INSIGHT-HXMT Observations of the New Black Hole Candidate MAXI J1535−571: Timing Analysis

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Abstract

We present X-ray timing results of the new black hole candidate MAXI J1535−571 during its 2017 outburst from Hard X-ray Modulation Telescope (INSIGHT-HXMT) observations taken from 2017 September 6 to 23. Following the definitions given by Belloni, we find that the source exhibits transitions from the low/hard state to the hard intermediate state, and eventually to the soft intermediate state. Quasi-periodic oscillations (QPOs) are found in the intermediate states, which suggest different types of QPOs. With the large effective area of Hard X-ray Modulation Telescope (HXMT), we are able to present the energy dependence of the QPO amplitude and centroid frequency up to 100 keV, which has rarely been explored by previous satellites. We also find that the phase lag at the type-C QPOs centroid frequency is negative (soft lag) and strongly correlated with the centroid frequency. Assuming a geometrical origin of type-C QPOs, the source is consistent with being a high-inclination system.

Key words: black hole physics – stars: individual (MAXI J1535−571) – X-rays: binaries

1. Introduction

Black hole transients (BHTs) spend most of their lives in quiescence, and are detected during outbursts in which their spectral and timing properties change with time. During a typical outburst, they go through the low hard state (LHS), hard and soft intermediate states (HIMS, SIMS), high soft state (HSS), then again through the intermediate states and back to the LHS, following the classification given in Belloni (2010; see Remillard & McClintock 2006 for an alternative classification, and Motta et al. 2009 for a comparison). In the LHS, the X-ray spectrum can be approximately described by a power law with a spectral index of $\sim 1.6$ (2–20 keV band), and an exponential cutoff at $\sim 100$ keV. This hard X-ray emission is thought to arise from the Comptonization of soft disk photons in a hot corona. The corresponding power density spectrum (PDS) shows strong ($\sim 30\%$ rms) band-limited noise, and sometimes low-frequency quasi-periodic oscillations (LFQPOs). While the X-ray spectrum in the HSS is dominated by a soft thermal component, modeled with a multi-temperature disk–blackbody with a typical temperature of $\sim 1$ keV at the inner disk radius, its PDS shows weak (down to a few percent fractional rms) power-law noise.

Compared to the two main states, which show consistent behaviors, other states are complex and more difficult to classify and to interpret; both disk and power-law components are clearly present in the energy spectra, and the main feature of the PDS is LFQPOs with a centroid frequency ranging from a few mHz to $\sim 30$ Hz. Several types of LFQPOs have been identified and classified into types A, B, and C (Remillard et al. 2002; Casella et al. 2005). The study of LFQPOs is...
essential to our understanding of the accretion flow around black holes, though their origin is still under debate. One of the promising scenarios for type-C QPOs is that the oscillations are produced by Lense–Thirring precession of the inner accretion flow (Ingram et al. 2009). Evidence in support of this scenario is inferred from the modulation of the reflected iron line equivalent width (Ingram & van der Klis 2015) and the centroid energy (Ingram et al. 2016) during a QPO cycle using phase-resolved spectroscopy of type-C QPOs, the inclination dependence of QPO phase lags (van den Eijnden et al. 2015), and the absolute variability amplitude (Motta et al. 2015). In addition, it is important to consider the energy dependence of the QPO properties, such as fractional rms, centroid frequency, and time-lag (Tomsick & Kaaret 2001; Rodriguez et al. 2004; Qu et al. 2010; Yadav et al. 2016). This can bridge over the energy spectra and the timing variability.

A new X-ray transient, MAXI J1535−571, was independently discovered by MAXI/GSC (Negoro et al. 2017a) and Swift/BAT (Barthelmy et al. 2017; Kennea & Evans 2017) on 2017 September 02 (MJD 579998). The radio (Russell et al. 2017), sub-millimeter (Dincer 2017), near-infrared (Dincer 2017), and optical (Scaringi & ASTR211 Students 2017) counterparts were detected soon after the discovery of the source. MAXI/GSC and ATCA follow-up observations indicated the source to be a black hole candidate (BHC), judging from its X-ray spectral shape and rapid X-ray variability (Negoro et al. 2017b), as well as the radio versus X-ray luminosity ratio (Russell et al. 2017). Later MAXI/GSC and Swift observations suggested that the source was undergoing a hard-to-soft state transition (Kennea 2017; Nakahira et al. 2017; Palmer et al. 2017; Tao et al. 2018). LFQPOs have been detected by Swift/XRT and NICER (Gendreau et al. 2017; Mereminskii & Grebenev 2017). Using NICER data, Miller et al. (2018) analyzed the spectrum of MAXI J1535−571 observed on September 13. Their results gave a spin of 0.994 (2), and an inclination angle of 67.4(8)°. Xu et al. (2018) performed spectral fits of NuSTAR observations using a relativistic reflection model, and estimated a black hole spin of $a > 0.84$ and a high inclination angle of $57.2^{+1.0}_{-0.9}$ and $75.4^{+2.0}_{-2.0}$.

In this paper, we study the temporal variation of the source using Hard X-ray Modulation Telescope ($Insight$-HXMT) observations. In Section 2, we describe the observations and data reduction methods. The results are presented in Section 3. A discussion and conclusions follow in Sections 4 and 5.

2. Observations and Data Analysis

Following the MAXI/GSC and Swift/BAT discovery of MAXI J1535−571, we triggered $Insight$-HXMT Target of Opportunity observations. Our follow-up observations started on 2017 September 6 and ended on 2017 September 23, when the source was unobservable due to the constraint on the satellite due to the Sun. During this period, the detectors were switched off from September 07 to 12 owing to the X9.3 solar flare.13 Our sample contains 31 pointed observations, with each observation covering several satellite orbits. The observation log is shown in Table 1.

$Insight$-HXMT (Zhang et al. 2014), the first Chinese X-ray astronomical satellite, consists of three slit-collimated instruments: the High Energy X-ray Telescope (HE), the Medium Energy X-ray Telescope (ME), and the Low Energy X-ray Telescope (LE). HE contains 18 cylindrical Na(I)/Cs(I/Na) phoswich detectors which are sensitive in the 20–250 keV range with a total detection area of about 5000 cm²; ME is composed of 1728 Si-PIN detectors which are sensitive in the 5–30 keV range with a total detection area of 952 cm²; and LE uses the Swept Charge Device, which is sensitive in the 1–15 keV range with a total detection area of 384 cm². There are three types of field of view (FoV): $1° \times 6°$ (FWHM, full-width half-maximum) (also called the small FoV), $6° \times 6°$ (the large FoV), and the blind FoV, used to estimate the particle-induced instrumental background. Since its launch, $Insight$-HXMT has undergone a series of performance verification tests by observing the blank sky, standard sources, and sources of interest. These tests showed that the satellite works smoothly and efficiently, and allowed calibration of the instruments and background estimation.

We use the $Insight$-HXMT Data Analysis software (HXMTDAS) v2.014 to analyze all the data, filtering them according to the following criteria: (1) pointing offset angle <0.05°; (2) elevation angle >6°; (3) value of the geomagnetic cutoff rigidity >6. We only select events that belong to the small FoV. Since the LE detector can be saturated due to the bright Earth and local particles, we need to create good time intervals (GTIs) manually. For some observations there is no GTI for the LE detector. Since the detailed background model is still in progress, we use the blind FoV detectors to estimate the $Insight$-HXMT background, with a systematic error of 10%. We derive the background as $B = N \times C_b$, where $B$ is the background count rate of the small FoV in a given energy band, $N$ is the ratio of the number of small FoV detectors to that of blind FoV detectors, and $C_b$ stands for the blind FoV detector count rate in the same energy band as $B$. Using blank sky observations, we tested the reliability of this method.

To study the variability, we produced the PDS from 64 s data intervals with a time resolution of 1/128 s for each observation; in a few cases, an inspection of the PDS showed significant variations in the QPO frequency between different orbits, which were therefore split. The PDS was subjected to Miyamoto normalization (Miyamoto et al. 1991) after subtracting the Possion noise. It was fitted with a combination of Lorentzians (Nowak 2000; Belloni et al. 2002) using the XSPEC v12.9.1 between 0.01 Hz and 32 Hz. The best-fit reduced $\chi^2$ values were less than 1.5 (for a degree of freedom of ~138), with a typical value of 1.2. We estimated the total fractional variability ($\text{rms}$ of the PDS) in the range 0.1–32 Hz. We also produced 16 s cross-spectra between the 1–3 and 3–7 keV light curves of $Insight$-HXMT/LE (defined as $C(j) = X_2(j)X_1^*(j)$), where $X_1$ and $X_2$ are complex Fourier coefficients for the two energy bands at frequency $f_j$ and $X_2^*(j)$ is the complex conjugate of $X_2(j)$, and calculated the average cross-spectrum vectors for each observation. The phase lag at frequency $f_j$ was computed from the observed variance of $C(j)$ in the real and imaginary directions. For phase lag spectra, positive lag values mean that the hard photons are lagging the soft ones. To quantify the phase lag behavior of the QPOs, we computed their phase lags in a range centered at the QPO centroid frequency and spread over its width (Reig et al. 2000).

13 https://www.solarmonitor.org/goes_pop.php?date=20170906&type=xray
14 http://www.hxmt.org/index.php/dataan
No application of dead-time correction is given in the PDS and the cross-spectrum, since dead time (τd) should not be an issue in our analysis. In *Insight-HXMT*, τd is around 20 μs for HE and LE and 250 μs for ME; thus the frequency range commonly analyzed in BHCs is well below 1/τd.

### 3. Results

#### 3.1. Fundamental Diagrams

We plot the diagrams commonly used for the study of BHTs in Figures 1 and 2. For comparison, we also show the MAXI/GSC\(^{15}\) and *Swift/BAT*\(^{16}\) results taken from the web sites for each instrument.

The background-subtracted and dead-time-corrected *Insight-HXMT* light curves and hardness of MAXI J1535–571 are shown in Figure 1 (left panels). The LE count rate (1–12 keV) slowly rose from its initial value, reached a peak of 3212 cts s\(^{-1}\) on MJD 58015, and then stayed stable at that level. The ME count rate (6–38 keV) increased from 355 cts s\(^{-1}\) on MJD 58002 to 271 cts s\(^{-1}\) on MJD 58014, and decreased abruptly to 522 cts s\(^{-1}\) on MJD 58015, followed by several rises and falls. The HE count rate (26–100 keV) showed a decrease in the early phase, then was similar to the ME. Hardness is defined as the count rate in the 3–12 keV energy band divided by that in the 1–3 keV energy band. We found that the hardness remained the same (∼2.1) in the first several exposures around MJD ∼58002, but suddenly decreased to ∼1.5 on MJD ∼58008, and then slowly decreased to a low level. The trends of the light curves and hardness observed by *Insight-HXMT*, MAXI/GSC and *Swift/BAT* are consistent with each other.

The hardness–intensity diagram (HID) and the hardness–rms diagram (HRD) are shown in the left panel of Figure 2. Because only the rising part of the outburst was observed by *Insight-HXMT*, the source exhibited part of the standard q-shaped pattern. A relatively complete pattern is described by MAXI data in the right panel, with *Insight-HXMT* observations marked with red points. The outburst starts at the lower right of the figure, corresponding to the LHS, where the fractional rms remains at ∼26%. When the intensity increases, the source on the HID starts moving to the upper left, and the fractional rms drops to ∼15% on MJD 58008. In the corresponding PDS,

\(^{15}\) <http://maxi.riken.jp/star_data/J1535-572/J1535-572.html>

\(^{16}\) <https://swift.gsfc.nasa.gov/results/transients/weak/MAXIJI1535-571/>
strong type-C QPOs are detected (see Section 3.2), indicating that the system is in the HIMS. It is not possible to decide the precise transition position from the *Insight*-HXMT observations, as the instruments were switched off during that period. After several days in the HIMS, the fractional rms suddenly decreases to 1.9% on MJD 58015, and type-B QPOs (see Section 3.2) are seen in the PDS, indicating the system is in the SIMS. Then, the source moves irregularly in the HID but remains in the upper left. The fractional rms increases to 7.7%, then decreases to ∼2%.

### 3.2. Power Density Spectra

Figures 3–6 show results of the PDS. In Table 2, we present a summary of the results on LFQPO parameters, i.e., the centroid frequency ($\nu$), the coherence parameter $Q(=\nu/\Delta\nu)$, and the rms of the QPOs; $\Delta\nu$ is the FWHM of the QPO.

Figure 3 shows the QPO evolution with time. In Figure 4, we show six representative PDSs of *Insight*-HXMT/ME whose corresponding positions are indicated by red arrows in Figure 3. At the beginning of the outburst (the first four exposures), the PDS shown in Figure 4(a) is very similar to those observed in other black holes during their typical LHSs (Belloni 2010), and can be fitted with two broad Lorentzian components. Later (from MJD 58008 to MJD 58014, Figures 4(b) and (c)), the PDSs show a strong type-C QPOs, sometimes with its second harmonic, and the centroid frequency of QPO decreases from 2.5 to 1.7 Hz and then increases to 3.3 Hz. During the ME count rate decline on MJD 58015 (see Figure 1), we detect a 9.98 Hz QPO with a rather low rms amplitude (5.3%) and a weak red-noise component at very low frequency, indicating that it may be type-B (Figure 4(d)). The dynamical PDS for the first 2000 s of this observation shows a rapid transition (see Figure 5). During the first ∼800 s, the PDS reveals appearances of type-B (with a QPO frequency ∼10 Hz). During the decrease phase in the light curve, no significant QPO with ME is detected. The HE data show a similar behavior, while the LE is saturated during this time. From MJD 58017 to the end of our sample (MJD 58023), the behavior of PDS is rather complex. On MJD 58017, while the ME rate increases, we detect a ∼10 Hz QPO with a high rms amplitude (∼13%) compared to the previous one (Figure 4(e)). Even though the QPO centroid frequency is different from previous type-C QPOs, the rms suggests that this QPO is type-C. After this, the QPO (∼12 Hz) becomes weaker and broader with a low-amplitude red-noise component (Figure 4(f)), suggesting a transition to a type-A QPO.

The PDSs of the HE and LE detectors are approximately the same in evolution. In Figure 6 we present the PDSs of the three detectors for two observations, in which the shape of the PDS significantly evolves with energy.

In order to quantitatively study the energy-dependent behavior of the QPO properties, we extract power spectra in several energy bands. To improve the statistics, we only derive the energy dependence of the type-C QPOs with high amplitude. The fractional rms and the centroid frequency of the type-C QPOs as functions of photon energy are shown in Figures 7 and 8, with the QPO frequencies and obsID marked in each panel. We consider the background contribution to the fractional rms calculation. The formula is $\text{rms} = \sqrt{\text{P} \cdot (S + B)}/S$ (Bu et al. 2015), where $S$ and $B$ stand for source and background.
count rates, respectively, and $P$ is the power normalized according to Miyamoto et al. (1991). In the region where LE and ME or ME and HE overlap, there is good agreement between the two detectors. In all cases, the rms increases with photon energy up to $\sim 20$ keV, from $\sim 5\%$ in the lowest energy band up to $\sim 13\%$ during the HIMS, and from $\sim 1\%$ to $\sim 15\%$ during the SIMS, and stays more or less constant afterwards, while no significant decrease is seen above 30 keV. The QPO centroid frequencies are also related to photon energy. Unlike the rms, it does not have a unified trend. In four panels of Figure 8 (the top two of each column), with increasing photon energy, the frequencies first increase and then decrease after $\sim 10$ keV. In the bottom two panels of the first column, the frequency is almost constant and independent of photon energy. However, it shows a monotonically increasing trend with photon energy in the remaining panels.

3.3. Phase Lags

Phase lags between soft and hard variabilities are computed from the LE data. Due to the statistics limit, only the first period is selected for further study. Figure 9 shows the phase lags as a function of frequency in the HIMS. Due to poor statistics, lags became hard to measure at high frequencies; thus we plot them only below 16 Hz. During the HIMS, the lags of the fundamental QPO are negative, while the harmonic nearly always show positive phase lags. We also derive phase lags at the QPO centroid frequency and its harmonic (shown in Figure 10). The lags of the fundamental QPO are strongly correlated with centroid frequency, with a trend toward zero when the QPO frequency decreases.

4. Discussions

4.1. Outburst and Source States

In this work, we have presented timing results of a new BHC MAXI J1535−571 during its outburst in 2017 using Insight-HXMT data. The outburst evolution is consistent with the scenario typically observed in BHCs (Belloni et al. 2005; Belloni 2010; Muñoz-Darias et al. 2011). Based on the combined timing and color properties, we have identified three main states according to the classification criteria given by Belloni (2010). The source experienced a state transition from the LHS to the HIMS in the early phase, and then to the SIMS. Figure 2 shows typical hardness and timing properties of the canonical LHS, although the vertical branch of the HID is completely observed. The PDS is dominated by strong
Figure 4. Power density spectra (PDSs) for the six representative observations selected from Figure 3 using the *Insight*-HXMT/ME data (6–38 keV). The solid line shows the best fit with a multi-Lorentzian function (dotted lines). QPO fundamental and harmonic centroid frequencies are indicated.

Figure 5. Top panel: 2000 s segment of light curves of observation P011453500701 (16 s bin). Bottom panel: corresponding dynamical PDS, where darker points correspond to higher power. Inset: average power spectrum from the first ~800 s (top) and the rest (bottom). The count rate is 6–20 keV for the ME detector.

Table 2

| ObsID | Type | QPO ν0 (Hz) | Q0 (%) | rmsb (%) |
|-------|------|-------------|--------|---------|
| 119   | C    | 2.57 ± 0.01 | 9.3 ± 0.4 | 11.0 ± 0.2 |
| 120   | C    | 2.71 ± 0.01 | 10.1 ± 0.5 | 11.3 ± 0.2 |
| 121   | C    | 2.74 ± 0.01 | 9.2 ± 0.4 | 11.4 ± 0.2 |
| 122   | C    | 2.37 ± 0.01 | 6.9 ± 0.3 | 11.0 ± 0.2 |
| 201   | C    | 1.78 ± 0.01 | 8.3 ± 0.4 | 10.3 ± 0.2 |
| 301   | C    | 2.08 ± 0.01 | 8.5 ± 0.4 | 10.7 ± 0.2 |
| 401   | C    | 2.76 ± 0.01 | 10.3 ± 0.5 | 11.5 ± 0.2 |
| 501   | C    | 3.35 ± 0.01 | 9.6 ± 0.3 | 12.4 ± 0.2 |
| 601   | C    | 3.34 ± 0.01 | 9.4 ± 0.4 | 12.2 ± 0.2 |
| 701   | B    | 10.06 ± 0.05 | 9.7 ± 1.5 | 5.3 ± 0.2 |
| 902   | C    | 9.37 ± 0.01 | 12.4 ± 0.3 | 12.4 ± 0.1 |
| 903_a | C    | 7.28 ± 0.03 | 4.3 ± 0.2 | 13.0 ± 0.2 |
| 903_b | C    | 8.79 ± 0.01 | 7.5 ± 0.2 | 13.0 ± 0.2 |
| 904_a | C    | 9.20 ± 0.02 | 11.4 ± 0.7 | 4.4 ± 0.1 |
| 904_b | A    | 11.13 ± 0.10 | 6.6 ± 0.8 | 3.9 ± 0.2 |
| 904_c | A    | 12.9 ± 0.4 | 3.0 ± 0.6 | 6.5 ± 0.5 |
| 905   | A    | 13.4 ± 0.8 | 4 ± 3 | 4.3 ± 1.0 |
| 906   | A    | 12.28 ± 0.11 | 7.1 ± 1.7 | 5.0 ± 0.4 |
| 907   | A    | 12.5 ± 0.2 | 3.7 ± 0.6 | 5.9 ± 0.4 |
| 908   | A    | 11.10 ± 0.05 | 6.9 ± 0.5 | 7.5 ± 0.2 |
| 909   | A    | 12.7 ± 0.3 | 3.6 ± 1.2 | 6.3 ± 0.9 |
| 910   | A    | 13.9 ± 0.3 | 5.5 ± 1.8 | 5.3 ± 0.6 |
| 911   | A    | 12.9 ± 0.3 | 5.2 ± 1.6 | 3.1 ± 0.6 |
| 912   | A    | 12.5 ± 0.3 | 3.0 ± 0.7 | 6.1 ± 0.5 |
| 913   | A    | 12.1 ± 0.2 | 3.6 ± 0.5 | 6.6 ± 0.4 |
| 914   | A    | 12.0 ± 0.2 | 3.7 ± 0.7 | 6.1 ± 0.4 |
| 915   | A    | 11.15 ± 0.07 | 5.6 ± 0.5 | 7.6 ± 0.3 |
| 916   | A    | 10.76 ± 0.12 | 6.6 ± 1.6 | 4.6 ± 0.3 |
| 917   | A    | 11.32 ± 0.18 | 8 ± 3 | 4.2 ± 0.4 |
| 918   | A    | 11.38 ± 0.10 | 6.8 ± 1.3 | 6.5 ± 0.5 |

Notes.

a 105: P011453500NNN, NNN = 105.  

b QPO centroid frequency, Q0, and amplitude were computed from the ME detector in the energy band 6–38 keV.
58014. From MJD 58015, $\Gamma$ increased from $\sim2.0$ to $\sim2.5$. The inner disk temperature and the disk flux ratio stabilized at low values before MJD 58015, then jumped to a high value thereafter.

4.2. Quasi-periodic Oscillations

LFQPOs, consisting of three types (type-A, -B, and -C), are observed in the range 1.78–13.88 Hz (see Table 2).
Type-C QPOs are observed in the HIMS, similar to XTE J1859+226 (Casella et al. 2004), and in the early stages of the SIMS, with a higher centroid frequency, by all three detectors. When type-C QPOs are observed in the SIMS, a hard flaring occurs, suggesting an association with the hard component. Their frequencies are correlated with count rates and hardness, similar to those observed in other BHTs (Tomsick & Kaaret 2001; Belloni et al. 2005). The QPO frequencies observed by Insight-HXMT are consistent with the NICER results, which gave a QPO frequency between 1.9 and 2.8 Hz during September 12, 10:53:39 and September 13, 22:40:40 (Gendreau et al. 2017). In our case, the QPO frequency is between 1.78 and 2.74 Hz during September 12, 10:38:59 and September 14, 08:06:59.

The second harmonics of type-C QPOs are constantly detected in LE and HE observations, but only in some of the ME observations, which might due be to the low signal-to-noise ratio...
(see Figures 4 and 6). For observation P011453500301, the second harmonic is clearly detected in the ME energy band, thus we can measure the fractional rms as a function of photon energy for both the QPO and its second harmonic (see Figure 11). The relation of the rms of the second harmonic QPOs with photon energy has been observed in XTE J1550−564 (Li et al. 2013a) and GRS 1915+105 (Yadav et al. 2016). However, while it displays an arch-like relation whose maximum amplitude appears at ∼7 keV in XTE J1550−564, the rms of the harmonic QPO increases up to ∼10 keV and then seems to decline until ∼30 keV, with a large uncertainty, in GRS 1915+105. Using frequency-resolved spectroscopy, Axelsson & Done (2016) found that the second harmonic spectrum is dramatically softer than the QPO spectrum and the time-averaged spectrum, and can be described by an additional soft Comptonization component. The reason for the lack of a second harmonic in the ME observations may be physical. However, beyond ∼30 keV the fractional rms of the second harmonic increases with photon energy, suggesting that the second harmonic may be related to an additional component (i.e., the reflection component).

Type-B QPOs are usually detected when a source experiences a rapid transition to the SIMS. Fast transitions have been observed in GS 1124−68 (Takizawa et al. 1997), XTE J1859+226 (Casella et al. 2004), and GX 339-4 (Belloni et al. 2005). A very sharp threshold in count rate was observed, suggesting a transition. However, for MAXI J1535−571 the QPO has a frequency around ∼10 Hz, which is different from the typical frequency of ∼6 Hz. A correlation of type-B QPO frequencies with the power-law flux has been reported by Motta et al. (2011) and Gao et al. (2017). The higher frequencies of type-B QPOs could indicate that MAXI J1535−571 has a higher hard luminosity compared to other systems. Jet ejections are thought to be associated with type-B QPOs and the X-ray flux peak (Fender et al. 2009). In MAXI J1535−571, a type-B QPO is found in correspondence with the count rate peak (see Figure 1). Future multi-wavelength observation are needed to verify the existence of relativistic jet emissions during the X-ray flux peak.

Type-A QPOs are observed in the SIMS, with a clear QPO peak at around 10 Hz present only in the ME and HE observations. Similar behavior has been reported in GX 339-4 (Belloni et al. 2005).

### 4.3. Energy Dependence of QPO Parameters

For the first time we have studied the fractional rms and the centroid frequency of the QPO as a function of photon energy up to 100 keV (see Figures 7 and 8).

The QPO rms amplitude increases with photon energy up to ∼20 keV and stays more or less constant in all observations. The background estimation we applied is based on the blind FoV detectors. The background consists of the cosmic X-ray and particle background including cosmic rays, albedo radiation, and South Atlantic Anomaly (SAA) induced background for a low-Earth orbit satellite (Xie et al. 2018). Since there is no sign of other bright sources in the MAXI images,17 most of the LE detector background comes from the cosmic X-ray background (dozens counts s−1), which can be neglected compared to the high count rate in MAXI J1535−571. However, for ME and HE, the background is dominated by the particle background, which is related to the position and attitude of the satellite. The HE and ME background typically accounts for ∼10% to ∼20% for sub-energy bands, except for the highest sub-energy band of the HE detector which can be around 50%. In order to investigate the accuracy of our background estimation, we applied several blank sky observations, and found that the count rate ratio between the small FoV and the blind FoV detectors is independent of time. Our background estimation method is thus reasonable for rms calculation.

In addition to MAXI J1535−571, similar energy dependence relations for type-C QPOs were found in GRS 1915+015 (Rodriguez et al. 2004; Yan et al. 2012, 2013; Yadav et al. 2016), H1743–322 (Li et al. 2013b), XTE J1859+226 (Casella et al. 2004), and XTE J1550−564 (Li et al. 2013a), in which a corona origin of type-C QPOs is considered. For GRS 1915+105, HEXTE results showed that the QPO rms decreases above 20 keV (Tomsick & Kaaret 2001). However, Rodriguez et al. (2004) found that this cut-off was not always present, but rather related to compact jets, which contribute to the hard X-ray component mostly through synchrotron emission. You et al. (2018) computed the fractional rms spectrum of the QPO in the context of the Lens–Thirring precession model (Ingram et al. 2009). They found that the rms at higher energy $E > 10$ keV becomes flat when the system is viewed with large inclination angle. Our result is consistent with the simulation.

The correlation between the centroid frequency of QPOs and the photon energy shows three different shapes: flat, positive, and “arch”-like. For energies $<20$ keV, this relation in GRS 1915+105 (Qu et al. 2010; Yan et al. 2012, 2018) and XTE J1550−564 (Li et al. 2013a) evolves from a negative correlation to a positive one when the QPO frequency increases, but with a different turnover QPO frequency. The pattern in H1743–322 shows no apparent turnover frequency, which might be due to the lack of observational data for the hard state (Li et al. 2013b). The energy dependence of the QPO frequency could be caused by differential precession of the inner accretion flow (van den Eijnden et al. 2016). The inner-part flow causes a higher QPO frequency than the outer-part flow, and the evolution of the spectral properties of the inner and outer parts can cause the frequency–energy relation to change from negative to positive. When the inner-part flow has a harder spectrum than the outer-part flow, this causes a positive correlation. In MAXI J1535−571, the turnover of the

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17 http://maxi.riken.jp/star_data/J1535-572/J1535-572.html
relation at high energy, $E > 10$ keV, would suggest that this is due to the reflection bump being prominent at those energies. The reflected spectrum is expected to be dominated by photons emitted by the outer-part flow, thus the reflected spectrum will show a relatively low precession frequency.

4.4. Phase Lag and Inclination Estimates

We have calculated the phase lag between the 1–3 and 3–7 keV energy bands, and found that the phase lags of the fundamental and the harmonic of type-C QPOs remain opposite: the lags of the fundamental peak are soft, while those of the harmonic are hard. As found in GRS 1915+105 (Lin et al. 2000; Reig et al. 2000; Qu et al. 2010), and XTE J1859+226 (Casella et al. 2004), the lag is strongly correlated with the centroid frequency of the QPO, and decreases with increasing frequency.

Recently, from the inclination dependence of phase lags in a sample of 15 black hole binaries, van den Eijnden et al. (2017) found that the phase lags of type-C QPOs strongly depend on inclination, in evolution with both QPO frequency and sign. All samples possess a slightly hard lag at low QPO frequencies. At high frequencies, high-inclination sources turn to soft lags while lags in low-inclination sources become harder. These results support the geometrical origin of type-C QPOs.

MAXI J1535−571 clearly follows the trend of high-inclination sources presented in van den Eijnden et al. (2017). Xu et al. (2018) performed a spectral analysis of NuSTAR observations in the hard state, and found that the energy spectra can be well fitted by two different models which both consist of a multi-temperature thermal component, but with different reflection models (one for relxillpPc+relxillCp and the other for relxillpPc+relxillCp). They found that the inclination angles are $57.4^{+0.8}_{-0.7}$ and $75.6^{+0.8}_{-0.7}$ respectively. The spectral fitting result from NICER suggested a similar inclination of $67.4^{+0.8}_{-1.0}$ (Miller et al. 2018). Both are consistent with our phase lag result.

5. Conclusion

We have presented a timing analysis of the new BHC MAXI J1535−571 using Insight-HXMT observations. The main results of the study are as follows.

1. The source exhibits state transitions from the LHS to the HIMS, and then to the SIMS.
2. For the first time an energy dependence of the QPO fractional rms and frequency is observed up to 100 keV. While the energy dependence rms is consistent with other black hole binaries observed by RXTE, Insight-HXMT reveals that the frequency–energy relation changes dramatically.
3. Assuming a geometric origin of type-C QPOs, MAXI J1535−571 is consistent with being a high-inclination source.

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