Evolution of the temporal and the spectral properties in 2010 and 2011 outbursts of H 1743-322

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Abstract

The Galactic black hole candidate H 1743-322 exhibited two X-ray outbursts in rapid succession: one in August 2010 and the other in April 2011. We analyze archival data of this object from the PCA instrument on board RXTE (2-25 keV energy band) to study the evolution of its temporal and spectral characteristics during both the outbursts, and hence to understand the behavioral change of the accretion flow dynamics associated with the evolution of the various X-ray features. We study the evolution of QPO frequencies during the rising and the declining phases of both the outbursts. We successfully fit the variation of QPO frequency using the Propagating Oscillatory Shock (POS) model in each of the outbursts and obtain the accretion flow parameters such as the instantaneous shock locations, the shock velocity and the shock strength. Based on the degree of importance of the thermal (disk black body) and the non-thermal (power-law) components of the spectral fit and properties of the QPO (if present), the entire profiles of the 2010 and 2011 outbursts are subdivided into four different spectral states: hard, hard-intermediate, soft-intermediate and soft. We attempt to explain the nature of the outburst profile (i.e., hardness-intensity diagram) with two different types of mass accretion flow.

Keywords: X-Rays:binaries, Black Holes, shock waves, accretion disks, Stars:individual (H 1743-322)

1. Introduction

Galactic transient black hole candidates (BHCs) are the most fascinating objects to study in X-ray domain since these sources exhibit evolutions in their timing and spectral properties during their outbursts. Several attempts (McClintock & Remillard, 2006; Belloni et al., 2005; Remillard & McClintock, 2006; Debnath et al., 2008; Nandi et al., 2012) were made for a thorough study on the temporal and spectral evolutions of the transient black hole (BH) binaries during their outbursts. Various spectral states were identified during different phases of the outburst. In general, four basic spectral states (Hard, Hard – Intermediate, Soft – Intermediate, Soft) are observed during the outburst of a transient BHC (McClintock & Remillard, 2006; Belloni et al., 2005; Nandi et al., 2012). One can find detailed discussions about these spectral states and their transitions in the literature (Homan & Belloni, 2005a; Belloni, 2010c; Dunn et al., 2010; Nandi et al., 2012). It was also reported by several authors (Fender et al., 2004; Homan & Belloni, 2005a; Belloni, 2010c; Nandi et al., 2012) that the observed spectral states form a hysteresis loop during their outbursts. Also, these different spectral states of the hysteresis-loop are found to be associated with different branches of a q-like plot of X-ray color vs intensity i.e., the hardness-intensity diagram (HID) (Maccarone & Coppi, 2003; Homan & Belloni, 2005a).

The transient low-mass Galactic X-ray binary H 1743-322 was first discovered (Kaluzienski & Holt, 1977) with the Ariel-V All-Sky Monitor and subsequently observed with the HEAO-1 satellite (Doxsey et al., 1977) in X-rays during the period of Aug-Sep, 1977. During the 1977-78 outburst, the source was observed several times in the hard X-ray band of 12 – 180 keV energy range with the HEAO-1 satellite (Cooke et al., 1984). The observation revealed that the soft X-ray transient (based on the 1 – 10 keV spectral properties) also emits X-rays in the energy range of 10 – 100 keV (Cooke et al., 1984). White & Marshall (1984) categorized the source as a potential black hole candidate (BHC) based on the ‘color-color’ diagram using the spectral data of the HEAO-1 satellite.
After almost two decades, in 2003, the INTEGRAL satellite discovered signatures of renewed activity in hard X-rays (Revnivtsev et al., 2003) and later, RXTE also verified the presence of such an activity (Markwardt & Swank, 2003). During the 2003 outburst, the source was continuously and extensively monitored in X-rays (Parmar et al., 2003; Homan et al., 2005b; Remillard et al., 2006; McClintock et al., 2009), IR (Steeghs et al., 2003), and in Radio bands (Rupen et al., 2003) to reveal the multi-wavelength properties of the source. The multi-wavelength campaign on this source during its 2003 and 2009 outbursts were also carried out by McClintock et al. (2009); Miller-Jones et al. (2012) respectively.

The low-frequency as well as high frequency quasi-periodic oscillations (QPOs) along with a strong spectral variability are observed in the 2003 and other outbursts of the source in RXTE PCA data (Capitanio et al., 2005; Homan et al., 2005b; Remillard et al., 2006; Kalemci et al., 2006; Prat et al., 2009; McClintock et al., 2009; Stiele et al., 2013). These have resemblance with several other typical Galactic black hole candidates (e.g., GRO J1655-40, XTE J1550-564, GX 339-4 etc.). Another important discovery of large-scale relativistic X-ray and radio jets associated with the 2003 outburst (Rupen et al., 2004; Corbel et al., 2005) put the source in the category of ‘micro-quasar’. This was also confirmed by McClintock et al. (2009), from their comparative study on the timing and the spectral properties of this source with XTE J1550-564.

Recently in 2010 and 2011, the transient black hole candidate H 1743-322 again exhibited outbursts (Yamaoka et al., 2010; Kuulkers et al., 2011) with similar characteristics of state transitions (Shaposhnikov & Tomsick, 2010a; Shaposhnikov, 2010b; Belloni et al., 2010a,b, 2011) as observed in other outburst sources (Homan & Belloni, 2005a; Nandi et al., 2012). Recently, Altamirano & Strohmayer (2012) reported a new class of accretion state dependent 11 mHz QPO frequency during the early initial phase of both the outbursts under study.

RXTE has observed both these outbursts on a daily basis, which continued for a time period of around two months. We made a detailed study on the temporal and the spectral properties of H 1743-322 during these two outbursts using archival data of PCA instrument on board RXTE satellite. Altogether 49 observations starting from 2010 August 9 (MJD = 55417) to 2010 September 30 (MJD = 55469) of the 2010 outburst are analyzed in this paper. After remaining in the quiescence state for around seven months, H 1743-322 again became active in X-rays on 2011 April 6 (MJD = 55657), as reported by Kuulkers et al. (2011). RXTE started monitoring the source six days later (on 2011 April 12, MJD = 55663). Here, we also analyze RXTE PCA archival data of 27 observations spread over the entire outburst, starting from 2011 April 12 to 2011 May 19 (MJD = 55700). The preliminary results of this work were already presented in COSPAR 2012 (Debnath et al., 2012).

Apart from the 2010 and 2011 outbursts, there are six outbursts of H 1743-322 observed by RXTE in recent past. Detailed results of these outbursts have already been reported in the literature (Capitanio et al., 2009; McClintock et al., 2009; Dunn et al., 2010; Chen et al., 2010; Coriat et al., 2011; Miller-Jones et al., 2012) and the evolution of all outbursts typically follow the ‘q-diagram’ in the hardness-intensity plane (see for example, Maccarone & Coppi, 2003; Homan & Belloni, 2005a), except the 2008 outburst which does not follow the ‘standard’ outburst profile and is termed as the ‘failed-outburst’ (Capitanio et al., 2009).

Although the mass of the black hole has not yet been measured dynamically, there are several attempts to measure the mass of the black hole based on the timing and spectral properties of H 1743-322. From the model of high frequency QPOs based on the mass-angular momentum (i.e., spin of the black hole) relation, Pétri (2008) predicted that the mass can fall in the range between 9M_\odot to 13M_\odot.

The evolution of QPO frequency during the outburst phases of the transient BHCs has been well reported for a long time (Belloni & Hasinger, 1990; Belloni et al., 2005; Debnath et al., 2008; Nandi et al., 2012). Same type of QPO evolutions were observed during both the rising and the declining phases of these two outbursts as of other black hole candidates, such as, 2005 outburst of GRO J1655-40 (Chakrabarti et al., 2005, 2008), 1998 outburst of XTE J1550-564 (Chakrabarti et al., 2009) and 2010-11 outburst of GX 339-4 (Debnath et al., 2010; Nandi et al., 2012). The successful interpretation of these QPO evolutions with the Propagating Oscillatory Shock (POS) model (Chakrabarti et al., 2005, 2008) motivated us to fit the QPO evolutions of the recent outbursts of H 1743-322 with the same model. From the model fit, accretion flow parameters are calculated (see, Table 1 below).

This Paper is organized in the following way: In the next Section, we discuss about the observation and data analysis procedures using HEASARC’s HEASoft software package. In §3, we present temporal and spectral results of our observation. In §3.1, the evolution of light curves (2-25 keV count rates) and hardness ratios of the 2010 and 2011 outbursts of H 1743-322 are discussed. In §3.2, we compare the evolution of the hardness-intensity diagrams of these two outbursts. In §3.3, we show the time evolving (decreasing or increasing) nature of QPO frequency observed during rising and declining phases in both the outbursts (2010 and 2011) of H 1743-322 and apply the propagating oscillatory shock (POS) model to explain the variations of the centroid QPO frequency over time. In §3.4, we present the spectral analysis results and classify the entire duration of the outbursts into four spectral states: hard, hard-intermediate, soft-intermediate and soft. Finally, in §4, we present the brief discussion and concluding remarks.

2. Observation and Data Analysis

The campaigns carried out with RXTE cover the entire 2010 and 2011 outbursts of H 1743-322 starting from 2010 August 9 (MJD = 55417) to 2010 September 30 (MJD = 55469) and from 2011 April 12 (MJD = 55663) to 2011 May 19 (MJD = 55700). We analyzed archival data of the RXTE PCA instrument and follow the standard data analysis techniques as done by Nandi et al. (2012). The HEASoft 6.11 version of the software package was used to analyze the PCA data. We extract data from the most stable and well calibrated proportional counter unit 2 (PCU2; all the three layers are co-added).
For the timing analysis, we use the PCA Event mode data with a maximum timing resolution of 125\(\mu\)s. To generate the power-density spectra (PDS), we use the "powspec" task of XRONOS package with a normalization factor of "2" to have the expected ‘white’ noise subtracted rms fractional variability on 2-15 keV (0-35 channels of PCU2) light curves of 0.01 sec time bins. The power obtained has the unit of \(\text{rms}^2/\text{Hz}\). Observed QPOs are generally of Lorentzian type (Nowak, 2000; van der Klis, 2005). So, to find centroid frequency of QPOs, power density spectra (PDS) are fitted with Lorentzian profiles and fit error limits are obtained by using “fit err” command.

For the selection of QPOs in PDS, we use the standard method (see Nowak, 2000; van der Klis, 2005) based on the coherence parameter \(Q = \sqrt{\Delta\nu}\) and amplitudes (\(\%\) rms), where \(\nu, \Delta\nu\) are the centroid QPO frequency and full-width at half maximum respectively as discussed in Debnath et al. (2008). Here, for these two outbursts, observed \(Q\) values and amplitudes are varied from \(3 - 15\) and \(5 - 16\) respectively. In the entire PCA data analysis, we include the dead-time corrections and also PCA break down corrections (arising due to the leakage of propane layers of PCUs).

For the spectral analysis, the standard data reduction procedure for extracting RXTE PCA (PCU2) spectral data are used. The HEASARC’s software package XSPEC (version 12.5) is used for analyzing and modeling the spectral data. A fixed value of 1\% systematic error and the hydrogen column density (\(N_H\)) of \(1.6 \times 10^{22}\) (Capitanio et al., 2009) for absorption model \texttt{wabs}, are used to fit the spectra. 2.5 – 25 keV background subtracted PCA spectra are fitted with a combination of standard thermal (diskbb) and non-thermal (power-law) models or with only power-law component, where thermal photon contribution was much less (mainly in spectra from the hard and hard-intermediate spectral states). To achieve best fit, a single Gaussian Iron line \(\sim 6.5\) keV is also used. The fluxes of different model components of the spectra are calculated using \texttt{cflux} calculation method.

3. Results

The accretion flow properties during the outburst phases of the transient BHCs can be understood in a better manner by studying X-ray properties of these sources both in temporal and spectral domains. It is pointed out by Debnath et al. (2010) that depending upon the outburst light curve profiles, there are mainly two types of outbursting BHCs: one is ‘fast-rise slow-decay’ (FRSD) type and the other is ‘slow-rise slow-decay’ (SRSD) type. The source, H 1743-322 belongs to the first category. Although the general nature of the transient X-ray binaries is more complex (see for example, Chen et al., 1997).

3.1. Light curve evolution

For studying X-ray intensity variations of the 2010 and 2011 outbursts of H 1743-322, we extract light curves from PCU2 data of RXTE/PCA instrument in different energy bands: 2 – 4 keV (0 – 8 channels), 4 – 25 keV (9 – 58 channels), and 2 – 25 keV (0 – 58 channels). We have divided the 2 – 25 keV energy band in the above two bands because 2 – 4 keV photons mainly come from the thermally cool Keplerian disk, whereas the photons in the higher energy band (4 – 25 keV) come from the Comptonized sub-Keplerian disk (Compton corona). This fact may not be true always because the contributions for different spectral components also depend on accretion states. Variations of PCA count rates in 2 – 25 keV energy band and hardness ratios between 4 – 25 keV and 2 – 4 keV count rates of the 2010 and 2011 outbursts of H 1743-322 are shown in Fig. 1(a-b).

3.2. Hardness-Intensity-Diagram (HID)

In Fig. 2, we plot a combined 2 – 25 keV PCA count rates of the 2010 and 2011 outbursts against X-ray color (PCA count ratio between 4 – 25 keV and 2 – 4 keV energy bands), which are well known as HID (Fender et al., 2004; Homan & Belloni, 2005a; Debnath et al., 2008; Mandal & Chakrabarti, 2010; Nandi et al., 2012). The marked points A, B, C, D, E, F, G, and H are on MJD = 55417, MJD = 55420, MJD = 55424, MJD = 55425, MJD = 55450, MJD = 55455, MJD = 55458, and MJD = 55469 respectively for the 2010 outburst. Here points A and H respectively are the indicators of the start and the end of RXTE observations for the outburst and the points B, C, D, E, F, G are the points on the days where the state transitions from hard → hard intermediate, hard-intermediate → soft-intermediate, soft-intermediate → soft, soft → soft-intermediate, soft-intermediate → hard-intermediate, and hard-intermediate → hard, respectively occurred. Similarly, the points a, b, c, d,
Comptonized flow (Stiele et al., 2013). However, none of these models attempt to explain long duration continuous observations and the evolutions of QPOs during the outburst phases of transient BHCs. One satisfactory model namely shock oscillation model (SOM) by Chakrabarti and his collaborators (Molteni et al., 1996), shows that the oscillation of X-ray intensity could be due to the oscillation of the post-shock (Comptonizing) region. According to SOM, shock wave oscillates either because of resonance (where the cooling time scale of the flow is comparable to the infall time scale; (Molteni et al., 1996)) or because the Rankine-Hugoniot condition is not satisfied (Ryu et al., 1997) to form a steady shock. The QPO frequency is inversely proportional to the infall time ($t_{\text{infall}}$) in the post-shock region. The Propagating Oscillatory Shock (POS) model, which can successfully explain the evolutions of QPO frequency, is nothing but a special case (time varying form) of SOM.

As explained in our earlier papers on POS model (Chakrabarti et al., 2005, 2008, 2009; Debnath et al., 2010; Nandi et al., 2012) during the rising phase, the shock moves towards the black hole and during the declining phase it moves away from the black hole. This movement of the shock wave depends on the non-satisfaction of Rankine-Hugoniot condition which is due to the temperature and energy differences between pre- and post-shock regions. Moreover, sometimes in soft-intermediate states, QPOs are observed sporadically (for e.g., during the 2010-11 outburst of GX 339-4; see Nandi et al., 2012) and vanishes in soft spectral states and reappears in declining intermediate/hard states. This disappearance and appearance of QPO frequency depends on the compression ratio ($R$) due to the velocity/density difference in pre- and post-shock regions or could be due to the ejection of Jets (see Radhika & Nandi, 2013; Nandi et al., 2013). When $R = 1$, i.e., density of pre- and post-shock region more or less becomes the same, a shock wave vanishes, and so does the QPO.

We now present the results of the evolution of QPO frequency observed in both rising and declining phases of both the outbursts. So far in the literature, there is no consensus on the origin of QPOs despite its long term discovery (Belloni & Hasinger, 1990; Belloni et al., 2005), other than our group (Chakrabarti et al., 2005, 2008, 2009; Debnath et al., 2010; Nandi et al., 2012). In this work, we have tried to connect the nature of the observed QPOs and their evolutions during the rising and the declining phases of the current outbursts with the same POS model and find their implications on accretion disk dynamics. From the fits, physical flow parameters, such as instantaneous location, velocity, and strengths of the propagating shock wave are extracted. Detailed modeling and comparative study between QPO evolutions observed in the rising and the declining phases of the outbursts of transient BHCs will be presented in our follow-up works, where we will compare the POS model fit parameters with the spectral/temporal properties (such as count rates, hardness ratios, spectral fluxes, photon indices etc.) of the BHCs. This study can predict the mass of the BHCs, whose masses are not measured dynamically till now (for e.g., H 1743-322). Similarly, our study can predict the properties of QPOs in subsequent days, once the data for the first few days is available.

\[ e, f, g, \text{ and } h \text{ indicate } MJD = 55663, MJD = 55668, MJD = 55672, MJD = 55676, MJD = 55687, MJD = 55690, MJD = 55693, \text{ and } MJD = 55700 \text{ respectively for the 2011 outburst.} \]

In the Figure, both the plots show similar nature and state transitions during the outburst, except that in the 2011 outburst, the PCA count rate is observed to be lower in rising phase and in the hard state) and the observational data was not available.

Recently, Altamirano & Strohmayer (2012) also studied HIDs of both the outbursts. However, their analysis does not include spectral modeling of HIDs. From the detailed temporal and spectral study of these outbursts of H 1743-322, we have been able to connect different branches of the HIDs with different spectral states (see, Figs. 2, 6, 7). In the subsequent subsections, the variations of the spectral properties during the outbursts along with the POS model fitted evolutions of QPO frequency during the rising and the declining phases of the outbursts are discussed.

3.3. Evolution of QPO frequency and its modeling by POS solution

Studying temporal variability and finding QPOs in power density spectra (PDS) is an important aspect for any black hole candidate (BHC). It is observed (mainly at hard and hard-intermediate spectral states) that the frequency of QPOs are seen to evolve with time. LFQPOs are reported extensively in the literature, although there is some uncertainty about the origin of these QPOs. So far, many models are introduced to explain the origin of this important temporal feature of BHCs, such as trapped oscillations and disko-seismology (Kato & Mannmoto, 2000), oscillations of warped disks (Shirakawa & Lai, 2002), accretion-ejection instability at the inner radius of the Keplerian disk (Rodriguez et al., 2002), global disk oscillations (Titarchuk & Osherovich, 2000), and perturbations inside a Keplerian disk (Trudolyubov et al., 1999), propagating mass accretion rate fluctuations in hotter inner disk flow (Ingram & Done, 2011), and oscillations from a transition layer in between the disk and hot

Figure 2: Hardness Intensity Diagram of the 2010 (solid curve) and 2011 (dotted curve) outbursts as observed with RXTE/PCA are shown. Here $A - H$ and $a - h$ indicate the start/state transitions/end of our observations from the 2010 and 2011 outbursts respectively.
available.

The monotonically increasing nature of QPO frequency (from 0.919 Hz to 4.796 Hz for the 2010 outburst and from 0.428 Hz to 3.614 Hz for the 2011 outburst) during the rising phases and the monotonically decreasing nature of QPO frequency (from 6.417 Hz to 0.079 Hz for the 2010 outburst and from 2.936 Hz to 0.382 Hz for the 2011 outburst) during the declining phases of the recent successive two outbursts of H 1743-322 are very similar to what is observed in the 2005 outburst of GRO J1655-40 (Chakrabarti et al., 2005, 2008), 1998 outburst of XTE J1550-564 (Chakrabarti et al., 2009), and 2010 outburst of GX 339-4 (Debnath et al., 2010; Nandi et al., 2012). This motivated us to study and compare these evolutions with the same POS model solution. We found that during the rising and the declining phases of these two outbursts of H 1743-322, QPO evolutions also fit well with the POS model. The POS model fitted parameters (for e.g., shock location, strength, velocity etc.) are consistent with the QPO evolutions of GRO J1655-40, XTE J1550-564, and GX 339-4. The POS model fitted accretion flow parameters of the 2010 and 2011 outbursts of H 1743-322 are given in Table 1. Only noticeable difference observed during the present QPO frequency evolutions of H 1743-322 with that of the 2005 outburst of GRO J1655-40 and 2010-11 outburst of GX 339-4 is that during both the rising phases of GRO J1655-40 and GX 339-4 outbursts, the shock was found to move in with a constant speed of $\sim 2000$ cm s$^{-1}$, and $\sim 1000$ cm s$^{-1}$ respectively, whereas during the same phases of the current two outbursts of H 1743-322, the shock was found to move in with an acceleration. On the other hand, during the declining phase for all these outbursts of GRO J1655-40, GX 339-4, and H 1743-322, the shock was found to be moved away with constant acceleration. It is also noticed that during both the rising and the declining phases of the 2010 outburst, the shock moved away with an acceleration twice as compared to that of 2011 outburst. It seems to be an interesting result, which may occur due to the lack of supply of matter (mostly Keplerian) into the disk from the companion that could have created a sudden ‘void’ in the disk for the shock to move away rapidly outward.

According to the POS solution (Chakrabarti et al., 2008, 2009; Debnath et al., 2010; Nandi et al., 2012), one can obtain the QPO frequency if one knows the instantaneous shock location or vise-versa and the compression ratio ($R = \rho_s/\rho_\infty$, where $\rho_s$ and $\rho_\infty$ are the densities in the post- and the pre-shock flows) at the shock. According to POS model in the presence of a shock (Chakrabarti & Manickam, 2000; Chakrabarti et al., 2008), the in-fall time in the post-shock region is given by

$$t_{\text{infall}} \sim r_s/v \sim R_{s}(r_s-1)^{1/2},$$

where, $r_s$ is the shock location in units of the Schwarzschild radius $r_s = 2GM/c^2$, $v$ is the velocity of propagating shock wave in cm s$^{-1}$.

The QPO frequency happens to be inversely proportional to the in-fall time scale from the post-shock region. According to the shock oscillation model (Molteni et al., 1996), oscillations of the X-ray intensity are generated due to the oscillation of the post-shock region. This is also the centrifugal pressure supported boundary layer (or, CENBOL) which behaves as a Compton cloud in the Chakrabarti & Titarchuk (1995) model of two component accretion flow (TCAF). According to the numerical simulations of the sub-Keplerian (low-angular momentum) accretion which includes the dynamical cooling (Ryu et al., 1997) or the thermal cooling (Molteni et al., 1996; Chakrabarti et al., 2004), the frequency of the shock oscillation is similar to the observed QPO frequency for BHs. Thus, the instantaneous QPO frequency $\nu_{QPO}$ (in s$^{-1}$) is expected to be

$$\nu_{QPO} = \nu_0/t_{\text{infall}} = \nu_0/[Rr_s(r_s-1)^{1/2}].$$

Here, $\nu_0 = c/r_g = c^3/2GM$ is the inverse of the light crossing time of the black hole of mass $M$ in unit of $s^{-1}$ and $c$ is the velocity of light. In a drifting shock scenario, $r_s = r_s(t)$ is the time-dependent shock location given by

$$r_s(t) = r_0 + \nu_0 t/r_g,$$
Figure 4: Variations of the QPO frequency with time (in day) of the declining phase of the (a) 2010 outburst and (b) 2011 outburst which are fitted with the POS model solution (dashed curve). The diamond indicates the last event when the QPO was observed on (a) 2010 August 17 and (b) 2011 April 23, not included in the fits.

Figure 3: (a) Variations of the QPO frequency with time (in day) of the rising phase of the (a) 2010 outburst and (b) 2011 outburst with the fitted POS model when the QPO was observed on (a) 2010 August 17 and (b) 2011 April 23, not included in the fits.

Figure 5: Variation of the shock locations (in $r_g$) during the rising and the declining phases of the (a) 2010 and (b) 2011 outbursts of BHCH 1743-322 (see text for details).

5a) within ~ 7 days. Also, we found that during this period, the shock velocity is varied from ~ 180 cm s$^{-1}$ to ~ 1133 cm s$^{-1}$ with an acceleration of ~ 140 cm s$^{-1}$ d$^{-1}$ and the shock compression ratio $R$, which is inverse of the shock strength $\beta$, is changed from 1.39 to 1.00. Unlike 2005 GRO J1655-40 or 2010 GX 339-4, we did not start with the strongest possible shock ($R = 4$) in the present case. This is because RXTE missed this object in the first few days of observation. In the first ‘observed’ day, the shock has already moved in and the QPO frequency is already too high (~ 1 Hz). According to our model, if the RXTE monitoring started a few days earlier, we would have observed mHz QPOs as in other black hole sources. The compression ratio $R$ decreased with time by the relation $1/R \rightarrow 1/R_0 + \alpha(t_d)^2$, where $R_0$ is the initial compression ratio (here $R_0 = 1.39$), $t_d$ is the time in days (assuming first observation day as 0$^{th}$ day). Here, $\alpha$ is a constant (= 0.0060) which determines how the shock (strength) becomes weaker with time and reaches its lowest possible value when $R = 1$. In principle, these parameters, including shock propagation velocity can be determined from the shock formation theory when the exact amount of viscosity and cooling effects are supplied (Chakrabarti, 1990).

- Declining Phase

The source is seen to move to this phase on 2010 September 16 (MJD = 55455), when a QPO of 6.417 Hz frequency is observed. On subsequent days, the observed frequency of the QPO decreases, and it reaches to its lowest detectable value of 79 mHz on the 2010 September 30 (MJD = 55469) within a period of ~ 13.6 days. Before Sept. 16th, QPOs are sporadically observed at around 2 – 2.5 Hz starting from 2010 September 11 (MJD = 55450). According to the POS model fit (shown in Fig. 4a), the shock is observed to recede back starting from ~ 65 $r_g$ till ~ 751 $r_g$ (Fig. 5a). The shock compression ratio $R$ appears to remain constant at 3.33. Also, during this phase, the shock velocity varies from ~ 560 cm s$^{-1}$ to ~ 1578 cm s$^{-1}$ due to an acceleration of 75 cm s$^{-1}$ d$^{-1}$. 

\[ \text{acceleration} = 75 \text{ cm s}^{-1} \]
3.3.2. 2011 QPO Evolutions

The QPOs are observed in 19 observations out of a total of 27 observations spread over the entire outburst. Out of these 19 observations, 11 are observed in the rising phase and the remaining 8 are in the declining phase of the outburst.

- Rising Phase

During this phase of the outburst, a QPO of frequency 0.428 Hz is observed on the first RXTE PCA observation day (2011 April 12, MJD = 55663). Similar to the rising phase of the 2010 outburst, QPO frequencies are observed to be increasing with time and reached its maximum value of 3.614 Hz (as observed by RXTE) on 2011 April 21 (MJD = 55672). On 2011 April 23 (MJD = 55674) and 2011 April 25 (MJD = 55676), the frequencies of the observed QPOs are seen to be at 3.562 Hz and 3.306 Hz respectively. The evolutionary track of the QPO frequency is fitted with the POS model (Fig. 3b) with the method and found that the shock moved away from the black hole with accelerating velocity and constant shock strength ($\beta \sim 0.36$ i.e., $R \sim 2.78$). During the outburst phase of ~ 10 days, the shock wave was found to move from ~ 118 $r_g$ to ~ 411 $r_g$ (Fig. 5b) with a change of velocity from ~ 460 cm s$^{-1}$ to ~ 912 cm s$^{-1}$ due to an acceleration of 45 cm s$^{-1}$ d$^{-1}$.

- Declining Phase

The source is observed to reach at this phase of the QPO evolution on the 2011 May 9 (MJD = 55690), where the QPO of frequency 2.936 Hz is observed. Subsequently, as in the 2010 outburst, the frequency of the observed QPO decreased with time and reached to its lowest detectable value of 0.382 Hz on 2011 May 19 (MJD = 55700). Three days prior to the start of this phase of QPO evolution, QPO of 2.215 Hz is observed on 2011 May 6 (MJD = 55687). This behavior was also seen in the declining phase of the 2010 outburst. Here also we have fitted with the POS model solution (Fig. 4b) as the 2010 outburst
and soft (SS) (see, Homan & Belloni (2005a) for the definitions of these basic spectral states). Out of these four spectral states, the low frequency quasi-periodic oscillations (LFQPOs) are observed during hard, hard-intermediate and soft-intermediate spectral states while according to POS, the QPO evolutions are observed only during the hard and hard-intermediate spectral states. In soft-intermediate states, QPOs are observed sporadically. In general, observed QPOs during the hard and hard-intermediate spectral states are of ‘C’ type (van der Klis, 2004) with Q-value ≥ 3 and rms ≥ 10% and during soft-intermediate spectral state are of ‘B’ type with lesser Q and rms value. During both the outbursts, these four spectral states are observed in the same sequence and completed a hysteresis-type loop, with hard spectral state in both the start and the end phases while other three spectral states in between. It is to be noted that during the spectral evolution, the soft state is observed only once, during the mid-region of the outburst (see, Fig. 1(a-b), Fig. 2, Fig. 6, and Fig. 7). In Table 2, the model fitted values of the disk black body temperature \( T_{\text{in}} \) in keV and power-law photon index \( \Gamma \) and their flux contribution to the spectra in 2.5 – 25 keV energy range for seven observations, selected from seven different spectral states of the 2010 and 2011 outbursts are enlisted.

Daily variations of the model fitted parameters and their flux contribution in 2.5 – 25 keV spectra of the 2010 and 2011 outbursts are plotted in Figs. 6 & 7 respectively. The variations of the black body temperature \( T_{\text{in}} \), the power-law photon index \( \Gamma \) and their flux contributions in 2.5 – 25 keV energy range are shown in these Figures. These variations justify the spectral classifications. The Figures also show clearly that the evolutions of the spectral parameters and model fluxes are similar during the same spectral states of the two consecutive outbursts of H 1743-322.

### 3.4.1. 2010 spectral evolution

#### (i) Rising Hard State:
Initial ~ 3 days of the RXTE observations (from MJD = 55417.3 to 55419.1) belong to this spectral state, where the spectra are fitted with only power-law (PL) component. So, during this phase, the spectra are dominated by the non-thermal photons without any signature of thermal photons. The QPO frequency is observed to increase monotonically from 0.919 Hz to 1.045 Hz.

#### (ii) Rising Hard-Intermediate State:
In the following ~ 5 days (up to MJD = 55424.1), the source is observed to be at the hard-intermediate spectral state. Initial 3 days spectra are fitted without diskbb component, but in the rest of the two days spectra are fitted with the combination of diskbb (DBB) and power-law components. This is because as the day progresses, the spectra started becoming softer, due to enhanced supply of Keplerian matter. During this state the spectra are mostly dominated by the non-thermal PL photons, although the thermal DBB rate is increased. The QPO frequency is found to be increased monotonically from 1.045 Hz to 4.796 Hz.

#### (iii) Rising Soft-Intermediate State:
On the following day (MJD = 55425.2), the observed QPO frequency is decreased to 3.558 Hz. After that no QPOs are observed for the next several days. We refer this particular observation as the soft-intermediate spectral state, because of sudden rise in DBB photon flux from its previous day value, whereas the PL flux does not increase very much.

#### (iv) Soft State:
The source is observed at this spectral state for the next ~ 24 days (up to MJD = 55448.8), where spectra are mostly dominated by thermal photons (i.e, low energy DBB photons). No QPOs are observed during this spectral state (see Figs. 6 & 7).

#### (v) Declining Soft-Intermediate State:
For the following ~ 6 days (up to MJD = 55454.5), the source is observed at this spectral state. Here, \( T_{\text{in}} \) and \( \Gamma \) values are observed to be almost constant at ~ 0.70 keV and ~ 2.20 respectively. During this phase, disk black body flux is observed to be constant at ~ \( 0.45 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1} \), although there is an initial rise and then steady fall in the PL flux. Sporadic QPOs of ~ 2 Hz are observed during this spectral phase.

#### (vi) Declining Hard-Intermediate State:
The source is observed to be in this spectral state for the next ~ 3.5 days (up to MJD = 55457.1), where first two days spectra are fitted with combination of DBB and PL component and remaining day’s spectrum is fitted with only PL component. The reason behind this is that as the day progresses, spectra became harder, because of lack of supply of Keplerian matter from the companion. It was also found that during this phase, the observed QPO frequency is monotonically decreased from 6.417 Hz to 2.569 Hz.

#### (vii) Declining Hard State:
This spectral state completes the hysteresis-like loop of the spectral state evolution (see Fig. 2). The source has been observed during this spectral state till the end of RXTE PCA observation of the 2010 outburst. In this phase of evolution, the spectra are dominated by the non-thermal (power-law) flux. So, we fitted 2.5 – 25 keV spectra with only PL model component. Similar to the previous spectral state, the
QPO frequency is found to be monotonically decreasing from 1.761 Hz to 79 mHz during this phase.

3.4.2. 2011 spectral evolution

(i) Rising Hard State: Initial ~ 5 days of PCA observations (from MJD = 55663.7 to 55668.5) belong to this spectral state, where spectra are fitted with only non-thermal power-law (PL) component. During this spectral state, the energy spectra (2.5–25 keV) are mostly dominated by non-thermal photons without any signatures of thermal photons. The observed QPO frequency is found to be monotonically increased from 0.428 Hz to 0.807 Hz.

(ii) Rising Hard-Intermediate State: In the next 3 observations (up to MJD = 55672.8), the source was observed to be in this spectral state, where first 2 days spectra are fitted without diskbb component, but remaining day’s spectrum is fitted with the combination of diskbb (DBB) and power-law components. As the day progresses spectrum became softer, because of supply of more Keplerian matter (i.e., thermal emission) from the companion. During this state, the QPO frequency is observed to be increased monotonically from 0.885 Hz to 3.614 Hz.

(iii) Rising Soft-Intermediate State: The source is observed to be in this spectral state for the next ~ 4.5 days (up to MJD = 55676.4), where $T_{in}$ and $\Gamma$ values are observed to be almost constant at ~ 0.90 keV and ~ 2.20 respectively. A sharp rise in 2.5–25 keV DBB flux over the previous state value is observed, where as the PL flux in the same energy range is observed to be nearly constant. As in the 2010 outburst, here also sporadic QPOs of frequency ~ 3.5 Hz are observed during this spectral state.

(iv) Soft State: Next ~ 8 days (up to MJD = 55684.6), the source is observed to be in this spectral state, where $T_{in}$ and $\Gamma$ values are varied from ~ 0.90 to ~ 0.80 keV and from ~ 2.30 to ~ 2.20 respectively. During this phase, the spectra are mostly dominated by low energy DBB flux (i.e., thermal emission) with decreasing in nature. QPOs are not observed during this state, which are also missing during the soft state of the 2010 outburst (see Figs. 6 & 7).

(v) Declining Soft-Intermediate State: On the next day (MJD = 55687.6), the source is observed to be in this spectral state with a weak presence of thermal emission and the energy spectra started dominating by the PL flux. The particular observation showed a QPO signature at 2.215 Hz.

(vi) Declining Hard-Intermediate State: After that up to MJD = 55691.5, the source was observed to be at this spectral state, where spectra are fitted without diskbb component. The spectra are dominated by non-thermal PL photons, because of lack of supply of Keplerian matter. QPOs are also observed during this spectral state and found to be decreased monotonically from 2.94 Hz to 2.01 Hz.

(vii) Declining Hard State: At the final phase of the outburst, the source is found to be in the hard state again, which completes the hysteresis-like loop of the spectral state evolutions (see Fig. 2). Similar to the ‘canonical’ hard state in the rising phase, here we also found that diskbb component is not essential to fit the PCA spectra in 2.5–25 keV range, only PL component is sufficient to fit the spectra along with an Gaussian line at ~ 6.5 keV. At the same time, during this spectral state, the QPO frequency is found to be decreased monotonically from 1.798 Hz to 0.382 Hz.

4. Discussions and concluding remarks

We carried out the temporal and the spectral analysis of the data of the 2010 and 2011 outbursts of the black hole candidate H 1743-322. We studied the evolution of quasi-periodic oscillation frequency during the rising as well as the declining phases. We also studied the evolution of spectral states during both the outbursts. The variations of QPO frequencies can be fitted assuming that an oscillating shock wave progressively moves towards the black hole during the rising phase and moves away from the black hole in the declining phase. Fundamentally, it is possible that a sudden rise in viscosity not only causes the Keplerian rate to rise but also causes the inner edge to move towards the black hole. Initially, the higher angular momentum flow forms the shock far away, but as the viscosity transports the angular momentum, the shock moves in, especially so due to enhanced cooling effects in the post-shock region. The Keplerian disk moves in along with the shock.

This scenario accomplishes all that we observe in an outbursting source: (a) The QPO frequency rises/decreases with time in the rising/declining phase, mainly observed during the hard and hard-intermediate spectral states and during the soft-intermediate spectral state QPOs are seen sporadically (see Nandi et al., 2013). It is to be noted that shocks exist only in these states. (b) The spectrum softens as the Keplerian disk moves in with a higher rate. (c) At the intermediate state(s), the Keplerian and the sub-Keplerian rates are similar. (d) During the declining phase, when the viscosity is reduced, the shock and the Keplerian disk moves back to a larger distance and the QPO frequency is also reduced. (e) The outflows can form only from the post-shock region (CENBOL), namely, the subsonic region between the shock and the inner sonic point. In softer states,
the CENBOL disappears and the outflows also disappear. Our model predicts that since the QPOs could be due to the oscillation of the shocks, whose frequency is roughly the inverse of the infall time scale, the frequency gives the location of the shock when the compression ratio is provided. In our scenario, a strong shock ($R \sim 4$) starts at $\sim 1000 r_g$, but by the time it comes closer to the black hole, it becomes weaker due to the rapid cooling by enhanced Keplerian disk rate. QPO ceases to exist when the compression ratio is unity. These constraints allowed us to compute the shock strength as a function of time.

As far as the evolution of the spectral states during the two outbursts of the transient BHC H 1743-322 is concerned, this can be well understood by the detailed study of the spectral properties. During both the outbursts, it has been observed that the source starts from the hard state and finally return back to hard state again after passing through the hard-intermediate, soft-intermediate and soft spectral states. It completes hysteresis loop of $\text{hard} \rightarrow \text{hard-intermediate} \rightarrow \text{soft-intermediate} \rightarrow \text{soft} \rightarrow \text{soft-intermediate} \rightarrow \text{hard} \rightarrow \text{hard}$.

Several attempts have already been made to understand these type of hysteresis spectral state transitions in black hole sources and to find their correlations with HIDs (Meyer et al., 2007; Meyer-Hofmeister et al., 2009), but one can easily explain this type of evolution of spectral states with the TCAF model (Chakrabarti & Titarchuk, 1995), where the low-angular momentum sub-Keplerian matter flows in nearly free-fall time scale, while the high angular momentum Keplerian matter flows in the slow viscous time scale (Mandal & Chakrabarti, 2010). Initially the spectra are dominated by the sub-Keplerian flow and as a result, the spectra are hard. As the day progresses, more and more sub-Keplerian matter is converted to Keplerian matter (through viscous transport of angular momentum) and the spectra become softer, progressively through hard-intermediate (Keplerian rate slightly less than the sub-Keplerian rate), soft-intermediate (Keplerian rate comparable to the sub-Keplerian rate) and soft state (dominating Keplerian rate). When viscosity is turned off at the outer edge, the declining phase begins. At the declining phase of the outburst, the Keplerian rate starts decreasing, and the spectra start to become harder again. However, the spectrum need not be retrace itself, since the information about the decrease of viscosity had to arrive at the viscous time scale. This is a hysteresis effect. But the spectra still follows the declining soft-intermediate, hard-intermediate and hard states.

In this work, we successfully applied the POS model fit evolutions of QPO frequency during both the rising and declining phases of two (2010 and 2011) outbursts of H 1743-322 and shock wave parameters related to the evolutions are extracted. Earlier, the same POS model was also applied to explain the evolution of QPO frequency of other black hole candidates (e.g., GRO J1655-40, XTE J1550-564, GX 339-4, etc.) very successfully (Chakrabarti et al., 2005, 2008, 2009; Debnath et al., 2010; Nandi et al., 2012). All these objects seem to exhibit a similar behaviour as far as the QPO and spectral evolutions are concerned. In future, we will carry out detailed modeling and comparative study between QPO evolutions observed in other outbursts of H 1743-322 and other transient BHCs with this POS model and hence to understand accretion flow behaviours during the outburst phases more precisely. However, the basic questions still remain: (a) What are the sources of enhanced viscosity? (b) Does it scale with the mass of the black hole or the mass of the donor? (c) Is the duration of the high viscosity phase (i.e., the duration between the end of the rising phase and the beginning of the declining phase) predictable, or it is totally random and depends mostly on the physical conditions of the donor? (d) Which processes decide the total time interval for which an outburst may last? And finally, (e) What determines the interval between two outbursts? If the cause is the enhancement of viscosity, then clearly it may be also random. We are in the process of exploring these aspects through comparison of all the known candidates. Recently, we have been able to include TCAF model in XSPEC as a local additive model, and from the spectral fit using this model directly we obtain instantaneous location of the shock ($r_s$) and compression ratio ($R$) other than two component (Keplerian and sub-Keplerian) accretion rates (see Debnath et al., 2013a). As we know from the POS model, one can determine the QPO frequency if the values of $r_s$ and $R$ are known or vise-versa (see, Eqn. 2). So, from the spectral fit, we will be able to predict the observed QPO frequency. The preliminary result on this work is already presented in a Conference Proceeding (Debnath et al., 2013b).

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