2016 Outburst of H 1743–322: XMM-Newton and NuSTAR View

Swadesh Chand¹, V. K. Agrawal², G. C. Dewangan³, Prakash Tripathi³, and Parijat Thakur¹

¹ Department of Pure and Applied Physics, Guru Ghasidas Vishwavidyalaya (A Central University), Bilaspur (C. G.)-495009, India; parijat@associates.iucaa.in, pariathakur@yahoo.com
² Space Astronomy Group, ISITE Campus, ISRO Satellite Centre, Bangalore-560037, India
³ Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune-411007, India

Received 2019 November 14; revised 2020 March 18; accepted 2020 March 19; published 2020 April 24

Abstract

We report the detection of a type C quasi-periodic oscillation (QPO) along with an upper harmonic in the commensurate ratio of 1:2 in two observations of the low-mass black hole transient H 1743–322 jointly observed by XMM-Newton and NuSTAR during the 2016 outburst. We find that the QPO and the upper harmonic exhibit shifts in their centroid frequencies in the second observation with respect to the first one. The hardness intensity diagram implies that in contrast to the 2008 and 2014 failed outbursts, the 2016 outburst was a successful one. We also detect the presence of a broad iron Kα line at ~6.5 keV and a reflection hump in the energy range 15–30 keV in both of the observations. Along with the shape of the power density spectra, the nature of the characteristic frequencies and the fractional rms amplitude of the timing features imply that the source stayed in the low/hard state during these observations. Moreover, the photon index and other spectral parameters also indicate the low/hard state behavior of the source. Unlike the soft lag detected in this source during the 2008 and 2014 failed outbursts, we observe hard time lags of 0.40 ± 0.15 s and 0.32 ± 0.07 s in the 0.07–0.4 Hz frequency range in the two observations during the 2016 outburst. The correlation between the photon index and the centroid frequency of the QPO is consistent with the previous results. Furthermore, the high value of the Comptonized fraction and the weak thermal component indicate that the QPO is being modulated by the Comptonization process.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); Low-mass X-ray binary stars (939); Stellar mass black holes (1611)

1. Introduction

Low-mass black hole X-ray binaries consist of a low-mass companion star (≤1 M☉) gravitationally bound to a stellar-mass black hole (Steiner et al. 2012). The companion star feeds material to the black hole via Roche lobe overflow, resulting in the formation of an accretion disk. The viscous forces between the different layers of the accretion disk near the black hole raise the temperature up to 10⁷ K, and the source primarily emits X-rays (Steiner et al. 2012; Motta et al. 2017). Most of the black hole X-ray binaries (BHXRBs) are known to be transients that stay in quiescence for a long time and show outbursts very sporadically. These outbursts can last from several days to months, during which the luminosity of the source is increased by several orders of magnitude (Tanaka & Shibazaki 1996; Shidatsu et al. 2014; Plant et al. 2015). The BHXRBs can undergo generally four states during an outburst, namely, the hard state (HSS), the high/soft state (HIMS), the soft-intermediate state (SIMS), and the hard/soft state (HSS; Belloni et al. 2005). The classification of the states relies upon the detailed spectral and timing behavior of the source during an outburst.

The spectrum of the LHS is dominated by a hard power law with photon index <2 and a high-energy cutoff ≈100 keV (Motta et al. 2009; Shidatsu et al. 2014). The power-law component is thought to originate from the Compton up-scattering of the soft X-ray photons from the disk by the hot electrons in corona. The power density spectra (PDS) in the LHS state show strong variability with fractional rms ~30% (McCintock & Remillard 2006; Belloni et al. 2011; Zhou et al. 2013; Shidatsu et al. 2014; Ingram et al. 2017). The transition of the BHXRBs to the HSS occurs via the two intermediate states (HIMS and SIMS). However, the transition from the hard to soft is not a smooth one, and in many outbursts, several excursions to harder and softer states have been observed. As the source moves from the hard state to the soft state, the power-law component starts to steepen (up to Γ ~ 2.5), and the X-ray continuum becomes increasingly dominated by emission from an optically thick and geometrically thin accretion disk with a few percent of fractional rms variability (Shakura & Sunyaev 1973; Belloni et al. 2011). In the soft state, the accretion disk either reaches closer to the innermost stable circular orbit (ISCO) or extends down to the ISCO (Gierlinski & Done 2004; Steiner et al. 2010). It is worth mentioning here that there is an ongoing debate on the nature of extent of the accretion disk in the LHS. However, several workers have found that a hot advection-dominated accretion flow (ADAF), as proposed by Esin et al. (1997), replaces the geometrically thin and optically thick accretion disk, introducing a truncated inner disk (McCintock et al. 1995, 2001, 2003; Narayan & Yi 1995; Narayan et al. 1996; Esin et al. 2001; Plant et al. 2015). Another salient observational feature of BHXRBs is the X-ray reflection. This appears when the hard Comptonized X-rays from the corona are reflected from the disk, giving rise to a reflection hump in ~10–40 keV and a fluorescent iron line Kα line at ~6.4–6.9 keV. The iron line may be distorted by special and general relativistic effects (Fabian et al. 1989; Reynolds & Nowak 2003; Miller 2007; Ingram et al. 2017). Modeling of the broad iron line with relativistic reflection gives an alternative way to measure the inner disk radius. The modeling of the reflection continuum can also play a crucial role in understanding the inner accretion dynamics of the disk, as well as probe key parameters like the black hole spin and the disk inclination. It is worth mentioning here that the relativistic
reflection model RELXILL is being widely used to model angle-dependent X-ray reflection and allows one to estimate parameters such as the inner disk radius, black hole spin, disk inclination, iron abundance, and reflection fraction (Dauser et al. 2010; García & Kallman 2010; García et al. 2011, 2013; Dauser et al. 2013, 2014; García et al. 2014). Quasi-periodic oscillations (QPOs), which appear as broad peaks, are often observed in the X-ray emission from black hole transients (BHTs). QPOs are categorized into the following three types: (1) high-frequency QPOs (HFQPOs; ~30–450 Hz), (2) low-frequency QPOs (LFQPOs; ~0.05–30 Hz), and (3) very low-frequency QPOs (~mHz; Morgan et al. 1997; Belloni et al. 2000; Trudolyubov et al. 2001; Casella et al. 2005; Altamirano et al. 2011; Motta et al. 2011; Altamirano & Strohmayer 2012; Belloni et al. 2012; Alam et al. 2014; Agrawal & Nandi 2015). Depending on a few parameters such as the quality factor (Q) and the shape of the PDS continuum, low-frequency QPOs are classified into types A, B, and C. Type A QPOs appear as broad peaks around ~6–8 Hz with a few percent rms, whereas the type B QPOs show stronger rms (up to ~4%) compared to the type A QPOs. On the other hand, a type C QPO appears as a narrow and variable peak with strong fractional rms ≥10% (Casella et al. 2004; Motta et al. 2011). Though the exact mechanism for the origin of the QPOs is still not clear, it has been found in earlier studies that centroid frequencies of QPOs are correlated with the spectral index, as well as the disk flux (Sobczak et al. 2000; Titarchuk & Fiorito 2004; Shaposhnikov & Titarchuk 2007), indicating a coupling between QPOs and the structure of the inner disk (Shidatsu et al. 2014). 

Strong variability of BHXRBs may also be related to the time lags found between the lightcurves in different energy bands. Priedhorsky et al. (1979) and Nolan et al. (1981) first found the presence of time lags in Cygnus X-1, as well as several other BHXRBs. Many BHXRBs show hard X-ray lags, where the hard photons are found to be delayed with respect to the soft ones (Page et al. 1981; Miyamoto et al. 1988; Nowak et al. 1999a, 1999b; Grinberg et al. 2014). These hard X-ray lags are generally thought to originate in the propagation of mass accretion rate fluctuation in the accretion disk and are of magnitude 1% of the variability timescale (Arévalo & Uttley 2006; De Marco et al. 2013). On the other hand, the soft X-ray lags, where the soft X-ray photons lag the hard ones, are caused by the reflection of the coronal X-ray irradiation by the accretion disk. This time delay is called the reverberation lag and can provide important information about the geometry of the innermost region of the BHXRBs (De Marco et al. 2013; De Marco & Ponti 2016; De Marco et al. 2017; Kara et al. 2019).

The low-mass BHT H 1743–322 was discovered in 1977 using Ariel-V (Kaluziński & Holt 1977) and is located at 8.5 ± 0.8 kpc (Steiner et al. 2012). This source is well known for its transient nature and has shown frequent outbursts with an average interval of ~200 days (Shidatsu et al. 2012, 2014). After a prolonged gap from its discovery, the brightest outburst of H 1743–322 in 2003 was detected by INTEGRAL (Revnivtsev 2003) and RXTE (Markwardt & Swank 2003). RXTE observation of this outburst resulted in detection of a pair of HFQPOs at 240 and 160 Hz (Homan et al. 2005; Remillard et al. 2006). A similar timing signature has also been found in a few other dynamical BHXRBs (McClintock & Remillard 2006; McClintock et al. 2009). Using the Very Large Array (VLA) observation of the 2003 outburst and by applying a symmetric kinematic model for the jet trajectories, Steiner et al. (2012) estimated the source distance and inclination angle to be 8.5 ± 0.8 kpc and 75° ± 3°, respectively. They also found the spin parameter to be 0.2 ± 0.3 using the RXTE observation of the 2003 outburst. In addition, Sriram et al. (2009) found QPOs with a truncated accretion disk using the RXTE observations of the 2003 outburst when the source was in the steep power-law state. Before the 2008 October outburst, a few additional outbursts were detected that could not be studied extensively because of a lack of sufficient observations. However, the 2008 October outburst was termed a “failed outburst” as the source never reached the HSS because of a sudden decrease in the mass accretion rate (Capitani et al. 2009). Another outburst in 2009 July was detected by the Swift/BAT telescope (Krimm et al. 2009; Motta et al. 2010), which was followed by three more outbursts detected by RXTE in 2009 December, 2010 August, and 2011 April (Zhou et al. 2013). Using these 2010 and 2011 outbursts, Molla et al. (2017) estimated the mass of the black hole to be 11.2±1.16 M⊙ by combining two methods: the two-component advective flow (TCAF) model and the correlation between the photon index and QPO frequency (Dewangan et al. 2006). Apart from the above, a few successive outbursts were reported in 2011 December, 2012 January (Negoro et al. 2012), 2012 September (Shidatsu et al. 2012, 2014), and 2013 August (Nakahira et al. 2013). Following these outbursts, another outburst took place in 2014, which was observed quasi-simultaneously by both XMM-Newton and NuSTAR. Using the Swift/XRT monitoring of the 2014 outburst, Stiele & Yu (2016) reported the 2014 outburst as a failed one because the source never reached the HSS during the entire outburst. In addition to this, using the XMM-Newton observation of this outburst, the authors reported a low-frequency QPO and an upper harmonic at ~0.25 and ~0.51 Hz, respectively. Moreover, Ingram et al. (2017) used both the XMM-Newton and NuSTAR observations of the 2014 outburst and found a truncated accretion disk geometry when the source was in the LHS. The results from Stiele & Yu (2016) and Ingram et al. (2017) agree that the source stayed in the LHS during the 2014 outburst. Because two observations at different epochs jointly performed by XMM-Newton and NuSTAR during the 2016 outburst of H 1743–322 are still unexplored, it is worth examining in detail the behavior of the source in light of the various characteristics discussed above. Moreover, the 2016 outburst appears to be different from the 2008 and 2014 failed outbursts, as the 2016 outburst exhibits a full spectral state transition. In this paper, we carry out a systematic spectral and temporal study of H 1743–322 using these observations. A timing study using the NuSTAR data allows us to probe the nature of the timing features in the PDS beyond the energy range of XMM-Newton. We report the detection of a low-frequency QPO along with an upper harmonic in both epochs. We also find a shift in the centroid frequency of the QPO and the upper harmonic between the two epochs. We have also compared the characteristics of the PDS in the high-energy band using NuSTAR to those obtained from the XMM-Newton observations. We also study the energy dependence of the temporal parameters and compare them with previous studies. We have also found a hard lag and a log-linear increase in the time lag with energy in the energy-dependent time-lag spectra derived from XMM-Newton observations. In addition, we present a detailed broadband spectral analysis of joint XMM-Newton and NuSTAR spectral data in the 2.5–78 keV band, as
well as study the accretion disk and the relativistic reflection. We have also studied the relation between spectral and temporal parameters and discussed the possible origin of the variability in the system.

The remainder of the paper is organized as follows. We present the observations and data reduction in Section 2, and Section 3 contains the analysis and results of our spectral and temporal study. Finally, Section 4 is devoted to discussion and concluding remarks.

2. Observations and Data Reduction

2.1. Swift Monitoring

The 2016 outburst of H 1743–322 was detected and followed by Swift/XRT (Burrows et al. 2000; Hill et al. 2000). We analyzed all of the observations taken in the Swift/XRT window timing mode between 2016 March 1 and 2016 April 8 using the online data analysis tools provided by the Leicester Swift Data Centre4 (Evans et al. 2009). We derived the count rate in the 0.8–10 keV, 0.8–3 keV, and 3–10 keV bands, and to calculate the hardness ratio (HR), we divided the count rate in the 3–10 keV band by the count rate in the 0.8–3 keV band. Figure 1 shows the hardness intensity diagram (HID), which depicts that the source undergoes a full state transition during the 2016 outburst.

Figure 1. Hardness intensity diagram derived using the window timing-mode data of Swift/XRT from 2016 March 1 to 2016 April 8. The two blue squares indicate the two simultaneous XMM-Newton and NuSTAR observations on two different epochs, as used in this work.

Table 1

| Obs. No. | Instrument         | Obs. ID.    | Obs. Date  | Exp.(ks) | Obs. Mode |
|----------|--------------------|-------------|------------|----------|-----------|
| Epoch-1  | XMM-Newton/EPIC-pn | 0783540301  | 2016 Mar 13 | 142.6    | Timing    |
|          | NuSTAR/FPMA,FPMB   | 80202012002 | 2016 Mar 13 | 65.8     | Imaging   |
| Epoch-2  | XMM-Newton/EPIC-pn | 0783540301  | 2016 Mar 15 | 142.6    | Timing    |
|          | NuSTAR/FPMA,FPMB   | 80202012004 | 2016 Mar 15 | 65.6     | Imaging   |

XMM-Newton observed H 1743–322 twice on 2016 March 13 (hereafter Epoch-1) and 2016 March 15 (hereafter Epoch-2) for an exposure time of 142.6 ks each. Details of the XMM-Newton observations are given in Table 1. During these two observations, only the European Photon Imaging Camera (EPIC-pn) was employed in timing mode with a thick filter to observe the source. The Scientific Analysis System (SAS v.16.0.0) with the most recent calibration files was utilized to filter and produce the EPIC-pn event files. We did not find any soft proton background flaring from the extracted lightcurve of Epoch-1 in the energy range 10–12 keV. However, background flaring toward the end of the observation was detected in the 10–12 keV lightcurve of Epoch-2. To remove the flaring, we

---

4 http://www.swift.ac.uk/user_objects/
created a good time interval (GTI) file with count rate $\lesssim 1.7 \text{ s}^{-1}$. We then applied this GTI file and filtered the event list for the background flaring. We used a rectangular region of 17 pixels in width ($29 \leq \text{RAWX} \leq 46$), keeping the source in the centered position, and extracted the source spectra. A narrow rectangular region of five pixels in width ($05 \leq \text{RAWX} \leq 10$) toward the edge of the detector was used to extract the background spectra. Using the epatplot task within SAS, we found that both Epoch-1 and Epoch-2 observations were affected by pileup. In order to reduce the pileup effect, we used only the single-pixel events (PATTERN=0), as well as excised the three central columns from the source position of both of the observations. We then generated a Redistribution Matrix File (RMF) and Ancillary Region File (ARF) for each epoch using the tasks rmfgen and arfgen available within SAS, respectively. We also extracted the source and background lightcurves and corrected the source lightcurves for the background contribution using the SAS task “epiclccorr.”

2.3. NuSTAR

NuSTAR (Harrison et al. 2013) also observed H 1743–322 simultaneously with XMM-Newton in the two epochs, and the details of the observations are listed in Table 1. We reduced the data using the nupipeline task available within NuSTARDAS with the latest available calibration files. For both the FPMA and FPMB modules, we used a circular region of 30″ by keeping the source in the center and generated the source spectra. We used another circular region of the same size on the same detector away from the source to extract the background. We generated the corresponding RMF and ARF files using the task nuproducts available within NuSTARDAS.

3. Analysis and Results

3.1. Power Density Spectra

For the timing analysis, we used the Interactive Spectral Interpretation System (ISIS, V.1.6.2–40; Houck & Denicola 2000). We quote the errors at 90% confidence level. The PDSs from the background-subtracted lightcurves of the XMM-Newton/EPIC-pn observations were computed using the “POWSPEC” task within FTOOLS in the two energy bands 0.7–3 keV and 3–10 keV. After subtracting the contribution that is due to Poisson noise (Zhang et al. 1995), we normalized the PDSs according to Leahy et al. (1983) and then converted the variability power to the square fractional rms (Belloni & Hasinger 1990). Figure 2 shows the PDSs in the 0.7–3 keV and 3–10 keV bands for Epoch-1 and Epoch-2, where the presence of the low-frequency QPO along with upper harmonic at $\sim 1$ Hz and $\sim 2$ Hz is prominent. The PDSs in both of the energy bands exhibit identical shapes and require a zero-centered Lorentzian, as well as three peaked Lorentzian components for the QPO, upper harmonic, and band-limited noise (BLN) component. All of the best-fit parameters are listed in Table 2. The significance of detection of the QPO (upper harmonic) in the 0.7–3 keV band is 17.9$\sigma$ (3.1$\sigma$) and 19$\sigma$ (4.1$\sigma$), whereas that found in the 3–10 keV band is 43.4$\sigma$ (5.2$\sigma$) and 40.7$\sigma$ (6.6$\sigma$) for Epoch-1 and Epoch-2, respectively. This suggests that the significance of both the QPO and the upper harmonic remains more or less similar between Epoch-1 and Epoch-2 for each energy band, whereas their values are found to be increasing with the energy band in each epoch. From Table 2 it is clear that in both of the observations, the QPO and the upper harmonic are detected at $\sim 1:2$ ratio in each energy band. We also note that the centroid frequencies of the QPO and the upper harmonic do not change with energy in both epochs. However, we found that the centroid frequencies of the QPO (upper harmonic) in Epoch-2 are shifted toward higher frequencies by 0.04 ± 0.01 Hz (0.26 ± 0.1 Hz) in the 0.7–3 keV band and 0.06 ± 0.004 Hz (0.19 ± 0.06 Hz) in the 3–10 keV band with respect to those found in Epoch-1. The quality factor ($Q = \nu_{\text{central}}/\text{FWHM}$) of the QPO in each energy band is reduced in Epoch-2 compared to that in Epoch-1. However, the $Q$-factor for the upper harmonic remains almost similar for both of the energy bands and epochs. Although the fractional rms variability of the QPO does not change between Epoch-1 and Epoch-2 within each energy band, it is found to be higher in the 3–10 keV band than that obtained in the 0.7–3 keV band for each epoch (see Table 2). Apart from this, the fractional rms variability of the upper harmonic appears to be larger in Epoch-2 than in Epoch-1 in the 0.7–3 keV band, whereas it remains the same for both epochs in the 3–10 keV band.

In addition to the above, we carried out the timing analysis of H 1743–322 using the NuSTAR observations. For this analysis, we have considered only the 3–30 keV band as this band encompasses 97% of the source photons detected by NuSTAR in the 3–78 keV energy range (Stiele & Kong 2017). We derived the cross-power density spectra (CPDS) in the 3–10 and 10–30 keV energy bands using MaLTPyNT (Bachetti 2015). The signals from the two completely independent focal plane modules are used to generate the CPDS, which acts like a good alternative to the white-noise-subtracted PDS (Bachetti 2015). To generate the CPDS, we used time bins of 0.1 s with stretches of 512 s. Figure 3 shows the CPDSs derived from the NuSTAR observations for Epoch-1 and Epoch-2 in the 3–10 and 10–30 keV bands. The best-fit parameters are given in Table 3. The shape of the CPDS and the required best-fit model for both epochs in the 3–10 keV band are found to be the same as that obtained in the same energy band in XMM-Newton observations. The ratios at which the QPO and the upper harmonic are detected in each energy band are found to be consistent with the XMM-Newton observations. The shifts in the centroid frequencies of the QPO and the upper harmonic in Epoch-2 with respect to those in Epoch-1 are 0.08 ± 0.006 Hz and 0.36 ± 0.1 Hz toward the higher frequency side. As can be seen from Tables 2 and 3, the value of the quality factor ($Q$) and the fractional rms variability of the QPO, as well as the upper harmonic in both epochs, show a nature similar to those obtained from the XMM-Newton observations in the same energy band. In contrast to the XMM-Newton observations in this energy band, the significance levels of the QPO and the upper harmonic increase from 36.3$\sigma$ to 47$\sigma$ for the QPO and 5.4$\sigma$ to 8$\sigma$ for the upper harmonic in Epoch-2 with respect to Epoch-1.

The NuSTAR CPDS in the 10–30 keV band shows a shape similar to that in the 3–10 keV band. The QPO and upper harmonic in this band are found in the $\sim 1:2$ ratio in Epoch-2, similar to the CPDS in the 3–10 keV band. However, no signature of the upper harmonic was found in the 10–30 keV band of Epoch-1, which may be due to the lower signal-to-noise ratio (S/N) of CPDS compared to that in Epoch-2. The shift in the centroid frequency of the QPO in Epoch-2 with respect to Epoch-1 resembles that obtained in the 3–10 keV band of the NuSTAR observations and is 0.09 ± 0.01 Hz.
the QPO also exhibits a behavior similar to the 3–10 keV energy band.

In order to study the evolution of characteristic frequency and fractional rms amplitude with energy, we divided the full energy band of the XMM-Newton observations into eight equal, narrow bands of ~1 keV width, and we derived the

Table 2

| Parameter          | 0.7–3 keV | 3–10 keV |
|--------------------|----------|----------|
|                   | Epoch-1  | Epoch-2  | Epoch-1  | Epoch-2  |
| \( \nu_{\text{QPO}} \) (Hz) | 0.980 ± 0.005 | 1.020 ± 0.009 | 0.980 ± 0.003 | 1.040 ± 0.003 |
| FWHM\(_{\text{QPO}}\) (Hz) | 0.22 ± 0.02 | 0.33 ± 0.03 | 0.22 ± 0.01 | 0.30 ± 0.01 |
| \( Q_{\text{QPO}} \) | 4.50 ± 0.38 | 3.1 ± 0.3 | 4.4 ± 0.2 | 3.5 ± 0.1 |
| rms\(_{\text{QPO}}\) (%) | 13.0 ± 0.6 | 13.8 ± 0.5 | 18.8 ± 0.3 | 19.24 ± 0.2 |
| \( \nu_{\text{har}} \) (Hz) | 2.01 ± 0.07 | 2.26 ± 0.08 | 2.01 ± 0.04 | 2.20 ± 0.05 |
| FWHM\(_{\text{har}}\) (Hz) | 0.3 ± 0.2 | 0.9 ± 0.4 | 0.7 ± 0.2 | 0.76 (f) |
| \( Q_{\text{har}} \) | 6.5 ± 3.0 | 2.5 ± 1.5 | 2.8 ± 0.6 | 2.9 ± 0.1 |
| rms\(_{\text{har}}\) (%) | 4.5 ± 0.02 | 8.7 ± 1.9 | 8.7 ± 1.4 | 7.2 ± 0.7 |
| \( \nu_{\text{bln}} \) (Hz) | 0.17 ± 0.03 | 0.09 ± 0.05 | 0.18 ± 0.02 | 0.19 ± 0.01 |
| FWHM\(_{\text{bln}}\) (Hz) | 0.59 ± 0.04 | 0.8 (f) | 0.59 ± 0.08 | 0.59 ± 0.06 |
| \( Q_{\text{bln}} \) | 0.29 ± 0.03 | 0.11 ± 0.02 | 0.30 ± 0.001 | 0.33 ± 0.001 |
| rms\(_{\text{bln}}\) (%) | 10.3 ± 1.4 | 12.4 ± 0.9 | 13.0 ± 0.7 | 12.5 ± 0.5 |
| \( \nu_{\text{blnzero}} \) (Hz) | 0 (f) | 0 (f) | 0 (f) | 0 (f) |
| FWHM\(_{\text{blnzero}}\) | 4.9 ± 0.14 | 10\(^p\) | 8.5 ± 0.4 | 9.2 ± 0.9 |
| rms\(_{\text{blnzero}}\) (%) | 17.0 ± 1.5 | 10.5 ± 1.6 | 18.3 ± 1.3 | 18.4 ± 0.9 |

Note. “f” indicates fixed parameters, and “p” indicates parameters pegged at lower/upper bounds.
We calculated the characteristic frequency for the QPO, the upper harmonic, and the zero-centered BLN. Newton data were modeled with three Lorentzian components bands. The PDSs derived for each narrow energy band of XMM-Newton data indicate the best-observations because of the low S/N energy band. For this analysis, we excluded the NuSTAR Poisson-noise-subtracted and rms-normalized PDS in each energy band. Figure 3 shows the evolution of the characteristic frequency of the QPO, as well as its upper harmonic and zero-centered BLN as a function of energy. It is clear that the characteristic frequencies of the QPO and its upper harmonic show a flat nature without showing any significant dependence on energy for both epochs. The characteristic frequency of the zero-centered BLN also remains.

![Cross-power density spectra in the 3–10 keV and 10–30 keV bands derived from the NuSTAR observations for Epoch-1 (upper panel) and Epoch-2 (lower panel). Data points with filled squares (red) and filled circles (blue) represent the PDSs extracted in the 3–10 keV and hard 10–30 keV bands, respectively. The solid lines indicate the best-fitted model.](image)

**Figure 3.** Cross-power density spectra in the 3–10 keV and 10–30 keV bands derived from the NuSTAR observations for Epoch-1 (upper panel) and Epoch-2 (lower panel). Data points with filled squares (red) and filled circles (blue) represent the PDSs extracted in the 3–10 keV and hard 10–30 keV bands, respectively. The solid lines indicate the best-fitted model.

| Parameter | Epoch-1 3–10 keV | Epoch-2 3–10 keV | Epoch-1 10–30 keV | Epoch-2 10–30 keV |
|-----------|-----------------|-----------------|-----------------|-----------------|
| $v_{\text{qpo}}$ (Hz) | 0.980 ± 0.003 | 1.060 ± 0.005 | 0.980 ± 0.005 | 1.07 ± 0.01 |
| FWHM$_{\text{qpo}}$ (Hz) | 0.20 ± 0.01 | 0.35 ± 0.02 | 0.18 ± 0.02 | 0.34±0.03 |
| $Q_{\text{qpo}}$ | 4.9$^{+0.25}_{-0.27}$ | 3.1 ± 0.12 | 5.4$^{+0.4}_{-0.3}$ | 3.1$^{+0.1}_{-0.3}$ |
| rms$_{\text{qpo}}$ (%) | 16.1 ± 0.4 | 17.1 ± 0.3 | 15.4 ± 0.6 | 16.5$^{+0.2}_{-0.6}$ |
| $v_{\text{har}}$ (Hz) | 2.01 ± 0.1 | 2.37 ± 0.01 | ... | 2.25±0.07 |
| FWHM$_{\text{har}}$ (Hz) | 1.02 (f) | 0.99 (f) | ... | 0.23 (f) |
| $Q_{\text{har}}$ | 1.96 ± 0.1 | 2.4 ± 0.1 | ... | 9.7 ± 0.3 |
| rms$_{\text{har}}$ (%) | 7.13 ± 1.1 | 7.2$^{+0.2}_{-0.1}$ | ... | 4.4$^{+1.0}_{-0.3}$ |
| $v_{\text{bln}}$ (Hz) | 0.19 ± 0.02 | 0.19 ± 0.02 | 0.18 ± 0.03 | 0.13 (f) |
| FWHM$_{\text{bln}}$ (Hz) | 0.5 ± 0.01 | 0.5 ± 0.1 | 0.35$^{+0.13}_{-0.20}$ | 0.54$^{+0.16}_{-0.12}$ |
| $Q_{\text{bln}}$ | 0.38$^{+0.3}_{-0.2}$ | 0.360$^{+0.100}_{-0.001}$ | 0.52$^{+0.08}_{-0.06}$ | 0.23$^{+0.05}_{-0.07}$ |
| rms$_{\text{bln}}$ (%) | 10.3$^{+3.9}_{-2.2}$ | 12.4$^{+7.9}_{-5.0}$ | 8.5$^{+6.2}_{-1.8}$ | 9.2$^{+6.9}_{-1.6}$ |
| $v_{\text{blnzero}}$ (Hz) | 0 (f) | 0 (f) | 0 (f) | 0 (f) |
| FWHM$_{\text{blnzero}}$ | 6.6$^{+1.72}_{-1.32}$ | 10$^p$ | 4.5$^{+1.6}_{-1.3}$ | 10$^p$ |
| rms$_{\text{blnzero}}$ (%) | 15.5$^{+1.3}_{-1.2}$ | 14.8$^{+1.3}_{-1.5}$ | 15.0$^{+1.4}_{-1.6}$ | 14.0$^{+1.5}_{-1.1}$ |

Note. “f” indicates fixed parameters, and “p” indicates the parameters pegged at lower/upper bounds.
almost flat except for the slight decrease above ~6 keV. Figure 5 exhibits the rms spectra of the QPO, as well as its upper harmonic and zero-centered BLN component for both epochs, which demonstrate either a flat or slightly decreasing trend with the energy.

3.2. Frequency-dependent Lag and Lag–Energy Spectra

We used only XMM-Newton data and the GHATS package\(^5\) for the lag analysis. To evaluate the time lag as a function of temporal frequency, we extracted EPIC-pn lightcurves in the 1–1.5 keV and 1.5–4 keV bands. Each of these lightcurves was divided into 141 segments, each with a length of 983 s. We computed the Fourier transform for each segment and calculated the average cross-spectrum. Using the averaged cross-spectrum, we calculated the frequency-dependent time lag for both epochs\(^{5}\) (Uttley et al. 2014). As seen in the top panels of Figure 6, we found a hard lag of 0.40 ± 0.15 and 0.32 ± 0.07 s between the above-mentioned energy bands in the 0.07–0.4 Hz frequency range for Epoch-1 and Epoch-2, respectively. It is noteworthy that error bars are dominant below 0.1 Hz, and no time lag has been observed above 0.4 Hz in the time-lag–frequency spectra for both epochs. The coherence in the 0.2–0.4 Hz frequency range is also found to be closer to unity for both epochs. To study the variation of the time lag as a function of energy, we generated lightcurves in the 0.3–0.7, 0.7–1, 1–1.5, 4–5, 5–6, 6–7, 7–8, and 8–10 keV bands for both epochs. We considered the 1.5–4 keV band as the reference band. The energy-dependent time lag was estimated between each narrow energy band and the reference band. Figure 6 (bottom panels) depicts the averaged time lags, estimated in the frequency range 0.2–0.4 Hz, as a function of energy. This exhibits the increasing nature of the time lag with energy in a log-linear trend.

3.3. Energy Spectra

The time-averaged XMM-Newton/EPIC-pn spectral data in the 0.7–10 keV band and NuSTAR FPMA and FPMB spectral data in the 3–78 keV band were fitted simultaneously using ISIS (Version 1.6.2-40). The errors on the best-fitted parameters are calculated at 90% confidence level unless otherwise specified. A systematic uncertainty of 1% was added to each XMM-Newton/EPIC-pn and NuSTAR FPMA/FPMB data set to account for calibration uncertainty between different instruments (Ingram et al. 2017; Madsen et al. 2017). In order to use \( \chi^2 \) minimization to obtain the best fit, we grouped the EPIC-pn data to a minimum S/N of 5 and a minimum of 10 channels per bin. Similarly, we also grouped the FPMA and FPMB data to the same S/N used for the EPIC-pn data but with a minimum number of channels of five. Initially, we fitted the three spectral data sets jointly with a POWERLAW model modified by the Galactic absorption. We used the absorption model TBabs with the abundances given by Wilms et al. (2000) and the cross section as in Verner et al. (1996). We also multiplied the absorbed POWERLAW model with a constant factor to account for any difference in the relative normalizations of the three instruments. We fixed the constant factor to 1 for the FPMA data and varied it for the EPIC-pn and FPMB data. We noticed a discrepancy between the XMM-Newton and NuSTAR spectral data sets in the 3–10 keV band for both epochs. A similar discrepancy was found in the 2014

\(^5\) http://astrosat.iucaa.in/~astrosat/GHATS_Package/Home.html
outburst of H 1743–322 and was eliminated with the inclusion of an additional $E^{\Delta \Gamma}$ model by Ingram et al. (2017). We adopted the same procedure in our analysis. We fixed the value of $\Delta \Gamma$ at zero for both the NuSTAR FPMA and FPMB data sets and varied it for the EPIC-pn data. This model provided an unacceptable fit with $\chi^2$/dof equal to 8109.6/884 and 7699.6/883 for Epoch-1 and Epoch-2, respectively. Inclusion of the multicolored disk blackbody model (DISKBB; Mitsuda et al. 1984) to account for the thermal emission from the accretion disk improved the fit with $\chi^2$/dof = 6456.8/882 for Epoch-1 and $\chi^2$/dof = 6079.6/881 for Epoch-2. However, as shown in Figure 7, the model CONSTANT$E^{\Delta \Gamma}$TBABS(DISKBB+POWERLAW) resulted in strong residuals at $\sim$6–8 keV due to the presence of an iron line and reflection hump at $\sim$15–30 keV. Two additional emission line–like features in the XMM-Newton EPIC-pn spectra near 1.8 and 2.2 keV were also noticed. These lines most likely arise from the calibration uncertainties near the Si and Au edges, respectively (Hiemstra et al. 2011; Díaz Trigo et al. 2014). In addition to this, a broad excess around 1 keV is clearly noticeable in Figure 7, and a similar excess in EPIC-pn timing mode has been studied extensively by several authors (Boirin et al. 2005; Martocchia et al. 2006; Sala et al. 2008; Hiemstra et al. 2011; Alam et al. 2015). The reason behind the origin of this excess is not yet clear, but it is thought to be related to the instrumental calibration (Alam et al. 2015). In order to further clarify this, we fitted the Swift/XRT spectral data available for the same epochs as considered in this work with POWERLAW and TBABS, and we did not find any excess below 2.5 keV. This confirms the finding of the previous workers mentioned above that the excesses below 2.5 keV in the XMM-Newton/EPIC-pn spectral data arise from the calibration issues in the timing mode. We therefore excluded the EPIC-pn data below 2.5 keV in our spectral fitting.

We tried to fit the iron line excess seen at $\sim$6–8 keV by adding a GAUSSIAN model component to the above-mentioned model. We also replaced the POWERLAW model with the thermally Comptonized continuum model NTHCOMP. The model CONSTANT$E^{\Delta \Gamma}$TBABS(DISKBB+GAUSSIAN+NTHCOMP) (hereafter Model 1) provided an acceptable fit with $\chi^2$/dof = 855.2/842 and 791.2/841 for Epoch-1 and Epoch-2, respectively. The centroid energy of the iron line is found to be 6.6$\pm$0.1 keV with line width $\sigma = 0.9 \pm 0.1$ keV for Epoch-1 and 6.5$\pm$0.1 keV with line width $\sigma = 1.0 \pm 0.1$ keV for Epoch-2. The equivalent widths (EW) of the iron line are 147$^{+19}_{-25}$ eV and 167.7$^{+25.1}_{-33.0}$ eV for Epoch-1 and Epoch-2, respectively. From these calculated values, it is clear that the line energy, line width, and EW of the iron line are similar within error between the two epochs.

To fit the observed iron line and the reflection hump, we used the relativistic reflection model RELXILL (Dauser et al. 2014; García et al. 2014), which describes the broad iron line and reflected emission from an accretion disk illuminated by a power-law X-ray continuum with high-energy cutoff. We replaced both the GAUSSIAN and NTHCOMP components in Model 1 with RELXILL. Thus, the model CONSTANT$E^{\Delta \Gamma}$TBABS(DISKBB+RELXILL) (hereafter Model 2) resulted in the best fit with $\chi^2$/dof = 855.8/840 (Epoch-1) and 810.9/839 (Epoch-2). The best-fit model (Model 2) to the XMM-Newton/EPIC-pn and NuSTAR FPMA/FPMB data for both epochs is shown in Figure 8, whereas the corresponding best-fit parameters

Figure 5. Evolution of the fractional rms amplitude of QPO (filled circles), harmonic (filled triangles), and zero-centered BLN (filled squares) with energy for Epoch-1 (upper panel) and Epoch-2 (lower panel).
are listed in Table 4. In this, we fixed the inclination angle at 75° and the spin parameter at 0.2 as estimated by Steiner et al. (2012), which was also used by previous workers for H 1743–322 (Ingram & Motta 2014; Ingram et al. 2017). We also fixed the emissivity index ($q = 3$) for the whole disk by tying the break radius with the outermost disk radius at 400 $r_g$ (Stiele & Yu 2016; Ingram et al. 2017). For the absorption component, we kept the hydrogen column density parameter ($N_{\text{H}}$) free. In addition, the photon index ($\Gamma$), ionization parameter ($\xi$), and iron abundance ($A_{\text{Fe}}$) were allowed to vary freely. From

**Figure 6.** Frequency-dependent time lags between 1–1.5 keV and 1.5–4 keV band lightcurves for Epoch-1 (upper left panel) and Epoch-2 (upper right panel). A positive lag implies a hard lag. Lag–energy spectra for the averaged lag in the 0.2–0.4 Hz frequency range for Epoch-1 (lower left panel) and Epoch-2 (lower right panel). A log-linear trend of lag with energy can be seen. The reference band is always the 1.5–4 keV band, corresponding to the zero time-lag point.

**Figure 7.** Residuals show the deviations of the observed spectral data from the best-fitting CONSTANT$^{E^{\Delta T}}$TBABS$(\text{POWERLAW} + \text{DISKBB})$ models. The iron line excess in the 6–8 keV region and the reflection hump in the 15–30 keV region are prominent. Blue circles are for XMM-Newton/EPIC-pn spectral data, whereas purple and black are for NuSTAR FPMA and FPMB spectral data, respectively. The left panel represents Epoch-1, whereas the right panel represents Epoch-2.
Table 4
Best-fit Spectral Parameters of Joint XMM-Newton/EPIC-pn and NuSTAR/FPMA and FPMB Spectral Data

| Component | Parameter | Epoch-1                  | Epoch-2                  |
|-----------|-----------|--------------------------|--------------------------|
|           |           | 0.14 ± 0.01              | 0.13 ± 0.01              |
| TBabs     | N_{bol} (×10^{22} cm⁻²) | 2.3 ± 0.4                | 2.40 ± 0.05              |
|           | kT_{in} (keV) | 1.11 ± 0.03              | 1.2 ± 0.2                |
| DISKBB    |           | 4.70 ± 0.02              | 3.9 ± 0.2                |
| RELXILL   |           | 75 (f)                   | 75 (f)                   |
|           |           | 0.5 (f)                  | 0.5 (f)                  |
|           |           | 3 (f)                    | 3 (f)                    |
|           | r_{in}(ISCO) | 16.8 ± 5.9               | 10.0 ± 3.4               |
|           | r_{out}(r_g) | 400 (f)                  | 400 (f)                  |
|           | Γ         | 1.51 ± 0.04              | 1.51 ± 0.04              |
|           | A_Fe      | 3.0 ± 1.0                | 3.0 ± 1.0                |
|           | logξ      | 3.20 ± 0.09              | 3.20 ± 0.04              |
|           | E_{cut}   | 92.8 ± 14.0              | 91.9 ± 13.7              |
|           | R         | 0.3 ± 0.1                | 0.4 ± 0.1                |
|           | N_{bol} (×10⁻³) | 7.2 ± 0.2               | 6.8 ± 0.2                |
|           | χ²/dof    | 855.8 ± 840             | 810.9 /839              |
|           | F_{obs}   | 4.0                      | 3.8                      |

Note. "f" indicates fixed parameters, and "p" the X-ray flux in the 2.5–78 keV band in units of 10⁻¹⁰ erg cm⁻² s⁻¹.

The best spectral fitting, the value of the foreground absorption (N_{H}) is found to be 2.3 ± 0.4 and 2.40 ± 0.05 for Epoch-1 and Epoch-2, respectively. These values are found to be almost similar to those obtained by previous workers (see Parmar et al. 2003; Corbel et al. 2006; Miller et al. 2006; Shidatsu et al. 2014; Stiebel & Yu 2016). The disk is found likely to be truncated with inner radius (r_{in}) 16.8 ± 5.9 r_{isco} and 10.0 ± 3.4 r_{isco} for Epoch-1 and Epoch-2, respectively. Note that the truncation of the inner disk radius is not statistically significant as the uncertainties on the lower limit for the inner disk radius are large enough. However, the inner radii are similar within errors for both epochs. The photon index (Γ) is ~1.5 for both epochs. The high values of the ionization parameter (log ξ = 3.20 ± 0.09 and 3.20 ± 0.04 for Epoch-1 and Epoch-2, respectively) suggest that the disk is highly ionized. The reflection fraction (R) is far below unity (~0.3 and ~0.4 for Epoch-1 and Epoch-2, respectively). Finally, the disk temperature (kT_{in}) is high, with values of ~1.1 and ~1.2 keV for Epoch-1 and Epoch-2, respectively.

3.4. Spectral/Temporal Correlation

To study the connections between the temporal and spectral parameters, we divided each of the XMM-Newton/EPIC-pn and NuSTAR/FPMA and FPMB data sets into seven equal 20 ks time intervals, giving a total of 14 data sets. PDSs from the corresponding background-subtracted lightcurves of the XMM-Newton EPIC-pn data were derived, and the variation in the centroid frequency and the fractional rms amplitude of the QPO were obtained for each time interval of 20 ks. Since the significance of the upper harmonic is very low with respect to the QPO (see Section 3.1) and in the short intervals of 20 ks the S/N is poor, we have considered only the QPO for this part of the work. In addition, we have also excluded the NuSTAR data from the time-resolved temporal analysis, due to the small
number of photons in the short interval of 20 ks. For the time-resolved temporal and spectral analysis, all of the errors are derived at 68% confidence level. From the time-resolved spectral and temporal studies, we derived the photon index and the QPO frequency for each of these time intervals. Figure 9 shows the variation of the photon index ($\Gamma$) with QPO frequency, which shows the linear correlation between these two parameters.

For each of the time-selected spectral data sets, we also computed the disk fraction and the Comptonized fraction in 0.7–78 keV using Model 1 by dividing the total unabsorbed flux to the disk flux and the Comptonized flux, respectively. Figure 10 shows the evolution of the spectral and temporal parameters with time, where panels (a)–(d) represent the centroid frequency of the QPO, fractional rms amplitude of the QPO, disk fraction, and Comptonized fraction, respectively. It is clear from panels (a) and (b) that the centroid frequency and fractional rms amplitude of the QPO are weakly anticorrelated, with the correlation coefficient $R \sim 0.38$. However, the $p$-value of this correlation coefficient is found to be $\sim 0.09$, indicating that the anticorrelation appears not to be statistically significant. This might be due to the difficulty in constraining the model parameters of the timing features as a result of poor S/N in the short intervals of 20 ks. Moreover, the QPO frequency is weakly correlated with the disk fraction (see panels (a) and (c)), as well as weakly anticorrelated with the Comptonized fraction (see panels (a) and (d)), with the correlation coefficients $R \sim 0.44$ and $\sim 0.56$, respectively. These two relations are found to be statistically significant with $p$-values of $\sim 0.05$ and $\sim 0.02$, respectively.

### 4. Discussion and Concluding Remarks

We performed a temporal and spectral analysis of H 1743–322 using the joint observations by XMM-Newton and NuSTAR in two different epochs during the 2016 outburst. The HID derived from the Swift/XRT observations (see Figure 1) indicates that the source was in the hard state during the XMM-Newton and NuSTAR observations, and the source undergoes a full spectral state transition during the 2016 outburst. This is in contrast to the 2008 and 2014 outbursts, where the source was in the hard state during the entire outburst (Capitanio et al. 2009; Stiele & Yu 2016).

We have detected a QPO along with its upper harmonics at high significance levels in the 0.7–3 keV, 3–10 keV, and 10–30 keV bands in XMM-Newton and NuSTAR data in both epochs. The absence of the upper harmonic in the 10–30 keV band of the NuSTAR data in Epoch-1 is due to the poor S/N of the data. The shape of the PDSs and the fractional rms amplitude of the QPO, derived in all of the above-mentioned energy bands (see Tables 2 and 3), suggest that the QPO is of type C (Casella et al. 2004; Motta et al. 2011). The NuSTAR observations provided the opportunity to investigate the nature of the variability of H 1743–322 in the hard band (10–30 keV). The similar shape of the PDSs in the different energy bands clearly indicates the energy-independent nature of the PDSs.

We noticed that the centroid frequencies of the QPO and its upper harmonic in Epoch-2 are shifted toward the higher frequency side with respect to Epoch-1 for each energy band. These shifts may indicate a certain geometrical change in the system between the two epochs. In the 2010 and 2011 outbursts, Altamirano & Strohmayer (2012) reported the presence of a
QPO along with an upper harmonic at the frequency ratio of 1:2 and a shift less than \( \sim 2.2 \text{ mHz} \) in the QPO frequency of H 1743–322 between the two successive RXTE observations. In the failed outburst of 2014, Stiele & Yu \( \text{Yu 2015, 2016} \) also detected a QPO and upper harmonic at the same ratio of 1:2 using a single XMM-Newton observation.

On the other hand, the unchanged shape of the PDS with energy (see Figures 2 and 3) and the absence of a strong energy dependence of the characteristic frequency of the QPO, as well as its upper harmonic and the zero-centered BLN component (see Figure 4), are consistent with the LHS of the system observed during the rising phase of the outburst (Stiele & Yu \( \text{Stiele & Yu 2015, 2016} \)). As in Figure 5, the LHS of the system is also supported by either a flat or slightly decreasing trend of the rms amplitude of the zero-centered BLN with increasing energy in both epochs (Stiele & Yu \( \text{Stiele & Yu 2015, 2016} \)). Similar rms spectra below 10 keV were also found in a few other BHXRBs such as XTE J1650–500 and XTE J1550–564 in the LHS (Gierliński & Zdziarski \( \text{Gierliński & Zdziarski 2005} \)).

As mentioned in Section 3.3, the centroid energy, width, and equivalent width of the iron line, found during the 2016 outburst, do not change between the two epochs and are consistent with those found by Stiele & Yu \( \text{Stiele & Yu 2016} \) based on the XMM-Newton observation of the 2014 outburst. The X-ray power-law shape in both epochs is similar \( (\Gamma \sim 1.5) \) and is generally found in the LHS. Furthermore, the inner disk radius \( (r_{\text{in}}) \) estimated during the 2016 outburst is found likely to be truncated away from the ISCO for both epochs, although this is not statistically significant, due to the large values of uncertainties on the lower limit (see Table 4). These results are consistent with those found by Ingram et al. \( \text{Ingram et al. 2017} \) during the 2014 failed outburst of H 1743–322. However, the accretion disk temperature appears to be high for both epochs. We note that a high inner disk temperature with a low value of \( \Gamma \) representing a hard state of H 1743–322 is also reported by previous workers (see McClintock et al. \( \text{McClintock et al. 2009} \); Chen et al. \( \text{Chen et al. 2010} \); Motta et al. \( \text{Motta et al. 2011} \); Cheng et al. \( \text{Cheng et al. 2019} \)). The high disk temperature may be due to irradiation of the disk by hard X-rays from the corona. The illuminating X-rays likely get absorbed by the disk and the disk gets thermalized, which may result in the increase of the disk temperature (Gierliński et al. \( \text{Gierliński et al. 2009} \)). The high values of ionization parameter \( (\log \xi \approx 3.2) \) obtained in both epochs indicate high irradiation of the accretion disk by hard X-ray photons from the coronal region. As mentioned in Table 4, the energy spectra show a high-energy cutoff value at \( \sim 92 \text{ keV} \) for both epochs, which also indicates the characteristic of the LHS (Motta et al. \( \text{Motta et al. 2009} \); Alam et al. \( \text{Alam et al. 2014} \)). Moreover, the ratio between the disk-illuminating coronal intensity and the intensity that approaches the observer is called the reflection fraction \( (R) \), which is found to be far below unity for both epochs. Low values of the reflection fraction may also indicate a truncated inner disk radius (Fürst et al. \( \text{Fürst et al. 2015} \); García et al. \( \text{García et al. 2015} \)), although the truncation of the inner disk radius estimated here is not statistically significant. This can also be justified by the findings of Ingram et al. \( \text{Ingram et al. 2017} \), who also reported the reflection fraction to be less than unity along with a truncated disk for the same source in the 2014 outburst. The value of the iron line abundance is found to be high with respect to that obtained by Ingram et al. \( \text{Ingram et al. 2017} \).

As shown in the bottom panels of Figure 6, time-lag–energy spectra indicate the presence of a hard lag in H 1743–322 during the 2016 outburst, where the hard X-ray variations lag behind the soft X-ray variations. The hard lag is found to be \( 0.40 \pm 0.15 \text{ s} \) and \( 0.32 \pm 0.07 \text{ s} \) for Epoch-1 and Epoch-2, respectively.

![Figure 10](image-url)
Figure 2 indicates that the QPO does not contribute significant power in the frequency range 0.2–0.4 Hz, considered for estimating the average lags. This can also be confirmed from the top panels of Figure 6, wherein the time lag above ~0.4 Hz is zero. The presence of a hard X-ray time lag is very common for X-ray binaries. Such hard lags can be explained in terms of a propagation fluctuation model (Lyubarskii 1997). According to this model, the fluctuations in the mass accretion rate are different at different radii of the accretion disk and propagate down to the central object after originating at the larger radii. As a result, the soft photons, originating from the outer part of the disk, get affected first by the fluctuation rather than the hard photons in the innermost region, and thus the hard photons lag the soft ones (see Ingram & Done 2011). The presence of a hard lag can also be attributed to the delay due to the Comptonization process (Uttley et al. 2014; De Marco & Ponti 2016). However, the lag due to the Comptonization does not completely follow the log-linear trend with energy (Uttley et al. 2011). Many previous researchers such as Pei et al. (2017), Sriram et al. (2009), Sriram et al. (2007), and Choudhury et al. (2005) invoked the truncated disk geometry to explain the hard lag, whereas Kara et al. (2019) found evidence of a hard lag when the disk is consistent with being at the ISCO. In active galactic nuclei (AGNs), the hard lag is commonly observed even if the accretion disk is found to be extended up to the ISCO (see, e.g., Kara et al. 2016; Epitropakis & Papadakis 2017). Hence, the presence of a hard lag in both BHXBs and AGNs is unlikely to be due to the disk truncation. It is also interesting that a soft X-ray lag has been reported during the 2008 and 2014 outbursts of H 1743–322 (De Marco et al. 2015; De Marco & Ponti 2016). However, these two outbursts were reported to be failed ones, whereas the 2016 outburst exhibits a full spectral state transition from the hard to soft state (see Figure 1), implying it is a successful one. As the luminosity may be the reason for the change in lag properties during the 2016 outburst from the 2008 and 2014 ones, we derived the Eddington-scaled luminosity ($L_{3–10\,\text{keV}}/L_{\text{Edd}}$) in the 3–10 keV band for the 2016 outburst, considering the mass and distance to the source to be the same as that used in De Marco & Ponti (2016). The values of $L_{3–10\,\text{keV}}/L_{\text{Edd}}$ are found to be 0.006 ± 0.002 and 0.005 ± 0.002 for Epoch-1 and Epoch-2, respectively. These values are nearly similar to the value of $L_{3–10\,\text{keV}}/L_{\text{Edd}}$ ~ 0.004 reported by De Marco & Ponti (2016) in the same energy band for the 2008 and 2014 outbursts. The similar values of the Eddington-scaled luminosity indicate that there may be other possible reasons for the change in the lag properties rather than the luminosity.

The correlation found between the QPO frequency and the photon index ($\Gamma$; see Figure 9) is very common in BHXBs, and an ample amount of study has been performed by Vignarca et al. (2003), Titarchuk & Fiorito (2004), Titarchuk & Shaposhnikov (2005), McClintock et al. (2009), and Stiele et al. (2011, 2013). Furthermore, Stiele et al. (2013) stated that the $\Gamma$–QPO frequency correlation can be explained through the “sombrero” geometry, where the black hole is surrounded by a quasi-spherical corona and the accretion disk enters the corona by a small amount. Such a $\Gamma$–QPO frequency correlation indicates that the QPO properties are strongly related to the geometry of the coronal region.

Although the weak anticorrelation between the centroid frequency and fractional rms amplitude of the QPO in Figure 10 is not statistically significant, it might still give some indication of the type C nature of the QPO (McClintock et al. 2009), in addition to the obtained shape of the PDS (see Figure 2) and the fractional rms value of the QPO (see Table 2). However, there may be a possibility of achieving a better significance of this anticorrelation by considering the larger data set with a higher S/N. The disk fraction is always less than 3% and shows a weak correlation with the QPO frequency, as well as a weak anticorrelation with the QPO fractional rms amplitude. In this regard, it is worth mentioning here that, based on the study of BHXBs XTE J1550–564 and GRO J1655–40, Sobczak et al. (2000) suggested that the strong correlation between the disk flux and the QPO frequency could imply the regulation of the QPO frequency by the accretion disk. Apart from this, it was also pointed out that not only does the accretion disk regulate the QPO frequency but also the QPO phenomenon is closely related to the power-law component, which acts like a trigger only when the threshold value is ~20% of the total flux. For H 1743–322, we have found that the Comptonized fraction is weakly anticorrelated with the QPO frequency, as well as weakly correlated with the QPO fractional rms amplitude, and is always greater than 97% (see Figure 10), which indicates that the maximum amount of the total flux is coming from the Comptonized component. The weak anticorrelation between the QPO frequency and the power-law flux was also found for type C QPOs in the BHXB GX 339–4 by Motta et al. (2011). Moreover, the high value of the Comptonized fraction and the weak value of the thermal disk component clearly support the LHS behavior of H 1743–322 during the 2016 outburst period and is in accordance with the above-mentioned temporal and spectral parameters.

We thank the anonymous referee for useful comments that have improved the quality of the paper. This research has made use of archival data from the XMM-Newton, NuSTAR, and Swift observatories through the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by the NASA Goddard Space Flight Center. The NUSTARDAS, jointly developed by the ASI Science Data Center (ASDC, Italy) and the California Institute of Technology (Caltech, USA) is used to process the NuSTAR data. The Science Analysis System (SAS), provided by the ESA science mission with instruments and contributions directly funded by ESA Member States and the NASA (USA) is used to process the XMM-Newton data. This research has also made use of the Swift online data analysis tools provided by the Leicester Swift Data Centre (http://www.swift.ac.uk/user_objects/). The authors express their sincere thanks to David P. Huenemoerder for his help in using the ISIS package. This research has made use of the General High-energy Aperiodic Timing Software (GHATS) package developed by T.M. Belloni at INAF–Osservatorio Astronomico diBrera. S.C. and P.T. acknowledge the financial support of ISRO under AstroSat archival data utilization program DS-2B-13013(2)/8/2019-Sec.2. P.T. expresses his sincere thanks to the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, India, for granting supports through the IUCAA associateship program. S.C. is also very much grateful to IUCAA, Pune, India, for providing support and local hospitality during his frequent visits to accomplish the final shape of this paper.
