Implementation of Two Component Advection Flow Solution in XSPEC

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ABSTRACT
Spectral and Temporal properties of black hole candidates can be explained reasonably well using Chakrabarti-Titarchuk solution of two component advective flow (TCAF). This model requires two accretion rates, namely, the Keplerian disk accretion rate and the halo accretion rate, the latter being composed of a sub-Keplerian, low angular momentum flow which may or may not develop a shock. In this solution, the relevant parameter is the relative importance of the halo (which creates the Compton cloud region) rate with respect to the Keplerian disk rate (soft photon source). Though this model has been used earlier to manually fit data of several black hole candidates quite satisfactorily, for the first time, we made it user friendly by implementing it into XSPEC software of GSFC/NASA. This enables any user to extract physical parameters of the accretion flows, such as two accretion rates, the shock location, the shock strength etc. for any black hole candidate. We provide some examples of fitting a few cases using this model. Most importantly, unlike any other model, we show that TCAF is capable of predicting timing properties from the spectral fits, since in TCAF, a shock is responsible for deciding spectral slopes as well as QPO frequencies.

Key words: X-Rays: binaries, Stars:individual (H 7143-322, GX 339-4, GRO J165540), Black Holes, Spectrum, Accretion disks, Shock waves, Radiation hydrodynamics

1 INTRODUCTION

Compact objects, such as black holes, neutron stars, etc. are identified by electromagnetic radiations emitted from the accreting matter. Understanding the spectral and timing properties of this radiation is essential for model builders and theorists alike. In a binary system, matter from the companion star accrets into the black hole through the Roche lobe, and/or through capturing its motion dominated advective flow or BDAF) the matter is advected by the hot electrons of the ‘Compton’ cloud (Sunyaev & Titarchuk 1980, 1985). There are many speculations regarding the nature of this Compton cloud ranging from a magnetic corona (Galeev, Rosner & Vaiana 1979), to hot gas corona over the disk (Haardt & Maraschi 1993; Zdziarski et al. 2003). Since the formation process of a static corona around an accretion disk is totally unknown, and since a low angular dynamic flow may naturally act as a corona, Chakrabarti & Titarchuk (1995, hereafter CT95) proposed that a disk having two distinct components, a Keplerian disk submerged inside a sub-Keplerian halo is enough to explain all the spectral properties very satisfactorily. Observational evidences also started to support this so-called two-component advective flow (TCAF) (e.g., Soria et al. 2001; Smith, Heindl & Swank 2002; Wu et al. 2002; Cambier & Smits 2013). While creating a self-consistent TCAF solution, the properties of a viscous transonic flow was made use of, in which a flow having viscosity above a critical value naturally forms a Keplerian disk and the region with a lower viscosity, due to centrifugal barrier, forms a shock wave, typically, at a few tens of Schwarzschild radii. The post-shock region (from the shock and the inner sonic point) basically evaporates the Keplerian component and together acts as a Compton cloud which produces a power-law component (hard photons) with exponential cut-off in the spectrum through thermal Comptonization. From the inner sonic point to the horizon of the black hole (bulk motion dominated advective flow or BDAF) the matter is advected

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rapidly to the black hole. The bulk motion in this region also up-scatters the soft photons and produces a second power-law component even when the temperature of the region is zero. If the centrifugal barrier is not strong enough, the shock may not form, but the flow still slows down. The spectral properties in this case are discussed in Chakrabarti [1997, hereafter C97]. The CENtrifugal pressure supported BOundary Layer or CENBOL, referred to the post-shock region or centrifugal force dominated region, which is also the base of the outflows where the pre-jet is launched, plays the most important role in the black hole physics. As usual, this CENBOL, pre-jet and BDAF intercept soft photons from the Keplerian disk and reprocess them to high energies via inverse Compton scattering. In this letter, we will implement the TCAF solution to study spectral properties of black hole candidates (BHCs) using widely used user-friendly spectral analysis software package, developed by GSFC/NASA, called XSPEC. For the sake of concreteness, we focus only the cases where only the CENBOL is present. We ignore the effects of BDAF and pre-jet. In our next version of analysis, these components and spin of the black hole would be included.

The Galactic transient black hole candidates are very interesting objects to study in X-rays because these sources generally show rapid evolutions in their temporal and spectral properties during their outburst phases, which are strongly correlated to each other (see for a review, Remillard & McClintock 2006). In general, four basic states - hard, hard-intermediate, soft-intermediate, and soft states are observed during an outburst of the BHCs (see, Nandi et al. 2012, and references therein). The evolutions of these spectral states are observed, which indeed form a hysteresis loop during the outburst with hard states are found to be at the beginning and end time of the outbursts, whereas soft and intermediate spectral states are observed in between. The evolution of spectral states are strongly dependent on the variation of the accretion rates. According to the TCAF solution, accretion flow rates may be controlled by a physical parameter, such as the magnetic viscosity, perhaps owing to the enhanced magnetic activity of the companion (Wu et al. 2002, Nandi et al. 2012, Debnath et al. 2013). During the rising phase of the outburst, viscosity may cause an increase in the accretion rate of the Keplerian matter. As the viscosity is reduced, the Keplerian rate is reduced and declining phase starts. The Keplerian disk itself recedes away leaving behind only the low-angular sub-Keplerian flow causing a hard state. Thus, a rigorous fit with TCAF model is expected to throw light on how the accretion rates and the flow geometry evolve with time.

In general, low and intermediate frequency quasi-periodic oscillations (LFQPOs) are observed in hard and intermediate (hard-intermediate and soft-intermediate) spectral states of transient black hole candidates. These QPOs are reported extensively in literature, although still there are debates on the origin of these QPOs. However, according to the shock oscillation model (SOM) by Chakrabarti and his collaborators, LFQPOs are originated due to the oscillation of the post-shock region (Molteni, Sponholz & Chakrabarti 1996, hereafter MSC96; Chakrabarti, Acharya, & Molteni 2004, hereafter CAM04; Garain, Ghosh & Chakrabarti 2014, hereafter GGC14) when the resonance occurs between the infall time scale and the cooling time scale in CENBOL. During oscillation, the shape of the Compton cloud and the degree of interception change periodically. Since from our spectral fit, we can directly extract values of physical parameters related to this shock wave, we can also predict what should be the frequency of the observed low frequency QPO (if present; see §4.1 for details).

The paper is organized in the following way: in the next section, we briefly describe properties of the TCAF model. In §3, we discuss the method of the implementation of the TCAF model in XSPEC for spectral fittings. In §4, TCAF model fitted results obtained from the spectral fit of three different BHCs. Finally, in §5, we make concluding remarks and our future work plans.

2 A BRIEF DESCRIPTION OF TCAF MODEL

The TCAF model (CT95, C97) has been described in detail in the literature and has been proven to be a stable configuration by extensive numerical simulations (Giri & Chakrabarti 2013). The model requires two accretion rates: one is the rate of the Keplerian component and the other is the rate of the low-angular momentum, sub-Keplerian halo, in which Keplerian disk is immersed. Two other essential parameters are the shock location and the compression ratio of the flow at the shock respectively. These two parameters provide the height of the shock, calculated using the pressure balance condition (Chakrabarti 1989). The density and temperature distribution of the flow and especially in the post-shock region are calculated using two temperature equations and continuity equations as discussed in CT95. The CT95 code also computes the optical depth, average electron temperature of the CENBOL, the spectral index etc. self-consistently by adding the relevant cooling and heating processes such as arising due to bremsstrahlung, Comptonization, inverse bremsstrahlung and inverse Comptonization. Synchrotron cooling process was not included in this version. CT95 considered only strong shock case. In order to take care of the weaker shocks also, we generalized the expression for the shock height ($H_{\text{shk}}$) and shock temperature ($T_{\text{shk}}$) in the following way:

$$H_{\text{shk}} = \left( \frac{X(R - X)^2}{R^2} \right)^\frac{1}{2}$$

and the shock temperature is given by,

$$T_{\text{shk}} = \frac{m_p(R - 1)c^2}{2\pi^2k_b(X - 1)}$$

where, $m_p$, $R$, $k_b$ $X$, and $\gamma$ are the mass of the proton, compression ratio, Boltzmann constant, shock location and adiabatic constant of the flow respectively. We also incorporate the spectral hardening correction (see, Debnath, Mondal & Chakrabarti 2014a, hereafter DMC14) depending on the accretion flow rate as in Shimura & Takahara (1995), Paczyński & Witt (1980) pseudo-Newtonian potential $\Phi_{\text{PN}} = -\frac{\mu M_{\text{BH}}}{2\pi G}$ has been used to describe the geometry around the black hole.

3 PROCEDURE OF IMPLEMENTATION OF TCAF INTO XSPEC

To fit a spectrum with the TCAF model using HEASARC’s spectral analysis software package XSPEC, which already has a number of inbuilt theoretical models, we need to first generate a model fits file by varying five different input parameters: Keplerian rate (disk rate $m_{\text{t}}$), sub-Keplerian rate (halo rate $m_{\text{s}}$), mass of the black hole $M_{\text{BH}}$, location of the shock $X$, and the compression ratio $R$ and use it as a system model. In order to fit the spectra in XSPEC, we generated an additive table model fits file named (TCAF.fits). We first incorporated changes as regards to shock strength as described above in the CT95 model code (for details see, DMC14) and generated ~ 4 × 10^3 model spectra by solving the theoretical radiative-hydro code of CT95. For each spectrum, we provide five input parameters
by varying five input parameters ($\dot{m}_d$, $\dot{m}_b$, $M_{BH}$, $X_s$, and $R$) in the following ranges: (i) $0.1 - 12.1 M_{Edd}$, (ii) $0.01 - 12.01 M_{Edd}$, (iii) $5 - 15$ Solar mass ($M_\odot$), iv) $6 - 456 r_g$, and v) $1 - 4$, respectively. Here, $M_{Edd}$ is the Eddington rate. These model spectra are used as input files to a program written in FORTRAN, to generate the model fits file.

At present, we have fitted the spectra after keeping model fits file as a local additive table model. At the time of spectral fitting using the TCAF, one needs to supply six model initial guess parameters: i) Keplerian rate ($\dot{m}_d$ in units of $M_{Edd}$), ii) sub-Keplerian rate ($\dot{m}_b$ in units of $M_{Edd}$), iii) black hole mass ($M_{BH}$) in units of $M_\odot$, iv) location of the shock ($X_s$ in units of Schwarzschild radius $r_g = 2GM_{BH}/c^2$), v) compression ratio ($R = \rho_s/\rho_s$, where $\rho_s$ and $\rho_b$ are densities of the post- and pre-shock matters) of the shock, and vi) the model normalization value ($\text{norm}$), which is equivalent to $\chi^{2}/\text{DOF}$, where $D$ is the source distance in 10 kpc unit and $i$ is the disk inclination angle. In the near future, the fits file will be made public, for the use of the scientific community. It would be available now upon request.

4 RESULTS: SAMPLE SPECTRA FITTED WITH TCAF MODEL

We now show the results of fitting of three $2.5 - 25$ keV back- ground subtracted RXTE/PCA spectra of three different black hole candidates, namely, H 1743-322, GX 339-4, GRO J1655-40. These observations are taken from the initial phase of the outbursts, where QPOs are observed. We carry out data analysis using the FTOOLS software package HeaSoft version 6.12 and XSPEC version 12.7. For the generation of source and background `.pha` files and spectral fittings using TCAF model we use the same method as mentioned in DMC14.

It is to be noted that the TCAF model in its present form (i.e., without incorporating pre-Jet and BDAF) is able to fit hard and intermediate state spectra with acceptable values of reduced $\chi^2$ ($\lesssim 2$). In the soft states, the shock does not form, and the inclusion of BDAF is required (see, DMC14) for an acceptable fit. As a result, the number of parameters is required, will be reduced to three. This will be carried out in the near future.

In Fig. 1, $2.5 - 25$ keV background subtracted PCA spectrum from Galactic transient black hole H 1743-322 of observation ID = 95360-14-02-01 (MJD = 55419.1070) from its 2010 outburst is shown. Fixed values of 1% systematic error, the hydrogen column density ($N_H$) of $1.6 \times 10^{22}$ cm$^{-2}$ (Debnath et al. 2013) for absorption model wabs, and $M_{BH}$ of $11.4 \pm 1.9$ (Debnath et al. 2014) are used to fit the spectrum. To achieve the best fit, a single Gaussian Iron line $6.39 \pm 0.19$ keV is also used. With these, the value of the reduced $\chi^2 = 1.430$ is achieved. For details about the model fitted parameters, see Table 1.

In Fig. 2, RXTE/PCA spectrum of Galactic outbursting BHC GX 339-4 fitted with combination of TCAF and single Gaussian line ($6.31 \pm 0.17$ keV) is shown. This observation (ID = 95409-01-14-04; MJD = 55300.3421) is selected from the rising phase of 2010-11 outburst of GX 339-4. For the spectral fitting, fixed values of $M_{BH} = 5.8 \pm 0.5$ (Hynes et al. 2003), $N_H = 5 \times 10^{21}$ (Debnath et al. 2010) for absorption model wabs and 1% systematic error are used. In this case, a value of the reduced $\chi^2 = 1.029$ is achieved.

In Fig. 3, TCAF model fitted RXTE/PCA spectrum from the 2005 outburst of the Galactic outbursting BHC GRO J1655-40 is shown. The spectrum is fitted with combination of two additive model components, namely, TCAF and a Gaussian line ($6.62 \pm 0.15$ keV). This observation of ID = 90704-04-01-00 (MJD = 53439.7603) is selected from the rising phase of 2005 outburst of the source. For the spectral fitting, fixed values of $M_{BH}$ equals to $7.02 \pm 0.22$ (Orosz & Balick 1997), $N_H$ equals to $7.5 \times 10^{21}$ (Debnath et al. 2008) for absorption model wabs and 1% systematic error are used. In this case, a value of the reduced $\chi^2 = 1.580$ is achieved.

4.1 Prediction of QPO frequencies from the spectral fits using TCAF model

Unlike any other model fits, TCAF model predicts timing properties from spectral fits. This is because the same shock which
defines the CENBOL boundary, i.e., the size of the Compton cloud, also causes low frequency QPOs as it oscillates. The presence of a shock wave does not always mean for the existence of QPOs. The shock oscillation takes place provided the cooling and the infall times scales are of same order (MSC96, CAM04, GGC14) or when the Rankine-Hugoniot relation is not satisfied even with two sonic points in the transonic sub-Keplerian flow (Ryu, Chakrabarti & Molteni 1997). The frequency of oscillation is inversely proportional to the infall time \( (\text{infall}) \) in post-shock region (see, Eqn. 3 below) when the cooling time scale is also similar. One can determine the QPO frequency \( v_{\text{QPO}} \) if the location of shock \( (X_s, r_g) \) and the compression ratio \( (R) \) are known (see, Eqn. 4 below). In the presence of a shock, the infall time in the post-shock region can be expressed as,

\[
\text{infall} \sim R X_s (X_s - 1)^{1/2}.
\]

The frequency of the observed QPOs becomes,

\[
v_{\text{QPO}} \sim \frac{R X_s^{1/2}}{C},
\]

where, \( C \) is a constant \( = \frac{M_{BH}}{10^{-5}} \). This shows that the derived \( R \) and \( X_s \) from the spectral fit leads to an estimate of the QPO frequency.

In all of the three spectra fitted in this paper, QPOs are observed. From the spectral fit, we have therefore estimated the frequency of the QPOs, which roughly match with the observed values (see, Table 1). This is unique in the context of model fits.

5 CONCLUDING REMARKS AND FUTURE PLAN

In this letter, we show how to implement the TCAF model in XSPEC as a local additive table model. In Figs. 1-3, we show the model fitted spectra, one each for the black hole candidates H 1743-322, GX 339-4, GRO J1655-40 respectively. We show that the TCAF model is quite capable to fit the black hole spectra. Moreover, fitting with TCAF model appears to be better than other conventional black body and power-law models because it can directly provide accretion rates from the spectral fit. The iterative procedure of CT95 also ensures that a no X-ray component reflected from the disk is required to be added. Not only that, unlike other models, TCAF has a predictive capability of the timing properties from the spectral fitted parameters. This is possible, because the same shock which decides the size of the Compton cloud parameters such as the optical depth and its average electron temperature (and thus the spectral index), also decides the QPO frequency. Detailed spectral study using TCAF model for the 2010-11 outburst of GX 339-4 (DMC14), and 2010 outburst of H 1743-322 will be published elsewhere. Detailed study on the evolution of QPO frequencies during the rising and the declining phases of the outburst will also be published elsewhere (Debnath et al. 2014).

The present version of TCAF which is implemented here does not include the subsonic pre-Jet which is originated from the CENBOL. Similarly, it does not include the innermost bulk motion dominated region of the advective flow (BDAF) whose effect would be to produce a power-law component even if the Compton cloud is cooled down. This will enable us to fit not only the very soft states, but also those states with broken power-law as well as the jet dominated flows. We have verified that our present model fits hard and intermediate states very satisfactorily. The work to extend the validity of TCAF is in progress and would be reported elsewhere.

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