

IS COMPTON COOLING SUFFICIENT TO EXPLAIN EVOLUTION OF OBSERVED QUASI-PERIODIC OSCILLATIONS IN OUTBURST SOURCES?

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ABSTRACT

In outburst sources, quasi-periodic oscillation (QPO) frequency is known to evolve in a certain way: in the rising phase, it monotonically goes up until a soft intermediate state is achieved. In the propagating oscillatory shock model, oscillation of the Compton cloud is thought to cause QPOs. Thus, in order to increase QPO frequency, the Compton cloud must collapse steadily in the rising phase. In decline phases, the exact opposite should be true. We investigate cause of this evolution of the Compton cloud. The same viscosity parameter that increases the Keplerian disk rate also moves the inner edge of the Keplerian component, thereby reducing the size of the Compton cloud and reducing the cooling timescale. We show that cooling of the Compton cloud by inverse Comptonization is enough for it to collapse sufficiently so as to explain the QPO evolution. In the two-component advective flow configuration of Chakrabarti–Titarchuk, centrifugal force-induced shock represents the boundary of the Compton cloud. We take the rising phase of 2010 outburst of Galactic black hole candidate H 1743-322 and find an estimation of variation of the α parameter of the sub-Keplerian flow to be monotonically rising from 0.0001 to 0.02, well within the range suggested by magnetorotational instability. We also estimate the inward velocity of the Compton cloud to be a few meters per second, which is comparable to what is found in several earlier studies of our group by empirically fitting the shock locations with the time of observations.

Key words: accretion, accretion disks – hydrodynamics – radiation: dynamics – shock waves – stars: black holes – stars: individual (H 1743-322)

1. INTRODUCTION

The study of temporal variability, including signatures of quasi-periodic oscillations (QPOs), is an important aspect of astrophysics of black holes. Several models in the literature attempt to explain the origin of low-frequency QPOs. They include perturbation inside a Keplerian disk (Trudolyubov et al. 1999), global disk oscillation (Titarchuk & Osherovich 2000), oscillation of a wrapped disk (Shirakawa & Lai 2002), and an accretion ejection instability at the inner radius of a Keplerian disk (Rodriguez et al. 2000). Titarchuk et al. (1998) envisages a bounded region surrounding compact objects, called the transition layer (TL), and identifies low-frequency QPOs as being associated with the viscous magnetoacoustic resonance oscillation of the bounded TL. Chakrabarti and his collaborators (Molteni et al. 1996; Chakrabarti et al. 2004) show that the oscillations of centrifugal pressure support accretion shocks (Chakrabarti 1990a), which could cause the observed low-frequency QPOs. According to the two-component advective flow (TCAF) model (Chakrabarti & Titarchuk 1995), the post-shock region itself is the Compton cloud. Because the shock is formed due to centrifugal force, where energy is dissipated and angular momentum is redistributed, the post-shock region is also known as the Centrifugal Pressure-supported Boundary Layer (CENBOL) of the black hole. This TCAF solution has been proven to be of stable configuration (Giri & Chakrabarti 2013) and Monte Carlo simulations of spectral and timing properties through a time-dependent radiative hydrodynamic code show the formation of QPOs very similar to what is observed (Garain et al. 2014). The Compton cloud becomes smaller because of higher viscosity as well as higher cooling. Higher viscosity causes the Keplerian disk on the equatorial plane to move in. This causes the Compton cloud to cool

down. This picture is clear from the two-component model of Chakrabarti & Titarchuk (1995) and the outburst source picture given in Ebisawa et al. (1996) based on it. To our knowledge, no other model except TCAF is found to be capable of explaining the continuous and simultaneous variation of spectral properties and timing properties (see, Debnath et al. 2008, 2010, 2013, 2014a; Nandi et al. 2012).

There are two main reasons behind oscillations of shock wave in an accretion flow. (1) Resonance oscillation: when the cooling timescale of the flow is comparable to the infall timescale (Molteni et al. 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 accretion rates, and the frequency should go up with the accretion rate. Not all QPOs may be of this type. Some sources (for example, the 2010 GX 339-4 outburst) show signatures of sporadic QPOs during rising soft-intermediate states (where QPO frequencies of ~ 6 Hz were observed for around 26 days; Nandi et al. 2012), although rise in the accretion rates. In these cases, the shock strength has to change in order for the resonance condition to hold well. (2) Non-steady solution: in this case, the flow has two saddle-type sonic points, but Rankine–Hugoniot conditions that were used to study standing shocks in Chakrabarti (1989) are not satisfied. Examples of these oscillations are given in Ryu et al. (1997), where no explicit cooling was used. Such types of QPOs are possible at all accretion rates outside the regime of type (1) QPOs mentioned above. QPO frequencies depend on viscosity (higher viscosity will remove angular momentum, bring shocks closer to the black hole, and produce higher-frequency QPOs), but not explicitly depend on the accretion rate. In any case, observed QPO frequency is inversely proportional to the infall time (t_{infall}) in the post-shock region. So, when low-frequency

(e.g., mHz to few Hz) QPOs are observed, generally during very early phase of an outburst or very late phase of an outburst of transient black hole candidates (BHCs), shocks are located very far away from black holes and the size of the CENBOL is large. As a result, the amount of cooling by photons from the Keplerian disk (Shakura & Sunyaev 1973) is high (Chakrabarti & Titarchuk 1995; Mondal & Chakrabarti 2013, hereafter Paper I) and CENBOL pressure drops, moving the shock closer toward black hole (Molteni et al. 1996; Das et al. 2010; Mondal et al. 2014a; Paper I) until the pressure (including centrifugal) is strong enough to balance the inward pull. A lower shock location increases the QPO frequency. Different BHCs show different oscillation frequencies during their evolution (both in rising and declining) phases. Using the Propagating Oscillatory Shock (POS) model by Chakrabarti and collaborators (Chakrabarti et al. 2005, 2008, 2009; Debnath et al. 2010, 2013; Nandi et al. 2012), one can satisfactorily explain origin and day-wise evolution of QPO frequencies during the rising and declining phases of outbursting BHCs. During the rising phase, shock moves toward black holes, increasing QPO frequencies monotonically with time, and the opposite scenario is observed during the declining phase, mainly in hard and hard–intermediate spectral states of the outbursts (see Debnath et al. 2013).

Recently, Debnath et al. (2014a) showed that observed QPO frequencies can be predicted from detailed spectral analysis using the TCAF model as a local additive table model in XSPEC. Mondal et al. (2014b) and Debnath et al. (2014b) also showed physical reasons behind the spectral state transitions from spectral model fitted parameters of TCAF model for two different Galactic BHCs, H 1743-322 and GX 339-4, during their outbursts. Basically, the same shock location obtained by fitting the spectra produces QPOs through oscillations. Therefore, spectral properties are interlinked with timing properties as far as the TCAF solution is concerned.

In this paper, our goal is to explain the origin of observed QPO evolution from a purely analytical point of view using Compton cooling. As the biggest uncertainty is that of the viscosity parameter, we would like to have an idea of how viscosity usually varies with distance in a known source. We consider a transient BHC H 1743-322 during its 2010 outburst. We hope that in the future, this behavior could be used to better predict QPO evolutions.

In 2010 August, H 1743-322 was found to be active in the X-ray spectrum (Yamaoka et al. 2010) with characteristics of temporal and spectral evolutions (Debnath et al. 2013) similar to those observed in other transient BHCs (for a review, see Remillard & McClintock 2006). A detailed source description is already in the literature (Debnath et al. 2013; Mondal et al. 2014b, and references therein).

The paper is organized as follows. In the next section, we discuss the governing equations of modified Rankine–Hugoniot (R-H) shock conditions in the presence of Compton cooling. In Section 3, we discuss the observed QPO evolution and what this tells us about viscosity variations in the disk as a function of radial distance. We also present a phase–space diagram of the flow in progressive days. Finally, in Section 4, we briefly discuss our results and make our concluding remarks.

2. SHOCK CONDITION AND SHOCK CONSTANT

We assume the accreting flow to be thin, axisymmetric, and rotating around a vertical axis. To avoid integrating in a direction transverse to flow motion, we consider that the

flow is in hydrostatic equilibrium in the vertical direction, as in Chakrabarti (1989). In TCAF, CENBOL is basically the post-shock region of a low angular momentum, sub-Keplerian flow. It is comparatively hotter, puffed up, and much like an ion-supported torus (Rees et al. 1982). Due to the inverse Compton cooling effect of intercepted low-energy photons from a Keplerian disk, the energy of CENBOL decreases and is radiated away. The energy equation at the shock is modified by

$$\varepsilon_+ = \varepsilon_- - \Delta\varepsilon, \quad (1a)$$

where $\Delta\varepsilon$ is the energy loss due to Comptonization. The baryon number conservation equation at the shock is

$$\dot{M}_+ = \dot{M}_-. \quad (1b)$$

Since the gas is puffed up, R-H conditions (Landau & Lifshitz 1959) have to be modified so that only vertically integrated pressure and density parameters are important. This modification was first carried out in (Chakrabarti 1989), where pressure balance condition was modified using vertically integrated values:

$$W_+ + \Sigma_+ v_+^2 = W_- + \Sigma_- v_-^2. \quad (1c)$$

Here, W and Σ are pressure and density, integrated in the vertical direction (Matsumoto et al. 1984). In our solution, we use Equation (8a) of Paper I as an invariant quantity at the shock, which is given by

$$\frac{\left[M_+(3\gamma - 1) + \left(\frac{2}{M_+} \right) \right]^2}{2 + (\gamma - 1)M_+^2} = \frac{\left[M_-(3\gamma - 1) + \left(\frac{2}{M_-} \right) \right]^2}{2 + (\gamma - 1)M_-^2 - \zeta}, \quad (2)$$

where M , v , and γ are the Mach number, radial velocity, and adiabatic index of flow, respectively, $\zeta = 2\Delta\varepsilon(\gamma - 1)/a^2$. Here, a is adiabatic sound speed. We follow the same mathematical procedure and methodology as Paper I to find shock location for a given cooling rate. In the standard theory of thin accretion flows around black holes (Shakura & Sunyaev 1973), viscosity plays a major role. Giri & Chakrabarti (2013) show formation of Keplerian disk for the super-critical α parameter (Chakrabarti 1990b). The inflow angular momentum is transported outward by viscosity, allowing it to fall into the black holes. As the shock moves closer, the angular momentum must be adjusted by the viscosity so that the shock formation is theoretically allowed. For our viscosity calculation, we use the relation (Chakrabarti 1990b)

$$\dot{M}(\lambda - \lambda') = -r^2 W_{r\phi}, \quad (3)$$

where $W_{r\phi} = -\alpha P$ is the viscous stress, α being the Shakura & Sunyaev (1973) viscosity parameter. The angular momentum variation from Equation (4) can be written as

$$\Delta\lambda = \frac{\alpha r a^2}{v}, \quad (4)$$

where $\Delta\lambda = (\lambda - \lambda')$ is the change in angular momentum (λ) due to viscous transport.

2.1. Methodology of the $\Delta\varepsilon$ Calculation

We analyze archival data of eight observational IDs of the *RXTE*/PCA instrument (only PCU2, all layers), starting from 2010 August 9 (Modified Julian Day, i.e., MJD = 55417.2) to 2010 August 16 (MJD = 55424.1), selected from the rising phase of the 2010 outburst of H 1743-322. We carry out data

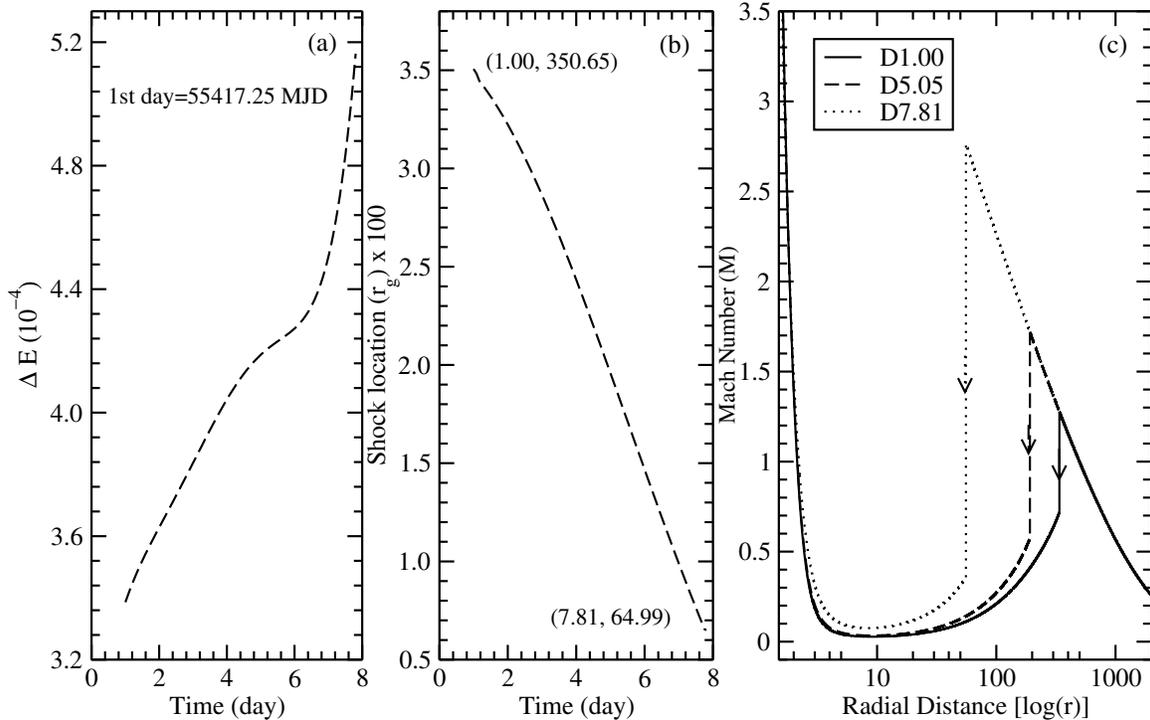


Figure 1. Variations of (a) cooling rate and (b) shock location with time (in days) during the rising phase of the H 1743-322 2010 outburst are shown. In panel (c), the mach number variation with logarithmic radial distance is shown.

analysis using the FTOOLS software package HeaSoft version HEADAS 6.14 and XSPEC version 12.8. For the generation of source and background ‘.pha’ files and spectral fitting (in the 2.5–25 keV energy range) using combined disk blackbody and power-law models, we use the same method as described in Debnath et al. (2013). After achieving a best fit based on the reduced chi-square value ($\chi^2_{\text{red}} \sim 1$), we integrate only the power-law component of the spectrum. This can be written as

$$\sum_{i=E_l}^{E_u} E_i F_{\text{Comp}}(i),$$

where E_l and E_u are the lower and the upper limits of the energy. For interstellar photoelectric absorption correction, we follow the prescription of Morrison & McCammon (1983). To calculate the cooling time of the Compton cloud (CENBOL) from the observed spectrum, we consider the distance correction in following way. We multiply the integrated spectrum by the model normalization value (norm) of $(4\pi D^2/\cos i)$, where D is source distance in 10 kpc unit and i is the disk inclination angle. In the case of H 1743-322, we use a source distance of $d = 8.5$ kpc and $i = 75^\circ$ (Steiner et al. 2012). We keep the hydrogen column density (N_{H}) frozen at 1.6×10^{22} atoms cm^{-2} for the absorption model *wabs* and assume a 1.0% systematic error for all observations (Mondal et al. 2014b).

3. RESULTS

In this paper, we study the origin and evolution of QPOs in the outbursting BHC H 1743-322 from a purely analytical point of view. In Chakrabarti & Titarchuk (1995) and Das & Chakrabarti (2004), it was shown that matter from the companion is heated due to compression and puffed up due to the centrifugal barrier to form a CENBOL. Low-energy photons from a Shakura & Sunyaev (1973) disk with an accretion rate of

\dot{m}_d are intercepted by CENBOL and are emitted as high-energy photons after inverse Comptonization. In Figure 1(a), we show that the rate of cooling of the CENBOL in progressive days during the rising phase of the outburst. As the day progresses, the amount of cooling increases and the shock moves toward the black hole (MSC96), which is shown in Figure 1(b). On the first observed day of the outburst (MJD = 55417.2), the location of the shock (X_s in Schwarzschild radius $r_g = 2GM/c^2$) was at $350.65 r_g$, and at the end of our observation (MJD = 55424.1), it reaches $\sim 64.99 r_g$. In Figure 1(c), we show the Mach number variation of the flow in first day (solid curve, shock was at $350.65 r_g$), 5.05th day (dashed curve, shock was at $191.69 r_g$) and 7.81th day (dotted curve, shock was at $64.99 r_g$) of the outburst. We calculate the velocity of movement of the shock to be $\sim 13.11 \text{ ms}^{-1}$, which roughly matches with the final velocity of the shock wave calculated from the POS model fit of the QPO frequency evolution (see Debnath et al. 2013). In Figure 2(a), we show variations of observed QPO frequencies with time. If the viscosity parameter α were constant throughout the outburst, then the variations of theoretically calculated QPO frequencies would be different. The dotted curve drawn for a viscosity parameter (α) 0.001 shows that QPO frequency increases at an almost constant rate. The dashed curve of Figure 2(a) is for the effect of non-linear variation of the viscosity, which is shown in Figure 2(b). As the day progresses, viscosity adjusts in such a way that the angular momentum can produce a shock at a suitable place that satisfies R-H conditions. Chakrabarti & Molteni (1995) and Giri & Chakrabarti (2012), with their extensive numerical simulations, showed that the angular momentum distribution depends on the viscosity parameter. In our solution, at the beginning of the outburst during the hard state from MJD = 55417.2 to MJD = 55420.2 (Debnath et al. 2013; MDC14), α varies from $1.3e-4$ to $5.9e-4$. During the hard-intermediate state from MJD = 55421.3 to MJD = 55424.1 (Debnath et al. 2013;

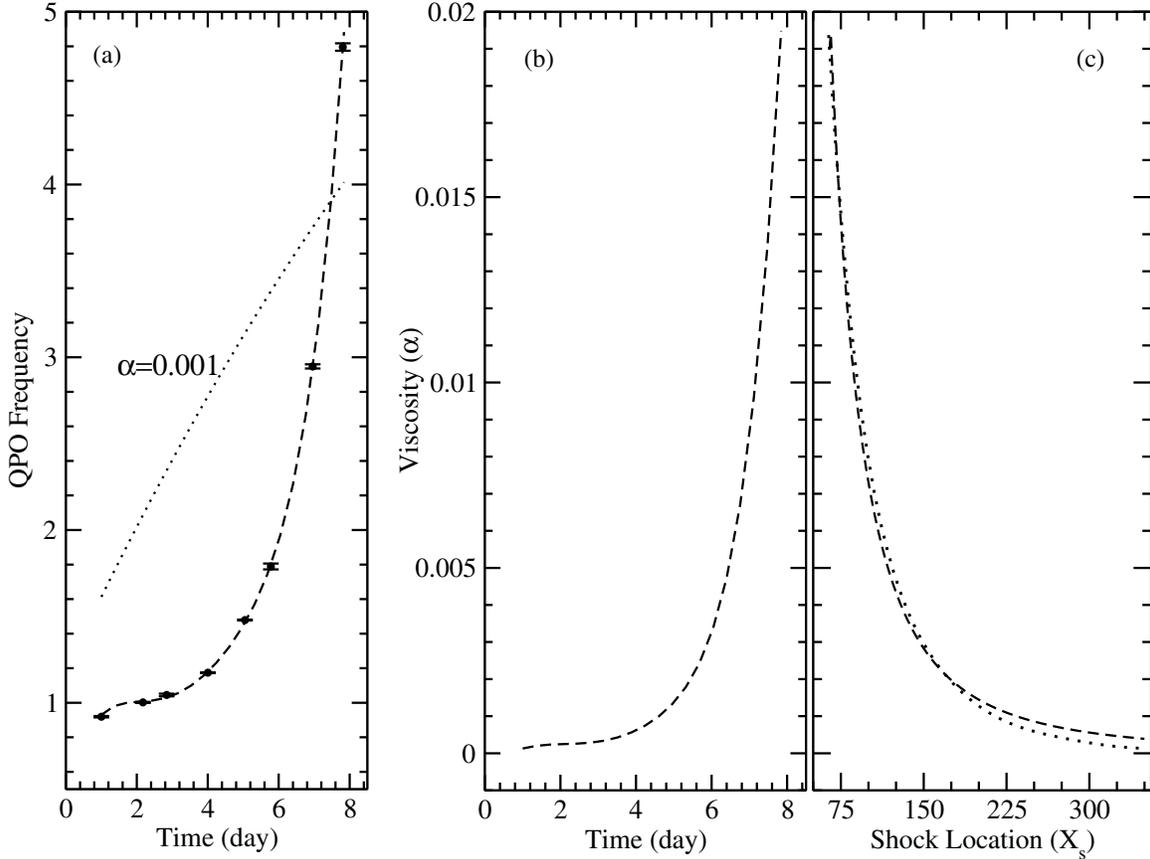


Figure 2. Variation of (a) QPO frequency with progressive days during the rising phase of the 2010 outburst of H 1743-322, both obtained from observation and analytical solutions. In panel (b), the variations of viscosity with time (in days) and (c) with shock location are shown. Here viscosity is calculated only for the sub-Keplerian component of the accretion flow.

Mondal et al. 2014b), α varies rapidly from $1.6e-3$ to $1.9e-2$. Our α calculation is for the sub-Keplerian component only. In Figure 2(c), we show the variation of α with shock location. The dashed curve shows the variation from our analytical solution, whereas the dotted curve is a fitted polynomial, which gives a general trend and could be used in other systems. We see that $\alpha \sim \mathcal{K} X_s^{-q}$, where \mathcal{K} ($=350.2$, with asymptotic standard error 6.29%) and q ($=2.34$, with asymptotic standard error 0.61%) are constants for this BHC. It should be noted that this viscosity parameter is computed for the sub-Keplerian flow component only.

4. DISCUSSIONS AND CONCLUDING REMARKS

QPOs in black hole candidates are very stable features. They are seen day after day, though the frequency may drift slowly as the object goes from the hard to the soft state in the rising phase. This is generally observed in most of the outbursting BHCs (Nandi et al. 2012; Debnath et al. 2013, and references therein). The propagatory oscillating shock solution can explain such frequency drifts very well (Chakrabarti et al. 2008; Debnath et al. 2013). This phenomenological model is found to be justified when we actually compute the shock drifts from radiated energy loss from a self-consistent transonic solution. We find that in order to have Rankine–Hugoniot conditions satisfied each day, the viscosity parameter must be evolving as well. If the outer boundary condition is kept fixed, an increase in the viscosity parameter causes the shock to drift outward,

(Chakrabarti & Molteni 1995; Giri & Chakrabarti 2012), but if the inner boundary condition is kept fixed, the shock moves inward (Chakrabarti 1990a; Das & Chakrabarti 2004). We find support of the latter phenomenon in an outbursting source where the matter supply is changing and the viscosity enhancement steadily brings the shock closer to the black hole. Cooling is found to rise day by day and so is α . Such a movement of the shock increases QPO frequency, as is observed. Our result establishes consistency in theoretical understanding of the observed data: as cooling increases, the observed QPO frequency increases due to drifting of the shock toward black hole in a way that the cooling timescale roughly matches with the infall timescale. This process brings the object toward the softer state, as is observed. Shock locations were found to be located at the right place (i.e., R-H conditions are satisfied) only if the viscosity is not strictly constant but gradually rises from 0.0001 to 0.02 from the first day to \sim seventh day. It should be noted that there are alternative models (Titarchuk & Fiorito 2004; Titarchuk et al. 1998) where the corona is supposed to oscillate at its eigen frequency and the viscosity required in this case is around 0.1–0.5. This appears to be too high compared to what we find in the present paper. The discrepancy could be due to the fact that the latter models rely on oscillations of a Keplerian disk with high angular momentum, and they require higher viscosity to reduce it drastically. On the contrary, in our case, the oscillating CENBOL is highly sub-Keplerian to begin with, therefore a little viscosity is enough the transport requisite angular momentum. This range of α we require is in the same

range as that obtained from numerical simulations (Balbus & Hawley 1991; Arlt & Rüdiger 2001; Masada & Sano 2009) of magnetorotational instability.

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