Delayed Outburst of H 1743–322 in 2003 and relation with its other outbursts

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Abstract

The Galactic transient black hole candidate H 1743–322 exhibited a long duration outburst in 2003 after more than two and a half decades of inactivity. The 2003 event was extensively studied in multi-wavelength bands by many groups. The striking feature is that the total energy released is extremely high as compared to that in tens of outbursts which followed. In this paper, we look at this event and study both the spectral and temporal properties of the source using two component advective flow (TCAF) paradigm. We extract accretion flow parameters for each observation from spectral properties of the decay phase and determine the mass of the black hole. We computed the energy released during all the known outbursts since 2003 and showed that on an average, the energy release in an outburst is proportional to the duration of the quiescent state just prior to it, with the exception of the 2004 outburst. A constant rate of supply of matter from the companion cannot explain the energy release in 2004 outburst. However, if the energy release of 2003 is incomplete and the leftover is released in 2004, then the companion’s rate of matter supply can be constant since 1977 till date. We believe that erratic behaviour of viscosity at the accumulation radius $X_p$ of matter as well as location the $X_p$ itself, rather than the random variation of mass transfer rate from the companion, could be responsible for non-uniformity in outburst pattern. We discuss several factors on which the waiting time and duration

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The Galactic transient low mass black hole candidate (BHC) H 1743–322 was discovered using HEAO-1 and Ariel-V satellites (Doxsey et al. 1977; Kaluzienski & Holt 1977) around 40 years ago. The binary system is at $R.A. = 17^h46^m15.61^s$ and $Dec = -32^\circ14'0.6''$ (Doxsey et al. 1977). It is located $8.5 \pm 0.8$ kpc away at inclination of $75^\circ \pm 3^\circ$ and its spin is $-0.3 < a < 0.7$ (Steiner et al. 2012). Multiple studies of various outbursts of this source estimated the mass of H 1743–322 but dynamically measured value is not available. Petri (2008) estimated the mass to be $\sim 9 - 13M_\odot$ based on certain high frequency QPO model. Shaposhnikov & Titarchuk (2009) with the use of another reference mass estimated its mass at $13.3 \pm 3.2M_\odot$ using their spectral index - QPO frequency correlation method. Recently, Molla et al. (2017) estimated its mass to be $11.21^{+1.65}_{-1.96}M_\odot$ based on timing and spectral properties of 2010 and 2011 outbursts. Bhattacharjee et al. (2017) used the Two component Accretion Flow (TCAF) model to fit data of 2004 outburst and estimated the mass to be in the same range.

During its 1977-78 outburst, the source was observed several times with the HEAO-1 satellite in hard X-rays (Cooke et al. 1984). After that it was dormant in X-rays for more than two decades. On 2003 March 21, the source was rediscovered by the INTEGRAL satellite (Revnivtsev et al. 2003). The duration of this outburst was long compared to its other outbursts and it was studied by various groups in different wave-bands to explore multi-wavelength properties of the source. Though this 2003 outburst was studied extensively by Parmar et al. (2003); Homan et al. (2005); Remillard et al. (2006a); McClintock et al. (2009) in X-rays, McClintock et al. (2009) in optical and near-infrared and Steeghs et al. (2003); Rupen et al. (2003) in radio bands etc., it has not been studied with physical accretion flow models such as, TCAF solution to obtain physical flow parameters. Furthermore, no attempt has been made to compare all these outbursts in terms of the total energy release, peak counts, duration of soft states and duration of outbursts and most importantly to have a general understanding of the behaviour of this source across the outbursts. Earlier, Yu & Yan (2009) and Yan & Yu
(2015) made comparative studies for several outbursts observed by RXTE. We use a similar method to compute the total energy release in this paper from the RXTE/ASM data or MAXI/GSC data and go beyond to understand the accretion flow properties and the nature of mass transfer rate from the companion.

The evolution of the spectral and the temporal properties during 2003 outburst is generally found to be similar to other classical outbursting sources, such as GRO J1655–40, XTE J1550–564, GX 339–4, etc. The presence of low-frequency as well as high frequency quasi-periodic oscillations (QPOs) (Homan et al. 2005; Remillard et al. 2006b), other than observation of strong spectral variability during this particular outburst of H 1743–322, makes it an ideal case to study in X-rays (Capitanio et al. 2005; Homan et al. 2005; Remillard et al. 2006a; Kalemcı et al. 2006; Prat et al. 2009; McClintock et al. 2009; Stiele et al. 2013). Large-scale relativistic X-ray and radio jets were also observed during the 2003 outburst (Rupen et al. 2004; Corbel et al. 2005), largest one appeared to have started about two weeks before the peak X-ray flux is reached.

Since the 2003 outburst, several recurring X-ray outbursts of roughly two months duration at every six months to two years gap have been observed. The integrated energy release in the 2003 outburst is several order of magnitude larger as compared to the other outbursts. The overall light curve of this event has many high and low counts giving it an unsettling look. Using TCAF model, the spectra of several outbursts of this source which occurred in 2004, 2010 and 2011 (Bhattacharjee et al. 2017; Debnath et al. 2013; Mondal et al. 2014; Molla et al. 2017) were fitted. The successful fits allow us to find the variation of the accretion rates of the Keplerian, the sub-Keplerian components of the flow, and the size of the Compton cloud on a daily basis. Because the normalization of TCAF (a factor between the computed spectrum and the observed spectrum by a specific instrument) is a constant, even from each independent sample of spectral data, we could estimate the mass of the black hole and not surprisingly they agree within acceptable error-bar. We therefore were motivated to fit the spectra of the 2003 outburst using TCAF which relies on steady state equations of the viscous (disk) and inviscid (halo) transonic flow. We also want to generate insight into this system as a whole, as it moved from one outburst to another.

In the next Section, we study the spectral and temporal properties of the X-ray data obtained during the 2003 outburst using TCAF model. In §3, we present the flow parameters and the black hole mass obtained from this
outburst. Because of the unsettling nature, conventional phenomenological model diskbb plus power-law gives very fluctuating disc and Compton cloud parameters during most of the days of this outburst (McClintock et al. 2009). It is possible that the flow accretion rate itself varies with radial distance either because some magnetic fields are taking away matter from various radii or because the flow supply from the accumulation radius itself is erratic and there was always a radial variation of the accretion rate of the Keplerian component. In either of these two cases, no existing model is capable of fitting the spectra satisfactorily. With the physical TCAF solution, which requires steady state flows, fits of those days become unsatisfactory, i.e., model fitted reduced $\chi^2$ values were found to be $> 2$. Hence, we had to choose the data near the end of the outburst where the disc became somewhat steady. In §4, we study all sky monitor data from RXTE and MAXI/GSC of all the outbursts since 2003 and compare their behaviour. We study the variations of total energy released per outburst and the amount of matter accumulated in the preceding quiescent state. In §5, we briefly present a scenario of how the disc may be evolving with time and draw our conclusions.

2. Observation and Data Analysis

The archival data from RXTE observations using All Sky Monitor (ASM) and Proportional Counter Array (PCA) unit 2 (PCU2) are used for temporal and spectral study. We also use MAXI/GSC one day average data to show source behaviour after RXTE era. We use Crab conversion factor of 75 Counts/sec for RXTE ASM data in $1.5 - 12$ keV energy band and $2.82$ photons sec$^{-1}$ cm$^{-2}$ for MAXI GSC data in $2 - 10$ keV energy range, to make count rates in generalized Crab unit as is usually done (see http://xte.mit.edu).

For the timing analysis, we use PCA Science Binned/Event mode data with maximum timing resolution of $125\mu$s to generate light curves for PCU2 data in $2-15$ keV (0-35 channels). The routine “powspec” was used to compute rms fractional variability on $2-15$ keV light curves of $\sim 0.01$s time bin. We obtain the power density spectra (PDS) after normalization and dead-time corrections. The QPO profiles are assumed to be Lorentzian functions and are decided on the basis of Q-factor, $Q = \nu / FWHM > 2$. We average QPO properties over each observation and find QPOs for all observations available throughout the outburst.
We use the spectra obtained from PCU2, the best-calibrated detector module in PCA (Jahoda et al. 2006) to carry out the spectral analysis of 2003 outburst data. These spectra are 16s binned “Standard2” data. The spectra were corrected for background and a systematic error of 1% (McClintock et al. 2009) was used to account for statistical errors in counts. For the analysis, HeaSOFT package version 6.19 was used with XSPEC 12.9.0 (Arnaud 1996). We use TCAF model (local model with fits file TCAF_x0.3.fits) following methods explained in greater details by Debnath et al. (2014, 2015a,b); Mondal et al. (2014, 2016); Molla et al. (2016, 2017); Jana et al. (2016); Chatterjee et al. (2016); Bhattacharjee et al. (2017) to obtain fits of the spectra along with tbabs (Wilms et al. 2000) to account for interstellar extinction. We take the fixed value of hydrogen column density at $N_H = 1.6 \times 10^{22}$ atoms cm$^{-2}$ (Capitanio et al. 2009). In most of the spectra, we add a Gaussian $Fe K\alpha$ emission line to get a better model fit. The central line energy and line width of Gaussian were kept in the range of $6.2 - 7.0$ keV and $0.1 - 0.8$ keV respectively.

3. Results of the 2003 Outburst

3.1. The Outburst profile

After its discovery in 1977, the source was completely dormant until its high flaring activity in 2003. Although a detection ($\sim 5 mCrab$) was reported by EXOSAT in 1984 (Parmar et al. 2003; Reynolds et al. 1999), it was just a passing detection at a quiescence level during slewing the telescope and was not an outburst. Another weak X-ray activity was reported by TTM in 1996 (Emelyanov et al. 2000) but RXTE, though active in this era, never mentioned about it. Thus we ignore both of these ‘events’. This outburst started on 21$^{st}$ March 2003 (Revnivstev et al. 2003) and ended in last week of October 2003 (Tomsick & Kalemci 2003). Since then, RXTE along with other satellites, obtained data from other outbursts of H 1743–322 in 2004, 2005, 2007, 2008, 2009, 2009/10, 2010 and 2011. In the years after RXTE was decommissioned, H 1743–322 continues to show outbursting behavior with a similar duration of $\sim 2$ months with a gap of $\sim 6$ months to $\sim$ year. Fig. 1 shows the RXTE/ASM 1.5 - 12 keV light curve (online violet) and the MAXI/GSC 2-10 keV light curve (online green) of H 1743–322 during RXTE (starting from Aug. 2002; MJD=52500) and MAXI era (Aug. 2009 to Jan. 2017), respectively. Usually, maximum RXTE/ASM 1.5 - 12 keV count rates during the outbursts of this BHC in RXTE era is $\sim 0.2 - 0.3$ Crab. The
2008 outburst of H 1743–322 was dubbed as “failed”, where the count rates did not go above 0.133 Crab (10 counts per second) (Capitanio et al. 2009; Zhou et al. 2013) and softer spectral states were not observed. However, Fig. 1 shows that during 2003 outburst, the maximum ASM 1.5 – 12 keV count rates reached 1.33 Crab (\(\sim 100\) counts per second). It is the brightest outburst that H 1743–322 has shown during RXTE era. Only a few other BH sources have ever reached more than this high value of count rates. The 2003 outburst lasted for the longest duration of \(\sim 8\) months, whereas other H 1743–322 outbursts lasted for \(\sim 2\) months.

It is clear that after the 2003 outburst, H 1743–322 underwent a fundamental change in its accretion disc configuration from which it has not reverted back till date. It did not show any major long outburst for more than two decades before 2003 outburst. However, afterwards, it has shown short duration (\(\sim 2\) months) outbursts every year. A stable quiescent configuration which existed between 1977/78 and 2003 outbursts seems to have been disturbed. During the outburst of 2003, the disc could be unsettled as no satisfactory fits with conventional models could be made. The source went to the Hard State at the end of 2003 outburst. This Hard State was found to differ from the pre-outburst Hard State because a disc black body
component continued to exist even after the Soft State was over (Capitanio et al. 2005; Lutovinov et al. 2004). This is unusual and warranted investigation as to whether the disc was really evacuated in 2003. Following the transition of H 1743–322 to the Hard State (Tomsick & Kalemci 2003) on MJD 52933, significant radio emissions were also found (Corbel et al. 2005). We discuss about the possible scenario later below.

In Fig. 2, we show how we fitted each outburst light curve (black lines with points) with Fast Rise and Exponential Decay (FRED) profile (online blue). The quiescent states generally have a count rate equivalent to about a few mCrab. A limit of 12mCrab was taken for all the outbursts so that energy release above may be integrated to measure the Integrated Counts released per outburst.

The Fast Rise Exponential Decay (FRED) profile was developed by Kocevski et al. (2003) and has since been used by many to interpolate the data gaps. The behavior of the light curve is described by the relation,

\[ F(t) = F_m \left( \frac{t}{t_m} \right)^r \left[ \frac{d}{d+r} + \frac{r}{d+r} \left( \frac{t}{t_m} \right)^{r+1} \right]^{(r+d)/(r+1)} \]

where, \( F_m \) is the maximum flux at time \( t_m \). The rising and decaying indices are represented by \( r \) and \( d \), respectively. We used this profile to fit ASM/GSC data of all outbursts of H 1743–322. In Fig. 2, we note that there are seven peaks in this data, we used a combination of seven FRED profiles to fit this outburst behaviour. Once proper fits were obtained, we used quiescent count value (12 mCrab) to mark the start and end of the outbursts. In Fig. 2, both start and end are shown with short vertical red lines drawn using the above criterion.

3.2. Spectral Analysis of declining phase of 2003 outburst

We studied the declining HIMS and HS data with the current version (v0.3) of the TCAF model fits file in XSPEC. A reasonable good spectral fit (reduced \( \chi^2 < 1.2 \)) with the TCAF solution during the declining phase (MJD 52936 – 50) was obtained. Fits in other regions of the 2003 outburst with the TCAF, were found to be unsatisfactory. There are two possibilities for this: (a) The accretion rate of Keplerian matter rushing in due to enhanced viscosity at the accumulation radius may develop radial dependence at time scales below viscous time because of which no model, which typically assumes steady rates, can fit the spectra. (b) Matter with high angular momentum may start shading gas all the way in the form of outflows. As a result a radial dependence in accretion rate may ensue which causes failure to fit the spectrum. Such issues do not arise for a phenomenological model such
Figure 2: FRED profile fitting on 2003 outburst data (blue). For all outbursts, the quiescent value of counts was taken to be equivalent to 12mCrab. A horizontal line (red) with this value of counts was drawn. The points where the FRED-fitted curve touches this line are the start (in the rising phase) and end (in the declining phase) of the outburst. Both start and end are shown with short vertical red lines. This method is followed for all outbursts of our study.
as a diskbb plus power-law model which does not question the origin of
the Compton cloud or the seed photons. The rising phase of the outburst is
highly jet dominated with large fluctuations in disc blackbody and power-law
component fluxes. The whole profile exhibits multiple-outbursting activities
within a single ‘2003’ outburst. We interpret this to be due to wild fluctuation
of viscosity at the accumulation radius in the outer disc. We discuss this later.

Five model input parameters, (i) black hole mass \((M_{BH}/M_{\odot})\), (ii) Ke-
plerian disc accretion rate \((\dot{m}_d/\dot{M}_{\text{Edd}})\), (iii) sub-Keplerian accretion rate
\((\dot{m}_h/\dot{M}_{\text{Edd}})\), (iv) the shock location, \((X_s/(r_g = 2GM_{BH}/c^2))\) and (v) com-
pression ratio at shock \((R=\text{ratio of post-shock and pre-shock densities})\) other
than normalization are used in TCAF-model. The spectral parameters ob-
tained from our analysis are shown in Table 1. From the spectral fits, the
mass of H 1743–322 is found to be in between \(9.4 M_{\odot}\) to \(12.5 M_{\odot}\). The av-
erage of the observed mass of the source is \(\sim 11.4 \pm 0.33 M_{\odot}\). TCAF enables
us to estimate the mass just by restricting the normalization to a constant
or nearly constant value (its actual number derived through the fits is not
important determining the mass itself). The normalization \((Norm)\) is found
in a narrow range \((0.61 - 0.67)\) with an average value of \(\sim 0.62 \pm 0.17\). The
shock-location \((x_s)\) moves outward from \(\sim 21r_g\) to \(\sim 372r_g\). The compression
ratio \((R)\) increases from \(\sim 1.1\) to \(\sim 2.3\). To obtain best fit, we used Gaus-
sian Fe-line at \(\sim 6.5\) keV for most of the observations. The mass obtained
from this analysis is in the same ball park as obtained in previous estimates
mentioned in §1. However unlike some other works, our mass measurement
is stand-alone. The evolution of all parameters during the declining phase
are shown in Fig. 3.
### Table 1: Spectral properties

| S.N. | Obs-Id | MJD | $m_d$ (52900+) | $m_h$ (52900+) | $M_{BH}$ (M☉) | $X_s$ | R | Norm. Gaussian | $\chi^2_{red}$/d.o.f. |
|------|--------|-----|----------------|----------------|---------------|--------|---|----------------|----------------------|
| 1    | X-24-00 | 36.047 | 2.49±0.02 | 0.485 | 9.37±0.11 | 20.4±0.3 | 1.08±0.01 | 0.62±0.03 | 6.95 | 1.19/40 |
| 2    | X-25-00 | 37.047 | 2.79±0.05 | 0.477 | 10.23±0.66 | 26.6±1.2 | 1.11±0.02 | 0.60±0.01 | 6.92 | 1.14/40 |
| 3    | X-26-00 | 38.016 | 2.58±0.03 | 0.456 | 13.97±0.86 | 32.4±1.4 | 1.08±0.02 | 0.61±0.03 | 7.00 | 1.16/40 |
| 4    | X-27-00 | 39.133 | 2.37±0.05 | 0.423 | 11.92±0.48 | 31.1±1.9 | 1.08±0.01 | 0.59±0.01 | 6.83 | 1.00/40 |
| 5    | X-28-00 | 42.156 | 1.81±0.05 | 0.336 | 12.18±0.90 | 42.9±1.2 | 1.09±0.02 | 0.62±0.05 | 6.72 | 0.57/40 |
| 6    | X-29-00 | 42.703 | 1.51±0.03 | 0.292 | 12.15±0.18 | 47.3±2.1 | 1.09±0.04 | 0.61±0.01 | — | 0.84/43 |
| 7    | Y-01-00 | 44.137 | 1.12±0.04 | 0.266 | 11.26±0.76 | 86.0±7.5 | 1.08±0.01 | 0.62±0.04 | 6.55 | 0.70/40 |
| 8    | X-30-00 | 45.180 | 0.88±0.03 | 0.240 | 12.54±0.94 | 136.5±8.6 | 1.11±0.01 | 0.64±0.06 | 6.66 | 0.59/40 |
| 9    | Y-01-01 | 46.105 | 0.74±0.06 | 0.231 | 10.99±0.47 | 179.2±2.3 | 1.33±0.04 | 0.62±0.03 | 6.74 | 1.11/40 |
| 10   | X-31-00 | 47.043 | 0.70±0.02 | 0.199 | 10.49±0.13 | 222.3±6.4 | 1.60±0.08 | 0.67±0.06 | 6.70 | 0.89/40 |
| 11   | X-32-00 | 48.211 | 0.65±0.02 | 0.173 | 11.33±0.71 | 254.5±14.3 | 1.67±0.09 | 0.63±0.04 | 6.65 | 0.91/40 |
| 12   | Y-01-02 | 49.195 | 0.59±0.03 | 0.149 | 11.17±0.68 | 299.1±3.9 | 1.97±0.09 | 0.66±0.04 | 6.62 | 0.88/40 |
| 13   | X-34-00 | 50.457 | 0.53±0.02 | 0.102 | 12.41±0.17 | 372.3±9.9 | 2.31±0.08 | 0.64±0.04 | 6.69 | 0.95/40 |

X=80137-01; Y=80137-02
The state transition from the Hard-Intermediate State to Hard State which occurred on $MJD \, 52942.1$ is indicated by a vertical line in Fig. 3. This is done on the basis of changes in shock location and compression ratio. Since TCAF analysis covers only the declining HIMS and HS regions of the outburst, we rely on spectral and temporal analysis of McClintock et al. (2009) using combined disc blackbody, power-law and broken power-law models. Based on the degree of importance of thermal (disc black body) and non-thermal (power-law or broken power-law) components and nature of QPOs (if present), as suggested by Debnath et al. (2013), we can classify the entire 2003 outburst into four spectral states, Hard (HS), Hard-Intermediate (HIMS), Soft-Intermediate (SIMS) and Soft (SS). The nature of the variations of hardness ratios also confirms our classification. As of other transient BHCs (GRO J1655–40, GX 339–4, MAXI J1659–152, MAXI J1543–564) reported previously (see, Chakrabarti et al. 2008; Nandi et al. 2012; Debnath et al. 2008, 2015a,b; Chatterjee et al. 2016), monotonic evolutions of QPO frequencies are observed in HS and HIMS from both the rising and declining phases of the outburst and sporadic QPOs are seen during SIMS from both rising and declining phases of the outburst and no low frequency QPOs are observed in SS. It seems that spectral transition occurs from HS (Rising phase) to HIMS (Rising phase) on 2003 March 31 ($MJD=52729.8$), on 2003 April 6 ($MJD=52735.7$) from HIMS (Rising phase) to SIMS (Rising phase), on 2003 June 30 ($MJD=52830.4$) from SIMS (Rising phase) to SS, on 2003 October 18 ($MJD=52930.9$) from SS to SIMS (Declining phase), on 2003 October 24 ($MJD=52936.0$) from SIMS (Declining phase) to HIMS (Declining phase) and finally on 2003 October 30 ($MJD=52942.7$) from HIMS (Declining phase) to HS (Declining phase). This last transition is marked with a vertical line in Fig. 3.

3.3. Study of QPO evolution with POS Model

In TCAF paradigm, the shock oscillations and consequent oscillations of Comptonized X-rays result in Low Frequency QPOs (Chakrabarti & Manickam 2000). Type-C QPOs are the results of near resonance between cooling time and infall (compressional heating) time of the post-shock region (Molteni et al. 1996; Chakrabarti et al. 2015) or non-fulfillment of Rankine-Hugoniot conditions (Ryu et al. 1997). Weak resonances result in the formation of type-B QPOs. When shocks are not produced but the centrifugal barrier is formed, and the oscillations are tentative, different regions oscillating in different phases, form type-A QPOs. The declining phase of the
2003 outburst of H 1743–322 shows signatures of type-C QPOs and transitions from HIMS to HS as seen in other outbursts (Debnath et al. 2013, 2015a; Molla et al. 2016). We study the evolution of QPO frequency during this declining phase using the so-called propagating oscillatory shock (POS) model (Chakrabarti et al. 2005, 2008; Debnath et al. 2010, 2013; Nandi et al. 2012). In this case, the shock is propagating and oscillating at the same time, giving rise to variation of QPO frequencies since both the time scales are also changing. The equation for QPO frequency in this model is 

$$\nu_{QPO} = \frac{\beta}{[X_s(X_s-1)^{1/2}]},$$ 

where ‘$$\beta = 1/R_0 \pm t_d^2/\alpha$$’ is the shock strength, ‘$$R_0$$’ is the compression ratio ‘$$R$$’ on the first day of QPO evolution, $$t_d$$ is the time in days and $$\alpha$$ is a constant number deciding how ‘$$R$$’ strengthens or weakens with QPO evolution period. The instantaneous shock location is given as, 

$$X_s(t) = X_{s0} \pm V(t) t_d/M_{BH}$$ 

where $$X_{s0}$$ is the shock location on the first day, ‘-’ sign is used for rising phase when shock comes closer to the black hole and ‘+’ sign is used for the declining phase when the shock location increases with time. The instantaneous velocity of shock is given by $$v(t) = v_0 \pm ft_d$$ where $$v_0$$ is the velocity on the first day and ‘$$f$$’ is the acceleration/deceleration of the shock.

We study the QPO evolution in the declining phase of the 2003 outburst.
from October 24 (start of HIMS) till November 2 (the last day when QPO was observed) for the duration of 9 days. A best fit of the evolution was obtained using the average mass which was found from TCAF model present above with a slowly accelerating \((f = 8 \text{ cm s}^{-1} \text{ day}^{-1})\) shock wave. The shock starts to move outwards on \(MJD = 52936.05\) from \(\sim 73r_g\) at \(\sim 294 \text{ cm/sec}\) and reaches \(\sim 158r_g\) at \(367\text{ cm/sec}\) on the last day when QPO was observed. This is normal and is seen in all other outbursting objects. Fig. 4 shows the theoretical values of QPO frequencies plotted along with observed values. Table 1 shows the POS-model fitted parameters during the QPO evolution.

4. Comparison among the Outbursts of H1743–322

During our analysis, we found that the 2003 and part of 2004 (see also Bhattacharjee et al. 2017) outbursts are very unsettling in the sense that either the model fitted parameters fluctuate on a daily basis as in the phenomenological diskbb plus power-law model or it is impossible to fit the data with TCAF which satisfactorily fitted other outbursts (Mondal et al. 2014; Molla et al. 2017). Thus the disc structure is clearly non-steady and evolving. Therefore, we wanted to compare all the outbursts observed till date and and draw some conclusions about the general scenario about disk evolution and supply rate of matter from the companion.
Table 2: QPO evolution fitting with POS model

| S.N. | Obs-Id | MJD   | \(QPO_{freq}\) | \(QPO_{freq}\) | \(X_s\) | \(v\) | \(R\) |
|------|--------|-------|----------------|----------------|--------|------|------|
|      |        |       | (Days)         | (Hz.)          | (Hz.)  | (\(r_g\)) | (cm/s) |     |
| 1    | X-24-00| 52936.0| 7.82±0.32      | 7.82           | 73.7   | 300  | 1.78 |
| 2    | X-25-00| 52937.0| 6.97±0.11      | 6.72           | 81.3   | 308  | 1.79 |
| 3    | X-26-00| 52938.0| 5.86±0.12      | 5.82           | 89.1   | 315  | 1.80 |
| 4    | X-27-00| 52939.1| 5.86±0.17      | 4.94           | 98.5   | 324  | 1.82 |
| 5    | X-28-00| 52942.2| 2.85±0.09      | 3.16           | 126.6  | 348  | 1.95 |
| 6    | X-29-00| 52942.7| 2.80±0.14      | 2.92           | 132.0  | 353  | 1.99 |
| 7    | Y-01-00| 52944.1| 2.44±0.09      | 2.34           | 147.0  | 364  | 2.10 |
| 8    | X-30-00| 52945.2| 2.00±0.03      | 1.99           | 158.4  | 373  | 2.21 |

X=80137-01; Y=80137-02

At the outset we must mention that the black hole outbursts are totally different from the dwarf novae outbursts in that the high energy radiation observed in the former clearly indicates interaction of the Compton cloud with the disc, and both could be emitting X-rays. It is also clear that for black hole candidates, the so-called Compton cloud must change its property very fast and this is possible if there is a steady supply of sub-Keplerian and hot halo matter which makes and constantly replenishes the Compton cloud. TCAF model is based on exact solutions of transonic flows whose topologies change fundamentally at a critical viscosity parameter. For sub-critical parameter, the flow still forms shocks close to the centrifugal barrier as in an inviscid flow (Chakrabarti, 1990). However, for a super-critical viscosity, the barrier is removed and a Keplerian disc passing through the inner sonic point outside the horizon is formed instead. In TCAF, the formal component with low angular momentum and viscosity surrounds the Keplerian disc with high angular momentum and viscosity located at the equatorial plane (Chakrabarti, 1995). This TCAF configuration was later used by Chakrabarti (1997 and references therein) to study the spectral properties. This configuration has been verified to be stable by extensive numerical simulation of Giri & Chakrabarti (2013). Since the Compton cloud is the post-shock region where the Keplerian disc is also truncated, TCAF uses a minimum set of parameters to fit the spectra. On the contrary, in a dwarf novae outburst, both components
need not be present simultaneously. In fact the accretion may switch from high viscosity flow to low viscosity flow due to limit cycle behavior (e.g., Lasota 2001). The main reason is that in the black hole accretion, the outgoing radiation is emitted from a few hundred Schwarzschild radius where the infall time is much shorter compared to the viscous time scale. On the contrary, the size of a white dwarf could be about 3000 Schwarzschild radius and the physics of novae is decided by what happens very very far at a much cooler disc. The outbursts in both the cases are dictated by viscosity. If viscosity is not enough, matter cannot proceed towards the compact object and is piled up at some location (pile-up radius or accumulation radius) away from the black hole, say at $X_p$, till some instability raises the viscosity to drive the piled up matter towards the compact object and causing the outburst. Thus the piling radius is a function of viscosity available and could change from one outburst to another. We believe that this is precisely what is happening in the object under study.

Another point to remember is that during an outburst, the energy that is released is primarily from the gravitational energy of accreting matter. Since matter is piled up at $X_p$ and not accreted during the quiescent states, the emission is weaker in the quiescent state and it catches up during the outburst. Our main goal would be to see if the net energy released in a given outburst is proportional to the net amount of matter that is supplied by the companion during the period in between two outbursts (from peak flux of one till the peak flux of the previous one). Given that the spectral features did not change from one outburst to another (i.e., same fraction of gravitational energy release is observed in the same energy range), the observed energy release in our specific band may be assumed to be proportional to the net energy release for each of the outbursts.

4.1. ASM and GSC data of H 1743–322

In order to compare all the outbursts, we obtained the total integrated counts (I.C.) observed during each outburst with RXTE/ASM and MAXI/GSC modified in ‘Crab sec’ unit with appropriate conversion factors. From Fig. 1 it is clear that in the light curve from MAXI/GSC, the profiles are well defined. So, the outburst of 2010, which is common in both RXTE/ASM and MAXI/GSC, was used as a reference (normalization of I.C.) while comparing the events from two instruments. Figure 5a shows the I.C. per day of outburst, normalized with respect to 2010 event (Normalized counts per day of outburst) as shown in Table 2. The area of each histogram represents the
Figure 5: (a) The I.C., normalized with I.C. in 2010 outburst received by the same instrument, i.e., by ASM or GSC, per day of outburst. All data before 2010 are from ASM and the rest are from GSC. (b) The I.C. normalized as before with I.C. of 2010 per day of preceding period (peak flux to peak flux). For 2003 outburst, we considered previous outburst to be in 1977. (c) Same as Panel b, except that the excess I.C. of the 2004 outburst, over the average I.C. (shown by horizontal solid line) is transferred into the 2003 outburst. Data without this transfer (as in the middle panel) are shown with circles.

I.C. while the width represents the duration. We clearly see that the 2003 outburst is stronger by orders of magnitude than any other outburst which followed. Generally, the I.C. shows a gradual decrease. This can be easily converted into total energy release rate (see also, Yan & Yu 2015) using the prescription (see http://xte.mit.edu) and taking proportional energy after conversion from RXTE to MAXI.

In Fig. 5b, we show the I.C. per day of the preceding period (measured as the peak flux to peak flux of two successive outbursts) of each outburst with day. We note that the energy release rate of the 2004 outburst is very high for the short accumulation period as compared to the other outbursts. Interestingly, if for the sake of argument, we assume that 2004 outburst also releases a part of the energy not released by the 2003 event, then we can distribute the total of 2003 and 2004 energy emission rate evenly from 1977 till 2004. In that case, we find that the average emission due to 2004 outburst comes down to the level where all other outbursts generally reside (Fig. 5c).
One of the reasons why we felt that 2004 outburst is anomalous is that its \( \sim 115 \) days of duration is much larger than the durations of all outbursts afterward and much of the data cannot be fitted by any conventional models, indicating a non-steady flow. Furthermore, as mentioned in the introduction, there appeared to be a leftover Keplerian disc even after the 2003 outburst was over. So, may be, the 2003 outburst was prematurely halted for lack of viscosity and restarted again in 2004 when the condition was more favourable.
Table 3: Peak data and Ratio of integration counts (I.C.) with I.C. of 2010, during various outbursts of H 1743–322

| Year   | Peak Day (MJD) | Peak Count (Crab) | Duration (Days) | Quiescent† Period (Days) | Ratio of I.C.†† |
|--------|----------------|-------------------|----------------|--------------------------|----------------|
| **ASM** |                |                   |                |                          |                |
| 1977   | 43404.0        | 0.730 ± 0.09      | —              | —                        | —              |
| 2003†† | 52752.5        | 1.421 ± 0.162     | 230.5          | 2635.5                   | 20.75 ± 4.22   |
| 2004   | 53243.7        | 0.295 ± 0.008     | 112.2          | 491.2                    | 4.37 ± 1.07    |
| 2005   | 53603.2        | 0.189 ± 0.012     | 49.5           | 359.5                    | 0.98 ± 0.21    |
| 2007   | 54461.4        | 0.260 ± 0.093     | 62.8           | 858.2                    | 2.05 ± 0.44    |
| 2008   | 54764.7        | 0.093 ± 0.014     | 60.0           | 303.3                    | 0.61 ± 0.19    |
| 2009   | 54988.2        | 0.224 ± 0.012     | 74.5           | 223.5                    | 1.12 ± 0.26    |
| **GSC** |                |                   |                |                          |                |
| 2009-10| 55205.8        | 0.171 ± 0.008     | 59.3           | 217.6                    | 0.94 ± 0.23    |
| 2010   | 55426.6        | 0.187 ± 0.019     | 55.5           | 220.8                    | 1.00 ± 0.21    |
| 2011   | 55675.5        | 0.141 ± 0.020     | 50.0           | 248.9                    | 0.65 ± 0.17    |
| 2011-12| 55929.0        | 0.055 ± 0.004     | 51.1           | 253.5                    | 0.36 ± 0.10    |
| 2012-13| 56204.6        | 0.045 ± 0.007     | 43.3           | 275.6                    | 0.28 ± 0.09    |
| 2013   | 56521.7        | 0.173 ± 0.015     | 48.0           | 317.1                    | 0.75 ± 0.20    |
| 2014-15| 56931.0        | 0.073 ± 0.009     | 52.3           | 409.3                    | 0.34 ± 0.11    |
| 2015   | 57189.4        | 0.045 ± 0.002     | 40.5           | 258.4                    | 0.28 ± 0.08    |
| 2016   | 57463.7        | 0.060 ± 0.006     | 43.5           | 274.3                    | 0.42 ± 0.09    |

† Quiescent period is the time duration from peak day of previous outburst to the concerned outburst.
†† Ratio of Integrated Count (I.C.) in each outburst with that of 2010 of corresponding instrument (ASM or GSC).
Dashes have been put where data was not available.
Peak values are obtained by fitting Lorentzian profile to the peak of each outbursts.
Data of 1977 are taken from Kaluzienski & Holt, 1977
††† Although quiescent period from 1996 to 2003 is 2635.5, we use the period from 1977 to 2003 in Fig. 5 after ignoring 1996 outburst as it was not detectable by ASM.
5. Discussion and Conclusions

The outbursting black hole candidate H 1743–322 is intriguing for several reasons. It remained more or less in quiescent state for about twenty five years till 2003 when it emitted a huge amount of energy for a period of several months. This type of ‘mega’ event has not been repeated since then, although outbursts are seen quite regularly. The 2003 outburst has a strange feature that it has been impossible to fit the data with a steady disc rate for almost the entire outburst except towards the end when the disc is settling down. The following outburst of 2004 also showed such un-settling behaviour with a high emission of energy and the data could be properly fitted only in harder states (Bhattacharjee et al. 2017). Since then all the outbursts are generally ‘well behaved’ and the data could be fitted throughout (Mondal et al. 2014; Molla et al. 2017).

In order to understand the general behaviour of the outbursts of this source, we first recall the limit cycle model of dwarf novae outbursts (Cannizzo, 1993) and discuss further. It is assumed that the accreting gas accumulates in quiescence and then suddenly accretes onto the central object during outbursts (e.g., Cannizzo, 1993). It is believed that changing of the phases is due to propagation of heating and cooling fronts which traverse the disc and cause phase transitions between low (neutral) and high (ionized) states. The column density changes drastically in these two phases. It is also believed that the low to high state transition can take place at any distance from the compact object (Cannizzo 1998). Earlier, we mentioned that in outbursting black hole sources the main triggering is done by enhancement of viscosity (Chakrabarti et al. 2005, Debnath et al. 2015a & Jana et al. 2016 and references therein). The process most likely follows this sequence: in low mass X-ray binaries (LMXBs) where the companion supplies matter through Roche lobe overflow, cannot proceed deep inside due to lack of viscosity. It starts to pile up at $X_p$ dictated by the prevailing viscous processes. At this low density quiescence states, before the outburst is triggered, the advective flow has a shock while the Keplerian disc remains at $X > X_p$. The piled up matter heats up the flow on the equatorial plane till convective instability sets in to increase a large viscosity. Alternatively, magnetic fields advected by the flow from the Companion are anchored at the piled up matter and could create a large wind/jet and remove angular momentum at the same time. Thus the material is released and starts to rush in. Indeed in 2003, a strong radio emission was observed much before the peak X-ray flux was
Figure 6: A possible scenario of the evolution of the disc structure around H 1743–322 in successive outbursts. (a) The piling radius $X_p = X_{p2003}$ is very high prior to 2003 outburst and thus considerable matter had to be accumulated before high viscosity released the matter and triggered the outburst. (b) Location of piling radius $X_p = X_{p2004} < X_{p2003}$ of 2004 outburst where some matter of previous outburst remained while the Keplerian disc from 2003 outburst is still fading away. (c) Piling radius at subsequent outburst is closer to the black hole and takes shorter time before new triggering occurs (d).
achieved. However, the disc on the equatorial plane remains Keplerian as long as the viscosity is supercritical (Chakrabarti, 1990). Otherwise, further formation of the Keplerian disc is halted and the outburst may not achieve the soft-Intermediate state and soft-state. When viscosity is totally turned off due to release of most of the stored matter at $X_p$, the outburst starts to decline and eventually reaches the quiescence state. However, the destruction of a Keplerian disc takes much longer time than its formation, since the two processes are very much different (Roy & Chakrabarti, 2017). During the formation of the Keplerian disc in the rising phase, viscous transport of angular momentum takes place. However, destruction of the Keplerian disc takes place by its slow mixing with the advective low angular flow which is much longer. By this time, the viscosity at $X_p$ may again increase and cause a further outburst. We suspect that the 2004 outburst was due to such a process. The duration soft-intermediate state in the rising phase is decided by the viscous time to create the Keplerian disc. Thus the duration of the soft-intermediate states in the rising and declining phases along with the presence of a soft state is a good indicator of the size of the Keplerian disc. The radiation emitted in these states is also an indicator of the total energy released, since these are the brightest states of an outburst. The processes mentioned above is valid only for LMXBs. For a high mass X-ray binary (HMXB), outbursts are not possible, since the angular momentum of winds is low and does not have to pile-up at a large $X_p$ and store huge matter outside the star in the absence of viscosity except at low $X_p$ where the centrifugal barrier is formed even with a low angular momentum. This is the reason why LMXBs exhibit outbursts while HMXBs such as Cyg X-1 only show some short-lasting flares when soft states are achieved.

Total amount of accumulation of matter at $X_p$ is guided by two physical processes: the steady transfer of matter from the companion through the Roche Lobe superposed by anomalous rate due to the intrinsic (magnetic or otherwise) activity of the companion. The total energy released in an outburst is an indicator of the total matter accumulated and thus should generally be proportional to the peak-to-peak time gap between two outbursts. Any deviation might be the result of variation in supply rate of matter due to companion’s activity.

After a careful scrutiny of the behaviour found in the data from outbursts of 2003 and 2004, one can now construct a scenario of what could have happened to the source during these years. A possible sequence is shown in Fig. 6. In 2003 outburst, $X_{p2003}$ must be far out in the disc (Fig. 6a) where
the flow is neutral and required a huge accumulation of matter in order to raise the temperature of the equatorial plane so that the resulting convective instability and the viscosity due to turbulence eventually can trigger the outburst after twenty five odd years. Most of this outburst phase is unsettling due to rush of matter causing variation of rates with radius. There could have been profuse outflows at \( X_p \) and outer disk as well to remove angular momentum. The accretion rate of the disc remained highly radial dependent and thus models which assume a fixed accretion rate cannot fit the spectra. From the nature of the variation of spectral and temporal properties during the 2003 outburst, we infer that a stable two-component configuration does not form until 2003 October 24 (MJD=52936), i.e., before the start of the HIMS (declining). From the behaviour of 2004 outburst, we find that it also does not show any steady disc except towards the end. It appears that some matter leaving \( X_{p2003} \) during 2003 event could not reach the inner disc but remained stuck at a new piling radius \( X_{p2004} < X_{p2003} \) possibly due to sudden fall of viscosity below critical value while the declining phase of 2003 outburst was still in place. Some more matter was accumulated here to trigger the 2004 outburst (Fig. 6b). This also proves that during the so-called quiescent state after 2003, the matter supply from the companion continues at a more or less constant rate and a weak Keplerian disc continues to emit a multicolor black body (Fig. 6b). Indeed, presence of such a disc around H 1743–322 in quiescence has been reported before (Capitanio 2005). Also, reduction of viscosity causes the Keplerian disc to dissipate very slowly (Roy & Chakrabarti, 2017). Subsequent to 2004, accumulation of matter could be taking place at even closer \( X_p \) where the disc is hotter and ionized and does not require a large accumulation of matter to trigger the outburst (Fig. 6c). They last for \( \sim 2 \) months with a quiescence period of \( \sim 6 \) months to \( \sim 2 \) years. We also observed from Fig. 5a, a general trend of weakening of the outbursts as time progresses (Fig. 6d). It is possible that after a few such outbursts, it would again remain inactive for two-three decades. The origin of this super-cycle of outbursts remains unclear and could be related to the properties of the companion.

There are many comparative studies of various episodes of outburst of an object (e.g., Yan & Yu 2015 and references therein), though no detailed analysis regarding disc flow properties were made. However, we felt that combining the data of RXTE/ASM and MAXI/GSC one could have an idea of matter transfer rate from the companion. What we established is that if we assume that every flare essentially cleans up the disc and removes the
accumulated matter during the preceding period between the peak flux days, then we cannot explain the huge energy release of 2004 outburst unless we assume that the matter supply rate, only in the 2003-2004 outburst time gap, was unusually high, which we have no reason to believe. We propose that 2004 outburst released part of the energy which was due to be released in 2003 itself and perhaps because of sudden decline of disc viscosity, the 2003 outburst stopped prematurely. Thus, for example, if we combine the energy release at 2003 and 2004 and treat them together, the average energy release rate becomes almost constant. Other outbursts till date also follow a similar rate, though there were some fluctuations presumably due to other effects, such as the mass ejections from the companion, or ablation of matter from the companion due to irradiation of X-rays onto the companion, etc. The accumulation radius could be decreasing from one outburst to the next, as is evidenced from the progressively weaker outburst profile. We believe that a similar behaviour should be found in other recurring transient BHCs, such as GX 339–4, 4U 1630–472, V404 Cyg etc. where several outbursts have been observed. The determination of the detailed dynamics is outside the scope of this paper and will be discussed elsewhere.

In this paper, we presented several new results. We not only analyzed the 2003 declining phase data with TCAF model, and obtained the black hole mass independently from each fit using the consideration of constant normalization in TCAF, but also came to a general conclusion regarding the supply rate of the companion which appears to be constant. From our analysis of the spectral properties of the declining phase of the outburst with TCAF solution we find no unusual behaviour. The mass of the black hole obtained from the present analysis is quite consistent with the value proposed by Petri (2008) and others (Shaposhnikov & Titarchuk 2009; Molla et al. 2017; Bhattacharjee et al. 2017). One important property of fitting with TCAF is that the normalization \( N \) in a fit, is supposed to be a constant for a steady two component disc. This normalization is the ratio of the derived spectrum and the observed spectrum by a specific instrument and is a function of intrinsic property of the system, such as the mass of the black hole, distance of the object and the inclination angle of the disc. We find that in 2003, \( N \approx 0.6 \). However, for 2004 outburst, \( N \approx 13 \) (Bhattacharjee et al. 2017) which is close to what Molla et al. (2016) found for 2010 and 2011 outbursts. This gives us another proof that the basic disc properties may have changed from an unsettled in 2003 to a settling nature by the end of 2004 outburst. However, since the mass appears to be in the same ball park
in all the outbursts, it proves that the derived mass itself is not dependent on the exact value of the normalization.

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