Inclusion of TCAF model in XSPEC and study accretion flow dynamics around black hole

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Introduction:

- Galactic transient black holes undergo peculiar temporal and spectral changes during their outburst phases.

- Several spectral states are identified in their outbursts based on the evolution of their spectral and timing properties (McClintock & Remillard, 2006; Debnath et al. 2008, 2013; Nandi et al. 2012; Mondal et al. 2014).

- These objects also show low and intermediate frequency QPOs during hard, and intermediate spectral states. Sometime these objects also show high frequency QPOs.
Inbuild models available in XSPEC:

- Many theoretical and phenomenological models (such as, disk black body, power-law, CompST, etc.) are already in XSPEC.

Spectral fitting with **diskbb + power-law:**

Contribution from thermal (multi-color disk black body) and non-thermal component of accretion disk.

One can get temperature of multicolor soft photon source such as a Shakura-Sunyaev standard disk (Shakura & Sunyaev, 1973)

One can also extract spectral slope from the power-law component of the fit.

But physical information responsible for generating such spectra is missing.
Spectral fitting with models (CompST, etc):

Tells us that there is a multicolor soft photon source such as a Shakura-Sunyaev standard disk (Shakura & Sunyaev, 1973) and a so-called Compton cloud (Sunyaev & Titarchuk, 1980) which is a hot region of free electrons with certain optical depth and temperature.

However, cause of formation of standard disk, nature and origin of Compton cloud or cause of a specific spectral state remained missing.
A Schematic diagram of the accretion flow around the black hole.

Chakrabarti & Titarchuk 1995
Generating TCAF model fits file:

- Took Chakrabarti & Titarchuk 1995 (CT95) original code as a basic program to generate TCAF model fits file to include as a local additive table model for fitting black hole spectra.

- To fit spectra from all possible spectral states, several modifications are made in original CT95 code:
  
i) Variation of compression ratio \( R \) is allowed from 4 (strong) to 1 (weak). CT95 assumed only strong shocks for illustration purpose.

ii) Computation of temperature of post-shock region using this \( R \).

iii) Radial velocity of a rotating flow as in Chakrabarti (1997).

iv) Spectral hardening correction of Shimura & Takahara (1995), which depends on the accretion flow rate. We uniformly consider the correction factor \( f \) to be 1.8 to calculate effective temperature in emitted spectrum.
“TCAF_V0.1fits” file was created by using around 0.4 million (~4x10⁵) model spectra. The spectra were generated by varying five model input parameters.

For spectral with current TCAF model fits file, one needs to supply 6 initial input parameters:

i) \( \dot{m}_d \) (Keplerian or disk rate),

ii) \( \dot{m}_h \) (sub-Keplerain or halo rate),

iii) \( M_{bh} \) (black hole mass in solar mass unit),

iv) \( X_s \) (shock location in Schwarzschild radii \( r_g \)),

v) \( R \) (shock compression ratio),

vi) Normalization (which is equivalent to \( [(R_z^2/4\pi D^2) \times \sin(i)] \)), where \( R_z \) is effective height of Keplerian disk in Km at pre-shock region, \( D \) is source distance in 10 kpc unit and \( i \) is disk inclination angle with line of sight.
(a) TCAF model fitted 2.5–25 keV PCA spectrum of GX 339-4 (observation ID = 95409-01-14-04; MJD = 553 00, UT Date = 14/04/2010) with variation of $\chi$ is shown. (b) The unfolded model components of the spectral fit are show.

Six different spectra selected from 2010 outburst of GX 339-4, fitted with TCAF Model:

Broadening of ~ 6.5 keV Fe line was observed as we move from hard to softer states.
Characterization of GX 339-4 with TCAF Model:

Characterization of GX 339-4 with TCAF Model:

7 days delay

Characterization of GX 339-4 with TCAF Model:

H 1743-322 spectra fitted with TCAF Model:

(a) TCAF model fitted 2.5–25 keV PCA spectrum of H 1743–322 (observation ID = 95360-14-02-01; MJD = 55419, UT Date = 11/08/2010) with variation of $\chi^2$ is shown. (b) The unfolded model components of the spectral fit are show.

Characterization of H 1743-322 with TCAF Model:

Characterization of H 1743-322 with TCAF Model:

(a) Variation of PCA count rate as a function of 1/ARR and (b) disk rate as a function of halo rate for the entire outburst. Transitions from hard to hard-intermediate (rising) and vice versa (declining) take place when the ARR is at maximum. The soft state begins with the highest value of the individual rates. Duration of the hard-intermediate states in both phases occurs at a similar value of the ARR. For the ARR, 0.5, QPOs are sporadic or absent.

Characterization of MAXI J1659-152 with TCAF Model:

Origin of QPOs in black hole X-ray binaries:

- Low and Intermediate frequency (0.01 – 30 Hz) QPOs are generally observed in hard, intermediate spectral states of BHCs.

- For few BHCs, QPOs are also observed to increase monotonically in rising phase (hard and hard-intermediate spectral states) of the outburst and opposite scenario is observed in declining phase of the outburst (Nandi et al. 2012; Debnath et al. 2013).

- Sporadic QPOs are observed during soft-intermediate spectral states of the outburst (Debnath et al. 2010, 2013; Nandi et al. 2012).

- Many models (such as: perturbation inside a Keplerian disk (Trudolyubov et al. 1999), global disk oscillation (Titarchuk & Osherovich 2000), oscillation of warped disk (Shirakawa & Lai 2002), accretion ejection instability at the inner radius of a Keplerian disk (Rodriguez et al. 2000), etc.
Shock Oscillation Model (SOM) to find origin BHCs:

According to Shock Oscillation Model (SOM) by Chakrabarti and his collaborators (Molteni et al. 1996; Chakrabarti et al. 2004) QPOs are caused due to shock oscillation.

There are mainly two reasons behind oscillation of shock wave in an accretion flow:

i) **Resonance Oscillation**: when cooling time scale of the flow is comparable to the infall time scale (Molteni, Sponholtz & Chakrabarti 1996), this type of oscillation occurs. Such cases can be identified by the fact that when accretion of the Keplerian disk is steadily increased, QPOs may occur in a range of the accretion rates, and the frequency should go up with accretion rate.

ii) **Non-Steady Solution**: in this case, flow has two saddle type sonic points, but Rankine-Hugoniot conditions which were used to study standing shocks in Chakrabarti (1989) are not satisfied to form a steady shock (Ryu, Chakrabarti & Molteni 1997).
GRO J1655-40 during its 2005 outburst: Energy Dependent QPOs

Debnath, Chakrabarti, Nandi & Mandal, 2008, BASI, 36, 151
GRO J1655-40 during its 2005 outburst: QPO frequency Evolution (Rising Phase)

Debnath, Chakrabarti, Nandi & Mandal, 2008, BASI, 36, 151
GX 339-4 during its 2010-11 outburst: QPO frequency Evolution (Soft-Intermediate Phase)
GRO J1655-40 during its 2005 outburst: QPO frequency Evolution (Declining Phase)
**Propagating Oscillatory Shock (POS) Model: Governing Equations**

Infall time is denoted by,

$$t_{infall} \sim \frac{r_s}{v} \sim R r_s (r_s - 1)^{1/2}, \quad (1)$$

Where $r_g = \frac{2GM}{c^2}$ is the Schwarzschild Radius, and compression ratio $R = \rho_+/\rho_-$, where $\rho_+$ and $\rho_-$ are the densities of the post and pre-shock flows.

In the rising phase $R$ may vary as

$$1/R \rightarrow 1/R_0 + \alpha (t_d)^2,$$

where $\alpha$ is a constant which determines how the shock (strength) becomes weaker with time and reaches its lowest possible value when $R = R_0$.

QPO frequency which is inversely proportional to infall time is given by,

$$v_{QPO} = v_{s0}/t_{infall} = v_{s0}/\left[ R r_s (r_s - 1)^{1/2} \right]. \quad (2)$$

Shock may move towards (‘−’ ve sign) or away (‘+’ve sign) from the black hole, expressed as

$$r_s(t) = r_{s0} \pm v_0 t/r_g, \quad (3)$$
POS model to explain evolution of QPOs:

According to POS model (Chakrabarti et al. 2005, 2008; Debanth et al. 2013), the QPO frequency happens to be inversely proportional to the infall time scale from the post-shock region.

Rising phase of 2010 H 1743-322 outburst

Declining phase of 2010 H 1743-322 outburst

Debnath, Chakrabarti & Nandi, AdSpR, 52, 2143
Prediction of dominating QPO frequency from TCAF model fitted shock parameters:

From TCAF model fit, location \((r_s)\) and compression ratio \((R)\) of the shock wave can be extracted.

\[
v_{\text{QPO}} = \frac{C}{\sqrt{R \cdot r_s(r_s-1)}} , \quad \text{where} \quad C = M_{\text{BH}} \times 10^{-5}.
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>Obs. Id</th>
<th>(m_{i_d}) ((\dot{M}_{\text{Edd}}))</th>
<th>(m_{i_h}) ((\dot{M}_{\text{Edd}}))</th>
<th>(X_s) ((r_g))</th>
<th>(R)</th>
<th>(\chi^2/\text{DOF})</th>
<th>(v_{\text{QPO}}^*) (Obs.)</th>
<th>(v_{\text{QPO}}^*) (Predic.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H 1743–322</td>
<td>X-02-01</td>
<td>0.516 ((\pm 0.013))</td>
<td>0.189 ((\pm 0.081))</td>
<td>320.0</td>
<td>1.250</td>
<td>60.1/42</td>
<td>1.045 ((\pm 0.007))</td>
<td>1.228 ((\pm 0.293))</td>
</tr>
<tr>
<td>GX 339–4</td>
<td>Y-14-04</td>
<td>6.883 ((\pm 0.003))</td>
<td>6.087 ((\pm 0.349))</td>
<td>147.9</td>
<td>4.000</td>
<td>43.2/42</td>
<td>2.374 ((\pm 0.006))</td>
<td>2.356 ((\pm 0.265))</td>
</tr>
<tr>
<td>GRO J1655–40</td>
<td>Z-01-00</td>
<td>6.987 ((\pm 0.273))</td>
<td>1.733 ((\pm 0.232))</td>
<td>153.8</td>
<td>3.449</td>
<td>64.78/41</td>
<td>2.313 ((\pm 0.010))</td>
<td>2.172 ((\pm 0.529))</td>
</tr>
</tbody>
</table>

Notes. Here, \(X = 95360-14\), \(Y = 95409-01\) and \(Z = 90704-04\). DOF means degrees of freedom. * Only frequency of the primary dominating QPOs (in Hz) in mentioned.

Conclusions:

1) A systematic continuous study of spectral and timing properties of transient as well as persistent black hole objects is required.

2) LAXPC is more suitable to study faint objects than what RXTE PCA has done.

3) High Frequency was well as mHz QPOs in different phases of the outbursts of black hole candidates could be observed with LAXPC as because of large effective area.

4) From the spectral fit using current & future (modified with new physical processes) of the TCAF model fits file, we will be able to extract accretion flow parameters, such as disk & halo rates, shock location, shock strength etc. and understand accretion flow dynamics around the black hole in a better sense.

5) Classification of spectral states during outbursts can be well understood based on TCAF model fitted physical parameters (variation of accretion rate ratios, ARRs) and nature of QPOs (if present).

6) From TCAF model fitted shock parameters one can predict dominating QPO frequency.

8) In future, we will extend our work to other transient as well as persistent black hole candidates (for e.g., GRO J1655-40, 4U 1630-272, XTE J1550-564, GRS 1915+105, IGR J17091-3654, Cyg X-1, etc.) and will also try predict mass of some unknown objects.

9) To improve model fits file, we need to include bulk motion Componization, spin etc. into modified TCAF version.
Thank you