Spectral Signature of Mass Outflow in the Two Component Advection Flow Paradigm

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Abstract

Outflows are common in many astrophysical systems. In the Two Component Advection Flow (TCAF) paradigm, which is essentially a generalized Bondi flow including rotation, viscosity, and cooling effects, the outflow originates in the hot, puffed up, post-shock region at the inner edge of the accretion disk. We consider this region to be the base of the jet carrying away matter with a high velocity. In this paper, we study the spectral properties of black holes using TCAF that includes also a jet (JetTCAF) in the vertical direction of the disk plane. Soft photons from the Keplerian disk are up-scattered by the post-shock region as well as by the base of the jet and are emitted as hard radiation. We also include the bulk motion Comptonization effect by the diverging flow of the jet. Our self-consistent accretion-ejection solution shows how the spectrum from the base of the jet varies with accretion rates, geometry of the flow, and the collimation factor of the jet. We apply the solution to a jetted candidate GS 1354-64 to estimate its mass outflow rate and the geometric configuration of the flow during the 2015 outburst observed by NuSTAR. The estimated mass outflow to mass inflow rate is $0.12_{-0.02}^{+0.05}$. From the model-fitted accretion rates, shock compression ratio, and the energy spectral index, we identify the presence of hard and intermediate spectral states of the outburst. Our model-fitted jet collimation factor ($f_{\text{coll}}$) is found to be $0.47_{-0.09}^{+0.09}$.

Unified Astronomy Thesaurus concepts: Black hole physics (159); Accretion (14); X-ray astronomy (1810); Shocks (2086); Hydrodynamics (1963); Radiative transfer (1335); Jets (870)

1. Introduction

Observations show that jets are common in active galactic nuclei (AGNs), stellar mass black holes, and neutron stars (e.g., Hjellming & Rupen 1995; Mirabel & Rodríguez 1998; Miller-Jones et al. 2012; Blandford et al. 2019, and references therein). A proper understanding of the origin and acceleration of jets in compact objects is, however, lacking. Several models in the literature attempt to explain the origin, powering, and collimation of the jet. D'Silva & Chakrabarti (1994) suggested that only the dominant toroidal field in the disk would be enough to accelerate and collimate the jets. This has been recently verified using numerical simulations by Garain et al. (2020). Fender et al. (2010), from their observational studies, did not find any evidence of a jet powered by the spin energy of the black holes, and the authors speculated that this conclusion remained valid even for active galaxies and quasars. By contrast, Narayan & McClintock (2012) found a correlation between jet power and black hole spin energy. Thus, the role of the spin parameter in powering the jet is still unclear and more studies must be done to reach a firm conclusion. The hydrodynamic jets can also be collimated due to the strength of the jet—cocoon interaction and the collimation shock at the base of the jet (Bromberg et al. 2011).

Therefore, accretion-ejection around black hole systems has three components: the accretion disk, its static or dynamic corona, and the outflowing jet. It is well established that the standard disk (Shakura & Sunyaev 1973) emits soft photons, up-scattered by the hot Compton cloud at the inner region of the disk and emitted as hard radiation. The emergent radiation may get down-scattered by the diverging outflows for both sub-and super-Eddington accretion (Titarchuk & Shradi 2005; Kawashima et al. 2012, hereafter TS05). This effect changes the intrinsic continuum spectra of accretion disks with an additional bump (Sunyaev & Titarchuk 1980) in the power-law spectrum. The problem of photon propagation through a moving medium has been studied extensively in several works (Blandford & Payne 1981; Nobili et al. 1993; Titarchuk et al. 2003). There are numerous studies in this context in the literature, both in theory and in radiation hydrodynamic simulations (Eggum et al. 1988; King et al. 2001; Okuda 2002; Ebisawa et al. 2003; Ohsuga et al. 2005). In addition to down-scattering of hard radiation, a jet can also behave like an up-scattering Comptonizing medium of the soft photons from the disk. The presence of a soft-excess is a commonly observed spectral component for both X-ray binaries and AGNs. This can be originated if there is a warm Compton up-scattering medium present in the system. The excess component can also be associated to an intrinsic component with the disk, powered by the mass accretion rate (Done et al. 2012), and appearing as a reflection component (see Done et al. 2007 for a review). This distortion of the power-law continuum above $\sim 10$ keV could also be due to the down-scattering of hard radiation by the outflowing plasma rather than from a static reflecting medium (TS05). In addition to these spectral features, a converging flow falling onto the black hole near the event horizon can show a bulk motion effect (Chakrabarti & Titarchuk 1995; Titarchuk & Zannis 1998, hereafter CT95). Under such complex radiation components coming from the accretion-ejection system, it is important to ask, independent of how a jet is launched from the disk, what would be the overall X-ray spectrum in the presence of a jet, and what is the contribution from the base of the jet itself, especially the subsonic region, which is hot. Most importantly, it needs to be established whether there is any evidence of such a contribution.

Chakrabarti (1999; hereafter C99) postulated that the jets in black hole systems are formed out of the post-shock region, which is also called the CENtrifugal pressure dominated BOUNDary Layer, or CENBOL. This is the subsonic, hot region between the shock and the inner sonic point (Chakrabarti 1989) located just inside the marginally stable orbit. C99 also proposed that the entire outflow is produced by the CENBOL,
and the mass outflow rate directly depends on the compression ratio \( R = \frac{\rho_+}{\rho_-} \) of the shock itself, where \( \rho_- \) and \( \rho_+ \) are the densities of the flow in the pre-shock and post-shock regions. It was shown that the ratio of the mass outflow rate to inflow rate is indeed a function of \( R \) and varies in a nonlinear way apart from a geometric factor coming from the solid angles of the outflow and the inflow. For a very strong shock, which forms farther out, as in a hard state, the thermal driving force is low and the jet is not powerful. Similarly, in a soft state, when the shock is the weakest, the size of the base of the jet is negligibly small, and so the thermal driving force is also low and hence the ratio is also low. Only in between the two states is the ratio significant. Several hydrodynamic simulations showed that a few percent of accreting matter is indeed present in the jet (Molteni et al. 1994; Chattopadhyay et al. 2004; Garain et al. 2012). Singh & Chakrabarti (2011) studied jet properties of the flow when the energy dissipation is present at the shock and found a lower efficiency of the jet formation when viscosity is high.

In the Chakrabarti (1997; hereafter, C97) two component flow scenario, it is established that the emission from the CENBOL decreases as the accretion rate of the Keplerian disk increases, because both its size and temperature are reduced. This reduction of thermal pressure of CENBOL reduces the mass outflow rate. Thus, accretion rates, spectral states, and jet are interlinked. Observations have revealed evidence of prominent jets in hard and hard-intermediate spectral states (HS and HIMS; Fender et al. 2004). A transonic solution including real cooling (Mondal & Chakrabarti 2013) and outflows (Mondal et al. 2014a) showed that spectral states are related to the mass outflow rate, and a significant change in the energy spectral index is observed in the HS and the HIMS. These solutions are self-consistent in the sense that cooling and mass loss are incorporated in the flow equations before obtaining the spectra. Recent work by Nagarkoti & Chakrabarti (2016) using a viscous solution confirms that a significant amount of mass loss is centrifugally driven as suggested by Blandford & Payne (1982), though the disk may be sub-Keplerian in nature.

The interdependency of the accretion rate, CENBOL size, and quasi-periodic oscillations (QPOs) is also well known in the literature. During an outburst, when a source moves from the HIMS to the SIMS, the QPO type switches from type-C to type-B (e.g., Mondal et al. 2014b; Debnath et al. 2015; Chatterjee et al. 2016, and references therein). However, jet properties also change drastically, which is observed in large amplitude radio flares (Fender et al. 2004, 2009). Radhika & Nandi (2014) reported the accretion-ejection mechanism for the object XTE J1859+226 and pointed out that the QPOs disappear during the high ejection of jets. All of these are expected from the TCAF paradigm, since QPOs are known to be formed due to the resonance of various timescales inside CENBOL, which also produces jets. Interestingly, the highest outflow to inflow rate from the theoretical solution of C99 happens for an intermediate compression ratio of the shock, i.e., in hard and soft-intermediate states. Retaining CENBOL is possible only in a low viscosity state (Mondal et al. 2017).

The original TCAF solution of CT95 and C97 does not include the contribution from outflows and, therefore, the presence of significant outflows requires a modification of the model. This is the primary goal of this paper. Here, we concentrate on the effects on the emergent spectra when the base of the outflow also participates in the Comptonization of injected photons along with the CENBOL. We study the jet spectrum when the accretion rates, the geometry of the flow, and jet parameters vary. We also see the variation of the spectra from the jet with the variation of CENBOL size and shock compression ratio. The study of optical and radio observations (Brocksopp et al. 2001; Pahari et al. 2017) inferred the presence of a jet in the GS 1354-64 system; however, there has been very little study of this object as far as the effects of jets are concerned. We apply the solution to study this object, in order to throw some light on the accretion-ejection behavior during its 2015 outburst. In fact, from the fits of the modified TCAF model, we extract the jet parameters, such as the mass outflow rate, as well. In future, we aim to apply the solution to other well-known candidates that exhibit prominent jets.

The paper is organized as follows. In the next Section, we present the configuration of the jet and the equations we used to calculate the jet temperature and internal number density, etc. In Section 3, we present the results of the effects of mass loss on normal in TCAF output, mainly the spectral variation with location of the shock, shock compression ratio, and accretion rates. In Section 4, we calculate the mass outflow rate of the black hole candidate (BHC) GS 1354-64 during its 2015 outburst observed with NuSTAR. Finally, in Section 5, we briefly present our concluding remarks.

2. Equations and Jet Configuration

To extract the jet properties from a spectral fit, we consider a conical jet in the vertical direction of the flow, which originates in the post-shock region. The base of the jet is a part of the Compton cloud along with the CENBOL. In Figure 1, we present a cartoon diagram of the two component flow with a jet where a Keplerian disk resides at the equatorial plane, and it is surrounded by the low angular momentum flow (a dynamic halo). At the center, a black hole of mass \( m_{BH} \) is located. We show also the solid angles \( \Theta_o \) and \( \Theta_{in} \) subtended by the two outflow components and the axisymmetric torus created by the CENBOL respectively.
Table 1

| Pars. | Units | Default | Min. | Min. | Max. | Max. | Increment |
|-------|-------|---------|------|------|------|------|-----------|
| \( M_{\text{BH}} \) | \( M_\odot \) | 6.0 | 4.0 | 4.0 | 15.0 | 15.0 | 2.0 |
| \( m_a \) | \( M_{\text{edd}} \) | 0.01 | 0.001 | 0.001 | 2.0 | 2.0 | 0.05 |
| \( m_b \) | \( M_{\text{edd}} \) | 0.1 | 0.001 | 0.001 | 5.0 | 5.0 | 0.2 |
| \( X_r \) | \( r_s \) | 50.0 | 6.0 | 6.0 | 400.0 | 400.0 | 8.0 |
| \( g \) | | 5.0 | 1.1 | 1.1 | 7.0 | 7.1 | 0.2 |
| \( f_{\text{col}} \) | | 0.1 | 0.05 | 0.05 | 0.5 | 0.5 | 0.01 |

The spectrum emitted from the system contains (a) a modified blackbody component, which is coming from the Keplerian disk, (b) soft photons that are up-scattered from the disk by the hot electrons at the inner region of the disk and come out as hard radiation, (c) disk soft photons that also get up-scattered by the jet base, which modify the spectrum on the shoulder of the blackbody bump, and (d) hard radiation from the CENBOL that are down-scattered by the outflowing jet due to the Doppler effect. Components (a) and (b) are already computed in the original Chakrabarti & Titarchuk (1995) paper. For component (c) we use the same radiative transfer calculation incorporating the temperature and optical depth of the jet. Once we have the physical quantities of the jet medium and the spectral component (b), we use it to pass through the jet medium following TS05. Below, we discuss the equations used to estimate different physical quantities of the jet medium.

The radiation from the CENBOL may constantly heat up the jet and the jet may not get enough time to cool at least up to the sonic point. Thus, the ratio of the mass outflow rate to the mass inflow rate is derived for an isothermal base of the jet (C99), which is given by

\[
R_m = f_{\text{col}} f_0^{3/2} R \exp \left[ \frac{3}{2} - f_0 \right],
\]

where \( f_0 = \frac{R^2}{R_i^2} \) and \( f_{\text{col}}(=\Theta_0/\Theta_{\text{in}}) \) is the collimation factor. Here, \( \Theta_0 \) and \( \Theta_{\text{in}} \) are the solid angles subtended by the two outflow components and the inflow. We should mention that the \( f_0 \) factor diverges when \( R \sim 1 \). However, that does not create any complications in producing the spectrum, since when \( R \sim 1 \), the flow is not a TCAF and produces the blackbody spectrum only. It is clear that the mass outflow rate is a function of only \( R \) and \( f_{\text{col}} \). Here, \( f_{\text{col}} \) is a parameter and its value is varied in the range (see Table 1) to fit the observed data. One of the values of \( f_{\text{col}} \) is 0.1, which corresponds to \( \Theta_0 \sim 10^\circ \). Molteni et al. (1994) discussed that \( \Theta_{\text{in}} \) should depend on the strength of the centrifugal barrier. If the barrier is stronger, \( \Theta_0 \) and consequently the mass-loss rate is higher. The total accretion rate of the inflowing matter at the CENBOL after the mixing of the Keplerian and sub-Keplerian components is given by

\[
\dot{M}_{\text{in}} = \dot{M}_i + \dot{M}_h,
\]

here, \( \dot{M}_i \) and \( \dot{M}_h \) are the disk and halo rates, respectively, of the flow in units of \( \text{gm s}^{-1} \). Since in TCAF, the boundary layer, i.e., the CENBOL, is emitting the jet, the initial launching velocity of the ejecta comes from the temperature of the post-shock region, i.e., \( v_j \sim \sqrt{T_{\text{shock}}} \sim 0.1c \). However, it changes depending on the CENBOL location. The density at the base of the jet is calculated using

\[
\rho_j = \frac{\dot{M}_j}{\pi X_r^2 v_j},
\]

where \( \dot{M}_j(=R_m \dot{M}_{\text{in}}) \) is the rate of the mass outflow. As the height increases, the density of the outflowing matter falls as

\[
\rho_j = \rho_j 0 \left( \frac{r_j}{r_{j0}} \right)^{-2},
\]

where \( r_j \) and \( r_{j0}(=h_{\text{shock}}) \) are the (running) height of the jet and the fixed height of the base of the jet, respectively. The latter is basically the height of the shock (\( h_{\text{shock}} \)). We assume that the jet matter moves away subsonically until it reaches the sonic surface, the radius of which is given by (C99)

\[
r_c = \frac{f_0 X_r}{2}.
\]

We assume that the temperature of the jet (\( T_j \)) varies as \( \sim1/r_j \). In this work, we also consider the effects of the down-scattering of the Comptonized photons by the bulk motion of the outflowing jet as discussed in TS05. There are a number of sources that show evidence of strong reflection above \( \sim10 \text{keV} \). This distortion of the power-law continuum above this energy can also be originated from the down-scattering of the hard radiation by the outflowing plasma rather than from a static reflecting medium. This is discussed in CT95 and TS05. Here, we implement this to explain the excess radiation component present in the spectrum. We use the following equation from TS05 for the final down-scattered jet spectrum:

\[
F_{\text{BMC}} \propto \Phi_{\text{Comp}} \left[ 1 + N_{\text{in}} \frac{\bar{z}}{1 - \bar{z}} \right] \left( 1 - \alpha \right) - \frac{\varepsilon}{3\bar{z}_\bullet} - \frac{z}{\bar{z}_\bullet},
\]

where the second term in the bracket describes the pile-up and softening of the input Comptonization spectrum (\( \Phi_{\text{Comp}} \)), resulting from the down-scattering effect by the jet electrons. Here, \( N_{\text{in}}(=3\bar{z}_\bullet^2/8) \) is the number of average scattering, \( \varepsilon \) is the efficiency of the energy loss in the divergent flow (\( \sim2v_j/c\tau_0 \)). \( \bar{z} \) is the dimensionless photon energy, \( \bar{z}_\bullet \) is the dimensionless temperature, and \( \tau_0 \) is the optical depth of the scattering medium, namely, the base of the jet. The \( \Phi_{\text{Comp}} \) we used here is the spectrum emitted from the CENBOL due to the up-scattering of disk soft photons and \( \alpha \) is the energy spectral index estimated from the original TCAF code (CT95) to make the computation consistent. However, TS05 assumed this spectral component to be a cut-off power-law for a given \( \alpha \). The subscript BMC implies the bulk motion Comptonization.

The units of mass, length, speed, and accretion rates are \( M_\odot, r_s, \dot{M}_{\odot}, \) and \( \dot{M}_{\text{edd}} \), respectively, where \( M_\odot, G, M_{\text{BH}}, c, \) and \( M_{\text{edd}} \) are the mass of the Sun, the gravitational constant, the mass of the central object, the speed of light, and the Eddington accretion rate. Throughout the paper we follow these units for model parameters and physical quantities.

### 3. Results and Discussions

We show how the spectral properties change when the base of the jet is also a part of the Compton cloud. In Figure 2(a), we show the spectral variation of the jet component from the total...
emitted spectrum for different accretion rates (\(\dot{m}_h\)) when other flow parameters (\(\dot{m}_b\), \(M_{\text{BH}}\), \(X_s\), and \(R\)) are kept constant. We increase the accretion rates, i.e., the number of soft photons, and observe that the jet spectrum softens. Here, we use \(f_{\text{col}} = 0.1\), and other parameters are marked in the figure. An increase of the soft photon number also cools down the Compton cloud rapidly. Thus, the emitted jet does not have sufficient thermal energy to up-scatter the soft photons significantly. In Figure 2(b), we present the spectra of different spectral states by varying the accretion rates only, keeping all other parameters fixed. Here, the spectra vary from the HS to the SS and the same variation is reflected in the jet contribution in the spectra as well. Spectral states may change due to different sizes of the cloud and the compression ratio of the shock, since these two physical parameters are also related to the density and optical depth of the system.

Figure 3(a) shows the effects of the size of the Compton cloud (\(X_c = 10, 20, 40\), and 60) on the jet component of the total emitted spectrum. We see that as the size of the cloud increases, the jet spectral component becomes softer. As the base of the jet is the CENBOL, the jet component varies with shock location. A larger CENBOL, being farther from the black hole, already has a lower temperature (roughly \(\propto 1/X_c\)). Also, it intercepts more soft photons from the Keplerian disk, which reduces the overall CENBOL temperature (Chakrabarti 1997). Thus, the resulting temperature of the base of the jet becomes lower. Thus, the soft primary photons are not up-scattered many times. This causes the jet spectrum to be softer. In Figure 3(b), we show the jet component variation for different values of \(R\) (2.0, 2.5, 3.5, 4.5, and 6.0). We observe significant changes in the jet component, which becomes softer with increasing \(R\). From the C99 solution, we see that the mass outflow rate decreases when \(R\) is higher than \(\sim 4.0\). This affects the spectral shape; for instance, when \(R = 6.0\), the mass outflow rate is very low and consequently the spectrum is also softer. In Figure 3(c), we see the spectral hardening when the jet collimation factor (\(f_{\text{col}}\)) has changed from 0.05 to 0.3.

Figure 4(a) shows the variation of the net spectrum with (solid) and without jet (dashed line) contribution as a function of the shock compression ratio (\(R\)). We note that due to the presence of
the jet, the total spectrum becomes harder as compared to that without the jet. The variation of the total spectrum with $R$ is significant. In Figure 4(b), we show the total emitted spectra for different values of $R$ (a), and (b) $f_{\text{col}}$. In (a), we see that the spectrum becomes harder with increasing $R$. The new parameter ($f_{\text{col}}$) does not affect the CENBOL spectrum and thus the total spectrum without the jet contribution is the same for all (dashed line). The other parameters are $M_{\text{BH}} = 10.0$, $m_d = 0.001$, $m_b = 1.0$, and $X_s = 20.0$. Here, frequency is in units of Hz.

Figure 5. (a) Total emitted spectrum with (solid lines) and without (dashed lines) the jet contribution for different spectral states depending on the accretion rates when other parameters are fixed ($X_s = 20.0$ and $R = 3.0$). There is a significant change in the spectrum as compared with the soft state in presence of jet. (b) Total spectrum in the soft state in the presence of the jet (solid line) component when $X_s = 10.0$ and $R = 1.2$. In the soft state, the jet contribution is negligible and both of the spectra are the same. For both of the plots, $M_{\text{BH}} = 10.0$ and $f_{\text{col}} = 0.2$. Here, frequency is in units of Hz.

In Chakrabarti (1996), it was proposed that viscosity is mainly responsible for changing the relative rates, which is indirectly taken into account by the two accretion rates in TCAF. In Mondal et al. (2017), it was shown that the observed viscosity parameter indeed rises in the rising phase and decreases in the declining phase, thereby completing the full cycle of the observed states. In Figure 5(b), we choose typical model parameters for soft states. One can see that the jet contribution is negligible. There are many observations in the literature that show the correlation between observed spectral states with the jet (Fender et al. 2004; Belloni et al. 2005; Sriram et al. 2012). They also discussed correlations between the QPOs and the jet emissions in the HID diagram. All of these correlations fall in place once the computation of the outflow rate to inflow rate ratio as a function of the properties of the centrifugal barrier was made (C99). The theoretical result directly shows that, if
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Indeed the outflows are produced from CENBOL, then, the soft and extremely hard states are going to produce very little outflows. Only intermediate states have higher outflow rates for a given inflow rate. When the optical depth is higher at the base of the jet, it produces blobby jets (Chakrabarti et al. 2002, Nandi et al. 2001). In the soft state, due to cooling effects, this region is quenched and the mass outflow rate is reduced (see also Garain et al. 2012). Recently, Jana et al. (2017) estimated the X-ray flux from the base of the jet for the Swift J1753.5-0127 BHC using the TCAF model.

Until now, we have not shown the contribution of the BMC component in the spectral plots. In Figure 6 we show the emitted spectrum when hard photons from the CENBOL pass through the outflowing diverging jet. In Figure 6, we show the spectral components including the jet when the down-scattering effects of the CENBOL photons due to the bulk motion of the jet are considered. The black line shows the net spectrum when the BMC effect is also included, and the blue and indigo lines show the jet component with the BMC effect, respectively. Here, green and red lines are the disk blackbody and thermal Comptonization spectra obtained from the original C97 solution. The net spectrum clearly shows a bump, which is slightly higher in the JetCAF spectra as compared to the TCAF. TS05 explained that the bump is due to the BMC effects of the CENBOL photons caused by the diverging outflows discussed in CT95. In the next Section, we use both the TCAF and JetCAF models to fit the observed data, where we find the signatures of the BMC effect.

4. GS 1354-64

We now use our computed spectra to fit the data of the BHC GS 1354-64. GS 1354-64 is a dynamically confirmed low-mass X-ray binary with a black hole mass >7 M$_{\odot}$, ~2.5 days orbital period, and a distance of ~25–61 kpc (Casares et al. 2004, 2009). Reynolds & Miller (2011) reported the possible distance to be ~15 kpc, and this large difference is due to the extinction effects. Very recently, Gandhi et al. (2019) estimated the distance of this source to be less than or around 1 kpc from Gaia DR2 observations. The DR2 distance would make the source underluminous in both optical and X-ray wave bands. Apart from that, a large discrepancy also creates a large uncertainty in the estimation of the donor star classification and its intrinsic brightness. This candidate showed two confirmed outbursts: one in 1987 (Makino 1987), when the source entered into the soft state (Kitamoto et al. 1990), and one in 1997 (Brocksopp et al. 2001), when the source was in a pure hard state (Revnivtsev et al. 2000). In the same outburst for the first time, Fender et al. (1997) observed a radio counterpart. In late 2015 May, the optical brightness of this source was two times higher than the quiescent values reported by Russell & Lewis (2015). Recently, Koljonen et al. (2016) showed that the source has again entered into the hard state, studying multwavelength observations during its 2015 outburst. They also confirmed that optical and UV radiation are tightly correlated with the X-ray radiation, which is consistent with the emission from the jet.

We consider the NuSTAR (Harrison et al. 2013) observation of the 2015 June 13 (90101006002, hereafter X02) and July 11 (X04) outbursts. We consider the FPMA observation with 4.0–65.0 keV energy range data. The exposure times for these observations are ~24 ks and ~30 ks, respectively. For pipeline reduction and spectral file generation we use the nupipeline and nuproducts tasks. After successfully processing the data we do spectral fitting using (1) TAbsum(Gauss+TCAF) and (2) Tabsum(Gauss+JetTCAF). We follow the standard data extraction procedures using the NuSTARDAS and HEASoft packages and perform the spectral fitting using XSPEC. The details of the analysis procedure and the related fitting issues are discussed in Mondal & Chakrabarti (2019). For the spectral fitting of X02, we use the TCAF model generated fits file (Debnath et al. 2014) as a local additive table model, following the atable command in XSPEC. For the generation of model fit file, a large number of spectra are generated for the range between 10$^{18}$ and 10$^{21}$ Hz. During the fitting, we keep the black hole mass as a free parameter, and for both of the observations we keep $N_H$ fixed at $0.5 \times 10^{22}$ cm$^{-2}$ following the HEASARC column density tool (Dickey & Lockman 1990). Data fitting with TCAF gives a very good fit with reduced $\chi^2 = 1.046$. After successful fitting, we get the value of M$_{BH} = 7.22^{+0.25}_{-0.88}$. In Figure 7, we show the TCAF model-fitted spectra of X02.

For the fitting of X04, first, we attempt to fit the data using the TCAF model generated fits file. We tried with different combinations of model parameters; however, the quality of the fit is poor, with a reduced $\chi^2$ value > 2.5, as that version of the fits file does not include the jet contribution. After this, we fit the data with the JetCAF model keeping all parameters free, except for $N_H$. We see that the JetCAF model fits the observed data with much better statistics. In this case, we run the source code directly in XSPEC as a table model using the initpackage and Imod tools (Arnaud 1996). The model parameters range used in Imod to run JetCAF in XSPEC is shown in Table 1. The range of energy considered for the generation of the model spectrum to fit the data is between 10$^{17}$ and 10$^{20}$ Hz. For both of the models we assume an accretion efficiency of 0.1.

In Figure 8, we show the JetCAF model-fitted spectra. In the upper panel, the red curve shows the JetCAF model spectrum and the gray dots with error bars show the observed spectra. In the lower panel, we show the ratio of the data and model, which shows a good fit with a reduced $\chi^2 = 1.112$. For comparison with the TCAF model fit to the data, we overplotted the model
the observed data and the red line is the model spectrum. The data/model (D/M) ratio is shown in the lower panel. Data are rebinned for clarity.

Figure 7. NuSTAR FPMA data (X02) of GS 1354-64, fitted with the TCAF model as a local additive table model. Gray points with error bars show the observed data and the red line is the model spectrum. The data/model (D/M) ratio is shown in the lower panel. Data are rebinned for clarity.

The observed data and the red line is the model spectrum. The data/model (D/M) ratio is shown in the lower panel. Data are rebinned for clarity.

![Figure 7](image_url)

Table 2

| Parameters | TCAF | JeTCAF |
|------------|------|--------|
| \(E_\gamma\) [keV] | 6.40±0.06 | 6.45±0.06 |
| \(\sigma_{E_\gamma}\) [keV] | 0.06±0.06 | 0.04±0.04 |
| \(N_\gamma10^{-4}\) | 1.41±0.25 | 17.28±1.05 |
| \(M_{BH}[M_\odot]\) | 7.22±0.25 | 6.70±0.68 |
| \(m_0[M_\odot]\) | 0.038±0.003 | 0.084±0.003 |
| \(m_0[M_\odot]\) | 1.346±0.076 | 0.265±0.013 |
| \(X_\nu_1\) | 140.24±5.89 | 37.74±2.74 |
| \(R\) | 1.94±0.14 | 4.22±0.28 |
| \(f_{\text{osc}}\) | ... | 0.47±0.09 |

\(\chi^2 = 1.046\)

Note. The Gaussian model fitted line energy is \(E_\gamma\) and width is \(\sigma_{E_\gamma}\). Here, \(N_\gamma\) is the Gaussian model normalization in units of photons cm\(^{-2}\) s\(^{-1}\).

of the central black hole is \(\sim 7 M_\odot\). After reaching a good fit, we use the model-fitted parameters to recalculate the energy spectral index (\(\alpha\)) for X02 and X04. The calculated value of \(\alpha\) for X02 and X04 are 0.63 and 0.87, respectively. The values of \(\alpha\) and the accretion rates confirm that on the X02 day the source was in the “hard spectral state” and on the X04 day it was in the “intermediate spectral state” when the jet was observed. The ratio of outflowing and inflowing matter rates for this observation is 0.12±0.03, recalculated from the model-fitted parameters using Equation (1). The estimation of the error in the \(R_{\text{inh}}\) measurement is discussed in the Appendix. The above value of the mass-loss rate and the values of \(R\) during the outburst, which is common in centrifugally driven flows (Molteni et al. 1994, C99), show the strong signature of an outflowing jet. Our model-fitted mass is well within the range reported earlier for this source.

Earlier reports confirmed this outburst as a “failed outburst” due to the presence of only the hard state (El-Batal et al. 2016; Stiele & Kong 2016). From our model-fitted parameters, the \(\alpha\) value and high mass outflow rate, we identify the spectral state to be a hard (intermediate) state, like the earlier findings. It is to be noticed that the disk accretion rate increased by \(\sim 2.2\) times and entered into the region from which catastrophic cooling becomes significant according to the TCAF. As we discussed earlier, from the model-fitted parameters, the mass-loss rate, and energy spectral index, we confirm the presence of both hard and intermediate states.

This candidate showed a low-frequency QPO (\(< 0.2\) Hz) with increasing centroid frequency (Koljonen et al. 2016), which might be the indication of some instability occurring periodically. From the high flux behavior several authors argued that this source is similar to GRS 1915+105. Another possibility could be a periodic feedback from the jet (Vadawale et al. 2001; Chakrabarti et al. 2002). There has been no detailed dynamical light curve analysis on this object to date. If we consider the burst time (\(t_{b-b}\)) theory of C99 and estimate the periodicity of the burst from the model-fitted parameters, it gives \(\sim 20\) s (see Equation (24) of C99). The \(t_{b-b}\) value can also be estimated from the observed QPO frequency for this source (0.2 Hz), using (C99) \(t_{b-b} \propto \nu_{\text{QPO}}^{-\frac{1}{2}}\) \(\sim 25\) s. Both estimates are consistent with each other. This estimate also matches the 20 s periodicity observed in the light curve of this source during the RXTE era (see Figure 2 of Janiuk & Czerny 2011). There are several works in the literature (Belloni et al. 2000; Rao et al. 2000; Naik et al. 2002; Chakrabarti et al. 2004; Pal & Chakrabarti 2015) that discussed changes in different
classes of light curves in black hole candidates that occur in a matter of a few seconds. Such quick transitions are possible only if the changes in accretion/ejection processes are due to local effects at the base of the jet or due to the return flow onto the disk (e.g., see Chakrabarti et al. 2002), whereas burst-on and burst-off states of GRS 1915+105 were discussed as being due to the outflow interacting with the inner disk. Here, we suggest cycles inside a light curve due to the feedback effects from the outflows on a timescale of 20 s. It is possible and is seen in GRS 1915+105 and IGR 17091-3624 (Belloni et al. 2000; Rothstein et al. 2005; Pal & Chakrabarti 2015) very often. There has to be changes in the local disk rather than in the global disk.

5. Summary and Conclusions

In this paper, we study the spectral properties of the accretion flows around black holes when the jet is also included in the TCAP solution. We apply this JeTCAP solution to study the transient source GS 1354-64 during its 2015 outburst using the data from the NuSTAR satellite. We treat the base of the jet as an additional Compton cloud component that also scatters soft photons from the disk. We also include the effects of bulk motion of the diverging jet. Our jet configuration is self-consistent with the accretion dynamics in the sense that it estimates mass loss by solving flow equations, rather than considering it separately. In this model, the jet originates in the post-shock region (the CENBOL) of the flow, and the velocity of the outflowing matter is calculated from the average temperature of the CENBOL. We estimate the mass outflow rate from the inflow rate. We use a realistic outflow to obtain the optical depth and the temperature of the Compton cloud.

The mass outflow rate and the velocity are high in hard and intermediate states; thus the jet contribution to the spectrum is also modified significantly (due to bulk motion) during that time. In the soft state, the temperature is not high enough to accelerate the mass outflow. Thus, the spectrum remains nearly flat blackbody. We also see that the contribution of the jet to the overall spectrum varies with the size of the Compton cloud, the shock compression ratio, and the collimation factor. The overall fits using our simple consideration are acceptable, and we do not require the presence of a magnetic field or synchrotron emission to fit the data.

In this manuscript, we apply the model on the BHC GS 1354-64 and calculated the mass outflow rate during its 2015 outburst. In future, we aim to consider other jetted candidates using the same model. Our study shows that during the outburst, this candidate had a ratio of mass outflow to mass inflow rates of about 0.12^{+0.02}_{-0.03}. We suspect the reason behind the presence of the very low QPO frequency with varying centroid frequency is also an indication of micro-outbursts or feedback from the jet to the disk occurring on very small timescales (20 s). This is similar to what happened in GRS 1915+105 (also in IGR 17091-3624). It is true that the spin of the black hole is important for both studies of the disk and the jet; however, its effects cannot spread beyond a few gravitational radii, while the physics we discuss occurs in regions farther out. As we discussed earlier, the spin may or may not contribute to the powering of the jet. However, the present TCAP or JeTCAP model does not consider the spin effect. In future, we aim to implement that effect self-consistently in the model. A further study of this object is required to understand the jet feedback mechanism and the class transition in the light curve to understand the dynamics of the disk.

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Appendix

For the estimation of the error in $R_m$, we derived the relation:

$$
\sigma_{R_m} = \left( \frac{\partial R_m}{\partial R} \right)^2 \sigma_R + \left( \frac{\partial R_m}{\partial \text{col}} \right)^2 \sigma_{\text{col}},
$$

where $\sigma_R$ and $\sigma_{\text{col}}$ are the errors in the measurement of the shock compression ratio ($R$) and collimation factor ($\text{col}$), respectively. After doing a few steps of algebra, we get the values of $\frac{\partial R_m}{\partial R} = -0.05$ and $\frac{\partial R_m}{\partial \text{col}} = 0.24$, which give the value of $\sigma_{R_m} = \{+0.02, -0.03\}$.

References

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, XSPEC: The First Ten Years, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Belloni, T., Homan, J., Casella, P., et al. 2005, A&A, 440, 207
Belloni, T., Migliari, S., & Fender, R. P. 2000, A&A, 358, L29
Blandford, R., Meier, D., & Readhead, A. 2019, ARA&A, 57, 467
Blandford, R. D., & Payne, D. G. 1981, MNRAS, 194, 1033
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Brockopp, C., Jonker, P. G., Fender, R. P., et al. 2001, MNRAS, 323, 517
Bromberg, O., Nakar, E., Piran, T., & Sari, R. 2011, ApJ, 740, 100
Casares, J., Orosz, J. A., Zurita, C., et al. 2009, ApJS, 181, 238
Cassaes, J., Zurita, C., Shahzad, T., Charles, P. A., & Fender, R. P. 2004, ApJL, 613, L133
Chakrabarti, S., & Titarchuk, L. G. 1995, ApJ, 455, 623
Chakrabarti, S. K. 1998, ApJL, 464, L64
Chakrabarti, S. K. 1999, ApJL, 488, 313
Chakrabarti, S. K. 1999, A&A, 351, 185
Chakrabarti, S. K., Nandi, A., Choudhury, A., & Chatterjee, U. 2004, ApJL, 607, 406
Chakrabarti, S. K., Nandi, A., Manickam, S. G., Mandal, S., & Rao, A. R. 2002, ApJL, 579, L21
Chatterjee, D., Debnath, D., Chakrabarti, S. K., Mondal, S., & Jana, A. 2016, ApJL, 827, 88
Chattopadhyay, I., Das, S., & Chakrabarti, S. K. 2004, MNRAS, 348, 846
D’Silva, S., & Chakrabarti, S. K. 1994, ApJ, 424, 149
Debnath, D., Chakrabarti, S. K., & Mondal, S. 2014, MNRAS, 440, L121
Debnath, D., Mondal, S., & Chakrabarti, S. K. 2015, MNRAS, 447, 1894
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Done, C., Davis, S. W., Jin, C., Blaes, O., & Ward, M. 2012, MNRAS, 420, 1848
Done, C., Gierliński, M., & Kubota, A. 2007, A&ARv, 15, 1
Ebisawa, K., Zycki, P., Kubota, A., Mizuno, T., & Watarai, K.-y. 2003, ApJ, 597, 780
Eggum, G. E., Coroniti, F. V., & Katz, J. I. 1988, ApJ, 330, 142
El-Batal, A. M., Miller, J. M., Reynolds, M. T., et al. 2016, ApJL, 826, L12
Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105
El-Batal, A. M., Miller, J. M., Reynolds, M. T., et al. 2016, ApJL, 826, L12
Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105

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Fender, R. P., Gallo, E., & Russell, D. 2010, MNRAS, 406, 1425
Fender, R. P., Homan, J., & Belloni, T. M. 2009, MNRAS, 396, 1370
Fender, R. P., Tingay, S. J., Higdon, J., Wark, R., & Wieringa, M. 1997, IAUC, 6779, 2
Gandhi, P., Rao, A., Johnson, M. A. C., Paice, J. A., & Maccarone, T. J. 2019, MNRAS, 485, 2642
Garain, S. K., Balsara, D. S., Chakrabarti, S. K., & Kim, J. 2020, ApJ, 888, 59
Garain, S. K., Ghosh, H., & Chakrabarti, S. K. 2012, ApJ, 758, 114
Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103
Hjellming, R. M., & Rupen, M. P. 1995, Natur, 375, 464
Jana, A., Chakrabarti, S. K., & Debnath, D. 2017, ApJ, 850, 91
Janiuk, A., & Czerny, B. 2011, MNRAS, 414, 2186
Kawahashi, T., Ohsuga, K., Mineshige, S., et al. 2012, ApJ, 752, 18
King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJL, 552, L109
Kitamoto, S., Tsunemi, H., Pedersen, H., Ilovaisky, S. A., & van der Klis, M. 1990, ApJ, 361, 590
Koljonen, K. I. I., Russell, D. M., Corral-Santana, J. M., et al. 2016, MNRAS, 460, 942
Makino, F. 1987, IAUC, 4342, 1
Miller-Jones, J. C. A., Sivakoff, G. R., Altamirano, D., et al. 2012, MNRAS, 421, 468
Mirabel, I. F., & Rodríguez, L. F. 1998, Natur, 392, 673
Molteni, D., Lanzafame, G., & Chakrabarti, S. K. 1994, ApJ, 425, 161
Mondal, S., & Chakrabarti, S. K. 2013, MNRAS, 431, 2716
Mondal, S., & Chakrabarti, S. K. 2019, MNRAS, 483, 1178
Mondal, S., Chakrabarti, S. K., & Debnath, D. 2014a, Ap&SS, 353, 223
Mondal, S., Chakrabarti, S. K., Nagarkoti, S., & Arévalo, P. 2017, ApJ, 850, 47
Mondal, S., Debnath, D., & Chakrabarti, S. K. 2014b, ApJ, 786, 4
Nagarkoti, S., & Chakrabarti, S. K. 2016, MNRAS, 462, 850
Naik, S., Rao, A. R., & Chakrabarti, S. K. 2002, JApA, 23, 213
Nandi, A., Chakrabarti, S. K., Vadawale, S. V., & Rao, A. R. 2001, A&A, 380, 245
Narayan, R., & McClintock, J. E. 2012, MNRAS, 419, L69
Nobili, L., Turolla, R., & Zampieri, L. 1993, ApJ, 404, 686
Ohsuga, K., Morl, M., Nakamoto, T., & Mineshige, S. 2005, ApJ, 628, 368
Okuda, T. 2002, PASJ, 54, 253
Pahari, M., Gandhi, P., Charles, P. A., et al. 2017, MNRAS, 469, 193
Pal, P. S., & Chakrabarti, S. K. 2015, AdSpR, 56, 1784
Radhika, D., & Nandi, A. 2014, AdSpR, 54, 1678
Rao, A. R., Yadav, J. S., & Paul, B. 2000, ApJ, 544, 443
Revnivtsev, M. G., Borozdin, K. N., Friedhorsky, W. C., & Vikhlinin, A. 2000, ApJ, 530, 955
Reynolds, M. T., & Miller, J. M. 2011, ApJL, 734, L17
Rothstein, D. M., Eikenberry, S. S., & Matthews, K. 2005, ApJ, 626, 991
Russell, D. M., & Lewis, F. 2015, ATEL, 7637, 1
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 500, 33
Singh, C. B., & Chakrabarti, S. K. 2011, MNRAS, 410, 2414
Sriram, K., Rao, A. R., & Choi, C. S. 2012, A&A, 541, A6
Stiele, H., & Kong, A. K. H. 2016, MNRAS, 459, 4038
Sunyaev, R. A., & Titarchuk, L. G. 1980, A&A, 500, 167
Titarchuk, L., Kazanas, D., & Becker, P. A. 2003, ApJ, 598, 411
Titarchuk, L., & Shrader, C. 2005, ApJ, 623, 362
Titarchuk, L., & Zannias, T. 1998, ApJ, 493, 863
Vadawale, S. V., Rao, A. R., Nandi, A., & Chakrabarti, S. K. 2001, A&A, 370, L17