Accretion Flow Properties of Swift J1753.5-0127 during Its 2005 Outburst

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Abstract

Galactic X-ray binary black hole candidate Swift J1753.5-0127 was discovered on 2005 June 30 by the *Swift*/BAT instrument. In this paper, we make a detailed analysis of spectral and timing properties of its 2005 outburst using the archival data of the *RXTE*/PCA instrument. A simultaneous observation of *Swift*/XRT with PCA is also used to study the broadband features. Here, we study the evolution of the spectral properties of the source from spectral analysis with an additive table model fits file of the Chakrabarti-Titarchuk two-component advective flow (TCAF) solution. From the spectral fit, we extract physical flow parameters, such as the Keplerian disk accretion rate, sub-Keplerian halo rate, shock location, and shock compression ratio, etc. We also study the evolution of temporal properties, such as the observation of low-frequency quasi-periodic oscillations (QPOs), and the variation of X-ray intensity throughout the outburst. From the nature of the variation of QPOs, and accretion rate ratios (ARRs = ratio of halo to disk rates), we classify the entire 2005 outburst into two harder (hard-intermediate and hard) spectral states. No signatures of softer (soft-intermediate and soft) spectral states are seen. This may be because of a significant halo rate throughout the outburst. This behavior is similar to a class of other short-orbital-period sources, such as MAXI J1836-194, MAXI J1659-152, and XTE J1118+480. We estimate the probable mass range of the source to be in between $5.35^{+0.55}_{-0.60}\,M_{\odot}$ based on our spectral analysis.

Key words: accretion, accretion disks – stars: individual (Swift J1753.5-0127) – stars: black holes – shock waves – radiation: dynamics – X-rays: binaries

1. Introduction

Galactic black hole candidates (BHCs) are generally situated in binary systems. Some of these sources are transient in nature. These black hole X-ray binaries (BHXRB) spend most of their lifetime in the quiescent states. Occasionally, they show outbursts in which high-energy radiation intensity increases by a factor of a hundred or more. A possible explanation is that an outburst is triggered by the sudden rise in viscosity in the accreting matter coming from the companion (Chakrabarti & Titarchuk 1995; Ebisawa et al. 1996). The mass transfer from the companion to the compact object can occur via Roche lobe overflow or by wind accretion, depending on the nature of the companion. In general, if the companion is a low-mass K- or M-type star, Roche lobe overflow is expected. If the companion is a mass-losing high massive star, such as O-, A-, or B-type, winds form and the accretion of winds is expected. In a BHXRB, the matter does not fall radially on the compact object. Rather, it forms an inward-spiraling accretion disk around it. This disk emits electromagnetic radiation ranging from radio to γ-rays. High-energy radiation, such as X-rays, is very important to study the properties of black holes (BHs), as they come from regions close to the BH event horizon and therefore carry accurate information about the compact object.

In general, an X-ray spectrum consists of a multi-color blackbody-type component of soft photons and a power-law (PL)-type tail of hard photons. The multi-color blackbody component is believed to come from the standard accretion disk (Novikov & Thorne 1973; Shakura & Sunyaev 1973), while the PL component is believed to come from a hot-electron filled Compton cloud region (Sunyaev & Titarchuk 1980, 1985). In the two-component advective flow (TCAF) solution of Chakrabarti and his collaborators (Chakrabarti & Titarchuk 1995; hereafter CT95; Chakrabarti 1997), the so-called Compton cloud is replaced by the CENtrifugal pressure supported BOundary Layer (CENBOL). In the TCAF solution, the accretion disk consists of two components of accreting matter—a standard Keplerian disk with temperature modified by the reflection from a Compton cloud and a sub-Keplerian halo. The Keplerian disk is a high viscous disk with high angular momentum while the sub-Keplerian disk has a low viscosity and a low angular momentum. The sub-Keplerian halo piles up at the centrifugal barrier and an axis-symmetric shock is formed (Chakrabarti 1990). The soft photons from the Keplerian disk are inverse-Comptonized at the post-shock region and become hard photons. CENBOL is also considered to be the base of the jet (Chakrabarti 1999). Its oscillation is believed to cause low-frequency quasi-periodic oscillations (QPOs). QPOs are observed if resonance conditions are satisfied when the infall timescale roughly matches with the cooling timescale (Molteni et al. 1996; Chakrabarti et al. 2015) or the Rankine–Hugoniot conditions are not satisfied (Ryu et al. 1997). The observed frequencies of the QPOs are inversely proportional to the infall time in the post-shock region (Chakrabarti & Manickam 2000).

Recently, Debnath and his collaborators successfully included this most generalized accretion solution into HEASARC's spectral analysis software package XSPEC (Arnaud 1996) as an additive table model (Debnath et al. 2014; Mondal et al. 2014; hereafter MDC14; Debnath et al. 2015a, 2015b; hereafter DMC15, DMCM15, respectively; Jana et al. 2016; hereafter JDCMM16; Chatterjee et al. 2016; hereafter CDCMJ16;) to find the nature of the accretion flow properties of a few transient BH sources during their X-ray outbursts. Apart from the mass of the BH and the normalization, one requires four parameters (two types of accretion rates, shock location, and compression ratio) to fit a BH spectrum with the TCAF solution in XSPEC. Transient BHXRBs show several spectral states during an entire outburst, which could be well understood by observing variations of these physical flow parameters and the nature of QPOs. Four spectral states, namely hard (HS), hard-intermediate (HIMS), soft-intermediate (SIMS), and soft state (SS) are commonly observed in an outburst of a transient BHC (Belloni et al. 2005; Remillard & McClintock 2006). In a typical outburst, BHCs generally stay in the HS at the start of an outburst. After that, it enters into the HIMS, SIMS, and SS one-by-one. The shock moves closer to the BH as it moves to the softer state and before disappearing altogether in a soft/very soft state. The declining phase starts when the matter supply to the inner disk is turned off. During this phase of an outburst, the shock moves away from the BH and the spectra start to become harder. Generally SIMS, HIMS, and HS are observed one after another while completing the hysteresis loop of the spectral states (see Debnath et al. 2013 and references therein).

In general, in the harder states (HS and HIMS), the halo rate dominates, while in the softer states (SIMS and SS), the disk rate dominates. From the spectral fits of the data of each day with the TCAF solution, we can also estimate the mass of BH more accurately using the constant normalization method (Molla et al. 2016; hereafter MDCMJ16). According to the TCAF solution, model normalization (*N*) should not vary on a daily basis, since it only depends on the mass, distance, and disk inclination angle "*i*" of the disk, unless precession in the disk occurs to change the projected surface of the emission area or there are some significant outflow activities that are not included in the current TCAF model fits file. This method has been successfully applied to estimate masses of few transient Galactic BHCs, such as MAXI J1659-152 (MDCMJ16), MAXI J1836-194 (JDCMM16), MAXI J1543-564 (CDCMJ16), and H 1743-322 (Bhattacharjee et al. 2017; Molla et al. 2017). This motivated us to estimate the mass of Swift J1753.5-0127 using the same method. Moreover, Mondal et al. (2016) also estimated the spin parameter of BHC GX 339-4, from their spectral study of the relativistic broadening of the double Fe-line with combined TCAF-plus-LAOR model fits using *Swift*/XRT and NuSTAR/FMA data of the 2013 outburst.

Swift J1753.5-0127 was discovered by *Swift*/BAT on 2005 June 30 (Palmer et al. 2005) at the sky position of RA = $17^h53^m28^s.3$, decl. = $-01°27'09''.3$. It was also detected in optical (Halpern 2005) and radio (Fender et al. 2005). BHC Swift J1753.5-0127 has a short orbital period of 3.2 ± 0.2 hr (Zurita et al. 2007). However, Neustroev et al. (2014) suggested the orbital period is 2.85 hr. They also reported that the binary has a primary BH mass of less than 5 $M_\odot$ and a companion mass of 0.17–0.25 $M_\odot$ and disk inclination angle of >40°. Recently, Shaw et al. (2016) predicted the mass of the central BH to be greater than 7.4 $M_\odot$. Cadolle Bel et al. (2007) estimated the distance of the system is likely to be in between 4 and 8 kpc. However, from UV spectral study, Froning et al. (2014) calculated the source distance as <3.7 kpc for an inclination $i = 55°$ and <2.8 kpc for an inclination $i = 0°$. The secondary companion is also reported to be a K- or M-type main-sequence star (Cadolle Bel et al. 2007). A radio jet was also observed during the 2005 outburst of the source (Fender et al. 2005; Soleri et al. 2010). The source was active over 11 years before going into the quiescence state in 2016 November (Plotkin et al. 2016; Shaw et al. 2016). Nonetheless, it again shows activity in 2017 February (Kong 2017; Qasim et al. 2017).

Recent studies of different transient BHCs show that outbursts are of two types: type-I or classical type, where all spectral states (HS ⇌ SS via two intermediate states, HIMS and SIMS) are observed, and type-II or harder type, where SS (sometimes even SIMS) are absent. The latter type of outburst is generally referred to as a "failed" outburst. Our recent study of a few type-II outbursts of a few transient BHCs, such as the 2010 outburst of MAXI J1659-152 (Debnath et al. 2015b), the 2011 outburst of MAXI J1836-194 (Jana et al. 2016), and the 2000 outburst of XTE J1118+480 (D. Chatterjee et al. 2017, in preparation) confirms that short-orbital-period BHCs generally show this class of outbursts.

This paper is organized as follows. In Section 2, we briefly discuss the observation and data analysis procedure. In Section 3, we present the TCAF model-fitted spectral analysis result. There, we also present timing analysis results. We also estimate the mass of the BHC Swift J1753.5-0127 based on the TCAF model-fitted constant normalization method. Finally, in Section 4, a brief discussion and concluding remarks are presented.

2. Observation and Data Analysis

Two days after its discovery, *RXTE*/PCA monitored the source on a daily basis (Morgan et al. 2005). Here, we study the archival data of 44 observational IDs starting from the first PCA observed day; 2005 July 2 (Modified Julian Day, i.e., MJD = 53553.06) to 2005 October 19 (MJD = 53662.77) using XSPEC version 12.8. To analyze the data we follow the standard data analysis technique of the *RXTE*/PCA instrument as presented in Debnath et al. (2013, 2015a).

For timing analysis we use the PCA *Science Binned* mode (FS3f*.gz) data with a maximum timing resolution of 125 μs to generate light curves for well-calibrated Proportional Counter Unit 2 (PCU2; including all six layers) in 2–25 keV (0–59 channels) and 2–15 keV (0–35 channels). To generate the power-density spectra (PDS), the "powspec" routine of the XRONOS package is used to compute rms fractional variability on 2–15 keV light curves of the 0.01 s time bin. To find the centroid frequencies of the observed QPOs (ν_{QPO}^{Obs}) in PDS, we fit each QPO with a Lorentzian profile and use the "fit err" command to get "±" error limits.

For spectral analysis we use *Standard2* mode Science Data (FS4a∗.gz) of the PCA instrument. The 2.5–25 keV background-subtracted PCU2 spectra are fitted with both the TCAF-based model fits file and combined disk blackbody (DBB) and PL-model components in XSPEC. However, the spectra of the last eight observations were fitted only with PL, as no significant DBB component was needed. To achieve the best spectral fits, a Gaussian line of peak energy around 6.4 keV (iron-line emission) is used. Hydrogen column density (N_H) was kept frozen at 1.0×10^{21} atoms cm^{-2} for the absorption model *wabs*. For the entire outburst, we also use a fixed 1.0% systematic instrumental error for the spectral analysis. The XSPEC command "err" is used to find 90% confidence "±" error values for the model-fitted parameters after achieving the best fit based on a reduced chi-square value ($\chi^2_{red} \sim 1$).

There are two simultaneous observations (on 2005 July 08 and 10) of *Swift*/XRT and *RXTE*/PCA instruments. Here, we present results based on 2005 July 8 (Obs. ID = 00030090006). *Swift*/XRT observed the source in photon-counting mode with an exposure of ∼2 ks. We obtain *.pha*, *lightcurve* files using the standard *xrtpipeline* command. We combine *Swift*/XRT data with *RXTE*/PCA to analyze spectra in a broad 0.6–25 keV energy range. We use the 0.6–7.0 keV data of *Swift*/XRT with 3.0–25 keV *RXTE*/PCA data to obtain a 0.6–25 keV spectrum to have some overlap between the two instruments. We have performed the spectral analysis of this combined spectrum using the TCAF model fits file and *diskbb+Gaussian+powerlaw* models. A Gaussian line of ∼6.4 keV is required for the iron line to obtain the best fit. Two more Gaussian lines are also required at ∼1.3 keV and ∼0.7 keV to obtain the best fit.

To fit spectra using the TCAF-based model additive table fits file, one needs to supply five model input parameters such as (i) BH mass ($M_{\rm BH}$) in solar mass ($M_\odot$) unit, (ii) Keplerian accretion rate ($\dot{m}_d$ in Eddington rate $\dot{M}_{\rm Edd} = L_E/c^2$, where L_E is the Eddington luminosity and c is the velocity of light), (iii) sub-Keplerian accretion rate ($\dot{m}_h$ in $\dot{M}_{\rm Edd}$), (iv) location of the shock (X_s in Schwarzschild radius $r_s = 2GM_{\rm BH}/c^2$), and the (v) compression ratio ($R = \rho_+/\rho_-$, where ρ_+ and ρ_- are post and pre-shock densities, respectively) of the shock. Normalization is a function of the mass, distance, and inclination angle of the BHC. Thus, it is a constant and once it is determined for one outburst, it remains the same, though it is found to fluctuate within a narrow region due to errors in fits and possible inaccuracies in data. Thus, once the mass ($M_{\rm BH}$) and the normalization (N) are known, only four parameters are needed to fit the data unless there is precession or jet activity. The size of the hot Compton cloud, i.e., CENBOL and its nature (such as, height, temperature, optical depth, etc.), could be calculated from the shock parameters.

3. Results

Recent studies by our group show that the intricacies of accretion dynamics around BHC become transparent when the data are analyzed with the TCAF solution. This motivated us to study the accretion flow properties of the 2005 outburst of the well-known BHC Swift J1753.5-0127 under the TCAF paradigm. Here, we also study simultaneous *Swift*/XRT and *RXTE*/PCA data for our analysis. We study 44 observations between 2005 July 2 (MJD = 53553.06) and 2005 October 19 (MJD = 53662.77) *RXTE*/PCA data for our analysis. We use *RXTE*/PCU2 data for our spectral and timing analyses. To extract physical accretion flow parameters during the outburst of the source, 2.5–25 keV spectra are fitted with the current version (v0.3) of the TCAF model fits file. We also compare our results with the spectral analysis result using a DBB-plus-PL model. The combined DBB-plus-PL model provides only the gross properties of the accretion disk, such as disk temperature, photon index, and flux from thermal and non-thermal components, but the real physical reasons behind the observed spectra come by fitting with the TCAF solution. From the spectral fits, we estimate the mass of the BHC, since it is also an input parameter of the present TCAF model fits file. We also fit combined XRT+PCA data in a broad energy range (0.6–25 keV) observation on 2005 July 8. We also verify the obtained mass from this broadband spectrum.

3.1. Spectral Analysis with the TCAF Solution and with Combined DBB and PL Models

We use 2.5–25 keV *RXTE*/PCU2 data for spectral analysis of BHC Swift J1753.5-0127 during its 2005 outburst. DBB temperature ($T_{\rm in}$) and photon index (Γ) are obtained from the combined DBB-plus-PL model fit of the spectra. We also calculated individual model component fluxes (DBB and PL separately) in a 2.5–25 keV energy band to have a rough estimate of the photon contribution from the thermal (DBB flux) and non-thermal (PL flux) processes around the BH during the 2005 outburst. Spectral fits with the current version of the TCAF solution fits file provide us with two-component (Keplerian disk rate $\dot{m}_d$ and sub-Keplerian halo rate $\dot{m}_h$) accretion rates and shock parameters (location X_s and compression ratio R). These parameters, in turn, provide us with other physical quantities such as the viscosity, temperature, size, and optical depth of the Compton cloud.

In Figure 1(a), we show 2–25 keV PCU2 count rate variations with days (MJD), which seems to be a sharp rise and exponential decay type. In Figures 1(b) and (d), variations of the TCAF model-fitted two-component accretion rates (Keplerian disk rate $\dot{m}_d$, and sub-Keplerian halo rate $\dot{m}_h$) are shown. For comparison, in Figures 1(c) and (e), variations of the individual model components of the combined DBB and PL model-fitted spectra are shown.

In Figures 2(a) and (b), we show variations of the combined DBB-plus-PL model-fitted DBB temperature ($T_{\rm in}$ in keV) and PL photon index (Γ), respectively. The TCAF model-fitted ratio between the sub-Keplerian halo rate and Keplerian disk rate, i.e., accretion rate ratio (ARR = $\dot{m}_h/\dot{m}_d$), are shown in Figure 2(c). In Figure 2(d), we show the evolution of the observed (primary dominating) QPO frequencies with days. Note that the temperatures we get (∼1.2 keV) are higher than what Ramadevi & Seetha (2007); hereafter RS07) obtained (∼0.4 keV). We attribute this to the fact that they fitted with a *diskbb+smedge* ∗ *powerlaw*model. If we had followed their model, we would have gotten a similar temperature. In Figures 3(a)–(d), we show variations of the TCAF model-fitted shock location (X_s), compression ratio (R), normalization (N), andderived mass.

Depending on the nature of the variations of ARR and $\nu_{\rm QPO}^{\rm Obs}$, we classify the entire outburst into two harder spectral states in both the rising (Ris.) and declining (Dec.) phases, although many previous authors reported the entire outburst phase as the low HS (see, Cadolle Bel et al. 2007; RS07). The spectral states are also observed in the sequence: HS (Ris.) → HIMS (Ris.) → HIMS (Dec.) → HS (Dec.). Indeed, the sharp changes in the behavior of the shock location and shock strength are an indication that the spectrum became softer during HIMS state, as compared to that in HS state. In Figures 4(a)–(d), as examples of our fits, TCAF-fitted 2.5–25 keV *RXTE*/PCA spectra with residuals for four observations selected from four different states are shown. The observation IDs are: 91094–01–01–00 (MJD = 53553.05), 91094–01–01–03 (MJD = 53556.19), 91423–01–02–06 (MJD = 53564.91), and 91423–01–09–00 (MJD = 53612.75) are from HS (Ris.), HIMS (Ris.), HIMS (Dec.), and HS (Dec.), respectively. In Figure 5, the TCAF-fitted 0.6–25 XRT+PCA spectrum is shown along with $\Delta\chi$ variation. In Figures 6(a)–(d), we show unabsorbed theoretical TCAF model spectra (online solid black curves) with their two components i.e., blackbody