Spectro-temporal Studies of Rapid Transition of the Quasi-periodic Oscillations in the Black Hole Source H1743-322

K. Sriram1,2, S. Harikrishna1, and C. S. Choi2

1 Department of Astronomy, Osmania University, Hyderabad 500007, India; astrosriram@yahoo.co.in
2 Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea

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Abstract
An appearance or disappearance of quasi-periodic oscillations (QPOs) associated with the variation of X-ray flux can be used to decipher the accretion–ejection mechanism of black hole X-ray sources. We searched for and studied such rapid transitions in H1743-322 using archival data from the Rossi X-ray Timing Explorer and found eight such events, where a QPO vanishes suddenly along with the variation of X-ray flux. The appearance/disappearance of QPOs was associated with four events exhibiting type-B QPOs at ~4.5 Hz: one was a type-A QPO at \( \nu \sim 3.5 \) Hz, and the other three were connected to type-C QPOs at \( \sim 9.5 \) Hz. Spectral studies of the data revealed that the inner disk radius remained at the same location around \( 2 \)–\( 9 \) \( r_g \), depending on the model used, but power-law indices were varying, indicating that either a corona or a jet is responsible for the events. The probable ejection radii of coronas were estimated to be around \( 4.2 \)–\( 15.4 \) \( r_g \), based on the plasma ejection model. Our X-ray and quasi-simultaneous radio correlation studies suggest that the type-B QPOs are probably related to the precession of a weak jet, though a small and weak corona is present at its base, and the type-C QPOs are associated with the base of a relatively strong jet, which is acting like a corona.

Unified Astronomy Thesaurus concepts: Low-mass x-ray binary stars (939)

1. Introduction
A general understanding of the radiative and geometrical structure of the accretion disk in black hole X-ray binaries (BHXBs) exists now, but finer details such as the Comptonization region/corona, jet, disk winds, and their coupled dynamics with the Keplerian portion of the disk are not yet clearly understood. The Rossi X-ray Timing Explorer (RXTE) results have provided substantial information on the spectral and temporal evolution of the outbursts exhibited by BHXBs (McClintock & Remillard 2004; Remillard & McClintock 2006; Done et al. 2007). During the X-ray outburst, temporal and spectral parameters smoothly traverse across the “q”-shaped hardness intensity diagram (HID) (Belloni et al. 2011). The quasi-simultaneous X-ray and radio observations have enriched our understanding of the interrelationship between the disk and steady jet and the transient jet phenomena across the HID (Fender et al. 2004, 2009). An outburst starts with a low-hard/hard state, i.e., a right-aligned portion of the HID, where the disk is often considered to be truncated with an optically thin, high-temperature, Comptonized-zone/corona/sub-Keplerian flow in the inner region of the accretion disk along with a steady jet of low Lorentz factor (\( \Gamma_{\text{jet}} < 2 \)). As the X-ray luminosity increases, or near the peak of the outburst, the source occupies a large plane in the HID known as the hard intermediate and soft intermediate (Belloni 2010)/steep power-law states (HIMS/SIMS/SPL), where the disk is close to the last stable orbit or moderately truncated along with an optically thick, low-temperature corona in the inner region. The jet line in the HID falls in this state, where its activity turns on/off; however, the jets are transient/ballistic in nature with \( \Gamma_{\text{jet}} > 2 \) (Fender et al. 2004). Finally the source occupies the left-aligned portion of the HID with thermally dominated (TD) state properties. In this state, the disk is not truncated, it has extremely low Comptonizing emission, and the jet ceases to exist.

The X-ray power density spectrum (PDS) of the outburst also follows the q-shaped track in the HID. Strong broadband-limited noise along with a low-frequency quasi-periodic oscillation (LFQPO) (\( \lesssim 0.1 \) Hz) is seen at the onset of the outburst; as the disk approaches the BH, the QPO frequency increases up to \( \sim 10 \) Hz and high-frequency QPOs occur in HIMS/SIMS. The PDS becomes weak and the QPO is absent in the TD state (Belloni & Motta 2016). Based on the frequency and rms, these QPOs are classified into three different types, namely A, B, and C (Wijnands et al. 1999; Homan et al. 2001; Remillard et al. 2002; Casella et al. 2005). Among these, the appearance of a type-B QPO is always associated with the appearance of a jet line in the HID, and on a few occasions, sudden flux variations are also noticed. A type-B QPO varies in a limited frequency range of \( \sim 4 \)–\( 6 \) Hz, with a low quality factor (\( Q = \nu/\delta \nu \)) often observed at the peak of the X-ray outburst along with a moderate radio flux. Sudden flux variations or flip-flop transitions from type-B/C to type-C/B are rare and seen in very few BHXBs. These flux variations and type-B/A QPO transitions were seen in GX 339-4 (Miyamoto et al. 1991; Nespoli et al. 2003; Motta et al. 2011), XTE J1550-564 (Homan et al. 2001; Sriram et al. 2016), XTE J1859+226 (Casella et al. 2004; Sriram et al. 2013), H1743-322 (Homan et al. 2005), XTE J1817-330 (Sriram et al. 2012), MAXI J1659-152 (Kalamkar et al. 2011; Kuulkers et al. 2013), and MAXI J1535-571 (Stevens et al. 2018) with no sudden flux variation, and type-C/B QPO transitions were found in MAXI J1820+070 (Homan et al. 2020) and GRS 1915+105 (Soleri et al. 2008). A sudden flux variation of 45%, with the appearance of a type-C QPO in the low-flux state that disappeared in the high-flux state in 40 s, was observed in the BH source Swift J1658.2-4242 using the data from NuSTAR and XMM-Newton (Xu et al. 2019). Astrosat also observed a similar phenomenon at the peak of the outburst, and spectral results indicated a slight increase in the temperature of the inner disk along with no variation in the power-law index for the low- and high-flux states (Jithesh et al. 2019). Bogensberger et al. (2020) studied all the flip-flop
transitions of this source and concluded that change in the temperature of the inner disk is responsible for the sudden transitions.

The origin of LFQPOs is known to be associated with the inner region of the accretion disk, but its precise location is still unknown and various models predict different occurrence mechanisms. Stella & Vietri (1998) connected LFQPOs to the Lense–Thirring (LT) precession at a single radius in the Keplerian portion of the accretion disk. LT precession of a rigid inner flow can explain the mechanism of LFQPOs (0.1–10 Hz) (Fragile et al. 2007; Ingram et al. 2009; Ingram & van der Klis 2013). A non-rigid precession was proposed where a differential precession between the disk and jet components is required to explain the energy dependence of a QPO (van den Eijnden et al. 2016, 2017). The accretion–ejection instability (AEI) model explains QPOs of types A, B, and C as arising from the instability that transports energy from the magnetized accretion disk to the inner corona, wherein relativistic formalisms are needed to explain type-B and type-A QPOs (Tagger & Pellat 1999; Varniere & Tagger 2002; Varniere & Vincent 2016). Type-B QPOs are often associated with relativistic jets/ejecta (Motta et al. 2015; Fender et al. 2004, 2009); however, it is unclear how the precession of a jet or coupled jet–corona is associated with the production of type-B QPOs.

Since the sudden appearance/disappearance of QPOs often occurs close to the BH and their connection to the corona or jet is not properly understood, we study such rapid transition events in the BH source H1743–322. This source was discovered in 1977 by Ariel during a bright outburst and was accurately pinpointed by High Energy Astronomy Observatory 1 (HEAO 1; Kaluzienski & Holt 1977; Doxsey et al. 1977). It was detected in 1984 by EXOSAT (Reynolds et al. 1999) and by the TTM/COMIS telescope on board the Mir-Kvant observatory in 1996 (Emelyanov et al. 2000). But after its rediscovery by INTEGRAL on 2003 March 21 (Revnivtsev et al. 2003), extensive observations were made a few days later both in X-ray by RXTE (Markwardt & Swank 2003) and in radio by the Very Large Array (VLA; Rupen et al. 2003). Relativistic jets were observed as plasma blob ejections during the 2003 outburst, thus making it a microquasar (Corbel et al. 2005). After 2003, the source exhibited smaller outbursts from 2004 to 2011 (Kuulkers et al. 2008; Krimm et al. 2009; Zhou et al. 2013). This source is located at a distance of ~8.5 kpc with an inclination i ~ 75° and the mass of the BH is estimated to be 5–15 M⊙, with a spin of a = −0.25–0.75 (Steiner et al. 2012). It was also detected at optical and infrared wavelengths (Baba et al. 2003; Steeghs et al. 2003; Chaty et al. 2015) and the donor was found to be a late-type star located in the Galactic bulge. Apart from the detection of characteristic LFQPOs, a pair of high-frequency QPOs were reported at ~160 Hz and ~240 Hz by Homan et al. (2005) and at ~166 Hz and ~242 Hz by Remillard et al. (2006). McClintock et al. (2009) extensively studied the 2003 outburst in X-ray, radio, and optical bands and concluded that its properties closely match those of XTE J1550–564.

2. Data Reduction and Analysis

We used archival data from the RXTE Proportional Counter Array (PCA, Jahoda et al. 2006) for H1734–322 to search for sudden transition events during the outbursts in the years 2003, 2004, 2005, 2007/2008, 2008, 2009, 2009/2010, and 2011 (Markwardt & Swank 2003; Belloni et al. 2008; Krimm et al. 2009; Zhou et al. 2013); RXTE was then decommissioned on 2012 January 5. The longest outburst was the one in 2003, where 170 pointed observations were made with RXTE (see McClintock et al. 2009). Previous studies indicate that the sudden transition occurred around the peak of the outbursts in BHXBs and most of them are associated with the transition or disappearance of 3–8 Hz QPOs (e.g., Sriram et al. 2016). Hence we have selected 103 observations around the peak of the outbursts associated with the QPOs exhibited by the source. We extracted the PDS for all the observations and looked for the appearance/disappearance of the QPOs in these observations; we marked the transitions in the light curves by finely studying the PDS with a time resolution of 20 s. So we have selected the PCA data—‘standard 2’ and single-bit modes were used to obtain the light curves and spectra. PDSs were extracted (time bin = 1/512 s) during sudden flux variations. On eight occasions, QPOs suddenly appeared/disappeared as the flux varied. One such event, where a type-C QPO rapidly varied to a type-B QPO, was reported by Homan et al. (2005) but spectral analysis was not reported. In order to fit the PDS in units of (rms/mean)² Hz⁻¹ with the white noise level subtracted, a model consisting of a power law plus one or two Lorentzians was invoked to evaluate the QPO parameters. For these events, the best-calibrated PCU2 unit spectra were extracted in the 3.0–25.0 keV energy band. The updated background model, the PCA history file spanning the entire mission, the appropriate response matrix, and the calibrated database were used for extracting the spectra.³ A systematic error of 0.5% was added to the respective spectra. HEASOFT v6.19 software sub-packages were utilized to reduce the data. XSPEC v12.9 (Arnaud et al. 1996) was used for spectral analysis, and parameter uncertainties were calculated at the 90% confidence level, i.e., Δχ² = 2.71, or as mentioned otherwise.

3. Timing Analysis

A search for events associated with sudden transitions of QPOs in H1743–322 was undertaken. A total of eight observations were found (see Table 1) that exhibited sudden variations in their PDS and flux. The occurrences of type-A and type-B (filled circle) and type-C (open circle) QPOs are marked in the All-Sky Monitor (ASM) light curves of the 2003 and 2009 outbursts (Figure 1) and most of these QPOs occurred at the peak of the outbursts. We did not find such sudden variations in other outbursts exhibited by H1743–322. McClintock et al. (2009) classified these observations in SPL state; more specifically, type-B and type-A QPOs are associated with SIMS and type-C QPOs with HIMS. Figures 2 and 3 show the light curves in the 6.12–14.76 keV energy band. Vertical lines show the transitions where QPOs suddenly appeared/disappeared, marked by Q (QPO) and NQ (non-QPO) sections. Here appearance means that the QPO is present in the PDS of the respective section of the light curve and disappearance means that it is not. PDSs were extracted in the 3.68–5.71 keV and 6.12–14.76 keV bands and the results of the fits are presented in Table 2. Out of the eight, four events were found to display QPOs at ν ~ 4.5 Hz along with a harmonic, one event showed a QPO at ν ~ 3.5 Hz, and the remaining three displayed QPOs at ν ~ 9.5 Hz with no harmonic (see Table 2). QPOs with ν ~ 4.5 Hz have the properties of type-B QPOs (Casella et al. 2005; Motta et al. 2015) with a quality factor Q = ν / δν < 5 and fractional rms amplitude <5% in the energy band 6.12–14.76 keV

³ heasarc.gsfc.nasa.gov/docs/xte/pcanews.html
Table 1

| ObsID   | MJD (dd-mm-yyyy) | Start Time | End Time | Transition Time (s) |
|---------|------------------|------------|----------|---------------------|
| 80146-01-07-00 | 52751.039 (22-04-2003) | 00:56:13  | 01:58:15  | 30                  |
| 80146-01-13-00 | 52752.851 (23-04-2003) | 20:26:35  | 01:32:15  | 20                  |
| 80146-01-17-00 | 52756.186 (27-04-2003) | 04:28:13  | 06:03:15  | >2000               |
| 80146-01-25-00 | 52763.075 (04-05-2003) | 01:48:57  | 02:47:15  | 40                  |
| 80146-01-50-00 | 52766.290 (27-05-2003) | 06:58:07  | 09:51:15  | 20                  |
| 80135-02-02-000 | 52786.290 (28-05-2003) | 06:44:01  | 14:25:08  | 280                 |
| 80146-01-51-01 | 52788.520 (29-05-2003) | 12:28:58  | 14:05:15  | 30                  |
| 94413-01-03-04 | 54990.394 (08-06-2009) | 09:27:50  | 10:21:17  | 20                  |

Figure 1. ASM light curves indicating rapid transition events for the 2003 outburst (upper panel: open circles show type-C QPOs and filled circles show events associated with type-B QPOs) and the 2009 outburst (lower panel: the filled circle shows the type-A QPO event).
except in ObsID 80135-02-02-000, whereas QPOs at $\nu \sim 3.5$ Hz can be classified as type-A QPOs ($Q = 2.48$) and those at $\nu \sim 9.5$ Hz have $Q \sim 8$ with rms amplitude 4.7%–6.1%. Motta et al. (2015) did not report QPOs in ObsIDs 80146-01-17-00 and 80146-01-25-00 but found type-B QPOs in ObsIDs 80146-01-16-00 and 80146-01-26-00. The QPO parameters of the later observations were found to be similar in nature to those of earlier observations, as shown in Table 2.

In ObsID 80135-02-02-000, a type-C QPO at $\nu \sim 4.65$ Hz with $Q = 4.8$ along with a harmonic at $\nu = 9.28$ Hz suddenly varied to a type-B QPO with no harmonic at $\nu \sim 5.57$ with $Q = 3.5$, and this feature remained unchanged for the other three sections (not shown here; see Homan et al. 2005). The type-B QPOs are detected at a significance level of 6$\sigma$–8$\sigma$ and type-A QPOs at 2.8$\sigma$. In the three other observations, a type-C QPO around $\sim 9.5$ Hz disappeared in the PDS as the source varied rapidly. The quality factor of the type-C QPO is higher than that of the type-B QPO, a primary characteristic of type-C QPOs, and they are detected at a significance level of 8$\sigma$–10$\sigma$. Moreover, for a few observations, QPOs were absent in the low energy band but present in the higher energy bands. The absence of a QPO is shown in Figure 3 for one such observation, ObsID 80146-01-13-00.

Figure 2. Left: light curves in the 6.12–14.76 keV energy band with a bin time of 8 s. QPO (labelled Q) and non-QPO (NQ) sections are shown, their separation marked by a vertical line. QPOs of the ObsID 80135-02-02-000 data do not disappear and their transition is shown with A and B sections. Right: respective PDSs of QPO (Q) and non-QPO (NQ) sections.
4. Spectral Analysis

We performed spectral analysis for all the observations where QPOs either appeared or disappeared, and on one occasion transitioned from type-C to type-B. We used three different types of models to unfold the spectra in the energy band 3.0 – 25.0 keV, namely, model 1: \( wabs \times (\text{diskbb} + \text{power law}) \) (diskbb; Makishima et al. 1986); model 2: \( wabs \times (\text{diskbb} + \text{broken power law}) \) based on McClintock et al. (2009); model 3: \( wabs \times (\text{diskbb} + \text{CompTT}) \). For the fits, the hydrogen equivalent column density was fixed at \( N_H = 2.2 \times 10^{22} \text{ cm}^{-2} \) (McClintock et al. 2009). A few observations exhibited an Fe line, which was modeled using a Gaussian function with a centroid energy \( E_c = 6.4 \text{ keV} \) (fixed). The CompTT model has four parameters: input soft seed photon temperature \( kT_s \), electron temperature \( kT_e \), optical depth \( \tau \), and normalization (Titarchuk 1994). A spherical geometry of the plasma cloud was adopted for the fits. During the fits of model 3, the \( kT_s \) parameter was allowed to vary, but it was later fixed at its best-fit value in order to constrain the error bars; otherwise this parameter is pegged at zero during the fits.

It was found that observations with \( \nu \sim 4.5 \text{ Hz} \) and \( 3.5 \text{ Hz} \) QPOs fitted well when unfolded with model 1 (Figure 4). Disk normalization (\( N_{\text{diskbb}} \)) was found to be varying in all these observations along with the power-law index (\( \Gamma \)) from Q to NQ sections (Table 3). For example, in ObsID 80146-01-17-00, the change in \( N_{\text{diskbb}} \) is required at an \( F \)-test probability of \( 6.9 \times 10^{-30} \). All the observations displayed reasonably good fits when unfolded with model 2 (Tables 3 and 4). The broken
Table 2
Log of the QPO Parameters Associated with the Sudden Transition Observations

| Parameter | 80146-01-07-00 | 80146-01-13-00 | 80146-01-50-00 |
|-----------|---------------|---------------|---------------|
| Q         | NQ            | Q             | NQ            |
| LC        | 3.68–5.71     | 9.49 ± 0.27   | (weak)        |
|           | 6.12–14.76    | 9.70 ± 0.10   |               |
| LW        | 3.68–5.71     | 0.86 ± 0.55   | (weak)        |
|           | 6.12–14.76    | 1.08 ± 0.20   |               |
| Q         | 3.68–5.71     | 11.03         |               |
|           | 6.12–14.76    | 8.89          |               |
| rms (%)   | 3.68–5.71     | 1.92          |               |
|           | 6.12–14.76    | 4.73          |               |
| $\chi^2$/dof | 3.68–5.71   | 1.11          |               |
|           | 6.12–14.76    | 1.12          |               |

Notes. PDS power unit is $(rms/\text{mean})^2$ Hz$^{-1}$ and “weak” means the QPO is weak, $\leq 1\sigma$ with respect to the QPO normalization.

- Centroid frequency of the Lorentzian component.
- Fundamental centroid frequency.
- Harmonic centroid frequency.
- Width of the Lorentzian component.
- $\nu/\nu_0$, Quality factor of the fundamental frequency.
Figure 4. Unfolded spectra of QPO (Q)/non-QPO (NQ) and A/B sections where type-B and type-A QPOs were observed. Dashed lines show the model components (model 1).
### Table 3
Best-fit Spectral Parameters of the Different Sections (Q/NQ and A/B) of the Observations Exhibiting QPOs with $\nu \sim 4.5$ Hz and 3.5 Hz

| Parameter | 80146-01-17-00 | 80146-01-25-00 | 80135-02-02-000 | 80146-01-51-01 | 94413-01-03-04 |
|-----------|----------------|----------------|------------------|----------------|----------------|
| $kT_e$ (keV)$^a$ | 1.31 ± 0.01 | 1.24 ± 0.01 | 1.23 ± 0.01 | 1.19 ± 0.01 | 1.21 ± 0.01 | 1.24 ± 0.01 | 1.17 ± 0.01 | 1.17 ± 0.01 | 0.72 ± 0.03 | 0.76 ± 0.03 |
| $N_{\text{diskbb}}$ | 332 ± 12 | 471 ± 10 | 232 ± 7 | 273 ± 5 | 639 ± 17 | 529 ± 22 | 731 ± 15 | 849 ± 20 | 1089 ± 234 | 909 ± 151 |
| $\Gamma_e$ | 2.79 ± 0.03 | 2.70 ± 0.04 | 2.83 ± 0.03 | 2.69 ± 0.03 | 2.65 ± 0.04 | 2.65 ± 0.04 | 2.61 ± 0.03 | 2.41 ± 0.05 | 2.50 ± 0.07 | 2.32 ± 0.08 |
| $N_{\text{pl}}$ | 10.65 ± 1.01 | 5.36 ± 0.61 | 4.63 ± 0.48 | 2.57 ± 0.25 | 8.08 ± 0.88 | 12.17 ± 1.34 | 5.56 ± 0.49 | 3.25 ± 0.48 | 1.80 ± 0.41 | 1.09 ± 0.28 |
| diskbb flux$^c$ | 8.01 | 8.51 | 3.99 | 4.05 | 10.20 | 9.68 | 10.01 | 11.12 | 0.77 | 0.93 |
| Power-law flux | 7.34 | 4.37 | 2.97 | 2.14 | 7.27 | 10.98 | 5.58 | 4.71 | 2.17 | 1.91 |
| $\chi^2$/dof | 48/44 | 33/44 | 51/44 | 52/44 | 39/44 | 40/44 | 27/44 | 35/44 | 62/42 | 72/42 |
| $\nu/\nu_{\text{QPO}}$ | 5.12 ± 0.06/... | 4.29 ± 0.06/4.76 | ... | 4.65 ± 0.07/5.44 | 5.57 ± 0.08/... | 4.25 ± 0.07/... | ... | 3.46 ± 0.22/... | ... |
| $R_m$ (km)$^d$ | 37 ± 1 | 43 ± 1 | 31 ± 1 | 33 ± 1 | 51 ± 1 | 46 ± 1 | 54 ± 1 | 58 ± 1 | 66 ± 7 | 60 ± 5 |

Notes:

$^a$ Temperature of the inner disk of the diskbb model.

$^b$ Normalization of the diskbb model.

$^c$ Power-law index.

$^d$ Normalization of the power-law model (photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV).

$^e$ Unabsorbed flux for all the models in units 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$ in the energy band 3–25 keV.

$^f$ QPO centroid frequency.

$^g$ Quality factor.

$^h$ Inner accretion disk radius.

$^i$ $\Gamma_1$ and $\Gamma_2$ are the photon indices of the broken-power-law model.

$^j$ Break energy of the broken power law.

$^k$ Normalization (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV).
5. Robustness of Observed Spectral Variation

In order to check the significance of the spectral variations in Q and NQ sections and in A and B sections (Figures 2 and 3), we fitted the spectra of these sections simultaneously with the models discussed above and also with wabs × (SIMPL × diskbb) (Table 5). It was observed that three observations—80146-01-17-00, 80146-01-25-00, and 80146-01-51-01—exhibit changes in the power-law index of the SIMPL model between Q and NQ. The parameter $f_{\text{ew}}$ was found to be varying, for example, in ObsID 80135-02-02-000, and the variation of the disk normalization parameter was noticeable in ObsID 80146-01-13-00. In order to see the significance of the variation among these parameters, the STEPPAR function in XSPEC was invoked and confidence contours of 68%, 90%, and 99% were obtained for different sections of the observation. It can be seen that all the changes are significant at the 99% confidence level.

Moreover, we evaluated the F-test probability in order to check which spectral parameter is primarily varying from one section to another. For this procedure, we tied the spectral parameters of Q and NQ sections and froze the parameters as the best-fit values of the NQ section of the spectrum. Then we allowed the parameters to vary independently one by one as shown in Table 6. Figure 7(left) shows the square root of $\chi^2$ variation as the spectral parameters were independently varying in a stepwise manner. It can be seen that the residuals of other sections gradually approach their best-fit values as demanded.
by the data. The low value of the $F$-test probability for ObsID 80146-01-17-00 was observed at the $\Gamma_1$ parameter ($2.15 \times 10^{-94}$), which indicates that it is the primary parameter that needs to vary in order to explain the spectral difference between NQ and Q sections; similarly for ObsID 80135-02-02-000, $f_{\text{scat}}$ is the primary parameter ($6.54 \times 10^{-51}$).

6. Discussion and Results

The study of the rapid appearance/disappearance of QPOs is important in order to understand the disk–jet ejection or quenching phenomena in the inner accretion disk of BHXBs. In H1743-322, we found a total of eight events where the QPO has disappeared/appeared in different observations. The PDS study clearly suggests that they were four type-B QPOs with $\nu \sim 4.5$ Hz, one type-A QPO with $\nu \sim 3.5$ Hz, and three type-C QPOs with $\nu \sim 9.5$ Hz (Table 2). A rapid emergence of a type-B QPO around $\sim 5$–7 Hz within 10 s after a type-A QPO was noticed in GX 339-4 and was related to the spectral hardening of the flux (Nespoli et al. 2003). The power-law index was found to vary from $2.46 \pm 0.03$ to $2.29 \pm 0.03$ as a type-B QPO at $\sim 5.54$ Hz suddenly transitioned to a type-A QPO in a few tens of seconds in XTE J1817-330 (Sriram et al. 2012). In the case of XTE J1859+226, where type-B QPOs with $\nu \sim 6$ Hz varied to type-A and type-C QPOs ($\sim 7.6$–$8.7$ Hz) in different observations, the soft and hard fluxes varied by 3%–20% (Sriram et al. 2013). In one of the observations, a type-A QPO with $\nu \sim 7.6$ Hz suddenly appeared along with the hardening of the spectrum ($\Gamma \sim 2.40$ to $\Gamma \sim 2.27$) (Sriram et al. 2013). A type-A QPO varied to a type-B QPO at $\sim 3$ Hz and a harmonic of $\sim 6$ Hz was noticed in XTE J1550-564; both soft and hard components were found to change during the transition (Sriram et al. 2016). An appearance of a type-A (or type-B) QPO at 5.72 Hz was seen in MAXI J1535-571, which lasted for a few days (Stevens et al. 2018). In the case of Swift J1658.2-4242, a decrease in the X-ray flux variation by 45% was noted with a sudden production of type-C QPOs in 40 s (Xu et al. 2019). In the same source, type-C to type-A QPOs were found to be related to rapid flip-flop transitions, which were found to be associated with the change in temperature of the inner disk.

Figure 5. Unfolded spectra of QPO (Q) and non-QPO (NQ) sections for type-C QPO observations. Dashed lines show the model components (model 3).
Table 5
Best-fit Spectral Parameters of the Sections with QPO and non-QPO Using the Model wabs × (SIMPL\*diskbb)

| Parameter        | Q 80146-01-17-00 | Q 80146-01-25-00 | A 80135-02-02-000 | A 80146-01-51-01 | B 94413-01-03-04 |
|------------------|------------------|------------------|-------------------|-----------------|-----------------|
| $kT_{in}$        | 1.20 ± 0.02      | 1.19 ± 0.01      | 1.16 ± 0.01       | 1.15 ± 0.01     | 1.14 ± 0.01     |
| $N_{dbb}$        | 790 ± 52         | 738 ± 50         | 459 ± 26          | 409 ± 16        | 1135 ± 62       |
| $\Gamma_{simpl}$| 2.91 ± 0.07      | 2.76 ± 0.06      | 2.68 ± 0.05       | 2.71 ± 0.06     | 2.74 ± 0.06     |
| $f_{scat}$       | 0.121 ± 0.006    | 0.193 ± 0.010    | 0.151 ± 0.008     | 0.156 ± 0.008   | 0.223 ± 0.008   |
| $\chi^2$/dof     | 43/42            | 38/42            | 44/42             | 47/42           | 35/42           |
| $R_{in}$ (km)    | 56 ± 3           | 54 ± 3           | 43 ± 2            | 40 ± 1          | 67 ± 4          |
| Flux            | 15.26            | 12.87            | 6.94              | 6.18            | 17.41           |

| Parameter        | Q 80146-01-07-00 | Q 80146-01-13-00 | Q 80146-01-50-00 |
|------------------|------------------|------------------|-----------------|
| $kT_{in}a$       | 0.94 ± 0.03      | 0.93 ± 0.01      | 1.10 ± 0.02     |
| $N_{dbb}b$       | 1221 ± 92        | 1405 ± 110       | 1338 ± 120      |
| $\Gamma_{simpl}c$| 3.02 ± 0.01      | 3.05 ± 0.01      | 2.92 ± 0.02     |
| $f_{scat}d$      | 0.44 ± 0.04      | 0.53 ± 0.08      | 0.38 ± 0.02     |
| $\chi^2$/dof     | 52/42            | 51/42            | 40/42           |
| $R_{in}$ (km)    | 70 ± 5           | 75 ± 5           | 73 ± 6          |
| Flux            | 8.81             | 10.10            | 20.31           |

Notes.

a Temperature of the inner disk (keV).
b Normalization.
c Power-law index of the SIMPL model.
d Scattered fraction of the soft photons.
e Unabsorbed flux in the energy range 3.0–25.0 keV (10$^{-9}$ erg cm$^{-2}$ s$^{-1}$).
A type-C QPO at $\sim 4.5$ Hz along with an harmonic at 9 Hz was observed to vary to a type-B QPO at $\sim 3$ Hz in a few thousand seconds in MAXI J1820+070, but no spectral studies were reported (Homan et al. 2020). We found changes in $kT_{in}$ and $N_{diskbb}$ in a few observations associated with the type-B and type-C QPOs. Since the true radius of the inner disk ($R_{in}$) is affected by scattering and spectral hardening (Merloni et al. 2000; Done & Davis 2008), we used the relation $1.2 \times (N_{diskbb}/\cos \theta)^{1/2} \times (D/10 \text{ kpc})$ km to derive the true inner disk radius $R_{in}$ (Reynolds & Miller 2013). An inclination of 75° and a distance of 8.5 kpc were used to obtain $R_{in}$ in all observations for Q and NQ sections (Steiner et al. 2012, see Tables 3 and 4). We noted that $R_{in}$ is similar during type-B and during type-C QPOs, with an uncertainty of $\sim 10$ km ($\sim 1 \ r_g$, gravitational radius $r_g = GM/c^2$). In the scenario of a truncated accretion disk (Done et al. 2007), the lower-frequency QPO should arise from a region further out than the high-frequency QPO. But here it should be noted that the origins of type-B and type-C QPOs are different (Motta et al. 2011; Sriram et al. 2013; Belloni & Motta 2016). Such a similar radius (2–3 $r_g \sim 23–34$ km assuming a 7 $M_\odot$ BH for a spin parameter $a_* = 0.2$) is predicted by the model of a jet-emitting disk in the inner region of the accretion disk (Marcel et al. 2020).

Using model 1, $\Gamma$ was found to be softer whenever a type-B QPO was observed (e.g., ObsID 80146-01-25-00: $\Gamma = 2.83 \pm 0.03$ for Q and $\Gamma = 2.69 \pm 0.03$ for NQ; see Table 3). The change in power-law flux is relatively high when compared to diskbb flux. Similarly, model 2 exhibited steeper (soft) power-law indices $\Gamma_1$ for three observations—80146-01-17-00, 80135-02-02-000, and 80146-01-51-01 (Q and A sections)—and harder indices for others, whereas $\Gamma_2$ also varied significantly in three observations (Table 3).
understood in the framework of a multicomponent hot flow where the outer region of the hot Compton component (i.e., soft Compton component) excites the harmonic and the inner hot flow/jet is responsible for the fundamental QPO based on frequency-resolved spectroscopy (Axelsson et al. 2013; Axelsson & Done 2016; Hjalmarsdotter et al. 2016). We hypothesize that $\Gamma_1$ arises from the outer hot flow and $\Gamma_2$ is associated with the inner hot flow, probably the base of the jet.

In our study, we also detected disappearing harmonics along with the fundamental QPO, indicating that some portion of these flows is ejected away. On one occasion (ObsID 80135-02-02-000) a type-C QPO along with a harmonic transitioned to a type-B QPO where a slight change in $R_{in}$ was noted, but no consistent change was noted in $\Gamma$ (model 1). In model 2, $\Gamma_1$ has significantly changed but no variations were seen in $\Gamma_2$ and $R_{in}$. The broken power-law flux increased by 45% and the soft flux varied by 2% (Table 3). The variation in $\Gamma_1$ indicates that the outer region of hot flow was ejected away, leaving behind the inner hot flow or a jet.

Most of the observations associated with the type-B QPO strongly indicate the precession of a jet or a vertically extended corona structure (Ingram et al. 2009; Motta et al. 2011, 2015; Sriram et al. 2016; Jithesh et al. 2019; Xu et al. 2019; Bogensberger et al. 2020; Belloni et al. 2020). Phase-resolved spectroscopy of a type-B QPO in GX 339-4 vividly indicated that large-scale height precessing Comptonizing region, probably of the base of a jet, is needed to explain the non-sinusoidal nature of the fundamental wave (Stevens & Uttley 2016). A detailed study of phase difference in QPO harmonics in BHXBs led to the conclusion that the type-B QPO phase difference remains constant around 0.5–0.6 for most of the sources; however, it varies and increases with frequency for type-C QPOs. In order to explain this scenario, a precessing, optically thick jet is required to produce the type-B QPO, and the associated harmonic is due to the non-sinusoidal nature of the fundamental wave (de Ruiter et al. 2019). The type-B QPO does not show any coupling between itself and the broadband noise and it does not exhibit any dependence on inclination (Arur & Maccarone 2019, 2020). Motta et al. (2015) found that type-B QPOs are stronger in low-inclination systems and are associated with a different physical origin than that of type-C QPOs. They are somehow possibly connected to the jet, whose power is stronger in face-on

**Figure 7.** Left: square root of $\chi^2$ for the spectra of Q and NQ sections of ObsID 80146-01-17-00. The best-fit NQ spectrum is close to the zero residual (inverted triangles); as the spectral parameters of the model components are free to vary (see text), the residuals of the Q spectrum decrease. Right: similar study for the spectra of A and B sections of ObsID 80135-02-02-000.

### Table 6

| Parameters       | $\chi^2$/dof | $F$-test Probability |
|------------------|--------------|-----------------------|
| 80135-02-02-000  | wabs $\times$ (SIMPL$^*$diskbb) |                       |
| All fixed        | 12,860/92    | -                     |
| $\Gamma_{\text{SIMPL}}$ | 8446/90    | $5.94 \times 10^{-9}$ |
| $f_{\text{scat}}$ | 611/88      | $6.54 \times 10^{-3}$ |
| $kT_{\text{in}}$ | 78/86       | $5.94 \times 10^{-39}$|
| All freed        | 70/84       | $6.50 \times 10^{-3}$  |
|------------------|--------------|-----------------------|
| 80146-01-17-00   | Model 2      |                       |
| All fixed        | 36,032/96   | -                     |
| $kT_{\text{in}}$ | 16,899/94   | $3.50 \times 10^{-16}$|
| $N_{\text{diskbb}}$ | 12,184/92 | $2.91 \times 10^{-7}$  |
| $\Gamma_1$       | 101/90      | $2.15 \times 10^{-94}$|
| $E_0$            | 100/88      | 0.65                  |
| All freed        | 75/86       | $4.20 \times 10^{-3}$  |

**Note.** All fixed means, for example, that for ObsID 80146-01-17-00 the spectral parameters of Q and NQ sections are tied and the parameters are fixed as the best-fit values of the spectrum of the NQ section. Each model parameter was allowed to vary independently by freeing in Q and untying in NQ sections.
systems. This is also supported by the X-ray and radio correlation studies (Motta et al. 2018).

During the sudden disappearance of type-C QPOs, for example in ObsID 80146-01-13-00, $kT_{\text{in}}$ varied from 1.32 keV to 1.47 keV along with a consistent variation in $R_{\text{in}}$, but $kT_{\text{e}}$ did not fluctuate much (model 3). However, $kT_{\text{e}}$ varied significantly in two other observations when $kT_{\text{e}}$ is fixed, and similar changes were observed from model 2 (Table 4). In Table 4, the power-law flux increased by 38% and the disk flux by 9% for model 3, and they increased by 32% and 11%, respectively, for model 2. In all the three observations, the hard flux changes more than the soft flux. This low-temperature corona of high optical depth is possibly causing the type-C QPO, a characteristic of this spectral state (Done et al. 2007; Sriram et al. 2009). The disappearance of the QPO could be due to a partial ejection of this component, leaving behind a hotter component that is evident from the spectral results (model 3, Table 4). In all the three observations, $\Gamma$ 1 is found to be steeper in Q sections (variation was significant in one observation) and there is a decrease in $kT_{\text{in}}$; no consistent variation in $\Gamma_2$ was observed between Q and NQ sections (Table 4).

One of the most promising models that can explain the type-C QPO is the LT precessing model, where the inner hot region precesses like a rigid body. Strong evidence associated with the LT precession model came from the detection of quasi-periodic modulation of the iron line in H1743-322; this modulation is due to the quasi-periodic illumination of the disk caused by the precession of the hot inner flow (Ingram et al. 2009; Ingram & Done 2012). This model clearly suggests that there should exist a truncation radius beyond which the disk does not precess. The bending wave sets the inner radius at $\sim8 r_g$ and $\sim10 r_g$ if the spin of the black hole is $a_*=0.5$ and 0.9, respectively. $H/R=0.2$ (ratio between vertical height and radius of the accretion disk) and an outer radius of $\sim6.5–50$ $r_g$ can successfully produce the LFQPOs (0.1–10 Hz) observed in BHXBs (Lubow et al. 2002; Fragile et al. 2007; Ingram et al. 2009). As discussed above, most of the observational evidence related to the type-B QPO leads to a possible jet origin and a precessing jet in the inner region. This model also warrants a truncation in the disk, possibly arising due to the base of a jet, with the jet being the source of hard X-rays via Comptonization (Reig & Kylafis 2015, 2019; Liska et al. 2018; Kylafis & Reig 2018; Kylafis et al. 2020).

7. Constraining the Inner Radius Using the SIMPL Model

Spectral results indicate that the disk is almost at the last stable orbit of $2–4 r_g$, and determining the inner disk radius exactly is difficult for various reasons such as color correction and distance. Also during the spectral fitting, the power-law index diverged in the softer portion of the spectrum, which affects the inner disk radius (Steiner et al. 2009). In order to overcome this problem, we used a model wabs x (SIMPL * diskbb) to unfold the spectra of Q and NQ sections (Table 5). This model gave a reasonable fit ($\chi^2$/dof higher) and larger inner disk radius than that derived from the models mentioned earlier (for more details see Steiner et al. 2009). Soft photons were up-scattered, resulting in $f_{\text{scat}}=0.10–0.55$, and the power-law index of the SIMPL model ($\Gamma_{\text{SIMPL}}$) was found to vary from 2.32 to 3.05 (see Table 5). It was noticed that whenever the type-B QPO of $\nu\sim4.5$ Hz was present, it is associated with a softer $\Gamma_{\text{SIMPL}}$ and a harder $\Gamma_{\text{SIMPL}}$ was noted for a non-QPO section, as observed in the other models too. We found no noticeable variation in the inner disk radius during the sudden disappearance of QPOs except in ObsID 80146-01-13-00, where $R_{\text{in}}$ varied by at least 6 km (see Table 5). In ObsID 80135-02-02-000 (type-C to type-B), we found no appreciable change in $\Gamma_{\text{SIMPL}}$ or the disk parameters. The only parameter that varied was the scattering fraction $f_{\text{scat}}$ for the soft photons converting into the power-law component, which varied from 0.16 to 0.22, a 38% change. Since there is no noticeable change in $R_{\text{in}}$ and $\Gamma_{\text{SIMPL}}$, the increase in $f_{\text{scat}}$ along with the flux can be explained if the vertical structure of the jet has increased in height proportionally, thus intercepting a greater number of soft photons from the disk. Similar non-movement of the inner disk radius came from the study of MAXI J1659-152, where type-B QPOs varied from 1.6 to 4.1 Hz but movement of $R_{\text{in}}$ was not noticed from spectral study, clearly indicating that these QPOs do not originate from the disk (Yamaoka 2012). Similar spectral studies also suggest that $R_{\text{in}}$ does not vary much during the emergence of type-B QPOs (Nespoli et al. 2003; Sriram et al. 2012, 2013, 2016; Jithesh et al. 2019; Xu et al. 2019; Bogensberger et al. 2020). Results from model 2 did not exhibit any significant variation in $R_{\text{in}}$ in four of the observations (Table 3).

8. Disappearance of QPOs and Possible Ejection Heights

As noticed in PDSs both type-B and type-C QPOs disappear, suggesting that the jet is changing its properties or the inner hot flow is being ejected away. Here we constrain the vertical height of the inner region using the plasma ejection model (Beloborodov 1999) because most of the observations connected to the type-B QPO point toward a phenomenon of jet ejection during the outburst (Fender et al. 2009; Motta et al. 2011). In the ejection model, the power-law index is related to the outflowing ejecta along the jet, $\Gamma=1.9/B^{1/2}$, $B=\gamma(1+\beta)$ ($\beta=v/c$ and $\gamma=1/(1–\beta^2)^{1/2}$). The radio observations of H1732-322 displayed different apparent bulk velocities during different outbursts (for more details see McClintock et al. 2009). Based on the radio observations, Corbel et al. (2005) found $\beta=0.79$ for the 2003 outburst and $\beta>0.57$ based on decelerating jet knots, while Miller-Jones et al. (2012) constrained $\beta$ to be 0.19–0.28 for the 2009 outburst. Assuming $\beta=0.79$ as observed in the 2003 outburst, the ejection height should be around $3 r_g$; based on $\Gamma\sim2.3–2.9$ from spectral fits, the ejection must occur at a height of 15.4–4.2 $r_g$, but the time of radio ejection does not correspond to the time associated with the X-ray events reported in the present work. For $\beta=0.19–0.28$, the ejection heights were found to be $\sim50–25$ $r_g$. It should be noted that for radio ejection occurred on MJD 54,984.9 was $\sim5.36$ days earlier than the rapid transition of the type-A QPO in the present work (see Table 7). The heights were calculated assuming the velocities $v=\beta c$ to be escape velocities. In the case of observations of the $\sim9.5$ Hz QPO, neither disk parameters nor $\Gamma_{\text{SIMPL}}$ varied significantly; however, $f_{\text{scat}}$ was found to be increasing along with the flux, indicating that a jet was present. Now we can assume that during the occurrence of a type-C QPO, there was a precessing hot corona (Ingram et al. 2009) and this corona was extended in the vertical direction due to an ejection/transient jet intercepting a greater number of soft photons and emitting a higher flux. Theoretically, the presence of a strong steady jet during this transition can be ruled out because of high $H/R$, so sustaining a strong jet is not possible (King & Nixon 2018).
9. Transient QPOs: Their Association with Radio Emission and a Jet

Although there was no radio emission on MJD 52,756 and 52,763, radio emission was noticed before and after these dates, and the appearance and disappearance of type-B QPOs around ~4.5 Hz along with a harmonic were observed in X-rays (see Table 7). Again a radio flux of ~5.5 mJy at 8.46 GHz was observed during MJD 52,788.37, but no radio observation was reported for MJD 52,787.24. The type-B QPO at 4.2 Hz weakened on MJD 52,788.50. There was no VLA observation on MJD 52,751, but on MJD 52,752.53 a radio emission (~12.20 mJy at 4.86 GHz) was detected, which is much lower than that on MJD 52,750.60 (~23.10 mJy at 4.86 GHz). The spectral index, $\alpha$, on MJD 52,752.53 was ~0.11 (McClintock et al. 2009). The QPO at 9.66 Hz disappeared on MJD 52,752.97. This clearly suggests that there is an unstable jet associated with variable radio emission. X-ray emission was noticed on MJD 52,786.35 with a disappearance of the ~9.5 Hz QPO along with consistent radio emission at the same time (MJD 52,786.35) with ~16 mJy at 8.46 GHz (McClintock et al. 2009) and a spectral index $\alpha = -0.64$. During MJD 54,990.26, the source was in SIMS (Motta et al. 2010; Radhika et al. 2016) and our analysis shows that a type-A QPO at ~3.5 Hz has disappeared and the radio flux density is noted to be <1.0 mJy based on the VLA observations (Miller-Jones et al. 2012). There was an ejection event on MJD 54,989.2 with an inverted spectrum ($\alpha = 1.4 \pm 0.2$) and the radio brightness on MJD 54,991.4 was interpreted as decay from the original flare. We also noted that whenever type-B QPOs appeared/disappeared, the radio emission was found to be <10 mJy at 8.46 GHz whereas the transition connected with a type-C QPO at 9.5 Hz is associated with a radio emission >11 mJy. This suggests that a weaker radio jet is probably connected to type-B QPOs. In the table A5 of McClintock et al. (2009), the spectral index is found to be negative whenever there is a transition of a QPO reported in the present work. Espinasse & Fender (2018) proposed that negative $\alpha$ is often associated with a radio-quiet subset of BHXBs, and discrete ejecta evolving between thick and thin states of emission are probably responsible for the observed spectral indices; however, more studies are needed to confirm this scenario. Since simultaneous radio and X-ray observations are not available during the transitions of QPOs, no precise conclusion can be drawn relating to the variation of radio emission during these events. Table 7 shows the minimum time difference between the X-ray and radio emission during these observations.

The presence of a jet is evident from the radio observations for at least a few observations (Table 7). The inner disk radius during these events was found to be around ~2~6 $r_g$ (Tables 3 and 4, model 2), indicating that the disk is close to the last stable orbit. Type-C QPOs most probably are caused by the LT precession with a rigid inner flow or with a tilted thick disk–jet-like structure (Ingram et al. 2009; Liska et al. 2018). The base of the jet is probably coupled to the precessing inner flow, causing the jet to precess. We found that during the sudden appearance/disappearance of the observed QPOs, the jet was present, though it is difficult to say which physical component, i.e., a rigid inner flow or a jet, is connected to these QPOs and in what proportion. To produce the type-C QPO at 4.5 Hz, in LT precession geometry, the rigid inner flow requires an inner radius of $r_i = 6.7 r_g$ along with an outer radius of $r_o = 10.5 r_g$ (for $\Gamma = -0.5$, $\Sigma$ (surface density) $\propto r^{-\Gamma}$, spin $a = 0.3$, $H/R = 0.2$), estimated from the formula reported by Ingram et al. (2009). Similarly for the QPO at 9.5 Hz, $r_i = 5.5 r_g$ and $r_o = 6.1 r_g$ for $a = 0.2$. This theory successfully explains the production mechanism of type-C QPOs but not type-B QPOs, which are often connected to a jet-like structure (Fender et al. 2009; Motta et al. 2011). One of the main differences between type-C and type-B lies in the quality factor ($Q$), which is lower in the latter case, indicating that a precession of a non-rigid structure is possibly causing the low $Q$. Such a structure could be a jet, which cannot be precessing like a rigid body over large scale heights. Kylafis et al. (2020) showed that a type-B QPO is solely due to the precession of a jet, although a small precessing rigid inner flow is present, and a type-C QPO is due to the precessing rigid inner flow despite the presence of a jet. From our study, possible evidence for the inner rigid flow is the presence of a low-temperature compact corona of high optical depth as observed from the spectral fits where type-C QPOs are present (Table 4; Done et al. 2007). A similar physical component was not observed during the presence of type-B QPOs (for more details see Section 4).

Moreover, in their study $\Gamma$ was found to vary around 2.6~3.0 for an observation angle $i \sim 75^\circ$ and radius of jet $R_s = 150$~60 $r_g$ (see Figure 2 of Kylafis et al. 2020). The type-B QPOs presented in our study mostly have $\Gamma$ around ~2.5~2.9 (see Table 3), which mandates $R_s \lesssim 6 r_g$, and are close to the reported inner disk radius of ~3~6 $r_g$. Recently Marcel et al. (2020) have found that type-B QPOs require a small transition radius ($r_T$, truncation radius due to a jet in the inner region) around 2.5 $r_g$, but a relativistic treatment is needed in order to fully understand type-B QPOs in their model of a jet-emitting disk (Ferreira et al. 2006). At this radius ($<10 r_g$), a precessing ring-like structure that is broken and disassociated with the adjacent disk is also predicted in general-relativistic MHD simulations (Nixon et al. 2012, 2013; Nealon et al. 2015; Liska et al. 2020). No disk-breaking is observed in MHD and HD...
models, but more studies are required in this direction (Hawley & Krolik 2019). A precessing jet by a tilted black hole disk is also possible at a radius $\lesssim 10 r_g$ (Liska et al. 2018), and if a corona is considered along with a disk and jet configuration, the flux from the corona lags from that from the disk (Liska et al. 2019). In their general-relativistic MHD simulation with the approximation of a weak magnetic field, a jet extends to $<100 r_g$ in one direction and stalls as it torques with ambient medium for a given set of initial parameters (Liska et al. 2019). King & Nixon (2018) found that strong jets are not possible for thick disks ($H/\rho \sim 0.1$–0.3) but simulations have shown that jets are possible with $H/\rho = 0.3$; however, the strength of the jet depends on the magnetic field (Liska et al. 2018).

10. Conclusion

1. Eight observations displayed a sudden appearance or disappearance of QPOs, of which four were associated with type-B QPOs at $\sim 4.5$ Hz, one with a type-A QPO at $\nu \sim 3.5$ Hz, and the others were type-C QPOs exhibiting $\sim 9.5$ Hz.

2. Whenever a type-B QPO at $\sim 4.5$ Hz disappeared, the power-law index varied, vividly indicating that a transient jet is responsible for the accretion–ejection phenomenon. The presence of a jet is supported by the detection of quasi-simultaneous radio emission as discussed above. The sudden disappearance of QPOs indicates that some portion of the corona might have ejected away at a height of $4.2$–$15.4 r_g$ in the form of a transient jet.

3. ObsID 80135-02-02-000, where a type-C QPO along with a harmonic varied to a type-B QPO along with the disappearance of the harmonic, is associated with an increase in the scattered soft photon fraction ($f_{\text{scat}}$) and flux. This is possible if the inner corona or a jet-like structure is extended in height, and thus can intercept a greater number of soft photons.

4. During the observations, the inner disk radius was around $\sim 2$–$6 r_g$ (Tables 3 and 4) and $\sim 4$–$9 r_g$ based on the spectral fits using SIMPL model. We did not notice any sudden variation in $R_{\text{in}}$ during the transitions except in one observation (Table 5), which was associated with the type-C QPO.

5. During the disappearance of type-C QPOs, a change in $R_{\text{in}}$ was noticed in one of the observations, although no consistent variation was seen in the power-law index except in a few observations. Both flux and $f_{\text{scat}}$ were found to be increasing in two observations along with the disappearance of the QPO, suggesting that the corona or jet has increased in height.

6. A study of quasi-simultaneous X-ray and radio emission revealed that jet is present during both type-C and type-B QPOs, and a relatively stronger jet is present during type-C QPOs. The high quality factor of type-C QPOs suggests that these are not produced in the jet but instead occur at its base, which acts like a rigid inner flow/corona as discussed above. Our studies suggest that type-B QPOs are caused by the precession of a weak jet with a small and weak corona at its base in the inner region of the accretion disk. These results are similar to that reported by Kylafis et al. (2020) where a precessing jet model corroborated the type-B QPO; however, more observations are indeed required to confirm this scenario.

The rapid transition of QPOs in BHXBs provide an opportunity to understand the dynamics of the Keplerian flow and jet/corona. More studies are needed in order to investigate the contribution of the jet and ambient corona in modulating type-B and type-C QPOs in the inner region of the accretion disk.

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