Properties of the propagating oscillatory shock wave in the accretion flows around few transient black hole candidates during their outbursts

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In our study of the timing properties of few Galactic black hole candidates evolutions of the low and intermediate frequency quasi-periodic oscillations (LIFQPOs) are observed. In 2005, for explaining evolution of QPO frequency during rising phase of 2005 GRO J1655-40 outburst, Chakrabarti and his students introduced a new model, namely propagating oscillatory shock (POS) model. Here we present the results obtained from the same POS model fitted QPO evolutions during both the rising and declining phases of the outbursts of 2005 GRO J165540, 2010-11 GX 339-4, and 2010 & 2011 H 1743-322.

Keywords: Black Holes, shock waves, accretion disks, Stars:individual (GRO J1655-40, GX 339-4, H 1743-322)

1. Introduction

Generally, most of the transient black hole candidates (BHCs) show LIFQPOs ranging between 0.01 to 30 Hz in their power density spectra. More precisely these QPOs are observed during hard and intermediate (hard-intermediate or soft-intermediate) spectral states. Our study during the outburst phases of few Galactic transient black hole candidates (for e.g., GX 339-4, H 1743-322, GRO J1655-40, XTE J1550-564 etc.) show that during the rising phases QPO frequencies are observed to be increasing monotonically and during declining phases the sources show a monotonically decreasing nature of QPO frequencies. More precisely from the spectral study, it was noticed that these evolutions of QPO frequency are observed during hard and hard-intermediate spectral states.

2. Observation and Data Analysis

We used RXTE/PCA data of GRO J1655-40, GX 339-4 & H 1743-322 outbursts with a maximum timing resolution of 8 ms − 125 µs to generate power-density spectra (PDS), using “powspec” task of XRONOS package of HeaSOFT 6.11 with a normalization factor of ‘-2’ to have the ‘white’ noise subtracted rms fractional variability in 2 – 15 keV (0-35 channels of PCU2) light curves of 0.01 sec time bins. To find centroid frequency of QPOs, PDS are fitted with Lorentzian profiles.

3. Results

3.1. Origin of QPO and SOM model

Observations of LIFQPOs in black hole candidates are reported quite extensively in the literature and at the same time many theoretical or empirical models are introduced to explain this important temporal feature of BHCs. But one satisfactory
model namely shock oscillation model (SOM) by Chakrabarti and his collaborators in mid 90s, shows that the oscillation of X-ray intensity is actually due to the oscillation of the post-shock (Comptonizing) region. In this SOM solution, at the rising phase of the outburst, a shock wave moves toward the black hole, and at the declining phase of the outburst, a shock moves away from the black hole, which oscillates either because of a resonance (where the cooling time of the flow is approximately the infall time) or because the Rankine-Hugoniot condition is not satisfied to form a steady shock.

3.2. Evolution of QPO frequency and POS model

For explaining evolution of the QPO frequency during the rising phase of 2005 GRO J1655-40 outburst, Chakrabarti and his students introduced a new model, namely propagating oscillatory shock (POS) model. According to POS, the QPO frequency is inversely proportional to the infall time ($t_{infall}$) in post-shock region. For governing equations of POS model, see Eq.1-3 of Chakrabarti et al. (2008).

So far, we have studied QPO frequency evolutions during the outbursts of GRO J1655-40 (2005), GX 339-4 (2010-11), H 1743-322 (2010 & 2011) and XTE J1550-564 (1998). These evolutions are well fitted with POS model and from there accretion flow parameters related to evolutions are extracted. Here, we discuss a brief summary of model fitted results obtained from the QPO frequency evolutions of first three sources during their individual X-ray outbursts.

3.2.1. 2005 outburst of GRO J1655-40

During the rising phase, QPO frequency was increased monotonically from 82mHz to 17.78Hz. According to the POS model fit, shock moved from 1200 $r_g$ to 59 $r_g$ with a constant velocity ($v$) of $\sim 20$ m $s^{-1}$ with $R_0 = 4$ and $\alpha = 0.003$. During the declining phase, QPO frequency was decreased monotonically from 13.14Hz to 34mHz and this evolution was fitted with the same POS model. Here, we observed that initially (upto 3.5 days) shock moved very slowly (from 40 $r_g$ to 59 $r_g$) and then rapidly with high acceleration (on last QPO observed day at 3100 $r_g$). During the entire period, strength of the shock was kept constant with $R = 4$. 

Fig. 1. Variations of the QPO frequency with time (in day) of (a) the rising phases and (b) the declining phases of 2005 outburst of GRO J1655-40 (in left panel), 2010-11 outburst of GX 339-4 (in middle panel), and combined 2010 & 2011 outbursts of H 1743-322 (in right panel) are fitted with POS model (dashed/dotted curves).
3.2.2. 2010-11 outburst of GX 339-4

Evolution of QPO frequency from 102mHz to 5.69Hz observed during the rising phase of the outburst, where shock was observed to move from 1500 $r_g$ to 172 $r_g$ with a constant velocity ($v$) of $\sim 10 \ m \ s^{-1}$, $R_0 = 4$, and $\alpha = 0.0068$. During the declining phase, QPO frequency is found to decrease from 6.42Hz to 1.149Hz. According to POS, initial 4.2 days shock moved away slowly (from 84 to 155 $r_g$) with initial velocity ($v_i$) = 205 cm sec $^{-1}$ and acceleration =20 cm sec$^{-1}$ day$^{-1}$. After that as of GRO J1655-40, shock disappears with higher rate of acceleration (175 cm sec$^{-1}$ day$^{-1}$) with final velocity ($v_f$) = 1785 cm sec$^{-1}$.

3.2.3. 2010 and 2011 outbursts of H 1743-322

During rising phase of 2010 outburst, QPO frequency was increased from 0.92 to 4.79Hz, with the movement of shock wave from 428 to 181 $r_g$ with $R_0$=1.39, $\alpha = 0.006$, and an accelerating velocity, changing from 180 to 1133 cm/sec within a period of 6.81 days. Similarly, during 2011 rising phase, QPO frequency was increased from 0.43 to 3.61Hz with movement of shock wave from 550 to 217 $r_g$ with the help of an accelerating velocity (changing 340 - 1137 cm/sec) within a period of 9.16 days, $R_0 = 2$, $\alpha = 0.0055$. During declining phase of 2010 outburst, QPOs were observed to decrease from 6.42Hz to 79mHz with an accelerating velocity changing 560 to 1578 cm/sec and movement of shock wave from 65 to 751 $r_g$ within a period of 13.57 days, and $R = 2$ (constant). Similarly, during the 2011 declining phase, shock was found to move from 118 to 411 $r_g$ with an accelerating velocity (changing 460 - 912 cm/sec) and constant $R = 2.78$. As a result QPO frequency was observed to decrease from 2.94 to 0.38Hz with in a period of 10 days.

4. Discussions and Concluding Remarks

From the successful interpretation of evolutions of QPO frequency during rising and declining phases of transient BHCs with the POS solution,[3,7] we are certain that one can calculate the frequency of QPOs if one knows the instantaneous shock locations or vise-versa. We hope that this model will also be able to explain the evolutions of QPO frequency for other transient BHCs.

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