ACCRETION FLOW PROPERTIES OF MAXI J1543–564 DURING 2011 OUTBURST FROM THE TCAF SOLUTION

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ABSTRACT

We derive accretion flow properties of the transient black hole candidate (BHC) MAXI J1543–564 using the RXTE data. We use the two-component advective flow (TCAF) solution to fit the data of the initial rising phase of outburst (from 2011 May 10 to 15). The 2.5–25 keV spectra are fitted using the TCAF solution fits file as a local additive table model in XSPEC. We extract physical flow parameters such as the two-component (Keplerian disk and sub-Keplerian halo) accretion rates and sizes and the properties of the Compton cloud (post-shock region close to a black hole). Similar to other classical transient BHs, monotonic evolution of low-frequency quasi-periodic oscillations (QPOs) is observed during the rising phase of the outburst, which is fitted with the propagating oscillatory shock (POS) model, which describes how the Compton cloud properties change from day to day. From the nature of variations of TCAF model fitted physical flow parameters and QPOs, we only found hard-intermediate and soft-intermediate spectral states during this phase of the outburst under study. We also calculated the frequency of the dominating QPOs from the TCAF model fitted shock parameters and found that they roughly match with the observed and POS model fitted values. From our spectro-temporal study of the source with TCAF and POS models, the most probable mass of the BHC is found to be $12.6-14.0 \ M_{\odot}$, or $13.4_{-0.4}^{+0.6} \ M_{\odot}$.

Key words: accretion, accretion disks – radiation: dynamics – shock waves – stars: black holes – stars: individual (MAXI J1543–564) – X-Rays: binaries

1. INTRODUCTION

Compact objects such as black holes (BHs) do not emit radiation by themselves. They can be detected by electromagnetic radiation emitted by accreted matter falling on them. Most of the black hole candidates (BHCs) are observed in close binaries in our Galaxy. They accrete matter from their companions through Roche lobe flow and from the winds. Some BH candidates are transients in nature. Outbursts of these transient X-ray binaries exhibit daily variation of temporal and spectral properties, and each of these observations gives us an opportunity to understand the accretion processes around the respective BH from detailed spectral and temporal analysis. For this, one is required to have a realistic solution of the flow and its radiative properties that preferably has a minimum number of parameters. A sizable number of scientific papers are available in the literature from many groups (e.g., McClintock & Remillard 2006; Debnath et al. 2008, 2010; Tomsick et al. 2014) to model observations. In general, these candidates show hard (HS), hard-intermediate (HIMS), soft-intermediate (SIMS), and soft (SS) spectral states during any particular epoch of an outburst (see Debnath et al. 2013 and references therein). High- and low-frequency quasi-periodic oscillations (QPOs) have also been observed in their power density spectra (PDS) in some of these spectral states (see Remillard & McClintock 2006 for a review).

MAXI J1543–564 was first discovered by MAXI/GSC on 2011 May 8 (Negoro et al. 2011) at R.A. = $15^\circ 43^\prime 9.12^\prime\prime$, decl. = $56^\circ 25^\prime 15^\prime\prime 6$. The outburst of this source has been extensively observed by MAXI, Swift (e.g., Kennea et al. 2011), and RXTE (e.g., Altamirano et al. 2011). Munoz-Darius et al. (2011) confirm the source as a potential BHC from their spectral and timing analysis. The nature of the companion (or companions) is not confirmed since there was no significant variability in optical emission (Rau et al. 2011; Rojas et al. 2011; Russell et al. 2011). Stiebel et al. (2012) estimated a minimum distance of the source to be 8.5 kpc. Miller-Jones et al. (2011) report a weak radio emission on MJD = 55,695.73 (2011 May 14), which is consistent with the prediction made by Kennea et al. (2011) and Munoz-Darius et al. (2011) that the candidate made a transition from HIMs to SS between 2011 May 13 (MJD = 55,694.09) and 2011 May 15 (MJD = 55,696.65).

To study the flow properties of an outbursting BHC, one requires a solution that provides the mass, accretion rates, and size of the Compton cloud from the observed photon spectrum on each day. Recently, after inclusion of the two-component advective flow (TCAF) model (Chakrabarti & Titarchuk 1995, hereafter CT95), i.e., producing a model fits file using a very large number of theoretical spectra, into HEASARC’s spectral analysis software package XSPEC (Arnaud 1996) as a local additive table model, we found that TCAF is capable of extracting physical parameters of the flows on a daily basis (see Debnath et al. 2014, 2015a, 2015b; Mondal et al. 2014; Jana et al. 2016, hereafter DCM14, DMC15, DMC15, MDC14, JDCMM16, respectively). TCAF model fits extract two-component (Keplerian disk and sub-Keplerian halo) accretion rates, shock location (outer edge of the Compton cloud), and compression ratio from each observation. One can even obtain independent estimation of the probable mass from each observation. Combined together with the observational set, a reasonable mass of the BH from TCAF model fits (Molla et al. 2016) can be obtained. One can also have an idea of the observed frequency of the dominating QPOs (if present;
see DCM14), viscous timescale (see JDCMM16), etc., from the TCAF model fitted/derived physical flow parameters since it is considered to be a resonance oscillation of the Compton cloud boundary (i.e., the shock). Properties of different spectral states and their transitions could also be explained from the nature of the variations of accretion rate ratio (ARR; ratio of halo to disk rates) and QPOs (if present).

Low-frequency QPOs are commonly observed in hard and intermediate spectral states of transient BHCs. Generally, it has been observed that the frequency of these QPOs monotonically increases with time (day) during rising HS and HIMS and decreases with time during HIMS and HS of the declining phases of an outburst of a transient BHC. The evolutions of the observed QPO frequencies are explained with the propagating oscillatory shock (POS) model (Chakrabarti et al. 2005, 2008; Deb Nath et al. 2010, 2013; Nandi et al. 2012). According to POS, QPOs occur due to resonance between cooling and infall time of the post-shock region (Moltan et al. 1996; Chakrabarti et al. 2015) or due to nonsatisfaction of the Rankine–Hugoniot conditions (Ryu et al. 1997). According to POS, frequency of the QPOs is inversely proportional to the infall time of the advective flow in the Compton cloud. From the model fitted QPO evolution, one can get the shock location, velocity, compression ratio, etc. These shock parameters also could be verified with TCAF model fitted spectral parameters, since we are using the same shock in both cases. Thus, connectivity of the day-to-day variation of TCAF comes from the POS model.

The successful interpretation of accretion flow dynamics and QPO evolutions with TCAF and POS models, respectively, motivated us to study the early rising phase of the 2011 outburst of MAXI J1543–564 with these two models. In the next section, we briefly describe the data analysis technique using the HeaSoft package. In Section 3, we present spectral and temporal analysis results of the source with both TCAF and POS models. Here we also calculate QPO frequencies obtained from the TCAF model fitted shock parameters (location and compression ratios) and compare them with observed and POS model fitted ones. We also estimate a most probable range of the mass for this BHC from two methods discussed in Molla et al. (2016). Finally, in Section 4, we conclude our understanding of the accretion flow properties of this BHC during its very early phase of 2011 outburst from the TCAF model fit.

2. OBSERVATION AND DATA ANALYSIS

RXTE observed the source roughly on a daily basis starting from 2 days after its discovery (from 2011 May 10 to September 30). We analyze the first seven observations of the RXTE Proportional Counter Array (PCA) instrument in the rising phase of the outburst, starting from 2011 May 10 (MJD = 55,691.09) to 2011 May 15 (MJD = 55,696.66). For spectral and timing analysis, we follow the standard data extraction and analysis methods as defined in Deb Nath et al. (2013, 2015a, 2015b) using HEASARC’s software package HeaSoft version HEADAS 6.16 and XSPEC version 12.8.

PCA spectra in the 2.5–25 keV energy band are fitted with the current version (v0.3) of the TCAF model fits file as an additive table model in XSPEC, which needs to supply five model input parameters, namely, (i) BH mass ($M_{\text{BH}}$) in solar mass ($M_{\odot}$) units, (ii) Keplerian accretion rate ($\dot{m}_K$ in Eddington rate $L_{\text{Edd}}$), (iii) sub-Keplerian accretion rate ($\dot{m}_d$, in $L_{\text{Edd}}$), (iv) location of the shock ($X_s$ in Schwarzschild radius $r_g = 2GM_{\text{BH}}/c^2$), and (v) compression ratio ($R = \rho_+ / \rho_-$, where $\rho_+$ and $\rho_-$ are the post- and pre-shock densities, respectively) of the shock. For the strongest shock, $R$ could be 4–7, depending on the polytropic index of the flow. In our case of a hot and rotating advective flow, the flow is not highly supersonic, and thus we have weaker shocks. The model normalization ($N$) is not required explicitly, since it comes out through the fit, and all we require is that it remain in a narrow range during the entire phase of our observations. It is difficult to put $N$ as a single factor, since the Compton cloud is not in the same plane as the Keplerian disk (unlike in the disk blackbody model, where entire flow components are assumed in the same plane and a single inclination angle appears in normalizing the whole spectrum). In any case, $N$ is a function of constant (albeit unknown) physical parameters, such as mass of the BH, distance “$D$,” and inclination angle “$i$.”

For all observations, we assume the constant hydrogen column density ($N_H$) at $0.9 \times 10^{22}$ atoms cm$^{-2}$ (Kennea et al. 2011) for photon absorption model $\text{phabs}$ and a fixed 1% systematic instrumental error. To get a better fit, we use an additional Gaussian line of energy $\sim 6.5$ keV for the iron emission line. After achieving the best fit based on the reduced chi-square value ($\chi^2_{\text{red}} \sim 1$), the XSPEC command “$\text{err}$” is used to find 90% confidence positive and negative error values for the model fitted parameters. In Table 1, average values of these two ± errors are mentioned in the superscripts of the model fitted parameter values.

We looked for low-frequency QPOs, after generating PDS using the “powspec” task of the XRONOS package. This task computes rms fractional variability on 2–15 keV Proportional Counter Unit 2 (PCU2; including all six layers) light curves with a time bin of 0.01 s. These light curves are generated using the PCA Event mode data with a maximum timing resolution of 125 μs. To find centroid frequencies of the QPOs, PDS are fitted with Lorentzian profiles, and the “$\text{fit err}$” command is used to get ± error limits. The monotonic evolution of the QPOs during the initial five observations of the rising phase of the outburst is fitted with the POS model. In Table 2, we present the POS model fitted parameters (instantaneous shock location, velocity, compression ratio) along with QPO frequencies calculated/predicted using POS and TCAF models.

3. RESULTS

We make a detailed spectral and temporal study of the initial seven RXTE/PCA observations from the rising phase of the very first (2011) outburst of MAXI J1543–564 after its discovery on 2011 May 8. TCAF model fitted/derived spectral parameters are given in Table 1, and POS model fitted shock parameters along with observed or predicted QPOs (with POS and TCAF models) are given in Table 2.

In Figure 1, we show the 2011 MAXI J1543–564 outburst profile as observed by the MAXI satellite in the energy range of 2–10 keV. The region of the RXTE/PCA observations (from the rising phase of the outburst), which are presented in the current paper, is marked by the region between two arrows. In Figures 2(a)–(b), we show two TCAF model fitted spectra, selected from two different observed spectral states, HIMS (Ris.) and SIMS (Ris.), respectively. In Figure 3, variations of TCAF model fitted parameters, PCU2 rate, and observed QPOs during the initial rising phase of the outburst are shown. In Figures 3(a)–(d), variations of Keplerian disk rate $\dot{m}_d$, sub-
Table 1
TCAF Model Fitted Spectral Parameters

| m_d (M_⊙) | m_h (M_⊙) | ARR | X_r | R | M_BH | Norm | χ²/dof |
|------------|------------|-----|-----|---|------|------|--------|
| 0.022 ± 0.003 | 0.304 ± 0.012 | 13.8 ± 2.4 | 215.4 ± 3.2 | 2.76 ± 0.12 | 13.5 ± 0.2 | 12.0 ± 0.2 | 41.62/41 |
| 0.048 ± 0.002 | 0.278 ± 0.009 | 5.7 ± 0.43 | 203.0 ± 2.1 | 2.25 ± 0.07 | 13.8 ± 0.1 | 12.5 ± 0.2 | 42.61/41 |
| 0.132 ± 0.003 | 0.194 ± 0.006 | 1.47 ± 0.08 | 149.6 ± 3.3 | 1.58 ± 0.03 | 13.9 ± 0.2 | 12.2 ± 0.1 | 66.86/41 |
| 0.293 ± 0.009 | 0.160 ± 0.011 | 0.55 ± 0.05 | 124.4 ± 2.2 | 1.13 ± 0.03 | 13.8 ± 0.2 | 11.5 ± 0.2 | 60.92/41 |
| 0.492 ± 0.013 | 0.156 ± 0.009 | 0.32 ± 0.03 | 92.2 ± 2.7 | 1.07 ± 0.10 | 13.8 ± 0.3 | 12.4 ± 0.2 | 67.20/41 |
| 0.632 ± 0.021 | 0.187 ± 0.006 | 0.20 ± 0.02 | 50.0 ± 1.7 | 1.05 ± 0.10 | 13.8 ± 0.2 | 12.5 ± 0.2 | 69.34/41 |
| 0.656 ± 0.019 | 0.186 ± 0.012 | 0.29 ± 0.03 | 46.6 ± 1.9 | 1.05 ± 0.10 | 14.0 ± 0.3 | 12.7 ± 0.2 | 69.92/41 |

Note. m_d and m_h are the TCAF model fitted disk rate and halo rate (both in M_⊙). ARR (accretion rate ratio) is the ratio between m_h and m_d, i.e., m_h/m_d. Shock location (X_r) is in r_g and mass of the BH (M_BH) is in M_⊙. Here dof represents degrees of freedom; the ratio of χ² and dof is the χ²/dof. Note: average values of 90% confidence “±” parameter errors are mentioned in superscripts.

Table 2
QPO Evolution in Initial Rising Phase: Fitted with POS Model

| Obs. ID | MJD   | ν_obs (Hz) | ν_POS (Hz) | X_r | V (cm s⁻¹) | R | ν_TCAF (Hz) |
|---------|-------|------------|------------|-----|------------|---|------------|
| X-01-00 | 55,691.09 | 1.05 ± 0.02 | 1.04 | 210.0 | 2450.0 | 2.44 | 0.85 ± 0.06 |
| X-01-01 | 55,692.09 | 1.75 ± 0.02 | 1.65 | 163.4 | 2105.7 | 2.24 | 1.12 ± 0.14 |
| X-01-02 | 55,693.09 | 2.98 ± 0.02 | 2.82 | 132.0 | 1760.1 | 1.81 | 2.49 ± 0.27 |
| X-02-00 | 55,694.10 | 4.38 ± 0.05 | 4.56 | 115.9 | 1411.5 | 1.36 | 4.67 ± 0.27 |
| X-02-01 | 55,694.89 | 5.70 ± 0.09 | 5.89 | 114.1 | 1139.0 | 1.08 | 7.68 ± 1.11 |
| X-02-02 | 55,695.67 | 5.08 ± 0.17 | ... | ... | ... | ... | ... |
| X-02-03 | 55,696.68 | ... | ... | ... | ... | ... | ... |

Notes. Here, “X” = 96371-02 signifies the initial part of an observation ID. Here ν_obs is the observed QPO frequency, ν_POS is the theoretical QPO frequency calculated from the POS model fit, V is the velocity of the shock in cm s⁻¹, R is the shock compression ratio, and ν_TCAF is the calculated QPO frequency from TCAF model fitted shock parameters.

4 This type-B QPO of SIMS does not fit with the POS, since the origins of the type-B QPOs are different.

Figure 1.
Variation of 2–10 keV MAXI photon count rate in units of photons cm⁻² s⁻¹ for the entire 2011 outburst phase. The period of our RXTE/PCA observations (MJD = 55,691.09–55,696.66) presented in this paper is marked by the region in between two arrows.

Keplerian halo rate m_h, shock location X_r, and compression ratio R are shown. The variations of the total flow rate (m_d + m_h) and ARRs are shown in Figures 3(f) and (g), respectively. In Figures 3(e) and (h), variations of 2–15 keV PCU2 count rate and observed dominating QPO frequencies are shown, respectively. In Figure 4(a), we show POS model fitted monotonic evolution (increasing) of the QPO frequencies (type-C) for the five observations of MAXI J1543–564 that belong to the hard-intermediate state. In Figure 4(b), variations of the shock locations and compression ratios, obtained from the POS model fit, are also shown. In Figures 5(a) and (b), we show the variations of the TCAF model normalization and mass of the BH, respectively. In Figure 5(c), variation of the POS model fitted X_red with BH mass is shown.

3.1. Spectral Evolution of MAXI J1543–564: Analysis with the TCAF Solution
Evolution of spectral properties and accretion flow dynamics around the BH during the initial rising phase of the very first outburst of MAXI J1543–564 are clear from our analysis. From the variation of the fitted flow parameters and nature of QPOs (if present), we discover only two spectral states: HIMS and SIMS. We also note that on the first RXTE/PCA observed day (2011 May 10), the source is already in HIMS, although it was discovered on 2011 May 8. Since outbursting is unpredictable, it is not unusual to miss the initial hard states (see also DMC15 for the 2010 outburst of MAXI J1659-152).

HIMS (Rising): from the variations of PCU2 count and total flow rates, it is clear that as the day progresses, more matter from the companion reaches the BH, which increased the total X-ray intensity. Accretion flow dynamics becomes clear when we look into the variation of the rates of the two components, namely, the Keplerian disk (m_d) and the sub-Keplerian halo.
(\(m_h\)), the outer boundary of the Compton cloud (i.e., shock location \(X_s\)), and the compression ratio \(R\) parameters. On the first day of our observation, there is a clear dominance of halo rate (\(m_h = 0.304 \dot{M}_{\text{Edd}}\)) over disk rate (\(m_d = 0.022 \dot{M}_{\text{Edd}}\)), which maintains a moderately strong \((R = 2.76)\) shock far away \((X_s = 215 r_g)\) from the BH. As the day progresses, the shock

\[\Delta \chi\]

increases. Note that \(X\)-axis markers are modified by subtracting 55,600 from the actual MJDs.

Figure 2. TCAF model fitted spectra for the rising (a) HIMS and (b) SIMS for observations IDs 96371-02-01-01 (MJD = 55,692.09) and 96371-02-02-01 (MJD = 55,694.89), respectively, with \(\Delta \chi\) variations. Note that \(y\)-axes of the top panels are plotted in \(\text{EF}(E)\) with units of \(\text{keV} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}\).

Figure 3. Variations of (a) disk rate \((m_d)\) in \(\dot{M}_{\text{Edd}}\), (b) halo rate \((m_h)\) in \(\dot{M}_{\text{Edd}}\), (c) shock location \((X_s)\) in \(r_g\), (d) compression ratio \((R)\), (e) PCU2 count rate in counts per second, (f) total flow rate \((m_d + m_h)\) in \(\dot{M}_{\text{Edd}}\), (g) ARR, i.e., \(m_h/m_d\), and (h) observed QPO frequency in Hz with day (in MJD). Note that \(X\)-axis markers are modified by subtracting 55,600 from the actual MJDs.

Figure 4. (a) Variation of type-C QPO frequency with time (in day) during the rising phase of the 2011 outburst of MAXI J1543–564, fitted with the POS model solution (dashed curve). In panel (b), variation of the POS model fitted shock locations (in \(r_g\)) and compression ratios are shown.

Figure 5. Variations of TCAF model fitted (a) normalization (which shows a narrow range of \(\sim 11.5–12.7\)) and (b) mass of the BH with MJD. We observe a narrow mass range of \(\sim 13.5–14.0 M_{\odot}\). In panel (c) the POS model fitted variation of source mass with \(\chi_{\text{red}}^2\) is shown, which allows us to predict mass range if we restrict ourselves to \(\chi_{\text{red}} \leq 2.7\) for the best fit.
becomes weaker and moves toward the BH horizon, with a rise in the disk rate and a decrease in the halo rate. As a result of that, a decrease in accretion rate ratio (ARR) and a monotonic increase in dominating QPO frequency are observed. On the fifth observation day (2011 May 13; MJD = 55,694.89), $m_{bh}$ reaches its minimum value ($m_{bh} = 0.156 M_{\text{Edd}}$) with maximum observable (monotonically evolving) QPO frequency (5.70 Hz) and low ARR value ($0.32$). On this particular day, the outer boundary of the Compton cloud (i.e., $X_s$) reaches $\sim 92 r_g$, but the shock is weakened due to cooling by the high Keplerian rate. After this date only a weak centrifugal barrier can form, but no sharp shock boundary can form. This observation thus signifies the transition between two spectral states.

SIMS (Rising): the last two observations of our analysis fall in this spectral state. Variations of QPOs (sporadic) and TCAF model fitted parameters are similar to those seen in other classical objects (see MDC14, DMC15, DMC15). We observe a 5.08 Hz QPO on the first day and no QPO on the last day. During this phase of the outburst, the shock becomes much weaker ($R \approx 1.05$) and is located at the same effective distance ($X_s$). A clear dominance of the Keplerian disk rate over the halo rate is observed, which results in a low ARR.

3.2. Evolution of QPOs with the POS Model

In general, low-frequency QPOs are observed during hard and hard-intermediate spectral states of BHs. This is because of quasi-periodic variation in the post-shock region due to shock oscillation and the resulting oscillation of Comptonized X-ray intensity (Chakrabarti & Manickam 2000). It has been observed in several transient BHs that type-C QPOs (generally observed in HS and HIMS) evolve with time (day) during rising and declining phases of the outbursts and type-A or type-B QPOs are observed sporadically on and off during SIMS (see Deb Nath et al. 2008, 2013; Nandi et al. 2012). Although not everyone agrees on the origin of these QPOs, according to TCAF, these are easily explained by the resonance oscillation (type-C), weak oscillation (type-B) of the Compton cloud boundary (i.e., shock), or even the shock-free centrifugal barrier (type-A). For type-C QPOs, shock oscillation may occur due to fulfillment of the resonance condition between cooling and infall time of the post-shock region (Molitani et al. 1996; Chakrabarti et al. 2015) or due to the non-fulfillment of the Rankine–Hugoniot conditions (Ryu et al. 1997). The frequency of the QPOs is inversely proportional to the infall time from the location of the shock (i.e., outer boundary of the “CENTrifugal pressure dominated BOUNDary Layer,” or CENBOL, which acts as the “Compton cloud”; Chakrabarti & Manickam 2000). In the initial six PCA observations (2011 May 10 to 14, i.e., MJD = 55,691.09 to 55,695.67), similar to other classical transient BHs, evolution of type-C QPOs (from 1.05–5.70 Hz) is observed in the first 5 days of the outburst. On the sixth day, observed QPO (5.08 Hz) is of type-B. We study the evolution of the QPO frequency with the same POS model as in the earlier objects (Chakrabarti et al. 2005, 2008; Deb Nath et al. 2010, 2013; Nandi et al. 2012). According to POS, during the rising phase of the outburst, the shock moves in while monotonically reducing shock strength (as cooling increases due to increase in Keplerian rate), and it results in a monotonic rise in the QPO frequency. In contrast, during the declining phase of the outburst, the shock moves away from the BH since matter supply from the companion reduces, resulting in monotonic decrease in QPO frequency. For the sake of completeness, we again discuss governing equations of the POS model.

The equation to find QPO frequency is given by (Chakrabarti & Manickam 2000; Chakrabarti et al. 2005):

$$v_{QPO} = \beta /[X_s(X_s - 1)^{1/2}],$$

where the shock strength

$$\beta = 1/R = 1/R_0 \pm \alpha \dot{V},$$

$"R_0$" is the value of compression ratio $R$ on the first day (zeroth day), $\dot{V}$ is the time in days, and $\alpha$ is a constant number, which decides how $R$ becomes stronger or weaker with the QPO evolution period. The instantaneous shock location is defined as

$$X_s(t) = X_{s0} \pm \dot{V} t/M_{BH},$$

where $X_{s0}$ is the shock location on the first observation. The shock could be accelerating or decelerating. The instantaneous shock velocity is defined as

$$\dot{V}(t) = V_0 \pm \dot{V} t,$$

where $V_0$ is the velocity of the first observation and "$\dot{V}$" is the acceleration/deceleration. Here the "$+ve$" sign is for accelerating shock and the "$-ve$" sign is for decelerating shock wave propagation.

POS model fitted parameters of the QPO evolution during the initial 5 days (2011 May 10–13, i.e., MJD = 55,691.09 to 55,694.89) of our observation are presented in Table 2. We get best-fitted ($\chi^2_{red} = 0.90$) evolution for the mass of the BH $M_{BH}$ as 13 $M_\odot$. According to POS, the shock starts to move toward the BH from $\sim 210 r_g$ with an initial velocity of $\sim 2450$ cm s$^{-1}$ and a deceleration $f = -345$ cm s$^{-1}$ day$^{-1}$. It reaches $\sim 114 r_g$ on the last day of the QPO evolution. During this phase of the outburst, POS model calculated $R$ reduces from $\sim 2.44$ to $\sim 1.08$ with constant $\alpha = 0.037$, which roughly matches with TCAF model fitted $R$ values (see Col. (4) of Table 1).

3.3. Prediction of BH Mass with TCAF and POS Model Fits

Molla et al. (2016) estimated mass of the BHC MAXI J1659-152 with the spectro-temporal analysis methods, which motivated us to estimate the probable mass range of MAXI J1543–564. They used two methods: one is the TCAF model fitted (i) constant normalization parameter method, and the other is (ii) by studying evolution of the QPOs with the POS model. TCAF model normalization ($N$), being a factor that only depends on the mass and distance of the BH and the inclination angle "$i$" of the orbital plane, should not vary on a daily basis, unless the disk precesses and the projected surface has a variable emission area or there are significant outflow activities that are not included in the TCAF fits file.

While fitting 2.5–25 keV PCA spectra with TCAF, we kept all the parameters free and found that model normalization and mass come in narrow ranges of $\sim 11.5–12.7$, and $\sim 13.5–14.0 M_\odot$, respectively (see Cols. (7) and (6) of Table 1). The variations of these two parameters are shown in Figures 5(a)–(b). Similarly, when we are fitting the evolution of monotonically increasing QPOs during the initial 5 days of our analysis, we obtain the best fit using $M_{BH} = 13 M_\odot$. Now, we vary the mass of the BH in the POS equation to see the
deviations of the model fitted $\chi^2_{\text{red}}$ from the best-fitted value (= 0.90). This variation of $\chi^2_{\text{red}}$ with mass is shown in Figure 5(c). If we restrict ourselves to a $\chi^2_{\text{red}}$ value of <2.7 (90% confidence) for the best fits, we get a probable mass range of the source of $\sim$12.6–13.6 $M_\odot$. Combining these two methods, we determine the mass of the BHC to be in the range of $\sim$12.6–14.0 $M_\odot$ or $\sim$13.6–13.6 $M_\odot$. Our preferred mass is 13 $M_\odot$ since it is the POS model fitted mass value.

3.4. Prediction of QPOs with the TCAF Model

It is well known that the spectral and timing properties in BHCs are strongly correlated to each other as the location of the shock controls both properties (CT95: Chakrabarti & Manickam 2000; Debnath et al. 2013). This correlation is thus intrinsic to the TCAF solution since the spectral and timing features are the outcome of the solution of the same set of transonic flow equations. In JDCM16, a hysteresis diagram, namely, accretion rate ratio intensity diagram (ARRID), is plotted between ARR and PCA count rate, where different spectral states are found to be correlated with different branches of the diagram. In DCM14, dominant frequencies of the QPOs for three different BHCs (H1743–322, GX 339–4, and GRO J1655–40) were predicted using TCAF model fitted shock parameters. This could be done because the same shock parameters (namely, $X_s$, and $R$) that are used to define the size of the Compton cloud and matter densities in pre- and post-shock regions are also used to find QPO properties in the POS model. When the shock (outer boundary of CENBOL) oscillates, the size of the Compton cloud varies, causing a variation of X-ray intensities in the light curve. As a result, we observed QPOs in PDS. According to TCAF, using Equation (1), the frequency of the QPOs could be calculated with model fitted shock parameters ($X_s$ and $R$), if the mass of the BH is known.

We calculate the frequency of the dominant type-C QPOs observed in the first 5 days of the outburst, keeping mass of the BH as 13 $M_\odot$, and found that for the initial 4 days, it roughly matches with the observed and POS model fitted values, and on the fifth day a large deviation of $\sim$2.0 Hz from the observed one is observed (see Col. (9) of Table 2), indicating possible deviation from the resonance condition that was used in determining the shock oscillation frequency.

4. DISCUSSION AND CONCLUDING REMARKS

We study evolution of both spectral and timing properties during the very early phase of the very first outburst of MAXI J1543–564 after its discovery on 2011 May 8 (MJD = 55,689). To infer accretion for dynamics of the source, we use RXTE/PCA data from 2011 May 10 to 15. Spectra are fitted with the current version (v0.3) of the TCAF model fits file (see DMC15) to extract physical flow parameters (e.g., Keplerian and sub-Keplerian flow rates, shock locations, and compression ratios, mass, etc.) directly from spectral fits (see Table 1).

From the nature of the variations of ARRs and QPOs, we observe only two spectral states, HIMS and SIMS, which is consistent with the results of Kennea et al. (2011) and Munoz-Darias et al. (2011). We observe a transition between these two spectral states on the fifth observation day, i.e., 2011 May 13 (MJD = 55,694.89), since on this particular observation the maximum frequency of the monotonically increasing QPO is observed. Also, on this day, the ARR reaches a very low value. On the first day, we observe a high halo rate as compared to the disk rate, and as the day progresses, the shock moves in due to the shrinking of the Compton cloud, i.e., CENBOL. The CENBOL size is reduced since during these days ARR decreases from 13.8 to 0.32 due to the increase in disk rates and decrease in halo rates. The last two observations of our analysis belong to SIMS, since the QPO frequency decreases on the sixth observation and no QPO was present on the seventh observation. This sporadic nature is the signature of SIMS (see, e.g., Nandi et al. 2012; Debnath et al. 2013). A roughly constant low ARR value is also observed in these two observations, which is also consistent with the TCAF model fitted results for other objects (MDC14, DMC15, DMC15).

Type-C QPOs during the initial five observations of our analysis are independently fitted with the POS model to find instantaneous shock location, compression ratio, velocity of the propagation, etc. (see Table 2). This is the same model that was used to study monotonic evolutions of QPO frequencies during rising and declining phases of the outbursts of a few other classical transient BHCs by our group (e.g., GRO J1655–40, XTE J1550–564, GX 339–4, H1743–322, MAXI J1659–152, IGR J17091–3624). We compare POS model fitted shock parameters ($X_s$, and $R$) with those of the TCAF model fitted spectral results and found them to be roughly consistent. According to POS, during the evolution period of $\sim$4 days, shock location ($X_s$) changed from $\sim$210 $r_g$ to $\sim$114 $r_g$ and the shock strength is progressively weakened. This is due to loss of heat and pressure from the post-shock region due to inverse Comptonization as the Keplerian rate is increased.

We continued our analysis by estimating the probable mass of the BH by using methods given in Molla et al. (2016). In the constant TCAF model normalization method, we kept all the TCAF parameters free while fitting spectra and found narrow variations of the model normalization ($\sim$11.5–12.7) and mass ($\sim$13.5–14.0 $M_\odot$). Similarly, to fit QPO frequency evolution with the POS model, we supplied the mass of the BH and found the best fit for $M_{\text{BH}}$ to be 13 $M_\odot$. To get the best-fitted ($\chi^2_{\text{red}} \leq 2.7$) mass range, we refitted QPO evolution by varying $M_{\text{BH}}$ and found the probable mass range to be $\sim$12.6–13.6 $M_\odot$. Combining these two methods, we get a mass of MAXI J1543–564 in the range of $\sim$12.6–14.0 $M_\odot$.

We also calculated the frequency of the dominant type-C QPOs using TCAF model fitted shock parameters ($X_s$ and $R$) as in DCM15. According to Moltani et al. (1996) and Chakrabarti et al. (2015), the shock location coming from TCAF fits could be used to calculate the frequency of the QPOs after applying the resonance condition. For the initial 4 days, calculated QPO frequency roughly matches with the observed values and POS model fitted values, but on the fifth day we observe a large deviation, possibly because of the deviation from the resonance condition when HIMS ends.

It is to be noted that our TCAF code uses the Paczyński–Wiita potential (Paczyński & Wiita 1980) as a proxy to the nonrotating, Schwarzschild BH spacetime. We have ignored the effects of the spin since it affects physical properties of the flow very close to the horizon. Thus, results from possible softest states would be affected by the spin, which are not considered here. In our case of MAXI J1543–564 observations, the Compton cloud boundary is found to be far away from the BH, and thus the results are not sensitive to the spin.
We finally conclude that the nature of the evolution of the spectral and temporal properties of the source follows a similar trend to that observed in other transient BH sources (DCM14, DMC14, DMC15, DMCM15, JDMM16). Detailed study of the complete spectral and timing properties of the source is in progress and will be presented elsewhere.

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REFERENCES

Altamirano, D., Kalamkar, M., Yang, Y., et al. 2011, ATel, 3334, 1
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Casella, P., Belloni, T., & Stella, L. 2005, ApJ, 629, 403
Chakrabarti, S. K. 1997, ApJ, 484, 313
Chakrabarti, S. K., Debnath, D., Nandi, A., et al. 2008, A&A, 489, L41
Chakrabarti, S. K., & Manickam, S. G. 2000, ApJL, 531, L41
Chakrabarti, S. K., Mondal, S., & Debnath, D. 2015, MNRAS, 452, 3451
Chakrabarti, S. K., Nandi, A., Debnath, D., et al. 2005, IJP, 79, 841
Chakrabarti, S. K., & Titarchuk, L. G. 1995, ApJ, 455, 623 (CT95)
Debnath, D., Chakrabarti, S. K., & Mondal, S. 2014, MNRAS, 440, L121 (DCM14)
Debnath, D., Chakrabarti, S. K., & Nandi, A. 2010, A&A, 520, 98
Debnath, D., Chakrabarti, S. K., & Nandi, A. 2013, AdSpR, 52, 2143
Debnath, D., Chakrabarti, S. K., Nandi, A., & Mandal, S. 2008, BASL, 36, 151
Debnath, D., Molla, A. A., Chakrabarti, S. K., & Mondal, S. 2015a, ApJ, 803, 59 (DMCM15)
Debnath, D., Mondal, S., & Chakrabarti, S. K. 2015b, MNRAS, 447, 1984 (DMC15)
Jana, A., Debnath, D., Chakrabarti, S. K., et al. 2016, ApJ, 819, 107 (JDCMM16)
Kennea, J. A., Evans, P. A., Krimm, H. A., et al. 2011, ATel, 3331, 1
McClintock, J. E., & Remillard, R. A. 2006, in Compact Stellar X-ray Sources, Vol. 39, ed. W. Lewin & M. van der Klis (Cambridge, UK: Cambridge Univ. Press), 157
Miller-Jones, J. C. A., Tzioumis, A. K., Jonker, P. G., et al. 2011, ATel, 3364, 1
Molla, A. A., Debnath, D., Chakrabarti, S. K., et al. 2016, MNRAS, 460, 3163
Moltani, D., Sponholz, H., & Chakrabarti, S. K. 1996, ApJ, 457, 805
Mondal, S., Chakrabarti, S. K., & Debnath, D. 2015, ApJ, 798, 57
Mondal, S., Debnath, D., & Chakrabarti, S. K. 2014, ApJ, 786, 4 (MDC14)
Munoz-Darias, T., Motta, S., Stiele, H., et al. 2011, ATel, 3341, 1
Nandi, A., Debnath, D., Mandal, S., & Chakrabarti, S. K. 2012, A&A, 542, A56
Negoro, H., Nakahira, S., Ueda, Y., et al. 2011, ATel, 3330, 1
Paczynski, B., & Wiita, P. J. 1980, A&A, 88, 23
Rau, A., Greiner, J., Elliot, J., et al. 2011, Atel, 3365, 1
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Rojas, A. F., Masetti, N., & Minniti, D. 2011, Atel, 3372, 1
Russell, D., Lewis, F., Roche, P., et al. 2011, ATel, 3359, 1
Ryu, D., Chakrabarti, S. K., & Molteni, D. 1997, ApJ, 474, 378
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Stiele, H., Munoz-Darias, T., Motta, S., & Belloni, T. M. 2011, MNRAS, 422, 679
Sunyaev, R. A., & Titarchuk, L. G. 1980, ApJ, 86, 121
Sunyaev, R. A., & Titarchuk, L. G. 1985, A&A, 143, 374
Tomsick, J. A., Yamaoka, K., Corbel, S., et al. 2014, ApJ, 791, 70

The Astrophysical Journal, 827:88 (7pp), 2016 August 10

Chatterjee et al.