Accretion Flow Properties of three MAXI Black Hole Candidates: Analysis with the TCAF Solution

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Abstract

Recently after the implementation of Chakrabarti and his collaborators Two-component advective flow (TCAF) model into HEASARC's spectral analysis software package XSPEC as an additive table model, we found that it is quite capable to describe the underlying accretion flow dynamics around black holes with spectral fitted physical parameters. Properties of different spectral states and their transitions during an outburst of a transient black hole candidate (BHC) are more clearly understandable. One can even predict frequency of the dominating quasi-periodic oscillations (QPOs) from the TCAF model fitted shock parameters and even predict the most probable mass range of an unknown BHC from TCAF fits. This gives us a confidence that the description of accretion process is more clear than ever before. Recently we studied three MAXI/GSC discovered Galactic transient BHCs: MAXI J1659-152, MAXI J1836-194, MAXI J1543-564, with the TCAF solution to study accretion flow properties of these compact objects during their very first outbursts. We classified entire outbursts of these sources into different spectral states on the basis of nature of variations of TCAF model fitted physical flow parameters and observed QPOs. Probable mass ranges of these BHCs are also estimated from our study. Estimation of X-ray jet fluxes during the 2011 outburst of MAXI J1836-194 are also done.

Key words: X-Rays:binaries – stars individual: (MAXI J1659-152, MAXI J1836-194, MAXI J1543-564) – stars:black holes – accretion, accretion disks – ISM: jets and outflows – radiation:dynamics

1. Introduction

Transient black hole candidates (TBHCs) are very interesting objects to study in X-rays as they exhibit rapid evolutions in their temporal and spectral properties during outbursts, which are strongly correlated with each other. Several works are present in the literature (see, e.g., Debnath et al., 2008, 2013 and references therein), which explain variations of spectral and temporal properties of these objects during their X-ray outbursts. In general, it has been found that these objects exhibit different spectral states, such as *hard* (HS), *hard-intermediate* (HIMS), *soft-intermediate* (SIMS) and *soft* (SS) during their outbursts. They also exhibit low and high frequency quasi-periodic oscillations (QPOs) in some of these spectral states (see, Debnath et al. 2013 and references therein). The frequencies of QPOs are found to evolve with time during the rising and declining phases (more precisely, during hard and hard-intermediate spectral states) of the outbursts. According to the nature of the variations of temporal and spectral properties during outbursts, we can classify transient BHCs into two types: *i*) *type-I* or *classical-type*, where all spectral states are observed (HS $\rightleftharpoons$ SS via two intermediate, HIMS and SIMS spectral states), and *ii*) *type-II* or *harder-type*, where SS (sometimes even SIMS) could not been observed. The type-II type of outbursts are generally termed as 'failed-outbursts'.

It is well known that emitted spectrum of the radiation coming from BHCs is a *multi-color* in nature, and contains both *thermal* and *non-thermal* components. One component is basically the multi-color blackbody radiation from the standard Keplerian disk (Shakura & Sunyaev 1973), and the other is a power-law component, which is originated from the 'Compton' cloud (Sunyaev & Titarchuk 1980) composed of hot electrons, which is cooled down due to repeated Compton scattering of softer (lower energy) photons. In the *two component advective flow (TCAF) solution* of Chakrabarti & Titarchuk (1995; hereafter CT95), the role of so-called *'Compton cloud'* or *'hot corona'* is replaced by the

CENtrifugal pressure supported BOundary Layer (CENBOL), which automatically forms behind the centrifugal barrier due to piling up of the low viscosity (sub-critical) and low angular momentum optically thin matter, known as sub-Keplerian (halo) accretion component. In TCAF, the other component of accretion flow is the high viscous, optically thick and geometrically thin Keplerian (disk) component which is submerged inside the halo component. CENBOL being much hotter in general, the Keplerian disk is naturally truncated at the shock location close to the black hole. This Keplerian flow settles down to a standard SS73 disk when cooling is efficient. Low energy (soft) thermal photons from the Keplerian disk intercept with the CENBOL (composed of hot electrons) and emit as high energy (hard) photons by cooling down CENBOL through repeated Compton scatterings.

Recently, in 2014, Debnath and his collaborators have successfully been implemented TCAF solution into HEASARC's spectral analysis software package XSPEC as an additive table model to fit black hole spectrum. After that, they have been quite successful to explain accretion flow properties of few transient BHCs (such as, GX 339-4, H 1743-322, Swift J1753.5-1027, other than three MAXI objects, MAXI J1659-152, MAXI J1836-194, MAXI J1543-564) during their X-ray outbursts (Debnath et al., 2014; 2015a,b, 2017; Mondal et al., 2014; Jana et al., 2016; Chatterjee et al. 2016; Molla et al. 2016, 2017; Bhattacharjee et al. 2017). From the TCAF model fitted spectrum, one can not only directly obtain information about the instantaneous accretion rates of the two components (Keplerian disk rate $\dot{m}_d$ in $\dot{M}_{Edd}$ and sub-Keplerian halo rate $\dot{m}_h$ in $\dot{M}_{Edd}$), but also obtain crucial information on shock parameters (instantaneous shock location X_s in Schwarzschild radius r_g=$2GM/c^2$, and shock compression ratio R), which allows us to estimate frequencies of the dominating QPOs (if observed in PDS; see, Debnath et al. 2014). Depending upon the variations of *accretion rate ratio* (ARR = halo/disk rates) and nature of QPOs (shape, frequency, Q value, rms%), classification between different observed spectral states and their intermediate transitions are well understood. A strong correlation between the spectral and timing properties during the outburst period in the form of hysteresis loop, i.e, in ARR-intensity diagram (ARRID) was observed, where different spectral states are found to be correlated with different branches of the diagram (see, Jana et al. 2016). Most probable mass (M_{BH}) ranges of MAXI J1659-152, MAXI J1836-194, MAXI J1543-564, H 1743-322, etc. have been predicted from our spectral analysis with TCAF model fitted constant normalization (N) method (see, Molla et al. 2016, 2017; Jana et al. 2016; Chatterjee et al. 2016; Bhattacharjee et al. 2017).

In this *Conference Proceeding*, we will briefly discuss about the accretion flow properties of three MAXI objects (MAXI J1659-152, MAXI J1836-194, MAXI J1543-564) during their very first outbursts after discovery, obtained from our spectral and temporal analysis under TCAF paradigm (Debnath et al. 2015; Molla et al. 2016; Jana et al. 2016, 2017; Chatterjee et al.2016).

2. **MAXI J1659-152:** (Debnath et al. 2015b; Molla et al. 2016)

The source was discovered by MAXI/GSC on 2010 Sep. 25 at R.A.= $16^h59^m10^s$, Dec = $-15^\circ16'05''$ (Negoro et al. 2010). It is shortest orbital period (2.414 ± 0.005 hr) BH with acceptable ranges of distance, inclination angle, mass are 5.3−8.6 kpc, 60°−80°, 3−8 $M_\odot$ respectively. In Debnath et al. (2015b), we studied both the spectral and timing properties of the source during its 2010 outburst by analyzing $2-25$ keV RXTE/PCA data of 30 observational IDs, starting from 2010 Sep. 28 (MJD=55467) to 2010 Nov. 11 (MJD=55508). $2.5-25$ keV spectra are fitted with TCAF model *fits* file by keeping all model parameters ($\dot{m}_d$, $\dot{m}_h$, X_s, R, N) as free, except M_{BH} was kept frozen at 6 $M_\odot$. Depending upon the variations of ARR and nature of QPOs, we classified entire 2010 outburst into three spectral states (HS, HIMS and SIMS) in the sequence of: HIMS (Ris.)→SIMS→HIMS (Dec.)→HS (Dec.). On the first PCA observation day, source was already in HIMS (Ris.). Monotonic evolutions of low frequency QPOs during HIMS (Ris.) and HIMS-HS (Dec.) are observed and during the SIMS, QPOs are observed sporadically. No, signature of SS is observed during the outburst, which may be due high supply of low viscous halo matter both via accretion and wind, since it is a short orbital period BH.

In Molla et al. (2016), we refitted all spectra by keeping TCAF model normalization (N) in a fixed value (which is the average N value of the fitted normalizations, when all parameters were kept free) to estimate probable mass range of the source as $4.7-7.8$ $M_\odot$. We also verified this mass range with the estimated mass value ($5.1-7.4$ $M_\odot$) obtained from declining phase QPO frequency evolution, fitted with propagating oscillatory shock (POS) model (Chakrabarti et al. 2005, 2008; Debnath et al. 2010, 2013; Nandi et al. 2012). Finally, combining estimated mass ranges obtained from TCAF and POS models, we obtained a most probable mass range of the source as $4.7-7.8$ $M_\odot$ or $6^{+1.8}_{-1.3}$ $M_\odot$.

3. **MAXI J1836-194:** (Jana et al. 2016)

This short orbital period (< 4.9 hr), low inclination angle ($4^\circ-15^\circ$) angle and highly rotating ($a = 0.88 \pm 0.03$) BH was discovered on 2011 Aug. 29 simultaneously by SWIFT/BAT and MAXI/GSC (Negoro et al. 2011a) at R.A. = $18^h35^m43^s.43$, Dec = $-19^\circ19'12''.1$. Cenko et al. (2011) reported companion as a high massive B[e] star. The probable mass and distance of object were reported as $4-12\ M_\odot$, $4-10$ kpc respectively. The source was highly active in radios. In Jana et al. (2016), we studied spectral and timing properties of the source using RXTE/PCA data of 35 observational IDs starting from 2011 Aug. 31 (MJD=55804) to 2011 Nov. 24 (MJD = 55889). $2.5-25$ keV spectra are fitted with TCAF model *fits* file to extract physical flow parameters. Low frequency QPOs are observed sporadically throughout the outburst with a general trend of increasing nature of frequency during the rising phase and decreasing nature of frequency during declining phase. Depending upon the variations of TCAF model fitted flow parameters, ARRs and nature of QPOs, we classified entire 2011 outburst of the source into two harder states (HS and HIMS). These spectral states are observed in the sequence of: HS (Ris.)→HIMS (Ris.)→HIMS (Dec.)→HS (Dec.). We divided HIMS into two classes, since during the HIMS (Ris.), ARR decreased due to decreasing nature of $\dot{m}_h$ and increasing trend of $\dot{m}_d$. On the transition day between two HIMS (MJD=55820), ARR becomes minimum (due to maximum value of $\dot{m}_d$, and minimum value of $\dot{m}_h$) with maximum value of the observed QPOs. After that ARR increased and becomes maximum on the transition day between HIMS (Dec.) to HS (Dec.) due to rise in $\dot{m}_h$. There after during HS (Dec.), ARR decreased due to fall of both rates. During entire 2011 outburst, no signature of softer spectral states (SS and SIMS) are observed, which may be due to high supply of low viscous wind matter, since BH accretion disk is immersed inside the excretion disk of the B[e] companion.

To find correlation between spectral and timing properties, we draw ARRID and compared it with hardness-intensity diagram (HID; Debnath et al. 2008 and references therein). In ARRID (see, Fig. 4 of Jana et al. 2016), we plotted $2-25$ keV PCA count rates as a function of ARR. Different observed spectral states and their transitions are found to be more prominent in ARRID compared to HID (N.B.: point D, where transition between declining HIMS and HS is feasible only in ARRID). Observing peak differences between disk and halo rates during the entire outburst, we predicted viscous time scale as ~ 10 days. From our detailed spectral study with the TCAF solution, we also estimated probable mass range of the source as $7.5-11\ M_\odot$, since in the model mass is an input parameter. In Jana et al. (2017), we also calculated X-ray jet fluxes from spectral analysis using TCAF solution.

4. **MAXI J1543-564:** (Chatterjee et al. 2016)

The source was discovered by MAXI/GSC on 2011 May 8 at R.A.=$15^h43^m9^s.12$ and Dec.=$56^\circ25'15''.6$ (Negoro et al. 2011). Stiele et al. (2011) studied entire outburst of the source using spectral fits with combined *diskbb* and *simpl* models, where as in Chatterjee et al. (2011), we studied initial rising phase of the outburst with the TCAF solution. We analyzed initial seven observations of RXTE/PCA in the rising phase of the outburst, starting from 2011 May 10 (MJD=55691.09) to 2011 May 15 (MJD=55696.66). On the first observation day, the source was already in HIMS. From the nature of the variations of TCAF model fitted physical flow parameters, ARRs and QPOs, during we classified our observation period into two intermediate spectral states, HIMS and SIMS. Low frequency QPOs are observed during first six observations. During initial five observations a monotonic evolution (increasing trend) of type-C QPOs (from $1.05-5.70$ Hz) is observed and on sixth day, it decreased to 5.08 Hz. We defined fifth observation as the transition day between two outbursts. From TCAF model fits, Keplerian disk rate ($\dot{m}_d$) increased as outburst progressed, where as sub-Keplerian halo rate ($\dot{m}_h$) decreased initially upto the transition day and then slightly increased for last two observations. Shock is found to move inward with decreasing strength. Evolution of QPOs during HIMS, was also independently fitted with the POS model and instantaneous shock location and compression ratios are calculated, since according to the POS model, QPOs occur due to oscillation of the same shock (forms at the outer edge of the CENBOL) which we use in TCAF model code. We also predicted frequency of the observed type-C QPOs from TCAF model fitted shock parameters to compare those with observed and POS model fitted values, using the following relation,

$$\nu_{QPO} = \frac{\nu_{s0}}{t_{infall}} = \frac{c^3}{2GM_{BH}} \frac{1}{[R\ X_s(X_s-1)^{1/2}]},$$

where, ν_{s0} is the first observed QPO frequency and t_{infall} is the infall time.

In Chatterjee et al. (2016), we also estimated probable mass range of the source from our spectral and temporal analysis with the TCAF solution and the POS model respectively. From TCAF model spectral fits, M_{BH} was observed in the range of $\sim 13.5-14.0\ M_\odot$, where as from the POS model fitted QPO frequency evolution M_{BH} was found at 13 $M_\odot$ for the best-fit (χ^2_{red}=0.90). Then we varied M_{BH} in POS model code for both positive and negative values and observed, for 90% confidence ($\chi^2_{red} \leq 2.7$) allowed mass range could be $\sim 12.6-13.6\ M_\odot$. Then finally combining results obtained from both TCAF and POS models, we predicted mass range of the source as $\sim 12.6-14.0\ M_\odot$ or $13^{+1.0}_{-0.4}\ M_\odot$.

5. Discussions and Concluding Remarks

We studied spectral and temporal properties of three MAXI observed BHCs during their very first outbursts after discovery using RXTE/PCA data. Out of them two (MAXI J1659-152 and MAXI J1836-194) are shorter orbital period BHCs, where soft states were missing. These short orbital period sources belongs to a special category (*type-II* or *harder-type*) of sources (for e.g., XTE J1118+480, Swift J1753-0127, etc.) where accretion disks are dominated with the low angular momentum sub-Keplerian halo matters. During the outbursts, Keplerian disk rate does not rises much compared to the halo rate, such that it is able to cool down CENBOL completely. On the other hand, MAXI J1543-564 is a *type-I* or *classical-type*, where all spectral states are observed (see, Stiele et al. 2011).

Spectral fits of these three MAXI objects with the TCAF solution, provide us a direct evidence of two components accretion flows as they are observed to vary independently during the outbursts. Spectral study with the TCAF solution enables us not only to understand spectral properties of the BHCs but also to predict other timing and physical parameters associated with the BHs. Different spectral states and their transitions from one state to another are more clearly understandable from the variations of TCAF model fitted physical flow parameters and nature of QPOs. Frequency of the dominating type-C QPOs also could be predicted from TCAF model fitted shock parameters, since in TCAF we use same shock, whose oscillation is believed to the fact of QPOs. In ARRID, we saw that the correlation between spectral and timing properties of transient BHCs is more fundamental than so-called 'q'-diagram or HID. We also estimated probable mass range of the three MAXI sources from our TCAF model fitted spectral analysis within a good accuracy. We also estimated X-ray jet fluxes during the 2011 outburst of MAXI J1836-194 from our spectral study with the TCAF solution (see, proceeding of Jana et al. in this volume and Jana et al. 2017).

From our recent study of various BHCs with the TCAF solution including three MAXI objects discussed here, we can say that TCAF is the most accurate theoretical model to understand physics of accretion processes around a black hole, which was our decade long conjecture. Spectral fits with the model, not only explains spectral properties and but also capable to explains various timing features including QPOs of BHCs. One can also estimate physical source parameters, such as mass, spin from spectral fits with the TCAF model. Finally, it is needed to mention that we require only six model input parameters including the mass of the black hole and normalization to fit a spectrum with the TCAF solution.

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