Analysis of the reflection spectra of MAXI J1535-571 in the hard and intermediate states

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ABSTRACT

We report results on the joint-fit of the NuSTAR and HXMT data for the black hole X-ray binary candidate MAXI J1535-571. The observations were obtained in 2017 when the source evolved through the hard, hard-intermediate and soft-intermediate states over the rising phase of the outburst. After subtracting continuum components, X-ray reflection signatures are clearly showed in those observations. By modeling the relativistic reflection in detail, we find that the inner radius $R_{\text{in}}$ is relatively stable with $R_{\text{in}} \lesssim 1.55 R_g$ during the three states, which implies that the inner radius likely extends to the innermost stable circular orbit even in the bright hard state. When adopting $R_{\text{in}} = R_{\text{ISCO}}$, the spin parameter is constrained to be $0.985^{+0.004}_{-0.004}$ at 90% confidence (statistical only). The best-fitting results reveal that the inclination of the inner accretion disc is $\sim 70 \pm 45$ degrees, which notably conflicts with the apparent orientation of the ballistic jet ($\leq 45$ degrees). In addition, both the photon index and the electron temperature increase during the transition from hard to soft state. It seems that the corona evolves from dense low-temperature in the LHS to tenuous high-temperature after the state transition, which indicates that the state transition is accompanied by the evolution of the coronal properties.

Key words: accretion, accretion discs – black hole physics – methods: data analysis – X-rays: individual: MAXI J1535-571

1 INTRODUCTION

During a typical outburst of a transient black hole binary, the black hole binary goes through different spectral states with spectral and timing properties changes. As the source luminosity increases, it evolves from the low/hard state (LHS) to the hard and soft intermediate states (HIMS, SIMS), then enters into the high/soft state (HSS, Belloni et al. 2005; Remillard & McClintock 2006). It is generally agreed that the change of spectral states is induced by the evolution of the accretion geometry of the black hole binary system.

In the HSS, the source spectrum is dominated by thermal emission ($\sim 1$ keV) accompanied by a hard power-law tail. The accretion flow is composed of an optically thick and geometrically thin accretion disc (Shakura & Sunyaev 1973) with its inner radius likely at the innermost stable circular orbit (ISCO, Tanaka & Lewin 1995; Steiner et al. 2010). In the LHS, the spectrum is dominated by the hard powerlaw X-rays, together with the very faint thermal component detected sometimes. The hard X-rays are produced by the inverse Compton scattering of thermal emission in a region of hot plasma, the so-called corona, and can be well described by powerlaw with $\Gamma \sim 1.4 \pm 2.1$. In the model of Esin et al. (1997), at a low accretion rate, the disc is truncated before it reaches the ISCO, and an advection-dominated accretion flow, which is evaporated from the accretion disc (Meyer et al. 2000; Liu et al. 2002; Qiao & Liu 2010), is in the inner region. A disc with a truncated inner radius of several tens to hundreds of $R_g$ (the gravitational radius and calculated by $R_g = GM/c^2$) has indeed been inferred by modelling the disc component of some BHXRBs, e.g., XTE J1118+480 (Esin et al. 2001). With this truncated model, the transition from the LHS to the HSS can be well explained by the extending of inner radius down to the ISCO (Plant et al. 2014). This model has also been invoked to explain the positive correlation between the X-ray photon index and the reflection strength (Zdziarski et al. 1999; Ezhikode et al. 2020; Panagiotou & Walter 2020).

On the other hand, a black hole binary will experience HIMS and SIMS before it enters the HSS. The thermal emission and the hard X-ray emission are both strong, which leads to a softer spectrum than that in LHS. The HIMS-SIMS transition can be very rapid. They are normally distinguished by the differences in their timing properties. For instance, either a type A or a type B QPO appears in the SIMS, while a type C QPO is often shown in the HIMS. Black hole binary also shows very weak variability in SIMS (Belloni et al. 2005; Belloni 2010). These intermediate states, as the transition states between the
LHS and HSS, may provide import clues on the physical driver for state transition, thus it is important to investigate the properties of the accretion flow during the source in the HIMS and SIMS. In addition to the hard powerlaw and the thermal emission, the relativistic reflection spectrum is frequently reported (Fabian et al. 1989; García et al. 2014; Plant et al. 2014; Dong et al. 2020a,b; Feng et al. 2022) in the X-ray spectrum of both black hole X-ray binaries (BHXBs) and active galactic nucleus (AGNs). The reflection spectrum appears when a substantial flux of coronal photons are reflected from the surface of the disc. As a result, this reflected component includes absorption edges, fluorescent lines and a Compton hump. If the reflection emissions come from the region that is close enough to the black hole, it will be distorted by the relativistic effects, carrying the information of strong fields (Laor 1991). The study of reflection features can provide insights on the inclination, the iron abundance, and the ionization of the disc, as well as the geometry and the electron temperature of the corona. Moreover, the detailed modeling of reflection features is an important tool to measure the inner radius of the disc (García et al. 2015; Xu et al. 2020; Sridhar et al. 2020). If the inner radius is located at the ISCO, the spin of the black hole can then be estimated (Bardeen et al. 1972). The study of the reflection spectra in different states offers an opportunity to yield important insights on the co-evolution of the disc and corona. Interestingly, in contrast to the theoretical expectation (e.g., Esin et al. 1997; Meyer et al. 2000), it has been suggested that the inner accretion disc is not truncated by modelling the relativistic reflection in the LHS for some sources. For example, the inner radius is found to be very close to the ISCO for Cyg X-1 (Reis et al. 2010; Parker et al. 2015), GX 339-4 (García et al. 2015; Steiner et al. 2017), and MAXI J1820+070 (Buisson et al. 2019). Whether the truncation of the inner disc in LHS and at what phase the truncation appears are still in hot debate in recent years. MAXI J1535-571 is an X-ray transient discovered in LHS by MAXI (Negoro et al. 2017a) and Swift (Kennea et al. 2017), on September 2nd, 2017 (MJD 57999). Its X-ray spectral and timing properties (Negoro et al. 2017b), together with its bright radio signals (Russell et al. 2017), strongly suggest a black hole primary. MAXI J1535-571 was also observed in the optical and infrared bands (Scaringi & ASTR211 Students 2017; Dingcer 2017). Its X-ray spectra started to soften on September 10th (Nakahira et al. 2017; Kennea et al. 2017), followed by the intermediate state which lasted for 2 months (Shidatsu et al. 2017). During the LHS-HIMS-SIMS transitions, low frequency QPOs were detected (Huang et al. 2018; Stevens et al. 2018; Stiele & Kong 2018; Sreehari et al. 2019), and the evolution of compact jet and relativistic jet were reported (Russell et al. 2019, 2020). Russell et al. (2019) also constrained the jet inclination to be ≲ 45 degrees. The source is heavily absorbed with a line-of-sight (LOS) column density larger than 10^{22} cm^{-2} (Stevens et al. 2018; Cúneo et al. 2020, and the references therein). The source distance (D) is estimated to be 4.1^{+0.6}_{-0.5} kpc based on the analysis on HI absorption spectrum (Chauhan et al. 2019).

Xu et al. (2018) analyzed the NuSTAR data obtained on September 7th during which MAXI J1535-571 was in the bright phase of the LHS. They found a strong relativistic reflection component in the NuSTAR data. They reported no significant disc truncation and a rapidly rotating black hole (>0.84 and >0.987 with the relxillpcc and relxillpc model, respectively). Kong et al. (2020) found the spin was 0.7^{+0.2}_{-0.3} with the relxillpcc model using the data obtained by HXMT, also on the September 7th, but the exposure time was less than 1 ks. Miller et al. (2018) and Sridhar et al. (2019) constrained the spin parameter using NICER and AstroSat observations, respectively. Both observations were obtained when the source was in the start of the HIMS. The best-fitting model of the NICER data indicated a high spin of 0.994 ± 0.002, while AstroSat data indicated a moderate spin of 0.67^{+0.16}_{-0.04}. The inner radius and the spin are degenerate since they both affect the red wing of the fluorescent iron line. So, moderate spin may indicate a moderately truncated disc. The inconsistent values of spin also may attribute to the model difference.

Here we report a joint analysis of the NuSTAR (The Nuclear Spectroscopic Telescope Array, Harrison et al. 2013) and HXMT (Hard X-ray Modulation Telescope, or Insight-HXMT, Zhang et al. 2014) observations of MAXI J1535-571. We analyze 3 epochs data obtained as the source increased in intensity while undergoing transition from a bright-hard towards the soft state during the 2017 outburst. NuSTAR is the first focusing high-energy X-ray telescope in orbit which covers a broad energy band (3-79 keV) with unprecedented energy resolution and sensitivity in the hard X-ray band. HXMT, as the first Chinese X-ray astronomical satellite, includes three slit-collimated instruments: the Low Energy X-ray Telescope (LE, 1-15 keV), the Medium Energy X-ray Telescope (ME, 5-30 keV), and the High Energy X-ray Telescope (HE, 20-250 keV). The dataset from both satellites are not affected by photon pile-up effects. Similar spectra analysis of Cyg X-1 (Zhao et al. 2020) and MAXI J1820-070 (You et al. 2021; Zhao et al. 2021; Guan et al. 2021) using HXMT have been reported. The paper is organized as follows: in Section 2, we describe the detail of observations and data reduction; the data analysis and results are presented in Section 3; Section 4 includes discussions and Section 5 includes conclusions.

2 OBSERVATIONS AND DATA REDUCTION

We show MAXI J1535-571’s light curve and hardness ratio obtained by MAXI (Matsuoka et al. 2009) in Figure 1. In this paper, we analyze 3 NuSTAR observations (blue shadow in Figure 1) with exposure time of 8685, 2258 and 1531 seconds, respectively. Quasi-simultaneous HXMT observations are also analyzed with exposure time of 5614.5, 4316 and 3496 seconds, respectively. We mark HXMT observations as gray shadow in Figure 1. For the data in Epoch 1 (ObsID: 90301013002), the NuSTAR and HXMT are not observed simultaneously with the NuSTAR observation carried out less than 10
hours later than the HXMT observation. However, the NuSTAR and HXMT data show roughly the same reflection spectral features (iron emission line and Compton hump region), suggesting no significant change in the reflection component, we thus still jointly analyze the NuSTAR and HXMT data to increase the signal-to-noise ratio (SNR). The including of the HXMT/LE data enable us to perform spectral analysis down to 2.1 keV which will be valuable to detect the weak thermal emission in LHS. The details of observations of both satellites can be found in Table 1. The three epoch observations are in LH, HIMS and SIMS, respectively (Huang et al. 2018; Tao et al. 2018). In the following sections, we describe the observations and data reduction for NuSTAR and HXMT.

2.1 NuSTAR Data Reduction

The NuSTAR data were processed using NuSTAR Data Analysis Software (NuSTARDAS v2.0.0) with CALDB v20210524, which are included in HEASOFT v6.28. We created cleaned event files using the NUPipeline routine. The count rate exceeds 100 counts s⁻¹ in these 3 observations. Therefore, we set STATUEXP to be "STATUEXP=0". Especially for Obs. 1, we also set saacalc = 2, saamode = strict, and tentacle = NO to remove background flares, which is caused by enhanced solar activity. The X-ray spectra, backgrounds and instrument responses were generated using NUPRODUCTS. The spectra were extracted from a circular region with radius of 180” centred on MAXI J1535-571, while backgrounds were extracted from a circular region with radius of 180” located on the same detector. The spectra were grouped with GRPPHA to have at least 30 counts within an energy bin. We choose the 4-79 keV range for the spectral analysis.

2.2 HXMT Data Reduction

HXMT includes the Low Energy X-ray Telescope (LE), the Medium Energy X-ray Telescope (ME), and the High Energy X-ray Telescope (HE). We carried data reduction following the standard procedures for individual instruments, as the suggestions given by HXMT team. The data pipelines and tools of HXMT Data Analysis Software (HXMT-DAS) v2.04 were used. The HXMT spectra, were extracted based on the cleaned events files, which were filtered by the good time intervals (GTIs). The GTIs recommended by pipeline are intervals when (1) elevation angle greater than 10 degrees; (2) geomagnetic cut-off rigidities greater than 8 GeV; (3) satellite not in SAA and 300 seconds intervals near SAA; (4) pointing deviation to the source less than 0.04 degrees. We binned the spectra at least 30 counts within an energy bin. Then, the systematic uncertainties of 0.5%/0.5%/3% were added for LE/ME/HE to account for the instrumental uncertainties. For spectral analysis, we use 2.1-10 keV, 10-27 keV, 27-60 keV energy band for LE, ME and HE, respectively. The spectra at higher energies are dominated by the background.

Data in Epoch 1 was split into 5 continuous observations, and both Epoch 2 and 3 were split into 2. We used the following ways to check the spectral variability for all observations within one epoch. For each epoch, we performed a joint-fit with an absorbed powerlaw model to all spectra within this epoch. A constant multiplication factor was also included to account for the flux fluctuation. The parameters column density, photon index and normalization were linked among spectra. We find their data to model ratios are highly consistent. Additionally, if the photon index was allowed to be float among different observations, the value of it is consistent within the errors. Therefore, the source spectral shape is not significantly variable within each epoch. The average spectra were created with the ADDASCASPEC tool for each of the 3 epochs, and were used for the subsequent spectral analysis.

3 SPECTRAL ANALYSIS AND RESULTS

The spectral analysis are performed using XSPEC version 12.11.1 (Arnaud 1996), which is included as part of the HEASOFT v6.28. In all models, a multiplicative constant model is included using the constant model to account for the differences in the flux calibration between instruments. This constant is fixed at 1.0 for NuSTAR/FPMA, and allowed to vary for NuSTAR/FPMB and HXMT/LE, ME, and HE, unless otherwise noted. We use the tbabs model (Wilms et al. 2000) to model the neutral Galactic absorption, with the abundances of Wilms et al. (2000) and the cross-sections of Verner et al. (1996) adopted. All parameter uncertainties are quoted at 90% confidence level for one parameter of interest.

3.1 Fitting spectra individually

We initially jointly fitted the NuSTAR and HXMT data for each of the 3 epochs with an absorbed powerlaw model plus a multi-temperature thermal disc (diskbb) model (Mitsuda et al. 1984). There is no overlap in the coverage among the 3 instruments of HXMT. We therefore linked the 3 constant parameters together to prevent the degeneracy between the constant parameters for LE/ME/HE and the photon index $\Gamma$ of powerlaw. The remained parameters were linked for the NuSTAR and HXMT data. The iron line region between 4-8 keV and Compton hump region between 15-45 keV were ignored to avoid potential contribution to the powerlaw continuum. We note that the residual profiles in the high energy band for NuSTAR and HXMT are slightly different for Epoch 1. We find that this could be due to the change of the photon index $\Gamma$ of the the powerlaw continuum component between the NuSTAR and HXMT observations in Epoch 1. Indeed, the residuals for the NuSTAR and HXMT data are consistent if the photon index $\Gamma$ is fitted independently for the NuSTAR and HXMT data. Figure 2 shows the ratios of the data-to-model for 3 epochs. It is clear that significant reflection features are revealed in all of 3 epochs. The profile of the iron line appears to be relatively stable with its red wing extending below $\sim$5 keV over 3 epochs, indicating that the inner accretion disc may always be at the ISCO. On the other hand, the flux of the iron line decreases from Epoch 1 to 3 (Figure 3).

We then replaced the powerlaw model with a reflection model relxillCp (relxill v1.4.3, Dauzer et al. 2014; García et al. 2014) to fit the relativistically blurred reflection component in the data. The relxillCp model also internally includes a continuum component which is calculated using the Comptonization model nthcomp (Zdziarski et al. 1996; Życki et al. 1999). A distance reflection component, which is generally believed to originate from the reflection of the outer accretion disc, is also added using the model xillverCp (García & Kallman 2010). The total model is given by constant*tbabs(diskbb+relxillCp+xillverCp) in XSPEC. We fitted each epoch independently with this model.

1 http://hxmten.ihep.ac.cn/SoftDoc.jhtml

2 The systematic uncertainties are related to the spectrum energy, and 1%/2%/3% are recommended for LE/ME/HE. But we found that are overestimated for LE and ME (with a $\chi^2$ less than 1) when we compare the fit statistics between HXMT and NuSTAR. Therefore, the systematic error is set to 0.5% for LE and ME.
Table 1. Details of NuSTAR and HXMT observations

| Mission | Instrument | ObsID | MJD   | Start Time | End time | Exposure (s) | Count Rate$^a$ (cts s$^{-1}$) | Total counts$^b$ | State$^c$ |
|---------|------------|-------|-------|------------|----------|--------------|-----------------|----------------|----------|
| **Epoch 1** |
| **NuSTAR** | FPMA | 90301013002$^{d}$ | 58003.79 | 09-07 18:41:09 | 09-08 17:01:09 | 8685 | 648.3 ± 0.3 | 1.11×10$^7$ | LHS |
| | FPMB | ... | ... | ... | ... | 9077 | 601.2 ± 0.3 | |
| **HXMT** | LE | 11453500104 | 58002.72 | 09-06 17:11:13 | 09-06 20:22:09 | 1047 | 269.5 ± 0.5 | 8.13×10$^6$ | |
| | ME | ... | ... | ... | ... | 1331 | 268.8 ± 0.5 | |
| | HE | ... | ... | ... | ... | 1309 | 645.2 ± 1.6 | |
| | LE | 11453500105 | 58002.85 | 09-06 20:22:09 | 09-06 23:33:06 | 898 | 280.0 ± 0.6 | |
| | ME | ... | ... | ... | ... | 1218 | 274.0 ± 0.5 | |
| | HE | ... | ... | ... | ... | 1730 | 652.6 ± 1.3 | |
| | LE | 11453500106 | 58002.98 | 09-06 23:33:06 | 09-07 02:43:10 | 1057 | 289.6 ± 0.5 | |
| | ME | ... | ... | ... | ... | 1193 | 283.2 ± 0.5 | |
| | HE | ... | ... | ... | ... | 1543 | 664.6 ± 1.4 | |
| | LE | 11453500107$^{d}$ | 58003.11 | 09-07 02:43:10 | 09-07 05:54:06 | 937 | 296.4 ± 0.6 | |
| | ME | ... | ... | ... | ... | 1487 | 287.5 ± 0.5 | |
| | HE | ... | ... | ... | ... | 1837 | 666.2 ± 1.2 | |
| | LE | 11453500108 | 58003.25 | 09-07 05:54:06 | 09-07 09:05:03 | 1676 | 300.9 ± 0.4 | |
| | ME | ... | ... | ... | ... | 1960 | 293.6 ± 0.4 | |
| | HE | ... | ... | ... | ... | 378 | 671.9 ± 3.0 | |

| **Epoch 2** |
| **NuSTAR** | FPMA | 80302309002 | 58008.55 | 09-12 13:01:09 | 09-12 18:26:09 | 2258 | 1132.0 ± 0.7 | 5.05×10$^6$ | HIMS |
| | FPMB | ... | ... | ... | ... | 2418 | 1032.0 ± 0.7 | |
| **HXMT** | LE | 11453500144 | 58008.44 | 09-12 10:38:15 | 09-12 13:58:12 | 1137 | 979.3 ± 0.9 | 3.73×10$^3$ | |
| | ME | ... | ... | ... | ... | 2168 | 407.6 ± 0.5 | |
| | HE | ... | ... | ... | ... | 1684 | 462.3 ± 1.3 | |
| | LE | 11453500145 | 58008.58 | 09-12 13:58:12 | 09-13 00:41:28 | 3179 | 996.2 ± 0.6 | |
| | ME | ... | ... | ... | ... | 8202 | 414.2 ± 0.2 | |
| | HE | ... | ... | ... | ... | 9329 | 474.1 ± 0.6 | |

| **Epoch 3** |
| **NuSTAR** | FPMA | 80302309010 | 58017.21 | 09-21 04:51:09 | 09-21 10:46:09 | 1531 | 1818.0 ± 1.1 | 5.50×10$^6$ | SIMS |
| | FPMB | ... | ... | ... | ... | 1652 | 1643.0 ± 1.0 | |
| **HXMT** | LE | 11453500901 | 58017.10 | 09-21 02:26:26 | 09-21 06:00:41 | 1676 | 2251.0 ± 1.2 | 5.93×10$^3$ | |
| | ME | ... | ... | ... | ... | 2967 | 399.3 ± 0.4 | |
| | HE | ... | ... | ... | ... | 2467 | 326.3 ± 1.2 | |
| | LE | 11453500902 | 58017.25 | 09-21 06:00:41 | 09-21 09:21:07 | 1820 | 2259.0 ± 1.1 | |
| | ME | ... | ... | ... | ... | 2780 | 387.4 ± 0.4 | |
| | HE | ... | ... | ... | ... | 3697 | 326.3 ± 0.9 | |

Note. a. The count rate is shown within the energy band of 4.0-79.0 keV for NuSTAR/FPMA and FPMB, 2.1-10.0, 10.0-27.0, 27.0-60.0 keV for HXMT/LE, ME, and HE, respectively.

b. The total number of counts are shown for the two modules of NuSTAR and the three modules of HXMT combined spectra.

c. Spectral states labeled according to Huang et al. (2018) and Tao et al. (2018).

d. The NuSTAR and HXMT observations were analyzed by Xu et al. (2018) and Kong et al. (2020), respectively.

In order to test the potential evolution of the inner radius of the disc over the rise phase of the outburst, we fixed the spin ($a_\star$) of the black hole at its maximal value 0.998 ($R_{\text{ISCO}} = 1.235 R_g$). While the inner radius ($R_{\text{in}}$) of the disc was free in the relxillCP model. The outer radius of the disc ($R_{\text{out}}$) was fixed at the default value 400 $R_g$. We found that the best-fitting value of the iron abundance parameter $A_{\text{Fe}}$ was very close to the solar abundance in all the 3 epochs. We thus fixed $A_{\text{Fe}}$ at the solar abundance. The emissivity profile is described by a broken powerlaw in relxillCP, i.e., $\epsilon(r) \propto r^{-\alpha_{\text{in}}} \text{ for } r < R_{\text{br}}$ and $\epsilon(r) \propto r^{-\alpha_{\text{out}}} \text{ for } r > R_{\text{br}}$. $R_{\text{br}}$ is the break radius, while $q_{\text{in}}$ and $q_{\text{out}}$ are the index for the inner and outer regions, respectively. Our data, however, cannot constrain all the 3 parameters simultaneously. We thus used a simple powerlaw to describe the emissivity profile by linking the value of $q_{\text{out}}$ to that of $q_{\text{in}}$. All the other parameters (the inclination angle $i$, the ionization state log$\xi$, the electron temperature $kT_e$, and the normalization $N_{\text{rel}}$ in the relxillCP are free parameters.

The parameters in the xillverCP component were linked to those of relxillCP except for the ionization (log $\xi_{\text{rel}}$) and the normalization ($N_{\text{rel}}$) parameters. We initially fixed the log $\xi_{\text{rel}}$ of the xillverCP component at zero. Compared with the best-fitting results shown in Table A1, the statistics were degraded by $\Delta \chi^2 = 84.5$, 93.7, and 52.5 for 1 degree of freedom in Epoch 1, 2, and 3, respectively. The case that the distant reflection comes from ionized material is consistent with the previous studies (Xu et al. 2018; Sridhar et al. 2019), in which they reported that the ionization of the outer disc could be high (e.g. log $\xi_{\text{rel}} > 0$) and may be different from the inner disc region. We then set log $\xi_{\text{rel}}$ of the xillverCP component independent of that (log $\xi_{\text{rel}}$) of relxillCP. The two values of log $\xi$ are consistent within uncertainty for the Epoch 3, but they are quite distinct for the Epoch 1 and 2. Therefore, the two values of log $\xi$ in the xillverCP and relxillCP were linked for Epoch 3, while they were fitted independently for Epoch 1 and 2. In addition, we find that unlinking photon index (Γ) of powerlaw between the NuSTAR and
the \textit{HXMT} data can greatly improve the fitting result for Epoch 1 with \(\Delta \chi^2 = 387.52\) for one additional parameter. The values of photon index are constrained to be \(1.93^{+0.01}_{-0.02}\) and \(1.89^{+0.01}_{-0.02}\), respectively. The minor difference between values of \(\Gamma\) maybe attributed to the non-strictly simultaneous observation in Epoch 1.

This model can fit all the 3 epochs well, yielding reasonable statistics with \(\chi^2/\nu = 4576.52/4273 = 1.07\) and \(3296.63/3323 = 0.99\) and \(3317.74/2991 = 1.11\) for the Epoch 1, 2 and 3, respectively. Table A1 presents the details of independent fitting of each epoch. The best-fitting emissivity profile is steep in each of the 3 epochs, i.e. \(q > 9.81\) for Epoch 1, \(q = 7.33^{+1.44}_{-0.97}\) for Epoch 2, and \(q > 7.22\) for Epoch 3. Xu et al. (2018) also used the same model to fit the \textit{NuSTAR} data of Epoch 1. Our best-fitting results of Epoch 1 are consistent with their results, albeit they fixed \(q_{\text{out}}\) at 3 with \(R_{\text{in}} = 10 R_g\). Assuming the Newtonian case (Shakura & Sunyaev 1973; Novikov & Thorne 1973; Reynolds & Begelman 1997), i.e. \(q\) was fixed at 3, we got much worse fits with \(\Delta \chi^2 = 97.67, 52.23,\) and 38.87 for Epoch 1, 2 and 3, respectively.

The inferred LOS hydrogen column density \(N_H\) varies from \(\sim 6.95 \times 10^{22}\ cm^{-1}\) for Epoch 1 to \(\sim 5.4 \times 10^{22}\ cm^{-1}\) for Epoch 2 and 3. These best-fitting LOS column densities are higher than that expected from Galactic absorption \(1.40 \times 10^{22}\ cm^{-1}\), which may imply intrinsic absorption from the source. The variation of this excess absorption could attribute to the wind or the outer region of the disc. However, it can also be due to systematic uncertainty with the model, as such variation of the absorption is not typical in low-mass X-ray binaries. In addition, there is no evidence of the absorption lines detected in the X-ray spectra of MAXI J1535-571. To test whether a constant LOS absorption can fit the data, we performed a simultaneous fit to all the 3 epochs.

3.2 Fitting spectra simultaneously

The LOS column density \(N_H\), inclination angle of the disc \(i\), Fe abundance \(A_{Fe}\), and the black hole spin \(a_\ast\) were not supposed to vary among the 3 epochs, they were thus linked together. We again fixed \(A_{Fe}\) at solar abundance and \(a_\ast\) at the maximum 0.998. The \(i\) was left as free parameter. The remaining parameters were fitted independently for each epoch, and were set up as stated in Section 3.1. We refer this model as M1. The model can fit the data well with \(\chi^2/\nu = 11296.63/10591 = 1.07\). The best-fitting parameters for M1 are presented in Table 2. The components of the model together with the residuals are shown in Figure 4. A positive feature between 21-23 keV in \textit{HXMT} residuals (bottom panels of Figure 4), which is a known effect that is caused by the photoelectric effect of silver elements (You et al. 2021). Ignoring this energy range (only for the \textit{HXMT}/ME instrument) does not affect the results. We also note that an excess at high energy tail is shown in the residuals in Epoch 1. Such excess may be attribute to the weaker disc component in the joint-fit, as it is not seen when fit the spectra individually (Section 3.1) of which we got a stronger disc component with also a slightly larger \(kT_e\) and higher column density. Since the column density is expected to not vary dramatically among these 3 epochs. We therefore mainly report on the results from the joint-fit to 3 epochs (M1).

The best-fitting \(N_H\) is found to be \((5.48^{+0.05}_{-0.04}) \times 10^{22}\ cm^{-1}\). This high absorption is slightly larger than the result obtained from the \textit{Swift} \((\sim 3.6 \times 10^{22}\ cm^{-1}\), Kennea et al. 2017) and \textit{NICER} \((\sim 4.05 \times 10^{22}\ cm^{-1}\), Gendreau et al. 2017; \(\sim 4.89 \times 10^{22}\ cm^{-1}\), Miller et al. 2018). It is noteworthy that fixing \(N_H\) at a smaller value will significantly worsen the fit, e.g., \(\Delta \chi^2 = 186.91\) for 1 degree of freedom if \(N_H\) is fixed at \(5 \times 10^{22}\ cm^{-1}\).
The relatively weak thermal components showed in Epoch 1 and 2 are comparable, while a prominent thermal component is clearly shown in Epoch 3 (dashed line in the upper panels). We find that a steep emissivity index is required for all the 3 epochs \((q > 9.13\) for Epoch 1, \(q = 8.73^{+0.57}_{-0.40}\) for Epoch 2, and \(q > 9.50\) for Epoch 3). The parameter \(k_T\), which represents the temperature of the electrons in the corona, is constrained to be 18.13\(^{+0.53}_{-0.29}\) keV for Epoch 1, \(34.01^{+2.08}_{-2.08}\) keV for Epoch 2, and \(>322.30\) keV for Epoch 3. The reflection fraction \(R_t\) is approximate unity in all 3 epochs, indicating that half of the powerlaw photons irradiate the disc. The constant factor is low for LE/ME/HE of \(HXMT\) in Epoch 1, which is because of non-simultaneity. In addition, the inner radius of the accretion disc is broadly consistent among the 3 epochs with only minor difference, i.e., \(R_{in} = 1.51^{+0.04}_{-0.03} R_g\) for Epoch 1, \(R_{in} = 1.35^{+0.02}_{-0.03} R_g\) for Epoch 2, and \(R_{in} = 1.38^{+0.03}_{-0.02} R_g\) for Epoch 3. However, the best-fitting inclination angle, \(i = 72.80^{+0.86}_{-0.48}\) degrees, is much higher than that measured from radio jet.

Our results suggest that the inner radius of the accretion disc does not change significantly which may indicate that it extends to the ISCO. The best-fitting inclination angle, \(i = 72.80^{+0.86}_{-0.48}\) degrees, is much higher than that measured from radio jet.

We also tried to fit the data with the lamp-post model \(relxill1cp\). In this scenario, the hard X-ray photons are produced in a point source above the black hole spin axis (Miniutti & Fabian 2004). The height \(h\) of the corona, instead of \(q_{out}\) and \(R_{in}\) in \(relxill1cp\), is used to describe the illumination of the disc. The lamp-post configuration with a low height of the corona has been successfully used to explain the steep emissivity profile found.
We have presented the detailed multi-epoch analysis of the reflection spectra of the black hole binary candidate MAXI J1535-571 over its rising phase of the outburst in 2017. The data were observed quasi-simultaneously by NuSTAR and HXMT when the source was in the LHS (Epoch 1), HIMS (Epoch 2), and SIMS (Epoch 3). We initially fitted the 3 epochs independently. We then performed joint modelling of the data for the 3 epochs. After subtracting the continuum (absorbed thermal emission plus power law component), prominent reflection features including the relativistic Fe Kα line and the Compton hump are detected in each of the 3 epochs. The Fe Kα line profile does not change significantly among the 3 epochs, while its flux decreases gradually from Epoch 1 to 3. In addition to the smeared reflection from the disc close to the black hole, the distant reflection, which maybe reflected from the ionized surface of the outer disc or the companion, was also observed. The relxillcp and xillvercp models were used in this work to fit the relativistic and distant reflection, respectively. We found that the hydrogen column density changes when fitted the 3 epochs independently, which may be induced by the systematic issues. Therefore, we also fitted the data from the 3 epochs simultaneously with the hydrogen column density assumed to be the same.

The inclination of the accretion disc measured by modeling the X-ray reflection spectra is high (~70 degrees) in MAXI J1535-571. This is in agreement with the previous results by fitting NuSTAR, NICER, and AstroSat data in Xu et al. (2018), Miller et al. (2018), and Sridhar et al. (2019), respectively. The inclination we obtained is significantly larger than the jet inclination (~45 degrees) which is measured by analyzing the radio data (Russell et al. 2019). We also tried to fit the data with the inclination fixed at smaller values, e.g., less than 45 degrees. However, this always resulted in an unacceptable fit. Our results imply that the rotation axis of the inner accretion disc seems to be misaligned with the radio jet. Additionally, the jet and binary orbital plane is potentially misaligned. Such discrepancy has been previously reported in other systems like Cyg X-1 (Tomsick et al. 2014; Parker et al. 2015; Walton et al. 2016) and MAXI J1820+070 (Poutanen et al. 2022).

The reflection-based measurements constrained the spin of the black hole in MAXI J1535-571 to be > 0.987 (Xu et al. 2018), 0.994 ± 0.002 (Miller et al. 2018), 0.7±0.2 (Kong et al. 2020), and 0.67±0.16 (Sridhar et al. 2019) by analysing data obtained between September 7 and 13. Because of the strong degeneracy between the spin and the inner radius, the intermediate spin measured in the HIMS by Sridhar et al. (2019) may indicate that the disc is moderately truncated before it extending down to the ISCO. In this work, we use the NuSTAR and HXMT data observed on September 7 (LHS), 12 (HIMS) and 21 (SIMS) to study the potential evolution of the disc inner radius in MAXI J1535-571. We find that the inner radius does not change significantly in the three epochs with $R_{\text{in}} \leq 1.55R_{\text{g}}$. The lack of the disc truncation is inconsistent with the work by Sridhar et al. (2019), which may attribute to the high iron abundance assumed in their model. The phenomenon of the disc inner radius without receding or proceeding represents $R_{\text{in}} = R_{\text{ISCO}}$. The spin is estimated to be 0.985±0.002$^a$ via letting $a_*$ free instead of $R_{\text{in}}$ suggesting a rapidly rotating black hole in MAXI J1535-571, which is in agreement with Xu et al. (2018) and Miller et al. (2018).

Except the two key systematic parameters, i.e., the spin of the black hole and the inclination of the inner disc, were estimated, the properties of the thermal emission and the Comptonized component are also explored. The parameters related to them present good consistency between M1 and M2. We note that these two components

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**Figure 3.** Close-up of iron line profiles in Figure 2 for the NuSTAR and HXMT observations. In both panels, Epoch 1 is shown in black, Epoch 2 is shown in blue, and Epoch 3 is shown in magenta. The red wing appears to be relatively stable below ~5 keV during 3 epochs.
are exhibiting evolution. Epoch 1 is obtained when the source is in the bright phase of the hard state, while Epoch 2 is obtained at the beginning of the hard-to-soft state. In Epoch 3, of which the luminosity of the source is approaching the peak during the outburst, and the source stay in the soft intermediate state. From Figure 4, the flux is dominated by the powerlaw component in Epoch 1 and 2, while the powerlaw and thermal components are equivalently strong in Epoch 3.

The thermal emission observed above 2.1 keV is equally weak in Epoch 1 and 2, but becomes strong in Epoch 3. As listed in Table 2, the two best-fitting parameters, $T_{\text{in}}$ and $N_{\text{disc}}$, of model diskbb change significantly during the source transited from Epoch 2 to 3, which is in agreement with the results in Tao et al. (2018). It appears that the inner radius of the disc is slightly truncated in Epoch 1 and 2, which is inconsistent with the stable inner radius by modelling relativistic reflection components. Based on the results in Table 2, we calculated the unabsorbed disc flux (0.001-20 keV) for the 3 epochs, which are $\sim 3.97 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$, respectively. The flux does not show significant change from Epoch 2 to Epoch 3. This is inconsistent with the rise of the count rate shown in Figure 1, which indicates the increase of the accretion rate. The similar flux of the disc emission maybe led by the model without accounting for the Comptonization of the disc photons in corona. In the other hand, the effective temperature and the effective radius should be estimated after correcting the $T_{\text{in}}$ and $r_{\text{in}}$ by a hardening factor $f$. Because the model diskbb does not account for any effects from the general relativity or electron scattering. A positive correlation between $f$ and accretion rate was reported in Davis & El-Abd (2019) and Done & Davis (2008). Therefore, the abrupt change in the $T_{\text{in}}$ and $N_{\text{disc}}$ may be attributed from the change of accretion rate and hardening factor.

The photon index of $\Gamma \sim 1.82$ in Epoch 1 is typical of the hard state. The spectrum softens as the state transition progresses, in Epoch 2 ($\Gamma \sim 2.40$) and Epoch 3 ($\Gamma \sim 2.79$). $\Gamma$ is used to describe the slope of the powerlaw, a component produced by inverse Compton scatter of the thermal emission in the corona. $\Gamma$ is related to the electron temperature ($kT_e$) and optical depth ($\tau$) of the corona by formula (Zdziarski et al. 2020):

$$\Gamma = -\frac{1}{2} + \sqrt{\frac{9}{4} + \frac{1}{u\theta(1 + \theta + 3\theta^2)}}$$

where $\theta$ is determined by $kT_e/m_e c^2$, and $m_e c^2$, the rest mass of the electron, is equal to 511 keV. The term $u$ is the average number of scattering, which is calculated as follows (Zdziarski et al. 2020):

$$u = \tau(a + b\tau)$$

$$a = \frac{1.2}{1 + \theta + 5\theta^2}, \quad b = \frac{0.25}{1 + \theta + 3\theta^2}$$

The corona temperature, however, is challenging to be determined by X-ray spectral analysis because of the low sensitivity of the detectors at high energies (> 10 keV), until the launch of the NuSTAR mission. Indeed, NuSTAR observations have provided opportunities to detect the $kT_e$ in a large number of AGNs and X-ray binaries (Lohfink et al. 2015; Pahari et al. 2017; Lanzuisi et al. 2019; Yan et al. 2020).

Figure 4. Top panels: the best-fitting models for MAXI J1535-571. We fit 3 epochs simultaneously, but show the results for each of the epoch in an individual way for clarity. The total model is shown in thick-solid line; the thermal emission (diskbb) from the disc is shown in dashed line; the Comptonization component nthcomp is shown in dot-dashed line, and it is calculated internally by relxillcp. the relativistic and distant reflection are shown in dotted and thin-solid lines. For Epoch 1, the models for HXMT is very similar to that for NuSTAR, so only the lines for NuSTAR are presented for visual clarity. Middle and bottom panels: NuSTAR and HXMT residuals with 1σ, respectively. The blue and red are for FPMA and FPMB. The green, cyan, and orange are for LE, ME, and HE, respectively. The data has been rebinned here for display clearly.
The black hole candidate MAXI J1535-571 was caught by NuSTAR and HXMT at three different states during its 2017 outburst: LHS, HIMS, and SIMS. The results of this work on the broad-band reflection spectra by jointly-fit to these three states found that the inner radius of the disc should be stable at the ISCO. The spin $0.985^{+0.002}_{-0.004}$ indicates a fast rotating black hole in the system. A high inclination angle of the disc is indicated. During the LHS-HIMS transition, the Comptonized component becomes soft, the electron temperature increases slightly, and the thermal component from the disc is relatively comparable. Across the HIMS-SIMS transition, the Comptonized component continues to be soft, the electron temperature shows an abrupt increase, and the thermal component also contributes significantly. We calculated the $\Gamma - kT_e$ panel giving a range value 0.2-4 of the optical depth $\tau$ of the corona. The best-fitting results of $\Gamma$ and $kT_e$ imply that the $\tau$ varies from $\sim 4$ to $\sim 1.5$, and to $\sim 0.2$ over the state transitions. It is clear that the properties of the corona has changed. The corona evolves from dense low-temperature in the LHS to tenuous high-temperature after the state transition, which seems to imply that the physical properties of the corona has changed during the state transition.

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DATA AVAILABILITY

Data used in this article are publicly available from the NuSTAR mission (https://heasarc.gsfc.nasa.gov/docs/archive.html) and HXMT mission (http://hxmt.en.ihep.ac.cn).

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Figure 5. The relationship between $\Gamma$ and $kT_e$ calculated for the optical depth $\tau$ with value range 0.2-4. The black points are quoted from the best-fitting parameters in M1.

et al. 2020). On the other hand, a better statistics can be achieved by adding HXMT observations in this work. The values of $kT_e$ are constrained to be $\sim 18$, $\sim 34$, and $> 311$ keV for Epoch 1, 2, and 3 respectively. The unconstrained upper limit in Epoch 3 maybe caused by the extremely steep of the powerlaw and the signal to noise is not sufficient enough. The corona temperature change slightly from Epoch 1 to 2, but increases more than ten times in Epoch 3. The increased $\Gamma$ represents that the spectrum is becoming softer. If it is the case discovered in the LHS, the softening can be explained by the movement of the inner disc towards the black hole or the inflowing corona with a moderately relativistic velocity Zdziarski et al. (1999). More soft photons emitted from the disc will go into the Comptonization region. This will increase the cooling effect of the population of electrons, then the $kT_e$ of the corona decreases and the $\Gamma$ of the powerlaw increases. In this work, we found that the spectra become softer with steeper power index as the corona temperature increases during the LHS-HIMS-SIMS transition. This is inconsistent with this framework. Moreover, the inner radius has been stable at the ISCO during the 3 epochs. The behavior of the $\Gamma$ and $kT_e$ is similar to the behavior in GX 339-4 (Motta et al. 2009). Following the above equations, we calculated $\Gamma - kT_e$ plane assuming different values of $\tau$ (Figure 5). The optical depth experienced dramatic change. Its value decreased from $\sim 4$ (Epoch 1) to $\sim 1.5$ (Epoch 2), then to $\sim 0.2$ (Epoch 3). It seems that a dense low-temperature corona in the LHS evolves to a tenuous high-temperature corona after the state transition. The low optical depth of the corona in the SIMS may lead to inefficiency of the Compton scatterings in the corona, of which the cooling is substantially suppressed. Therefore, the corona temperature in Epoch 3 becomes much higher. The behaviour seems to imply that the state transition is accompanied by the coronal evolution. The detailed physical mechanism driving such evolution of the corona is beyond the scope of this work.

5 CONCLUSIONS

The black hole candidate MAXI J1535-571 was caught by NuSTAR and HXMT at three different states during its 2017 outburst: LHS, HIMS, and SIMS. The results of this work on the broad-band reflection spectra by jointly-fit to these three states found that the inner radius of the disc should be stable at the ISCO. The spin $0.985^{+0.002}_{-0.004}$ indicates a fast rotating black hole in the system. A high inclination angle of the disc is indicated. During the LHS-HIMS transition, the Comptonized component becomes soft, the electron temperature increases slightly, and the thermal component from the disc is relatively comparable. Across the HIMS-SIMS transition, the Comptonized component continues to be soft, the electron temperature shows an abrupt increase, and the thermal component also contributes significantly. We calculated the $\Gamma - kT_e$ panel giving a range value 0.2-4 of the optical depth $\tau$ of the corona. The best-fitting results of $\Gamma$ and $kT_e$ imply that the $\tau$ varies from $\sim 4$ to $\sim 1.5$, and to $\sim 0.2$ over the state transitions. It is clear that the properties of the corona has changed. The corona evolves from dense low-temperature in the LHS to tenuous high-temperature after the state transition, which seems to imply that the physical properties of the corona has changed during the state transition.
Table A1. Best-fitting Parameters of individual fits to 3 epochs

| Component | Parameter | Epoch 1 (LHS) | Epoch 2 (HIMS) | Epoch 3 (SIMS) |
|-----------|-----------|---------------|---------------|---------------|
| TBabs     | $N_H \times 10^{22}$ cm$^{-2}$ | $6.95^{+0.18}_{-0.19}$ | $5.5^{+0.26}_{-0.24}$ | $5.33^{+0.08}_{-0.09}$ |
| diskbb    | $T_{in}$ (keV) | $0.349^{+0.009}_{-0.016}$ | $0.349^{+0.014}_{-0.016}$ | $1.215^{+0.006}_{-0.013}$ |
| relxillCp | $\Gamma \log \xi_{rel}$ (erg cm s$^{-1}$) | $1.92^{+0.014}_{-0.016}$ | $2.4^{+0.021}_{-0.02}$ | $2.777^{+0.009}_{-0.10}$ |
| xillverCp | $R_t$ (degrees) | $77.8^{+0.66}_{-0.69}$ | $69.69^{+3.07}_{-2.88}$ | $68.88^{+5.5}_{-4.08}$ |
| constant  | $C_{FPMB}$ | $25.2^{+1.75}_{-1.29}$ | $34.12^{+3.68}_{-3.84}$ | $>277.43$ |
|           | $C_{LE}$ | $1.3^{+0.03}_{-0.02}$ | $1.44^{+0.06}_{-0.06}$ | $<1.44$ |
|           | $N_{rel}$ (keV) | $1.15^{+0.15}_{-0.16}$ | $1.3^{+0.24}_{-0.25}$ | $<1.15$ |
|           | $\Gamma_{HXTM}$ | $1.88^{+0.012}_{-0.016}$ | $11.88^{+3.32}_{-3.21}$ | ... |
|           | $N_{xillverCp}$ | $2.2^{+0.15}_{-0.15}$ | $3.68^{+0.15}_{-0.16}$ | ... |
|           | $xillverCp$ | $1.1^{+0.16}_{-0.15}$ | $6.87^{+2.28}_{-1.13}$ | $11.8^{+3.32}_{-3.21}$ |
|           | $\chi^2$ | $4576.52$ | $3296.6$ | $3317.74$ |
|           | $\nu$ | $4273$ | $3323$ | $2991$ |
|           | $\chi^2/\nu$ | $1.07$ | $0.99$ | $1.11$ |

Notes. Fitting 3 epochs individually with the model constant*\text{tbabs}(diskbb+relxillCp+xillverCp). The spin parameter $a_\ast$ is fixed at 0.998. The inner radius $R_{in}$ is free. The emissivity profile is assumed to be a single powerlaw, for which the emissivity index $\log \xi_{rel}$ and $log \xi_{xillCp}$ for relxillCp and xillverCp, respectively, which is linked for Epoch 3); Electron temperature ($kT_e$); Reflection fraction ($R_t$); Normalization constants of diskbb ($N_{disc}$), relxillCp ($N_{rel}$) and xillverCp ($N_{xill}$).