A study of the variation of geometry of accretion flows of compact objects through timing and spectral analysis of their outbursts

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ABSTRACT

Temporal and spectral variations of black hole candidates during outbursts have been reported in several publications. It is well known that during an outburst, source becomes softer in first few days and then returns to hard states after a few weeks or months. In this paper, we show variation of Comptonization efficiency (CE), defined to be the ratio of the number of power-law photons to the number of soft photons injected into a Compton cloud, as a function of time in several outbursts. Since power-law photons are generated through inverse Comptonization of the intercepted soft photons, CE is a measure of geometry of the Compton cloud. Our investigation indicates that all outbursts start with a large CE, which becomes very small after a few days, when the Compton cloud becomes small enough to intercept any significant number of soft photons. CE returns back to a larger value at the end of the outburst. We show co-variation of count rates, frequency of quasi-periodic oscillations, photon index and CE, and establish a general trend of disc geometry variation during outbursts in all systems under consideration.

Key words: accretion, accretion discs – black hole physics – X-rays: binaries.

1 INTRODUCTION

It is well known that black hole accretion flows in a compact binary system typically consist of a Keplerian disc which emits soft or low-energy photons and a hot Compton cloud which inverse Comptonizes soft photons into high-energy photons (Sunyaev & Titarchuk 1985). When a black hole spectral state changes from hard to soft and vice versa, the Compton cloud must change its shape and temperature (Chakrabarti & Titarchuk 1995; Tanaka & Lewin 1995). In a soft state, when the accretion rate in the Keplerian disc is high, the Compton cloud is smaller and cooler, while in a hard state, when the Keplerian disc rate is very low, the Compton cloud is larger and hotter. There are various models of the Compton cloud in the literature, ranging from a hot Corona, magnetic corona, to a post-shock region of an accreting low-angular-momentum flow which surrounds the standard Keplerian disc (Haardt & Maraschi 1991; Wandel & Liang 1991; Chakrabarti & Titarchuk 1995; Esin, McClintock & Narayan 1997; Chakrabarti & Manickam 2000; Jianiuch & Czerny 2000; Rao, Yadav & Paul 2000; Merloni & Fabian 2001; Zdziarski et al. 2003; Liu, Meyer & Meyer-Hofmeister 2005; Ohsuga, Kato & Mineshige 2005; McClintock & Remillard 2006; Neilsen, Remillard & Lee 2011). Along with spectral variations, a black hole candidate shows temporal variations also, which is sometimes quasi-periodic (Muno, Morgan & Remillard 1999; Chakrabarti et al. 2008; Chakrabarti, Dutta & Pal 2009). There are various explanations of quasi-periodic oscillations (QPOs) in the literature ranging from disc-seismology to oscillation of a post-shock region (Chakrabarti & Manickam 2000; Axelsson, Borgonovo & Larsson 2005; Kato 2005).

Outburst sources are ideal candidates to study changes in the size of the Compton cloud. This is because the object is known to be in a hard state at the beginning of an outburst, but in a matter of few days to a few weeks, it changes its states to several other states, thereby giving us a unique opportunity to study size variation of the Compton cloud very easily. From the spectral analysis, it appears that the following sequence is typically followed by most, if not all, outburst sources: hard → hard-intermediate → soft-intermediate → soft → soft-intermediate → hard-intermediate → hard (Chakrabarti et al. 2008, 2009; Belloni 2010; Nandi et al. 2012).

Recently, Pal, Chakrabarti & Nandi (2011) showed that average size of the Compton cloud in the variable source GRS 1915+105 changes in a very well defined way as it transits from one variability class to another. They computed a quantity called Comptonization efficiency (CE) which is the ratio of the number of power-law photons to the number of blackbody photons in the spectrum at a given instant. They show that CE is very small in softer classes and larger for harder classes. Within some of classes, there are pieces of evidence of rise and fall of count rates and spectral slopes in a matter of a few seconds. Since the number of hard photons depends on optical depth of the Compton cloud, we clearly see a change in optical depth of the Compton cloud in that time-scale. Furthermore,
we see that one variability class goes to another adjacent class whose CE is nearest.

In this paper, we study variation of the Compton cloud size during outbursts of several black hole candidates. We show that outbursts typically start with a large CE, i.e., a large-sized Compton cloud with a poor soft photon source. In the rising phase, this cloud becomes progressively smaller and smaller daily, till it became minimum when the object went to a soft state. Of course, the soft photon source gets stronger (soft photon intensity rises), and as a result, the cloud size shrinks (QPO frequency, assumed to be the oscillating frequency of the cloud, rises). In the declining phase of an outburst, the trend is exactly reversed. In this paper, we deal with black hole candidates which exhibited outbursts, such as H1743–322, GX 339–4, 4U 1543–47, XTE J1118+480, XTE J1859+226, GRO J1655–40 and XTE J1550–564. In the next section, we briefly discuss the objects of our study. In Section 3, we present the procedure of our analysis. Here, we compute the CE of all these outbursts both in the rising and declining phases. We show that CE changes with time very rapidly. In general, softer states were found to have a very low CE and the harder states (at the beginning of the rising phase and at the end of the declining phase) were found to have a very high CE. In Section 4, we present results and interpret them using physical models. Finally, in Section 5, we draw our conclusions.

2 OBJECTS OF OUR STUDY

We consider the following outburst sources in the study.

(a) The black hole candidate H1743–322 was first discovered by Ariel in 1977 August 5 (Kaluzienski & Holt 1977). Later, it was precisely located by High Energy Astronomical Observatory 1 (Doxsey et al. 1977). This object was classified as a black hole candidate by White & Marshall (1983). In 2003 March, an outburst along with an increase of source flux by a factor of 3 (60 mCrab in 15–40 keV energy range) was reported by INTEGRAL, where the X-ray properties of a black hole candidate were studied (Revnivtsev et al. 2003). Another outburst, along with an increase of source flux from 16 to 160 mCrab in 2–10 keV intensity, was reported by Swank (2004) in 2004 July. Several radio emissions are reported during the 2003 outburst (Rupen, Mioduszewski & Dhawan 2003). Later, from the ejected plasma, radio and X-ray synchrotron emissions are also reported (Corbel et al. 2005). The distance of the object is 8 kpc (Corbel et al. 2005) and mass is estimated to be $M = 10.0 M_{\odot}$ (McClintock et al. 2009; Chen et al. 2010). The outburst of 2009 was analysed by Chen et al. (2010). The outbursts of 2008 and other outbursts were analysed by Coriat et al. (2011) and Jonker et al. (2010). Spectral fitting is done with $n_{HI} = 1.6 \times 10^{22} \text{cm}^{-2}$ (Capitani et al. 2009).

(b) GX 339–4 is a stellar mass Galactic black hole candidate. This black hole candidate was first observed by an MIT X-ray detector of OSO-7 during the survey period between 1971 October and 1973 January in the energy range 1–60 keV. This Low Mass X-ray Binary is located at $(l, b) = 338.93, −4.427$ (Markert et al. 1973) with RA = $17^h 02^m 49.36$ and Dec. = $−48^\circ 47^\prime 22^\prime\prime.8$ (J2000). Optical observation leads to an estimation of mass function to be around $5.8 \pm 0.5 M_{\odot}$ (Hynes et al. 2003b) and $D = 5.8kpc$ (Hynes et al. 2004). The estimated mass of this object is $7.5 \pm 0.8 M_{\odot}$ (Chen 2011). During RXTE Rossi X-Ray Timing Explorer era, GX 339–4 had undergone several outburst phases (1998, 2002/2003, 2004/2005, 2006/2007 and 2010). It was observed several times by RXTE during the outburst period (Del Santo et al. 2009; Motta, Belloni & Joman 2009). In 2006, Krimm et al. (2006) reported the beginning of the 2007/2007 outburst of GX 339–4 with an increase in source flux to 230 mCrab in the 15–50 keV energy range by Swift–BAT. In 2010, Yamakoa et al. (2010) reported an increase in source flux from 17 to 26 $\pm 5$ mCrab in the 4–10 keV energy range for GX 339–4. In this paper, we will analyse data of the 2006/2007 and 2010 outbursts. For spectral analysis, $n_{HI} = 0.5 \times 10^{22} \text{cm}^{-2}$ is taken towards this source (Mendez & Van der Klis 1997; Kong et al. 2000).

(c) The black hole candidate 4U 1543–47 was discovered on 1971 August 17 by the Uhuru satellite (Matlisky et al. 1972). Since its discovery, X-ray outbursts have been observed in 1983, 1992 and 2002. Optical observation was found by Blissett et al. (1983) during the 1983 outburst. The 2002 outburst commenced on MJD 524 424 along with an increase in source flux from 0.054 to 1.65 mCrab in the 2–12 keV energy range and was observed simultaneously in X-rays by RXTE (Miller & Remillard 2002; Park et al. 2004), in radio by Molonglo Observatory Synthesis Telescope (Hunstead & Webb 2002; Park et al. 2004), and in optical and infrared by the YALO Telescope (Buxton & Bailyn 2004). Several multiwavelength observations are reported for the 2002 outburst of 4U 1543–47 (Kalemci et al. 2005). The black hole mass $9.4 \pm 0.2 M_{\odot}$, $D = 7.5 \pm 1.0$ kpc, $i = 20.7 \pm 1.0$ was reported by Park et al. (2004). Fourier-resolved spectroscopy is also carried out for the source during this outburst (Reig et al. 2006). For spectral analysis, interstellar absorption is taken to be $n_{HI} = 4.0 \times 10^{21} \text{cm}^{-2}$ (Dickey & Lockman 1990; Park et al. 2004).

(d) XTE J1118+480 was first discovered by All-Sky Monitor (ASM) by Remillard et al. (2000) in 2000 March, while Garcia et al. (2000) spectroscopically observed its optical counterpart. This object is observed simultaneously in the optical and infrared to determine the physical parameters of the black hole (Gelino et al. 2006). The orbital inclination angle is $68^\circ \pm 2^\circ$. This angle corresponds to a primary black hole mass of $8.53 \pm 0.60 M_{\odot}$. The distance of the black hole is $1.72 \pm 0.10$ kpc. This object has shown outbursts in 2000 (Hynes et al. 2000; McClintock et al. 2001; Chaty et al. 2003) and 2005 (Pooley 2005; Remillard et al. 2005; Rupen, Dhawan & Mioduszewski 2005; Zurita et al. 2005a, 2006; Hynes et al. 2006). Several authors have discussed disc–jet connection of this compact object (Kanbach et al. 2001; Hynes et al. 2003a) to explain source high-energy photons (Markoff, Falcke & Fender 2001; Yuan, Cui & Narayan 2005). Remillard et al. (2005) reported this outburst as a faint X-ray outburst as the source flux increases from 15 to 19 mCrab in the 2–12 keV energy band. Optical (Zurita et al. 2005a,b, 2006) and radio (Pooley 2005; Rupen et al. 2005) counterparts have also been observed. Spectral fitting is done with $n_{HI} = 1.3 \times 10^{23} \text{cm}^{-2}$ (Brockopp et al. 2010).

(e) X-ray transient XTE J1859+226 was discovered by the ASM onboard RXTE on 1999 October 9 (Wood et al. 1999). Smith (1999) reported the increase in source flux up to 1.37 mCrab in the 2–12 keV energy range. The mass and inclination angle are $4.5 \pm 0.6 M_{\odot}$ and $70^\circ$, respectively (Corral-Santana et al. 2011). The distance of the compact object is $11 kpc$ (Zurita et al. 2002). Spectral analysis is done with $n_{HI} = 2.21 \times 10^{21} \text{cm}^{-2}$ (Dickey & Lockman 1990).

(f) X-ray Nova GRO J1655−40 was first discovered by BATSE on board Compton Gamma Ray Observatory on 1994 July 27 (Zhang et al. 1994). The optical counterpart was discovered by Bailyn et al. (1995). The mass and inclination angle are $M = 7.02 \pm 0.22 M_{\odot}$ and $\theta = 69.5 \pm 0.1$ (Orosz & Bailyn 1997; Van der Hooft et al. 1998), respectively. The distance of the compact object is $3.2 \pm 0.2 kpc$ (Hjellming & Rupen 1995). In the last week of 2005 February, this source became active as the source.
flux increased from 0.3 to 4.1 mCrab in the 2–10 keV energy range (Markwardt & Swank 2005) and the outburst continued for 260 d (Shaposhnikov et al. 2007). Before this, several outbursts were reported of the same source (Sobczak et al. 1999b). The hydrogen column density is fixed at 0.89 × 10^{22} cm^{-2} (Zhang et al. 1997).

(g) X-ray transient XTE J1550–564 was first discovered by the ASM on 1998 September 7 (Smith 1998) and by CGRO (Wilson et al. 1998). The optical (Orosz, Bailyn & Jain 1998) and radio (Campbell-Wilson et al. 1998) counterparts were detected shortly after this. Optical photometry reveals a binary period of 1.541 ± 0.009 d (Jain et al. 2001) during the 1998 outburst. During this outburst, the presence of a superluminal jet is observed along with the massive X-ray flare (Hannikainen et al. 2001). Later observations revealed that the black hole has a mass of 10.0 ± 1.5 M⊙ and the companion star is a late-type subgiant (GBIV-K4III). The binary inclination angle is 72 ± 5° (Orosz et al. 2002). The distance of the black hole is 6.8 kpc (Sobczak et al. 1999a). In 1998, the luminosity of the compact object was reported to be 6.8 Crab in the 2–12 keV energy range (Rutledge, Fox & Smith 1999b). Interstellar absorption n_{HI} = 0.85 × 10^{22} cm^{-2} is taken (Tomsick, Corbel & Kaaret 2001).

3 ANALYSIS PROCEDURE

In this paper, we analysed RXTE data, and results are summarized in Table 1. We chose data sets by MJDS of outbursts obtained from the literature. These data are downloaded from HEASARC, NASA Archive. During the analysis, we exclude the data collected for elevation angles less than 10°, for offset greater than 0.02 and those acquired during the South Atlantic Anomaly passage. We selected PCU2 data as it was active most of the time. Here, we calculated 3.0–40.0 keV counts in kcts s^{-1} and plot them in the top panels of Figs 1–4, as described below. The power density spectrum (PDS) is generated by the standard FTOOLS task ‘powspec’ with a suitable normalization. Data are binned in 0.01 s to obtain a Nyquist frequency of 50 Hz as power beyond this is found to be insignificant. PDSs are normalized to give squared rms fractional variability per hertz. Evolution of QPO frequency is plotted in the second panel from top of Figs 1–4.

3.1 Spectral analysis

Spectral analysis of RXTE PCA data is done by using ‘standard2’ mode data which have 16 s time resolution. We constrained our energy selection from 3.0 to 40 keV from the observational data. The source spectrum is generated using the FTOOLS task ‘SAEXTRCT’ with 16 s time bin from ‘standard2’ data. The background fits file is generated from ‘standard2’ fits file by the FTOOLS task ‘runcabackest’ with the standard FILTER file provided with the package. The background source spectrum is generated using the FTOOLS task ‘SAEXTRCT’ with 16 s time bin from the background fits file. The standard FTOOLS task ‘pcarsp’ is used to generate the response file with appropriate detector information. Exposure time is corrected for source and background spectra with a deadtime correction factor. Spectral analysis and modelling was performed using theXSPEC (V.12) astrophysical fitting package. For model fitting of PCA spectra, we have used a systematic error of 0.5 per cent. Spectra are fitted with the diskbb and power-law models along with hydrogen column density for absorption. We use Gaussian for iron line as required for the best fit. During the fitting of spectra we adopted a technique introduced by Sobczak et al. (1999b), Pal et al. (2011) and Pal, Chakrabarti & Nandi (2013), to obtain spectral parameters.

We calculated error bars at 90 per cent confidence level in each case. Morrison & McCammon (1983) reported that interstellar absorption mainly affects photons from 0.03 to 10.0 keV. It is important to consider this effect in RXTE analysis since we need to count injected soft photons up to 10.0 keV as accurately as possible. We chose n_{HI} as appropriate for each candidate to take care of this effect.

3.2 Efficiency of comptonization

In the literature, the usual trend is to plot the hardness ratio HR (say the ratio of 6–40 keV photons divided by 2–6 keV photons) when it comes to understand how important Compton scattering is. However, there are several problems in this definition: (a) HR does not depend on the mass of the black hole, although hard (Comptonized) and soft photons change their meaning with the mass of the black hole. For instance, soft photons in the lower mass case could be Comptonized photons in the higher mass case. Thus, HR cannot be compared for two objects, or even in two episodes of the same object. To circumvent this problem, we define a new parameter (Pal et al. 2011, 2013) called CE which is defined purely on physical ground and independent of any model or mass of the black hole. Since for stellar mass black holes we expect peak radiation from a standard Keplerian disc to be at around 0.5–1 keV, and slope of the power-law tail is defined for the 2–10 keV region, we choose a range 0.1–40 keV to define CE, both ends being far from the expected values. We compute the total number of soft (seed) photons (N_{BB}) from the Keplerian disc from multicolour blackbody and the total number of power-law photons (N_{PL}) in ranges dynamically determined by best fits obtained after correcting observational data using energy-dependent absorption due to hydrogen column. Since these ranges are obtained dynamically, the ratio CE = N_{PL}/N_{BB} is independent of the mass of a black hole or any specific model of accretion flow. Hence, the CE of two different objects can be compared, which we do in this paper. Number of blackbody photons are obtained following Makishima et al. (1986). Here, we count the photons within the energy range starting from 0.1 keV to the best-fitting upper energy limit dbb, by first fitting the spectrum with the diskbb model alone (Sobczak et al. 1999b). The upper limit of blackbody energy dbb, is obtained from the consideration that the reduced χ^2 value from resultant fit should be ~1.0. This upper limit may vary with time and from one data set to another.

Comptonized photons N_{pl} are calculated by using the power-law equation given as

\[ P(E) = N(E) E^\alpha, \]

where \( \alpha \) is the power-law index and \( N \) is the total number of photons s^{-1} keV^{-1} at 1 keV. It is reported in Titarchuk (1994) that the Comptonization spectrum will have a peak at around 3 \( \times T_{in} \), where \( T_{in} \) is the temperature at the inner edge of the standard disc. Thus, the power-law is integrated from 3 \( \times T_{in} \) to 40 keV to calculate the total rate of Comptonized photons (photons s^{-1}). \( T_{in} \) and \( \alpha \) come from a spectral fit of each data. Here, we assume that the black hole is non-rotating. For rotating flows, the corresponding spectral properties of the standard disc have to be used.

4 RESULTS AND DISCUSSION

Observation IDs of data sets analysed in this paper are given in Table 1. In Table 2, spectral fitting parameters of sample data sets are shown. Error bars are calculated at 90 per cent confidence level in each case. To ease discussion, we keep the two-component advective flow (TCAF) model of Chakrabarti & Titarchuk (1995) at the back
Table 1. Observation IDs analysed in this paper.

| Object | Outburst | Analysis time | Obs ID |
|--------|----------|---------------|--------|
| XTE J1550–564 | 1998 | 08/09/1998 | 30188-06-03-00, 30188-06-01-00, 30188-06-01-01 |
|         | to 08/09/1998 | 30188-06-03-00, 30188-06-01-00, 30188-06-01-01, 30188-06-04-00 |
|         | 10/10/1998 | 30191-01-01-00, 30191-01-02-00, 30191-01-05-00, 30191-01-06-00 |
|         | 10/04/2000 | 50137-02-01-00, 50137-02-02-00, 50137-02-03-00, 50137-02-04-00 |
|         | 26/04/2000 | 50134-01-01-00, 50134-01-03-00, 50134-01-05-00, 50134-01-06-00 |
|         | 26/04/2000 | 50137-02-07-01, 50134-01-01-00, 50134-01-03-00, 50134-01-05-00, 50135-01-01-00, 50135-01-02-00, 50135-01-04-00, 50135-01-05-00, 50135-01-07-00, 50135-01-08-00 |
|         | 28/12/2006 | 92052-07-04-00, 92052-07-05-00, 92428-01-01-00, 92052-07-06-00 |
|         | 04/2008 | 92052-07-04-00, 92052-07-05-00, 92428-01-01-00, 92052-07-06-00 |
|         | 10/04/2000 | 92052-07-04-00, 92052-07-05-00, 92428-01-01-00, 92052-07-06-00 |
|         | 26/05/2007 | 92085-02-01-01, 92085-02-02-00, 92085-02-02-01, 92085-02-03-00 |
|         | 26/05/2007 | 92085-02-03-01, 92085-02-04-00, 92085-02-05-00, 92085-02-07-01, 92704-03-03-00, 92704-03-05-01, 92704-03-07-01, 92704-03-09-02, 92704-03-11-01 |
|         | 07/07/2008 | 94413-02-01-00, 94413-02-02-00, 94413-02-03-00, 94413-02-04-00 |
|         | 07/07/2008 | 94413-02-01-00, 94413-02-02-00, 94413-02-03-00, 94413-02-04-00 |
|         | 13/01/2005 | 90111-01-01-00, 90111-01-01-00, 90111-01-01-02, 90111-01-01-09 |
|         | 26/01/2005 | 90111-01-01-00, 90111-01-01-00, 90111-01-01-02, 90111-01-01-09 |
|         | 13/01/2005 | 90111-01-01-00, 90111-01-01-00, 90111-01-01-02, 90111-01-01-09 |
|         | 26/01/2005 | 90111-01-01-00, 90111-01-01-00, 90111-01-01-02, 90111-01-01-09 |
|         | 26/01/2005 | 90111-01-01-00, 90111-01-01-00, 90111-01-01-02, 90111-01-01-09 |
|         | 13/01/2005 | 90111-01-01-00, 90111-01-01-00, 90111-01-01-02, 90111-01-01-09 |
|         | 06/03/2005 | 90111-01-02-00, 90111-01-02-00, 90111-01-02-00, 90111-01-02-00 |
|         | 19/09/2005 | 90111-01-02-00, 90111-01-02-00, 90111-01-02-00, 90111-01-02-00 |
|         | 06/03/2005 | 90111-01-02-00, 90111-01-02-00, 90111-01-02-00, 90111-01-02-00 |
|         | 19/09/2005 | 90111-01-02-00, 90111-01-02-00, 90111-01-02-00, 90111-01-02-00 |
|         | 17/06/2002 | 70133-01-01-00, 70133-01-02-00, 70133-01-04-00, 70132-01-01-00 |
|         | 25/07/2002 | 70133-01-15-00, 70133-01-18-00, 70133-01-20-00, 70133-01-26-00 |

Disc geometry variation during outbursts

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of our mind. Of course, our result does not depend on any specific model, as long as there are sources of seed photons and hot electrons for inverse Comptonization of these seed photons.

4.1 XTE J1550−564

The outbursts of 1998 and 2000 of the Galactic black hole XTE J1550−564 are analysed in this paper. The 1998 outburst is analysed from MJD 510 64 (08/09/1998) to MJD 510 97 (10/10/1998). The result is shown in Fig. 1(a). Chakrabarti et al. (2009) reported that QPO was always observed, and thus the oscillating shock in the so-called propagating shock model (Debnath, Chakrabarti & Nandi 2010) does not disappear behind the horizon or the shock does not become weak enough. The post-shock region is known as the centrifugal pressure-supported Boundary Layer or the CENBOL. It is the Compton cloud in the TCAF model (Chakrabarti & Titarchuk 2001).
Table 2. Parameters for spectral fits of the sample data set with the diskbb plus power-law models. \( T_{bb} \) is blackbody temperature obtained from fitting, \( \text{dbb} \), is the upper limit energy of the disc blackbody spectrum. The column ‘Soft’ gives blackbody photons in the 0.1–dbb, keV range. The column ‘power law’ contains the power-law index \( \alpha \) obtained from our fitting. The column ‘hard photons’ contains rate at which Comptonized photons are emitted in the range \( 3 \times T_{bb} \) to 40 keV. CE is Comptonization efficiency.

| Compact object (Outburst) | Time (MJD) | QPO (Hz) | \( T_{bb} \) (keV) | \( \text{dbb} \) (keV) | \( \alpha \) (d.o.f.s) | Soft photons (kphotons s\(^{-1}\)) | Power-law index | \( \alpha \) (d.o.f.s) | Hard photons (kphotons s\(^{-1}\)) | CE (per cent) |
|--------------------------|-----------|----------|-------------------|-----------------|------------------|-------------------|-----------------|-----------------|-------------------|--------------|
| XTE J1550–564(1998)      | 510 65    | 0.3      | 1.74\(^{+0.10}_{-0.09}\) | 4.75            | 1.5(7)           | 43.89\(^{+8.15}_{-6.46}\) | 2.00\(^{+0.08}_{-0.06}\) | 1.3(71)         | 1.03\(^{+0.04}_{-0.03}\) | 2.35\(^{+0.02}_{-0.03}\) |
| XTE J1550–564(2000)      | 516 48    | 0.2      | 1.66\(^{+0.14}_{-0.12}\) | 6.0            | 1.7(8)           | 5.27\(^{+0.08}_{-0.10}\) | 1.19\(^{+0.04}_{-0.03}\) | 1.5(74)         | 0.06\(^{+0.01}_{-0.01}\) | 1.05\(^{+0.05}_{-0.03}\) |
| XTE J1550–564(2000)      | 516 65    | –        | 1.03\(^{+0.02}_{-0.02}\) | 8.5            | 1.4(9)           | 130.71\(^{+9.9}_{-10.0}\) | 2.14\(^{+0.03}_{-0.03}\) | 0.9(69)         | 0.55\(^{+0.02}_{-0.01}\) | 0.42\(^{+0.04}_{-0.04}\) |
| GX 339–4(2007)           | 541 41    | 1.7      | 1.85\(^{+0.06}_{-0.05}\) | 5.75            | 1.36(8)          | 49.38\(^{+4.4}_{-4.1}\) | 1.99\(^{+0.05}_{-0.05}\) | 1.6(74)         | 0.15\(^{+0.006}_{-0.005}\) | 0.31\(^{+0.04}_{-0.04}\) |
| GX 339–4(2007)           | 541 58    | 10.0     | 0.91\(^{+0.01}_{-0.01}\) | 8.5            | 1.8(10)          | 574.41\(^{+21.10}_{-20.14}\) | 2.13\(^{+0.04}_{-0.04}\) | 0.9(74)         | 0.32\(^{+0.02}_{-0.01}\) | 0.06\(^{+0.004}_{-0.003}\) |
| GX 339–4(2010)           | 552 91    | 0.3      | 1.54\(^{+0.11}_{-0.10}\) | 6.0            | 0.98(9)          | 24.49\(^{+3.96}_{-3.15}\) | 1.60\(^{+0.05}_{-0.05}\) | 1.2(79)         | 0.09\(^{+0.003}_{-0.003}\) | 0.37\(^{+0.06}_{-0.06}\) |
| GX 339–4(2010)           | 553 13    | –        | 0.93\(^{+0.01}_{-0.01}\) | 8.5            | 0.98(10)         | 186.29\(^{+7.53}_{-7.15}\) | 2.26\(^{+0.08}_{-0.08}\) | 1.1(79)         | 0.11\(^{+0.01}_{-0.009}\) | 0.06\(^{+0.007}_{-0.007}\) |
| H 1743–322(2008)         | 544 98    | 5.0      | 1.61\(^{+0.08}_{-0.07}\) | 5.75            | 1.2(8)           | 11.12\(^{+1.8}_{-1.5}\) | 1.5\(^{+0.1}_{-0.1}\) | 0.99(79)        | 0.03\(^{+0.002}_{-0.001}\) | 0.26\(^{+0.06}_{-0.05}\) |
| H 1743–322(2009)         | 549 90    | 3.65     | 1.13\(^{+0.03}_{-0.02}\) | 5.25            | 0.7(9)           | 136.00\(^{+6.99}_{-8.84}\) | 1.95\(^{+0.03}_{-0.03}\) | 1.5(79)         | 0.24\(^{+0.006}_{-0.006}\) | 0.18\(^{+0.02}_{-0.02}\) |
| XTE J1859+226(2000)      | 514 64    | 3.0      | 1.33\(^{+0.08}_{-0.07}\) | 5.5            | 1.1(9)           | 668.59\(^{+9.62}_{-10.5}\) | 2.24\(^{+0.06}_{-0.06}\) | 1.6(79)         | 0.33\(^{+0.02}_{-0.02}\) | 0.05\(^{+0.01}_{-0.01}\) |
| XTE J1859+226(2000)      | 514 80    | –        | 1.13\(^{+0.03}_{-0.03}\) | 7.5            | 0.8(8)           | 3832.64\(^{+120.66}_{-288.11}\) | 3.23\(^{+0.03}_{-0.03}\) | 1.1(75)         | 0.73\(^{+0.03}_{-0.02}\) | 0.07\(^{+0.002}_{-0.002}\) |
| XTE J1118+480(2005)      | 533 95    | –        | 1.05\(^{+0.05}_{-0.04}\) | 6.5            | 0.94(9)          | 312.01\(^{+47.95}_{-39.70}\) | 2.75\(^{+0.03}_{-0.03}\) | 1.6(75)         | 0.63\(^{+0.28}_{-0.26}\) | 2.20\(^{+0.40}_{-0.40}\) |
| GRO J1655–40(2005)       | 534 39    | 1.5      | 1.54\(^{+0.17}_{-0.13}\) | 5.75            | 0.9(7)           | 4.36\(^{+1.37}_{-0.86}\) | 1.46\(^{+0.03}_{-0.03}\) | 1.3(75)         | 0.10\(^{+0.02}_{-0.02}\) | 2.24\(^{+0.7}_{-0.7}\) |
| GRO J1655–40(2005)       | 535 91    | –        | 1.05\(^{+0.03}_{-0.03}\) | 10.0           | 0.8(11)          | 111.56\(^{+1.19}_{-1.17}\) | 2.17\(^{+0.02}_{-0.02}\) | 1.2(79)         | 0.04\(^{+0.02}_{-0.02}\) | 0.03\(^{+0.02}_{-0.02}\) |
| 4U 1543–47(2005)         | 524 60    | 7.9      | 1.03\(^{+0.02}_{-0.02}\) | 5.5            | 1.6(7)           | 401.31\(^{+30.17}_{-27.45}\) | 2.38\(^{+0.04}_{-0.04}\) | 1.3(79)         | 0.91\(^{+0.05}_{-0.04}\) | 0.23\(^{+0.02}_{-0.03}\) |
1995). In initial stages of the outburst, CE was around $2\pm 3$ per cent. CE gradually dropped to $\sim 0.001$ per cent as the peak of outburst is reached and the photon index became highest. Physically, this means a gradual decrease of size of CENBOL as the Keplerian disc rate rises and cools CENBOL down. After the peak, CE started to increase to $2\pm 3$ per cent in the decline phase, though it finally converged to $\sim 1$ per cent. Variation of QPOs during this outburst is discussed in detail in Chakrabarti et al. (2009).

We then analysed the 2000 outburst of the same source from MJD 516 44 (10/04/2000) to MJD 516 90 (26/05/2000). The result is shown in Fig. 1(b). The light curve looks qualitatively the same as that of the 1998 outburst. During this outburst, CE varied initially between 1.0 and 1.5 per cent, but after MJD 516 60, CE was reduced to less than 0.5 per cent. This indicates that oscillating shock was still present. After a few days, CE again increased to $\sim 1.5$ per cent before settling to an $\sim 1$ per cent. As the shock recedes from the black hole, optical depth initially rises, but then goes down as the CENBOL density drops rapidly. This may be the cause for CE to rise first and then to come down to $\sim 1$ per cent in both outbursts.

4.2 GX 339–4

We analysed the 2007 and 2010 outbursts of GX 339–4. The 2007 outburst was analysed from MJD 540 97 (28/12/2006) to MJD 542 47 (26/05/2007). The result is shown in Fig. 2(a). During the initial stage of the rising phase, CE remained roughly constant at $\sim 0.3$–0.4 per cent for about 40 d. Constancy of CE may mean that while CENBOL is getting smaller, density is becoming larger and thus optical depth remains roughly constant to intercept roughly a similar number of soft photons. After that, CE decreased sharply when the CENBOL disappeared. A sporadic shock is formed during soft and hard-intermediate states, raising CE. QPO remains absent for the next 80 d when CE varied between $\sim 0.05$ and 0.1 per cent. After that, CE was increased to $\sim 0.3$ per cent, close to its initial value.

The 2010 outburst was analysed from MJD 552 14 (18/01/2010) to MJD 553 24 (08/05/2010). The result is shown in Fig. 2(b). During the initial phase, CE remained constant at around 0.3 per cent for 80 d. After that, CE decreased sharply below 0.1 per cent.

4.3 H 1743–322

We analysed the outbursts of 2008 and 2009 of H 1743–322. The 2008 outburst was analysed from MJD 544 82 (16/01/2008) to MJD 545 00 (04/02/2008). Only the declining phase was observed by RXTE for this outburst. The result is shown in Fig. 3(a). Observation started when the object was in a softer state having a high photon index. CE also started from a minimum value of $\sim 0.1$ per cent. Eventually, at the end of the outburst, CE increased to the high state value of $\sim 0.3$ per cent.

The 2009 outburst was analysed from MJD 549 80 (29/05/2009) to MJD 550 19 (07/07/2009). During the rising phase, CE decreased from $\sim 0.4$ to 0.15 per cent within 10 d. During the declining phase, CE rose very slowly to 0.2 per cent. The result is shown in Fig. 3(b). In this case also, near constancy of CE indicates that optical depth is nearly constant even though a shock wave is receding as is obvious from time variation of QPOs (Chakrabarti et al. 2008, 2009; Nandi et al. 2012).

4.4 XTE 1859+226

We analysed the 2000 outburst of XTE 1859+226. The compact object was analysed from MJD 514 63 (12/10/1999) to MJD 516 00 (26/02/2000). The result of the analysis is shown in Fig. 4(a). During the onset phase, CE dropped sharply from $\sim 0.06$ to 0.003 per cent within 30 d. After that, CE remained low for around 20 d. There were bumps in CE at around MJD 535 10, and they could be due to higher accretion rates causing the CENBOL to swell by radiation pressure. In the last phase, CE returned back to a pre-burst value corresponding to a hard state. During this outburst, the QPO frequency increased gradually from 3 to 7.5 Hz from MJD 514 63 to 514 73, i.e. within 10 d. After that, QPOs did not reappear.

4.5 XTE 1118+480

We analysed the 2005 outburst of XTE 1118+480 and the result is shown in Fig. 4(b). Data are from MJD 533 83 (13/01/2005) to MJD 533 96 (26/01/2005). During this outburst, CE varied between 3 and 6 per cent. In not too many days, QPOs were observed during the outburst (Remillard et al. 2005).

4.6 GRO J1655–40

We analysed the 2005 outburst of GRO J1655–40 and the result is shown in Fig. 4(c). The compact object was analysed from MJD 534 35 (06/03/2005) to MJD 536 32 (19/09/2005). During this outburst, CE varied between 2 and 0.1 per cent. QPO variation has already been reported in Chakrabarti et al. (2008).

4.7 4U 1543–47

We analysed the 2002 outburst of 4U 1543–47 and the results are shown in Fig. 4(d). The compact object was analysed from MJD 524 42 (17/06/2002) to MJD 524 80 (25/07/2002). Here, CE varied between 0.3 and 0.01 per cent. In the case of this outburst, QPO was increased from 5 to 8 Hz from MJD 524 42 to MJD 524 60, and then decreased to 1 Hz from MJD 524 60 to MJD 524 80.

5 SUMMARY OF RESULTS AND A COMPARISON WITH GRS 1915+105

In Table 3, we summarize results of our analysis. Maximum and minimum values of CE, luminosity, QPO frequency and mass of compact objects are put together. It is instructive to compare results with those obtained for a highly variable black hole candidate GRS 1915+105 (Pal et al. 2011, 2013) which is believed to be in a soft-intermediate state of some long-duration outburst. Thus, Table 3 also gives results of this source. Since CE is defined in a way so as to eliminate the effects of the mass, our comparison is meaningful, even when the mass varies by a factor of more than 3. In GRS 1915+105, CE varies strongly with a low value for generally softer classes, to a high value for generally harder classes. We clearly note that the CE of GRS 1915+105 varies from 0.005 to 0.8, both ends being far from extreme values. These numbers indicate that if GRS 1915+105 underwent an outburst long ago, it is still in a soft-intermediate state. The CE of GRS 1915+105 was found to be very meaningful since the occurrence of variability class transitions of this object follows the sequence of increasing or decreasing CE (Pal et al. 2013).

6 DISCUSSIONS AND CONCLUSIONS

In this paper, we have analysed several black hole candidates which exhibit outbursts and shown the time dependence of CE, QPOs and the spectral index. We have tried to understand the results...
using the TCAF model of Chakrabarti & Titarchuk (1995) and its time varying form, namely propagatory oscillating shock model of the outbursts (Chakrabarti et al. 2008, 2009; Debnath et al. 2010; Dutta & Chakrabarti 2010), though any model which relies on soft photons and inverse Comptonization would be fine, since CE depends on the ratio of Comptonized photons and soft seed photons. In the TCAF model, a standard Keplerian disc is surrounded by a faster moving low-angular-momentum flow (sub-Keplerian) which produces a centrifugal pressure-supported shock where the flow is puffed up and produces the so-called Compton cloud to inverse Comptonize intercepted soft photons coming from the Keplerian disc. Oscillation of a post-shock region or CENBOL causes low-frequency QPOs in black hole candidates.

In the backdrop of this model, our goal is to study how the optical depth of the CENBOL changes with time in a generic outburst source. If we had computed hardness ratio or HR, where the soft and hard photons are counted using the same fixed energy bins, a comparison of its behaviour from one object to another would not be possible. This is because seed photons of one black hole could be a Comptonized photon for another. On the other hand, CE as defined by us characterizes soft and hard photons objectively and as such does not depend on mass of the black hole or its accretion rate. Thus, a comparison is possible. It is true that we restrict ourselves to 0.1 to 40 keV photons. However, for stellar mass black holes, these boundary values are far away from relevant energies in which respective photons are important.

We came to a conclusion that generally speaking, all outbursts start and end with a large Compton cloud size, though not necessarily with the highest optical depth. As the outburst progresses, CE becomes minimum at peak of an outburst, i.e. size of CENBOL becomes very small. We find that CE in outburst sources may vary from ~0.0 to ~3 per cent. In contrast, the variable source GRS 1915+105 has CE between 0.005 and 0.8 and has relatively high luminosity (even after factoring out effects of mass of the black hole), suggesting that it is in a soft-intermediate state which usually appears after the peak of a possible outburst. If so, in future, this source may slow down its activities when the viscosity in this system is reduced as in any other outbursting source.

We would like to stress that CE computed by us counts soft photons from 0.1 keV to an upper energy limit automatically detected by our fitting method. If we concentrated on photons in the observed 2–40 keV range and counted the number of soft photons, we would have obtained a different CE, in fact, much higher CE. This is because we would have grossly underestimated the number of soft photons. In Fig. 5, we show a comparison of CE computed by our method with ‘fracsctr’ obtained from the simpl model (Steiner et al. 2011) for GX 339–4 data. simpl is an empirical model of Comptonization which computes fraction of photons from an input seed spectrum which are scattered into a power-law component. fracsctr is the fraction (in the scale up to 1.0) of input seed photons that are Comptonized. The black and grey points are for the 2007 and 2010 outbursts. This plot shows variation of fracsctr with CE (per cent) computed in the 0.1–40 keV range.

Table 3. Variation of CE, luminosity and QPO for different compact objects during their outbursts. Data for GRS 1915+105 are presented for comparison.

| Compact object   | Outburst (Year) | Mass ($\sim M_\odot$) | CE$_{\text{min}}$ (per cent) | CE$_{\text{max}}$ (per cent) | $L_{\text{min}}$ ($L_{\text{Edd}}$) | $L_{\text{max}}$ ($L_{\text{Edd}}$) | QPO$_{\text{min}}$ (Hz) | QPO$_{\text{max}}$ (Hz) |
|------------------|-----------------|-----------------------|------------------------------|------------------------------|----------------------------------|----------------------------------|--------------------------|--------------------------|
| XTE J1550–564    | 1998            | 9.6                   | 0.0011                       | 2.78                         | 0.26                             | 1.2                             | 1.8                      | 12.7                     |
| XTE J1550–564    | 2000            | 9.6                   | 0.4                          | 1.7                          | 0.01                             | 0.17                            | 0.3                      | 6.3                      |
| GX 339–4         | 2007            | 7.5                   | 0.02                         | 0.4                          | 0.006                            | 0.26                            | 0.6                      | 10.0                     |
| GX 339–4         | 2010            | 7.5                   | 0.03                         | 0.375                        | 0.007                            | 0.16                            | 0.3                      | 6.0                      |
| H 1743–322       | 2008            | 10.0                  | 0.1                          | 0.3                          | 0.01                             | 0.04                            | 1.0                      | 5.0                      |
| H 1743–322       | 2009            | 10.0                  | 0.17                         | 0.37                         | 0.02                             | 0.18                            | 1.0                      | 3.7                      |
| XTE J1859+1226   | 2000            | 4.5                   | 0.004                        | 0.05                         | 0.01                             | 0.20                            | 3.0                      | 7.6                      |
| XTE J1118+480    | 2005            | 8.5                   | 2.2                          | 6.4                          | 0.0003                           | 0.001                           | –                       | –                        |
| GRO J1655–40     | 2005            | 7.02                  | 0.011                        | 2.24                         | 0.003                            | 0.22                            | 0.4                      | 8.0                      |
| 4U 1543–47       | 2002            | 9.4                   | 0.012                        | 0.33                         | 0.01                             | 0.59                            | 1.0                      | 8.0                      |
| GRS 1915+105     | –               | 14                    | 0.005                        | 0.8                          | 0.8                              | 1.4                             | 3.0                      | 10.0                     |

Figure 5. Variation of fracsctr with CE (per cent) for the 2007 and 2010 outbursts of GX 339–4 data. The black stars and grey circles, respectively, represent data of the 2007 and 2010 outbursts. This plot shows variation of fracsctr with CE (per cent) computed in the 0.1–40 keV range.
Figure 6. Variation of QPO frequency with CE (per cent) for all outbursts. The general trend is that the frequency increases as CE is decreased.

frequency, which is exactly what we observe! If we combine these results, then the TCAF model would predict that CE would be larger when the QPO frequency is smaller and vice versa. In Fig. 6, we show measured QPO frequencies as a function of our CE for all the outbursts discussed in this paper. We find that CE is inversely correlated with QPO frequencies, although the relationship is not very tight in some cases. This could be because of the presence of radio jets observed in all these outburst sources (Hjellming & Rupen 1995; Brockskopp et al. 2002; Kaaret et al. 2003; Buxton & Bailyn 2004; Kalemi et al. 2005; Migliari et al. 2007; Corbel & Tzioumis 2008; Casella et al. 2010; Corbel et al. 2010). While CE is influenced by electron clouds at the base of a jet (post-shock region in TCAF solution), QPO frequency is not directly affected by the jet, but only by the location of oscillating shock. This could be a primary reason why some outbursters do not show a tight correlation. However, this aspect requires further investigation.

It is also interesting to study variation of CE with luminosity in analogy with hardness ratio–intensity plots in the literature (Fender, Belloni & Gallo 2004). Since the hardness ratio is obtained from a fixed range of X-ray photons, independent of the mass of black hole, it is difficult to interpret what a conventional colour–colour diagram really means. In Figs 7(a) and (b), we plot CE versus luminosity for both outbursts of XTE 1550–564 and GX 339–4, respectively. In Fig. 7(a), the dark filled boxes represent the variation of CE (per cent) with the natural logarithm of luminosity in Eddington units during the 1998 outburst, and the grey filled circles represent same for the 2000 outburst. In Fig. 7(b), the black filled boxes represent the 2007 outburst of GX 339–4, while the grey filled circles represent the same for the 2010 outburst of GX 339–4. For all plots, arrows of corresponding colour are provided to understand evolution of data during outbursts. The figures provide an idea about the relation between the geometric size of the electron cloud and total luminosity during the outburst. In the case of XTE 1550–564, we observe that both outbursts started and ended with high CE, though the final value of CE is lower than its initial value. However, this could be due to incompleteness of observation during the onset of the outburst. The outburst of 2000 is clearly weaker and short lived. In both the cases, there is a hysteresis effect in those paths in the rising and declining phases are not the same. This is expected, since formation time and disappearance time of a Keplerian disc by viscous effects are not identical (Giri & Chakrabarti 2013). In the case of GX 339–4, both figures generally overlapped and thus both were of roughly equal strength. We note that CE is not necessarily highest at the beginning or end in all these cases, though it is close to highest values achieved during the outburst. This may be because CE is sensitive to the optical depth and not just the physical size of the CENBOL. This is also the reason why QPO frequency variation (sensitive to the size of CENBOL) is not tightly correlated with CE.

An important result is that the CE of GX 339–4 is much lower as compared to that of XTE J1550–564. Since with spin the size of the CENBOL shrinks at least by a factor of 2 (Chakrabarti 1996), the degree of interception would also be reduced by the same factor. It is well known that the spin of XTE J1550–564 is moderate (Steiner et al. 2011), while the spin of GX 339–4 is very high (Kolehmainen & Done 2010). It is possible that we are seeing effects of the large spin in GX 339–4 in our calculation also.

In order to show that soft photons beyond ddb really do not contribute significantly, we recomputed the above values with soft...
Disc geometry variation during outbursts

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