Relation between Quiescence and Outbursting Properties of GX 339-4

Riya Bhowmick1, Dipak Debnath1, Kaushik Chatterjee1, Shreeram Nagarkoti1,2, Sandip Kumar Chakrabarti1, Ritabrata Sarkar1, Debjit Chatterjee1,3, and Arghajit Jana1,4

1 Indian Centre for Space Physics, 43 Chalantika, Garia St. Road, Kolkata 700084, India; dipakcsp@gmail.com
2 St. Xavier’s College, Maitighar, Kathmandu 44600, Nepal
3 Indian Institute of Astrophysics, Koramangala, Bengaluru, Karnataka, 560034, India
4 Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

Received 2020 May 20; revised 2021 January 11; accepted 2021 January 19; published 2021 April 5

Abstract

Galactic black hole candidate GX 339-4 underwent several outbursting phases in the past two and a half decades at irregular intervals of 2–3 years. The nature of these outbursts in terms of the duration, number of peaks, maximum peak intensity, and so on varies. We present a possible physical reason behind the variation of the outbursts. From a physical point of view, if the supply of matter from the companion is roughly constant, the total energy released in an outburst is expected to be proportional to the quiescent period prior to the outburst when the matter is accumulated. We use archival data of RXTE/ASM from 1996 January to 2011 June and of MAXI/GSC from 2009 August to 2020 July. Five initial outbursts of GX 339-4 between 1997 and 2011 were observed by ASM and showed a good linear relation between the accumulation period and the amount of energy released in each outburst, but the outbursts after 2013 behaved quite differently. The 2013, 2017–2018, and 2018–2019 outbursts were of short duration and incomplete or “failed” in nature. We suggest that the matter accumulated during the quiescent periods prior to these outbursts was not cleared through accretion due to a lack of viscosity. The latter matter was cleared in the very next outbursts. Our study thus sheds light on long-term accretion dynamics in outbursting sources.

Unified Astronomy Thesaurus concepts: X-ray binary stars (1811); X-ray transient sources (1852); Black holes (162); Black hole physics (159); Accretion (14)

1. Introduction

Stellar-mass black hole candidates (BHCs) are mainly two types: transient and persistent. Transient BHCs most of the time stay in the “quiescence” phase. Occasionally, these low-mass X-ray binaries (LMXBs) become active and trigger an outburst. The easiest way to detect an LMXB is to detect the X-ray radiation coming from the accretion disk of these systems. The disk forms by the accreting matter from the companion via Roche-lobe overflow. The nature of two outbursts even for the same black hole (BH) is not similar. In an outburst, a rapid evolution of the spectral and temporal properties is observed. Generally, there are four defined spectral states of a BHC: hard (HS), hard intermediate (HIMS), soft intermediate (SIMS), and soft (SS); see Remillard & McClintock 2006 for a review). Type I or classical transient BHCs show all four spectral states, forming a hysterisis loop (HS → HIMS → SIMS → SS → SIMS → HIMS → HS) during an outburst, whereas type II or harder outbursts do not show softer states (SIMS and SS; see Deb Nath et al. 2017) during their outbursts. There are few exceptions of transient BHCs, such as H 1743-322 and the present source GX 339-4, which showed both types of spectral-state evolution. Low-frequency quasi-periodic oscillations (LFQPOs) are common features in hard and intermediate spectral states. Sometimes monotonous evolution of the LFQPOs is observed during HS and HIMS in both the rising and declining phases of an outburst. LFQPOs are generally observed sporadically in the SIMS (see Nandi et al. 2012; Deb Nath et al. 2013, and references therein). These three spectral states are also active in jets. Generally, we do not observe any outflows or LFQPOs in the SS.

To find a physical explanation for the accretion flow dynamics of BHs, many models have been put forward in the past decades. The two-component advective flow (TCAF) model is one such model, which was introduced in the mid-1990s (Chakrabarti & Titarchuk 1995; Chakrabarti 1997). It is a solution of radiative transfer equations considering both heating and cooling effects. According to this model, the accretion disk consists of two components of flows: a geometrically thin, optically thick high-viscous Keplerian flow and a low-viscous, optically thin sub-Keplerian flow or halo. The Keplerian flow accretes on the equatorial plane and is immersed within the sub-Keplerian flow. The sub-Keplerian matter moves faster than the Keplerian matter. Due to the rise in the centrifugal force close to the black hole, the halo matter temporarily slows down and forms an axisymmetric shock at the centrifugal barrier (Chakrabarti 1989, 1990). The postshock region is hot and puffed-up and is known as the centrifugal pressure supported boundary layer (CENBOL). Multicolour blackbody spectra are generated from the soft photons originating from the Keplerian disk. A fraction of the soft photons from the Keplerian disk are intercepted by the CENBOL. They are inverse-Comptonized by highly energetic, “hot” electrons of the CENBOL and produce hard photons. The power-law tail in the spectra is produced by these hard photons. When the radiative cooling timescale and the heating timescale roughly match, the CENBOL oscillates, and the emerging photons produce QPOs (Molteni et al. 1996; Ryu et al. 1997; Chakrabarti et al. 2015). This TCAF model has been implemented as an additive table in XSPEC to obtain direct estimation of flow parameters (Keplerian mass accretion rate, sub-Keplerian halo accretion rate, shock location and compression ratio) other than mass of the BH from spectral fits (Debnath et al. 2014). Accretion flow dynamics, evolution of spectral and temporal properties of many black holes are now
well understood from the variation of the model fitted flow parameters (see, Mondal et al. 2014, 2016; Debnath et al. 2015a, 2015b, 2017, 2020; Chatterjee et al. 2016, 2019, 2020; Jana et al. 2016, 2020a, 2020b; Bharatcharjee et al. 2017; Shang et al. 2019; Banerjee et al. 2020). Estimation of probable mass of the BHs, jet contribution in the observed X-ray flux, viscous time scale, etc. are also done from the spectral analysis using TCAF model based fits file (Molla et al. 2016; Jana et al. 2016, 2017).

GX 339-4 was first discovered in 1973 by satellite OSO-7 (Markert et al. 1973). The source is located at (l,b) = (338°93.4,27) with R.A. = 16°58′8″ ± 0′0′′8 and decl. = −48°41′ ± 12′ (Markert et al. 1973). According to Hynes et al. (2004), the distance of GX 339-4 is found to be 6 ≤ d ≤ 15 kpc from the study of high-resolution optical spectra of Na D lines. From optical and infrared observations, Zdziarski et al. (2004) estimated the distance to be d ≥ 7 kpc. Parker et al. (2016) estimated d = 8.4 ± 0.9 kpc from the reflection and continuum-fitting method using the X-ray spectrum. Since there are no eclipses in the X-ray and optical data of the system, Cowley et al. (2002) suggested that the inclination of the source must lie below i = 60°, and Zdziarski et al. (2004) gave an estimate of the inclination angle as 45° ≤ i ≤ 80°. Using relativistic reflection modeling, Parker et al. (2016) found an inclination of about 30° ± 1°. Heida et al. (2017) stated that the binary inclination is 37° < i < 78° from studies of near-infrared absorption lines of the donor star. According to Parker et al. (2016), the mass of the source is 9.0±1.2 M_☉, although Heida et al. (2017) estimated the mass as 2.3 M_☉ < M < 9.5 M_☉. Recently, Sreehari et al. (2019) have evaluated the mass of this BH in the range 8.28 − 11.89 M_☉ from temporal and spectral analysis. Miller et al. (2008) have suggested the spin parameter of the source to be a = 0.93 ± 0.01, whereas Ludlam et al. (2015) found the spin value to be a > 0.97, and from relativistic reflection modeling, Parker et al. (2016) estimated the spin to be a = 0.95±0.02.

The well-known Galactic BHC GX 339-4 is transient in nature, having regular outbursts every 2–3 years. Since its discovery in 1973, by the MIT X-ray detector (on board the OSO-7 satellite), it was observed by several satellites during different times, such as HAKUCHO, GINGA/ASM, LAC, BATSE, SIGMA, RXTE/ASM, and MAXI/GSC (Tetarenko et al. 2016). In a period of 46 years, the total number of outbursts was about 23. During the RXTE era (1996 onward), the source exhibited outbursts in 1997–1999, 2002–2003, 2004–2005, 2006–2007, and 2010–2011 with very-low-luminosity quiescent states between the outbursts. From 2010 onward, all of the outbursts (2010–2011, 2013, 2014–2015, 2017–2018, 2018–2019, and the latest 2019–2020) have been observed by MAXI/GSC.

Although there is debate on the triggering mechanism of an outburst, it is generally believed that an outburst in a black hole candidate is triggered by the sudden enhancement of viscosity at the outer edge of the disk (Ebisawa et al. 1996). The declining phase of an outburst starts when the viscosity becomes weaker. Recently, Chakrabarti et al. 2019 (hereafter CDN19) discussed a possible relation between the quiescence phase and the outburst phase of the recurring transient BHC H 1743-322. In this case, matter supplied by the companion starts to pile up at a pile-up radius (X_p) at the outer disk during the quiescence phase. An outburst could be triggered by a rapid rise of viscosity at this temporary reservoir far away from the BH. To find the relation between the outburst and quiescence periods, CDN19 computed the energy released during the outbursts of H 1743-322 and showed that, on average, the energy released in an outburst is proportional to the duration of the quiescent state (measured as peak-to-peak flux between two successive outbursts) just prior to the outburst. Since BHC GX 339-4 also underwent several outbursts as the BHC H 1743-322, it would be interesting to check if their conclusion holds for the present object as well.

The paper is organized in the following way. In the next section, we present observation and data analysis methods. In Section 3, we present our analysis results. Finally, in Section 4, we discuss our results and make concluding remarks.

2. Observation and Data Analysis

We use archival data from RXTE/ASM (in 1.5–12 keV energy range) and MAXI/GSC (in 2–10 keV energy range) for our study. Our analysis covers 10 outbursts of GX 339-4. The daily-average light curves are converted into Crab units using proper conversion factors. The Crab conversion factors 75 Counts/s for the ASM data (1.5–12 keV energy range) and 2.82 photons cm⁻² s⁻¹ for the GSC data (2–10 keV energy range) are used. For the analysis, we followed the same procedure as described in CDN19.

The nature of the outbursts is different from each other. The light curve of each outburst consists of multiple peaks. To fit each peak within an outburst, we use the Fast Rise and Exponential Decay (FRED) profile (Kocevski et al. 2003) as a model written in the ROOT data analysis framework of CERN. So to obtain the best fit, we require multiple FRED profiles. The combined FRED fit gives us the total energy released, that is, the integrated flux of each outburst. As in CDN19, here we also used a 12 mCrab flux value as an outburst threshold to calculate the outburst duration.

3. Results

A comparative study of the light curves of different sources and the energy released in each outburst helps one to understand the relation between the outburst and quiescence phases of black hole X-ray binaries. Here we study the light-curve profiles of the BHC GX 339-4. We fit the light curves of all of the outbursts with multiple FRED profiles. From the FRED-fitted curves, we calculate the integrated X-ray flux (IFX) in each outburst and make a comparative study. The fits also provide us with the peak flux and duration (in MJD) of each outburst.

3.1. Outburst Profile and Integrated Flux Calculation

Figure 1 shows the RXTE/ASM 1.5–12 keV light curve (online blue) of GX 339-4 from 1996 January to 2011 June and the MAXI/GSC 2–10 keV light curve (online red) starting from 2009 August to 2020 July. The 2013 (Fürst et al. 2015) and the 2017–2018 (Garcia et al. 2019) outbursts were reported as “failed” outbursts, as the source failed to make the state transition into the SS. The 2018–2019 outburst was also very short in duration and “failed” in nature (Paice et al. 2019). Figure 1 shows that the peak flux reached a maximum value.

http://xte.mit.edu
http://maxi.riken.jp
during the 2006–2007 outburst, and the peak flux value was at a minimum during the mini outburst of 2018–2019.

In Figure 1, we show zoomed-in preoutburst periods of the 1997–1999 outburst (MJD = 50,000 to MJD = 51,000) in the upper left corner and of the 2006–2007 outburst (MJD = 53,600 to MJD = 54,260) in the upper right corner. In the case of the 1997–1999 outburst, we can easily see that there are multiple small flaring activities before this outburst. Similarly, in the 2006–2007 outburst, there is also one significant small flaring activity (MJD = 53,778 to MJD = 53,886) before the outburst.

As mentioned earlier, we use multiple FRED profiles to fit the RXTE/ASM and MAXI/GSC light curves in all of the outbursts of the BHC GX 339–4. The shape of the light curve is described by the formula (Kocevski et al. 2003)

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

(1)

where $F_m$ is the peak value of the flux, and $t_m$ is the time at which the light curve has a peak value of flux. Here, $r$ denotes the rising index and $d$ denotes the decaying index. Figure 2 shows the FRED (online blue) fitted outburst profile (2010–2011 in this case), that is, the daily light curve (black lines with points). A large fluctuation in the residual is due to sudden spikes or dips in the data. We use a combination of six FRED profiles to fit the profile of the 2010–2011 outburst. To confirm the $k$-number (here six) of FRED profiles (here six) that are required for the best fit of the multi peaked outbursts, we used the Bayesian information criterion (BIC) selection method. Here, $k + n$ (n = 1, 2, ..) FRED model fits are excluded based on the threshold $\Delta(BIC) > 8$.

During the quiescent state, the outbursts have a flux equivalent to a few milli-Crab (mCrab). A limit of 12 mCrab is used as the threshold for the outbursts, and the energy released above this limit is integrated to measure the IFX released per outburst. After getting the best fit of the outbursts with the FRED model, we mark the start and the end of an outburst based on the threshold flux chosen to be 12 mCrab, as in CDN19. In Figure 2, the horizontal line (black) shows the 12 mCrab flux value. The two vertical lines (black) mark the start

**Figure 1.** Daily-average count rate (in mCrab) of RXTE/ASM (blue) in the 1.5–12 keV energy band and of MAXI/GSC (red) in the 2–10 keV energy band.

**Figure 2.** FRED profile fitting on 2010–2011 outburst data. The blue (online) curve is the total FRED-fitted curve, and the red (online) curves are FRED model fitted individual peaks. The flux value of 12 mCrab was taken as the quiescent value for all outbursts. A horizontal line (black) with a value of 12 mCrab is drawn. The points where the total FRED-fitted curve (blue) touches the 12 mCrab line are the start (in the rising phase) and end (in the declining phase) of the outburst. The beginning and end of the outburst are shown as the intersection points of the horizontal line with two vertical black lines in the rising and declining phases. Here, MJD = 55,149.5 is used as the zeroth day ($t_0$).
and the end of the outburst. The IFX is calculated from the combined model fit. We also calculate various parameters, such as peak flux ($F_m$), peak time ($t_m$), and the duration of the outburst from the combined FRED-fitted curve. Similar fits are done for all outbursts, and the parameters obtained are provided in Table 1. From the $t_m$ values of the outbursts, the periods of accumulation of matter from the companion onto the disk, as measured from the duration between the peaks of two successive outbursts, are also calculated for each outburst. In Table 2, FRED profile fitted parameters, the integral flux, and the duration of each peak (online red curves) of the outbursts are tabulated. The duration and IFX values are calculated within the 12 mCrab flux threshold of the individual model fitted curves. We also checked whether the sum of the individual IFXs matches the total integral flux (online blue curve) of the outburst.

From the archival data obtained from RXTE/ASM and MAXI/GSC, the count rates or fluxes and the corresponding uncertainties are converted into mCrab units using conversion factors. We formed three data sets for each outburst: (i) Set I, MJD versus flux values; (ii) Set II, MJD versus error-added flux value; and (iii) Set III, MJD versus error-subtracted flux value. We fitted these three data sets for each outburst with the FRED model and calculated the peak flux ($F_m$), peak time ($t_m$), duration, and the integrated flux value of the outburst from the combined FRED-fitted curve. We got the value of the variables from each of the three data sets. We calculated the differences of the main value (Set I) with error-added value (Set II) and the main value (Set I) with error-subtracted value (Set-III) of each variable obtained from these three data sets. By averaging those, we got the “±” errors in each of the variables.

In Figure 1, we see that the 2010–2011 outburst was observed by both the RXTE/ASM and MAXI/GSC instruments. The values of the variables calculated from both RXTE/ASM and MAXI/GSC data are very close to each other (given in Table 1). The value of IFX calculated from the RXTE/ASM data for the 2010–2011 outburst is 103.371 mCrab day, and the value of IFX calculated from the MAXI/GSC data is 103.829 mCrab day. Because there was less noise in the GSC data, we have taken the 103,829 value (the value of IFX of the 2010–2011 outburst calculated from the MAXI/GSC data) as a reference to normalize all other outbursts.

We observed some peculiarities in the 2013 and 2014–2015 outbursts. The 2013 outburst has a small peak flux of $\sim 51.58$ mCrab and a shorter duration of $\sim 84$ days. The accumulation period for the 2013 outburst is very high ($\sim 1228$ days) compared to the other outbursts of GX 339-4. In the very next outburst, in 2014–2015, although the accumulation period is small ($\sim 554$ days), it showed a higher peak flux ($\sim 619$ mCrab) and a longer outburst duration of $\sim 352$ days. The same peculiarity can be seen in the 2017–2018, 2018–2019, and 2019–2020 outbursts. For the 2017–2018 outburst, there is a large accumulation period of $\sim 1008$ days, but the outburst duration is small ($\sim 173.1$ days) and has a small peak flux value of 58.5 mCrab. In contrast, the 2019–2020 outburst has a small accumulation period of $\sim 314$ days, but the outburst has a high peak flux value of 800 mCrab. The possible reason for this behavior will be discussed in the following subsection.

For each outburst, we also calculated the value of IFX by simply integrating the flux values and calculated the normalized IFX with respect to the integral flux value of the 2010–2011 outburst (see Table 1). We noticed that the IFX values from the simple integration method do not differ much from that of the FRED fits. But, the use of the FRED model is a more scientific way to find the integrated flux and other parameters (peak flux, peak time, duration, and so on) of the outbursts. We have downloaded daily-average ASM and GSC count rate/flux data from the archive, but data for some days are missing. Sometimes there is also a sudden rise or dip in the light curves for one or two observations. We feel that these are data errors. So, determination of the parameters without fitting with the FRED profile will not give the information correctly. Thus, we use the value of the parameters that we get from the FRED-fitted curve of each outburst for our analysis.

### 3.2. Comparative Study of Outburst Fluxes

The count rates of one-day average data from RXTE/ASM and MAXI/GSC are converted to mCrab units with proper conversion factors (mentioned above). Then all of the outbursts are fitted with the multiple FRED profiles, and the total

| Outburst Year | Peak Day $(\text{MJD})$ | Peak Flux $(\text{mCrab})$ | Duration $(\text{Days})$ | Accumulation Period $(\text{Days})$ | Normalized IFX $\text{w.r.t.} ~ 2010–2011$ | Normalized IFX $\text{w.r.t.} ~ 2010–2011$ $(\text{simple integration})$ |
|---------------|------------------------|---------------------------|------------------------|--------------------------------|------------------------------------------|------------------------------------------|
| RXTE/ASM      |                        |                           |                        |                                |                                          |                                          |
| 1997–1999     | 50873.5                | 305.5 ± 33.5              | 686.0                  | 918.5                         | 0.946 ± 0.061                           | 0.951 ± 0.094                            |
| 2002–2003     | 52495.5                | 877.8 ± 9.6               | 454.3                  | 1622.0                        | 1.519 ± 0.066                           | 1.522 ± 0.096                            |
| 2004–2005     | 53303.4                | 484.4 ± 11.5              | 446.7                  | 806.9                         | 0.750 ± 0.050                           | 0.757 ± 0.072                            |
| 2006–2007     | 54152.8                | 972.0 ± 5.5               | 232.6                  | 849.8                         | 0.490 ± 0.059                           | 0.482 ± 0.038                            |
| 2010–2011     | 55308.2                | 689.8 ± 10.2              | 401.9                  | 1156.6                        | 0.995 ± 0.007                           | 0.986 ± 0.067                            |
| MAXI/GSC      |                        |                           |                        |                                |                                          |                                          |
| 2010–2011     | 55308.5                | 708.1 ± 14.7              | 399.2                  | 1156.3                        | 1.000 ± 0.051                           | 1.00 ± 0.076                             |
| 2013          | 56536.9                | 51.58 ± 3.5               | 84.0                   | 1228.4                        | 0.029 ± 0.007                           | 0.028 ± 0.006                            |
| 2014–2015     | 57090.7                | 619.3 ± 12.5              | 352.1                  | 553.8                         | 0.735 ± 0.041                           | 0.737 ± 0.069                            |
| 2017–2018     | 58098.7                | 58.5 ± 10.9               | 173.1                  | 1008.0                        | 0.047 ± 0.012                           | 0.049 ± 0.011                            |
| 2018–2019     | 58530.5                | 29.43 ± 10.8              | 115.7                  | 431.8                         | 0.022 ± 0.012                           | 0.025 ± 0.010                            |
| 2019–2020     | 58844.1                | 799.5 ± 15.1              | 238.9                  | 313.6                         | 0.335 ± 0.023                           | 0.336 ± 0.037                            |

**Notes.**

$^a$ The accumulation period is taken from the peak day of the previous outburst to the outburst of concern.

$^b$ The integral flux is obtained by a simple integration method and then normalized with respect to the integral flux of the 2010–2011 outburst.
integrated flux during each outburst is calculated in “mCrab day” units. We subdivided the IFX of each outburst by the reference value of IFX of the 2010–2011 outburst (observed by MAXI/GSC) to get the normalized IFX in each outburst. Figure 3(a) shows the IFX per day of outburst, normalized with respect to the 2010–2011 outburst per day (normalized flux of a day of an outburst). In Figure 3(a), the area of each bar represents the IFX of each outburst, and the width of each bar represents the duration of each outburst. This IFX can be converted into the total energy release rate (Yan & Yu 2015) using the prescription provided in http://xte.mit.edu. Figure 3(b) shows the normalized IFX per day in the accumulation period of each outburst. For the 1997–1999 outburst, the previous outburst is taken in 1995 (Rubin et al. 1998) and the peak flux value is taken on MJD = 49,955. We see that the normalized flux per day of accumulation is roughly constant except for the outbursts during and after 2013. In this Figure, we see that the normalized flux per day of accumulation is very low in the 2011 outburst come down to the average level as par with other outbursts (Figure 3(c)). A similar situation occurred during the 2003 outburst of the BHC H 1743-322 as well. Physically, we believe that, due to the lack of significant viscosity that triggered the 2013 outburst, only part of the matter accumulated at the pile-up radius could accrete. The rest joined the matter piled up subsequently, and when the viscosity was high enough, the 2014–2015 outburst started. In CDN19, a general cartoon diagram was presented to describe the flow behavior in H 1743-322, and we believe exactly the same flow dynamics are occurring here as well. Similar to the 2013 outburst, the 2017–2018 outburst was also “failed” in nature, and the leftover matter of these outbursts was released in the successive outbursts, that is, in 2018–2019 (mini outburst) and 2019–2020 (main outburst). We combined the energy released in these three outbursts and treated them as parts of a single outburst (see Figure 3(c)). From Figure 3(c), it is also evident that as time passed, the normalized IFX per day of accumulation showed a decreasing trend, particularly after the 2010–2011 outburst. This implies that there could be a nonconstant rate of supply of matter from the companion.

In Figure 4, we show what happens to a “failed” outburst as opposed to a complete normal outburst. Let us start with the configuration in the quiescent state (Figure 4(a)). After the

### Table 2

| Outburst (1) | K (2) | K1 (3) | K2 (4) | K3 (5) | K4 (6) | K5 (7) | K6 (8) | K Integral Flux (9) | K Duration (10) |
|--------------|------|--------|--------|--------|--------|--------|--------|-------------------|----------------|
matter from the companion crosses the Roche lobe and creates an accretion shock, the flow continues to move inward until the viscosity allows it to remain Keplerian (black annulus). The Keplerian disk halts at the pile-up radius $X_p$ (deep gray ring), where matter continues to pile up. Inside this radius, the hot, advective sub-Keplerian matter continues to flow, emitting a

Figure 3. (a) Histogram of the normalized flux per day of each outburst. The width of each bar shows the duration of the outburst. (b) The normalized flux per day of the accumulation period for each outburst. All integrated fluxes are being normalized using the 2010–2011 integrated flux value. For the 1997–1999 outburst, the previous outburst is taken in 1995 (Rubin et al. 1998). (c) Normalized flux per day of the accumulation period for each outburst, where the contribution from the 2013 outburst is transferred to the 2014–2015 outburst, and the contributions of 2017–2018 and 2018–2019 are transferred to the 2019–2020 outburst.

Figure 4. Possible flow dynamics in normal outbursts (a–b) and in failed outbursts (c–d).
litter X-ray in this state. When the piled-up matter becomes unstable and a possibly larger convective viscosity drains this accumulated matter completely and gradually, the outburst is triggered and reaches the final SS state via the HS, HIMS, and SIMS states, and the Keplerian disk reaches the inner stable orbit (Figure 4(b)). In a “failed” outburst, the disk may start in the same way (Figure 4(c)). However, a significant viscosity may not be sustained for a long time, and the Keplerian disk may not move in all the way to the marginally stable orbit. Only a fraction of the piled-up matter will be depleted to produce the TCAF, and due to the lower viscosity, the CENBOL does not reach the marginally stable orbit. In that case, the outburst will see at most in the hard intermediate or soft intermediate states (Figure 4(d)). Due to the partial evacuation of matter at the pile-up radius, the rest of the matter remains there and gets added to the newly supplied matter from the companion that is released in the next outburst.

4. Discussion and Conclusions

In the post-RXTE era (1996 onward), the source GX 339-4 showed several outbursts at irregular intervals of 2–3 years. The nature of each of these outbursts is different. There are differences in duration, accumulation period (quiescence phase), maximum peak intensity, and so on in these outbursts. Recently, Chakrabarti and his collaborators were quite successful in finding the physical reason behind the variations in the nature of outbursts of the Galactic transient H 1743-322 (see CDN19). They found a relation between the energy release at an outburst and the duration between the current and the previous peak times.

The supply of matter from the companion via Roche-lobe overflow continues in the rising as well as declining and quiescence phases. Generally, an outburst is triggered when the viscosity rises above a critical value, and the declining phase starts when the viscous effect is turned off (see Chakrabarti et al. 2005 and references therein). Matter from the outer disk inside the Roche lobe of the accretor may not be able to form a Keplerian disk up to the marginally stable orbit, due to lack of significant viscosity. Initially, due to low viscosity, this matter starts to accumulate at a location, far away from the black hole, known as the pile-up radius ($X_p$). With an increase in the amount of accumulated matter, the thermal pressure rises. As a result, turbulence and instability increase, which in turn increase the viscosity above the critical value. With this high viscosity, matter rushes toward the black hole in two Keplerian and sub-Keplerian components (TCAF) from $X_p$ and triggers an outburst. While releasing most of the stored hot matter at the pile-up radius ($X_p$), the viscosity is turned off, triggering an onset of the declining phase, followed by the quiescent state. The quiescence phase duration varies with $X_p$. For larger $X_p$, the quiescence phase duration is also high because a larger value of $X_p$ requires a higher viscosity to trigger the outburst; that is, more accumulation of matter is required, resulting in a larger duration of quiescence. Some examples were given in CDN19. The matter accumulated at $X_p$ from the peak day of the previous outburst up to the peak day of the ongoing outburst contributes to the current outburst. Thus the total energy released in an outburst reflects the amount of matter accumulated at the pile-up radius during the accumulation period prior to that outburst.

The relation between the outbursts and quiescence periods is also studied for the Galactic transient GX 339-4. To calculate the accumulation duration of the matter at $X_p$, we considered peak (of the previous outburst) to peak (of the considered outburst) durations, which also include the quiescence periods. We notice that the average energy released in an outburst is proportional to the period of accumulation just prior to it, with the exception of the outbursts that occurred in 2013, 2014–2015, 2017–2018, 2018–2019, and 2019–2020. We found that the 2013, 2017-2018, and 2018-2019 outbursts were “failed” outbursts, where the energy released was not complete. If we combine the energies released at the 2013 and 2014–2015 outbursts and treat them as parts of a single outburst, then the linear relation can be seen. The possible flow dynamics in “normal” and “failed” outbursts are shown in Figure 4. In Figure 4(c–d), only part of the matter is released as in the 2013 outburst. The leftover matter at the pile-up radius was combined with freshly supplied matter from the companion and produced the normal outburst of 2014–2015 with higher-than-expected flux. Similar to the 2013 outburst, the 2017–2018 is also an incomplete outburst. We also found that the 2019–2020 outburst released more than its share as in the 2014–2015 outburst. There was also a mini outburst of 2018–2019 between the 2017–2018 and 2019–2020 outbursts. We combined the energies released in the three successive outbursts of 2017–2018, 2018–2019, and 2019–2020 and treated them as the parts of a single outburst that took place in 2019–2020.

It is evident from Figure 3(c) that the normalized flux per day of the accumulation period showed a decreasing trend as time passed, particularly after the 2010–2011 outburst. This means that the supply rate from the companion seems to have decreased as the day progressed. In the near future, GX 339-4 may proceed to a long-duration quiescence phase.

In any case, our global picture of accumulation of matter at the pile-up radius and its release rate as per availability of viscous processes holds for the present source. This was also seen to be the case in outbursts of H 1743-322. In the future, we will verify the findings of our work with other transient BHCs, and the results will be reported elsewhere.

This work made use of ASM data of NASA’s RXTE satellite and GSC data provided by RIKEN, JAXA, and the MAXI team. R.B. acknowledges support from a CSIR-UGC NET qualified UGC fellowship (June 2018, 527223). D.D. and S.K. acknowledge support from the Govt. of West Bengal, India, and the ISRO-sponsored RESPOND project (ISRO/RES/2/418-17-18). K.C. acknowledges support from a DST/INSPIRE (IF170233) fellowship. D.C. and D.D. acknowledge support from a DST/SERB-sponsored Extra Mural Research project (EMR/2016/003918). A.J. and D.D. acknowledge support from a DST/GITA-sponsored India-Taiwan collaborative project (GITA/DST/TWN/P-76/2017). A.J. acknowledges the support of the Post-Doctoral Fellowship from Physical Research Laboratory, Ahmedabad, India, funded by the Department of Space, Government of India.

ORCID iDs
Riya Bhowmick https://orcid.org/0000-0002-7658-0350
Dipak Deb Nath https://orcid.org/0000-0003-1856-5504
Kaushik Chatterjee https://orcid.org/0000-0002-6252-3750
Shreeram Nagarkoti https://orcid.org/0000-0002-3187-606X
Sandip Kumar Chakrabarti https://orcid.org/0000-0002-0193-1136
References

Banerjee, A., Bhattacharjee, A., Debnath, D., & Chakrabarti, S. K. 2020, RAA, 20, 208

Bhattacharjee, A., Banerjee, I., Banerjee, A., Debnath, D., & Chakrabarti, S. K. 2017, MNRAS, 466, 1372

Chakrabarti, S. K. 1989, MNRAS, 240, 7

Chakrabarti, S. K. 1990, Theory of Transonic Astrophysical Flows (Singapore: World Scientific)

Chakrabarti, S. K. 1997, ApJ, 484, 313

Chakrabarti, S. K., Debnath, D., & Nagarkoti, S. 2019, AdSpR, 63, 3749

Chakrabarti, S. K., Mondal, S., & Debnath, D. 2015, MNRAS, 452, 3451

Chakrabarti, S. K., Nandi, A., Debnath, D., Sarkar, K., & Datta, B. G. 2005, IJP, 79, 841

Chakrabarti, S. K., & Titarchuk, L. G. 1995, ApJ, 455, 623

Chatterjee, D., Debnath, D., Chakrabarti, S. K., Mondal, S., & Jana, A. 2016, ApJ, 827, 88

Chatterjee, D., Debnath, D., Jana, A., & Chakrabarti, S. K. 2019, ApSS, 364, 14

Chatterjee, K., Debnath, D., Chatterjee, D., et al. 2020, MNRAS, 493, 2452

Cowley, A. P., Schmidtke, P. C., Hutchings, J. B., & Crampton, D. 2002, AJ, 123, 1741

Debnath, D., Chakrabarti, S. K., & Mondal, S. 2014, MNRAS, 440, L121

Debnath, D., Chakrabarti, S. K., Nandi, A., et al. 2008, BASI, 36, 151

Debnath, D., Chakrabarti, S. K., & Nandi, A. 2013, Adv. Space Res., 52, 2143

Debnath, D., Chatterjee, D., Jana, A., Chakrabarti, S. K., & Chatterjee, K. 2020, RAA, 20, 175

Debnath, D., Jana, A., Chakrabarti, S. K., Chatterjee, D., & Mondal, S. 2017, ApJ, 850, 52

Debnath, D., Molla, A. A., Chakrabarti, S. K., & Mondal, S. 2015b, ApJ, 803, 59

Debnath, D., Mondal, S., & Chakrabarti, S. K. 2015a, MNRAS, 447, 1984

Ebisawa, K., Titarchuk, L., & Chakrabarti, S. K. 1996, PASJ, 48, 59

Fürt, F., Nowak, M. A., Tomsick, J. A., et al. 2015, ApJ, 808, 122

Garcia, J. A., Tomsick, J. A., Sridhar, N., et al. 2019, ApJ, 885, 48

Heida, M., Jonker, P. G., Torres, M. A. P., & Chiavassa, A. 2017, ApJ, 846, 132

Hynes, R. I., Steeghs, D., Casares, J., Charles, P. A., & O’Brien, K. 2004, ApJ, 609, 317

Jana, A., Chakrabarti, S. K., Mondal, S., & Molla, A. A. 2016, ApJ, 819, 107

Jana, A., Debnath, D., Chakrabarti, S. K., Mondal, S., & Molla, A. A. 2014, ApJ, 786, 4

Nandi, A., Debnath, D., Mondal, S., & Chakrabarti, S. K. 2017, Adv. Space Res., 59, 1374S

Tetarenko, B. E., Sivakoff, G. R., Heinke, C. O., & Gladstone, J. C. 2016, ApJ, 822, 15

Yan, Z., & Yu, W. 2015, ApJ, 805, 87

Zdziarski, A. A., Gierlinski, M., Mikolajewska, J., et al. 2004, MNRAS, 351, 791