillations in the 2000 outburst of the galactic microquasar XTE J1550-564. *Astrophys. J.* 563, 928–933. doi: 10.1086/324027
- Muñoz-Darias, T., de Ugarte Postigo, A., and Casares, J. (2016). The featureless and non-variable optical spectral energy distribution of AXP 4U 0142+61. *Mon. Not. RAS*. L114–L117. doi: 10.1093/mnras/llw024
- Orosz, J. A., Groot, P. J., van der Klis, M., McClintock, J. E., Garcia, M. R., Zhao, P., et al. (2002). Dynamical evidence for a black hole in the microquasar XTE J1550-564. *Astrophys. J.* 568, 845–861. doi: 10.1086/338984
- Orosz, J. A., Steiner, J. F., McClintock, J. E., Torres, Manuel A. P., Remillard, R. A., Bailyn, C. D., et al. (2011). An improved dynamical model for the microquasar XTE J1550-564. *Astrophys. J.* 730, 75–103. doi: 10.1088/0004-637X/730/2/75
- Osaki, Y., Meyer, F., and Meyer-Hofmeister, E. (2001). Repetitive rebrightening of EG Cancri: evidence for viscosity decay in the quiescent disk? *Astron. Astrophys.* 370, 488–495. doi: 10.1051/0004-6361:20010234
- Plotkin, R. M., Bright, J., Miller-Jones, J. C. A., Shaw, A. W., Tomsick, J. A., Russell, T. D., et al. (2017). Up and down the black hole radio/X-Ray correlation: the 2017 mini-outbursts from swift J1753.5–0127. *Astrophys. J.* 848, 92–100. doi: 10.3847/1538-4357/aa8d6d
- Plotkin, R. M., Gallo, E., and Jonker, P. G. (2013). The X-ray spectral evolution of galactic black hole X-ray binaries toward quiescence. *Astrophys. J.* 773, 59–74. doi: 10.1088/0004-637X/773/1/59
- Qiao, E., and Liu, B. F. (2013). A model for the correlation of hard X-ray index with Eddington ratio in black hole X-ray binaries. *Astrophys. J.* 764, 2–9. doi: 10.1088/0004-637X/764/1/2
- Smith, D. A. (1998). XTE J1550-564. *IAUC*, 7008.1.
- Sobolewska, M. A., and Papadakis, I. E. (2009). The long-term X-ray spectral variability of AGN. *Mon. Not. RAS* 399, 1597–1610. doi: 10.1111/j.1365-2966.2009.15382.x
- Steiner, J. F., Remillard, R. A., Garcia, J. A., and McClintock, J. E. (2016). Stronger reflection from black hole accretion disks in soft X-ray states. *Astrophys. J.* 829, L22–L27. doi: 10.3847/2041-8205/829/2/L22
- Sturmer, S. J., and Shrader, C. R. (2005). XTE J1550-564: INTEGRAL observations of a failed outburst. *Astrophys. J.* 625, 923–930. doi: 10.1086/429815
- Tomsick, J. A., Corbel, S., and Kaaret, P. (2001). X-Ray Observations of XTE J1550-564 during the decay of the 2000 outburst. I. Chandra and RXTE energy spectra. *Astrophys. J.* 563, 229–238. doi: 10.1086/323689
- Trichas, M., Green, P. J., Constantin, A., Aldcroft, T., Kalfountzou, E., Sobolewska, M., et al. (2013). Empirical links between XRB and AGN accretion using the complete  $z < 0.4$  spectroscopic CSC/SDSS catalog. *Astrophys. J.* 778, 188–199. doi: 10.1088/0004-637X/778/2/188

## ACKNOWLEDGMENTS

We thank the members of the GZNU astrophysics group for many useful discussions and comments.

- Wang, J. M., Watarai, K. Y., and Mineshige, S. (2004). The hot disk corona and magnetic turbulence in radio-quiet active galactic nuclei: observational constraints. *Astrophys. J.* 607, L107–L110. doi: 10.1086/421906
- Wu, Q., and Gu, M. (2008). The X-ray spectral evolution in x-ray binaries and its application to constrain the black hole mass of ultraluminous X-ray sources. *Astrophys. J.* 682, 212–217. doi: 10.1086/588187
- Xie, F. G., Yan, Z., and Wu, Z. (2020). Radio/X-ray correlation in the mini-outbursts of black hole X-ray transient GRS 1739-278. *Astrophys. J.* 891, 31–39. doi: 10.3847/1538-4357/ab711f
- Xie, F. G., and Yuan, F. (2016). Interpreting the radio/X-ray correlation of black hole X-ray binaries based on the accretion-jet model. *Mon. Not. RAS* 456, 4377–4383. doi: 10.1093/mnras/stv2956
- Yan, Z., and Yu, W. (2017). Detection of X-ray spectral state transitions in mini-outbursts of black hole transient GRS 1739-278. *Mon. Not. RAS* 470, 4298–4306. doi: 10.1093/mnras/stx1562
- Yang, Q. X., Xie, F. G., Yuan, F., Zdziarski, A. A., Gierliński, M., Ho, L. C., et al. (2015). Correlation between the photon index and X-ray luminosity of black hole X-ray binaries and active galactic nuclei: observations and interpretation. *Mon. Not. RAS* 447, 1692–1704. doi: 10.1093/mnras/stu2571
- Yuan, F., Taam, R. E., Misra, R., Wu, X. B., and Xue, Y. (2007). Accretion disk spectra of the brightest ultraluminous X-ray source in M82. *Astrophys. J.* 658, 282–287. doi: 10.1086/511301
- Yuan, F., Yu, Z., and Ho, L. C. (2009). Revisiting the “fundamental plane” of black hole activity at extremely low luminosities. *Astrophys. J.* 703, 1034–1043. doi: 10.1088/0004-637X/703/1/1034
- Zhang, S. N. (2013). Black hole binaries and microquasars. *Front. Phys.* 8, 630–660. doi: 10.1007/s11467-013-0306-z

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2021 Dong, Liu, Ge, Liu, Zhi and You. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.