Wide-band view of High Frequency QPOs of GRS 1915+105 in ‘softer’ variability classes observed with AstroSat

Seshadri Majumder1, H. Sreehari2, Nafisa Aftab1, Tilak Katoch3, Santabrata Das1†, Anuj Nandi4‡

1Department of Physics, Indian Institute of Technology Guwahati, Guwahati, 781039, India.
2Indian Institute of Astrophysics, Bangalore, 560034, India.
3DAA, Tata Institute of Fundamental Research, Colaba, Mumbai, 400005, India.
4Space Astronomy Group, ISITE Campus, U. R. Rao Satellite Centre, Outer Ring Road, Marathahalli, Bangalore, 560037, India.

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ABSTRACT

We present a comprehensive temporal and spectral analysis of the ‘softer’ variability classes (i.e., θ, β, δ, ρ, κ, ω and γ) of the source GRS 1915+105 observed by AstroSat during 2016 – 2021 campaign. Wide-band (3 – 60 keV) timing studies reveal the detection of High Frequency Quasi-periodic Oscillations (HFQPOs) with frequency of 68.14 – 72.32 Hz, significance of 2.75 – 11σ, and rms amplitude of 1.48 – 2.66% in δ, κ, ω and γ variability classes. Energy dependent power spectra impart that HFQPOs are detected only in 6 – 25 keV energy band and rms amplitude is found to increase (1 – 8%) with energy. The dynamical power spectra of κ and ω classes demonstrate that HFQPOs seem to be correlated with high count rates. We observe that wide-band (0.7 – 50 keV) energy spectra can be described by the thermal Comptonization component (nthComp) with photon index (Γnth) of 1.83 – 2.89 along with an additional steep (ΓPL ~ 3) powerlaw component. The electron temperature (∆te) of 1.82 – 3.66 keV and optical depth (τ) of 2 – 14 indicate the presence of a cool and optically thick corona. In addition, nthComp components (1.97 ≲ Γnth ≲ 2.44, 1.06 × 10−8 ≲ Ftth (erg cm−2 s−1) ≲ 4.46 × 10−8) are found to dominate in presence of HFQPOs. Overall, these findings infer that HFQPOs are possibly resulted due to the modulation of the ‘Comptonizing corona’. Further, we find that the bolometric luminosity (0.3 – 100 keV) of the source lies within the sub-Eddington (3 – 34% LEd) regime. Finally, we discuss and compare the obtained results in the context of existing models on HFQPOs.

Key words: accretion, accretion disc – black hole physics – X-rays: binaries – stars: individual: GRS 1915+105

1 INTRODUCTION

The black hole X-ray binaries (BH-XRBs) occasionally exhibit High Frequency Quasi-periodic Oscillation (HFQPO) features that are potentially viable to probe the effect of strong gravity in the vicinity of the compact objects. The signature of QPOs is observed as a narrow feature with excess power in the power density spectrum (van der Klis 1988).

In general, QPO frequencies are classified in two different categories in BH-XRB systems, namely (a) Low-frequency QPO (LFQPO) with centroid frequency νQPO < 40 Hz, and (b) High-frequency QPO (HFQPO) with νQPO exceeding 40 Hz (Remillard & McClintock 2006). LFQPOs are common in BH-XRB systems, whereas HFQPOs are detected in few BH-XRBs observed with RXTE4, such as, GRS 1915+105 (65–69 Hz, Morgan et al. 1997, Belloni & Altamirano 2013a), GRO J1655–40 (300 and 450 Hz, Remillard et al. 1999, Strohmayer 2001a, Remillard et al. 2002), XTE J1550–564 (102 – 284 Hz, Honan et al. 2001; 188 Hz and 249 – 276 Hz, Miller et al. 2001), H 1743–322 (160 and 240 Hz, Honan et al. 2005; 166 Hz, 239 Hz and 242 Hz, Remillard et al. 2006), XTE J1650–500 (50 Hz and 250 Hz, Honan et al. 2003), 4U 1630–47 (100 – 300 Hz, Klein-Wolt et al. 2004), XTE J1859+226 (150 Hz and 247 Hz, Cui 2000) and IGR J17091+3624 (66 Hz and 164 Hz, Altamirano & Belloni 2012), respectively. However, the detection of HFQPOs in XTE J1650–500, 4U 1630–47, and XTE J1859+226 remain inconclusive due to their broad features with lesser significance (Belloni et al. 2012). The HFQPOs are detected by RXTE in high flux observations with intermediate hardness ratios. However, it is intriguing that not all observations with high flux do show this feature (Belloni et al. 2012). Typically, HFQPOs are observed with either one or two peaks in power spectra and the corresponding centroid frequencies are found to vary with time (Belloni & Stella 2014). In some instances, the simultaneous observations of HFQPOs of ~ 3 : 2 frequency ratio...
are reported in GRO J1655−40 and H1743−322 (Strohmayer 2001a; Remillard et al. 2002), which are possibly yielded due to the resonance between two epicyclic oscillation modes (Abramowicz & Kluzniak 2001). Further, the fractional variabilities (i.e., rms amplitudes) of HFQPOs, detected in various sources, are found to increase with energy (Miller et al. 2001). In particular, for GRS 1915+105, the percentage rms associated with 67 Hz increases from 1.5% (at ~ 5 keV) to 6% (at ~ 20 keV) (Morgan et al. 1997). In addition, Homan et al. 2001 measured time lags for ~ 282 Hz HFQPO and found either zero or negative time lags (soft photons lag hard photons) for XTE J1550−564 source. Also, hard phase lags (hard photons lag soft photons) were observed for 67 Hz HFQPO in GRS 1915+105 including other BH-XRBs as well (Cui 1999; Méndez et al. 2013). On the other hand, a negative phase lag was observed for 35 Hz feature, which appeared simultaneously with 67 Hz HFQPO in GRS 1915 + 105. Interestingly, the magnitude of these soft and hard lags are found to increase with energy (Méndez et al. 2013).

Needless to mention that the thermal and non-thermal spectral components of BH-XRB spectra reveal the characteristics of the underlying emission processes and the geometry of the accretion disc. In general, the thermal emissions are mostly originated from the different radii of the multi-temperature accretion disc (Shakura & Sunyaev 1973), whereas the high energy non-thermal emissions are emanated due to inverse-Compton scattering of seed blackbody photons reprocessed at the ‘hot’ corona surrounding the inner part of the accretion disc (Sunyaev & Titarchuk 1980; Tanaka & Lewin 1995; Chakrabarti & Titarchuk 1995; Mandal & Chakrabarti 2005; Iyer et al. 2015, and references therein). Alternative prescriptions of the jet based corona model are also widely discussed in the literature (Beloborodov 1999; Fender et al. 1999; Wang et al. 2021; Lucchini et al. 2021) including different coronal geometries (Haardt et al. 1993; Markoff et al. 2005; Nowak et al. 2011; Poutanen et al. 2018). Often, the presence of HFQPOs is found to be prominent largely in the softer states dominated by the disc emission (McClintock & Remillard 2006). Therefore, it is important to carry out the wide-band spectral modeling in the presence of HFQPO features.

GRS 1915+105, known as microquasar (Mirabel & Rodríguez 1994), is a very bright BH-XRB system which was discovered in 1992 with GRANAT mission (Castro-Tirado et al. 1992). The source possibly harbors a fast spinning Kerr black hole (McClintock & Remillard 2006) with spin > 0.98 measured by indirect means (Sreehari et al. 2020, and references therein). The mass and distance of the black hole are constrained as $12.4^{+2.8}_{-1.8} \, M_\odot$ and 8.6 kpc, respectively (Reid et al. 2014). Interestingly, GRS 1915 + 105 shows different types of structured variabilities in its light curves with time scale of seconds to minutes, and these are identified into 14 distinct classes (Belloni et al. 2000, Klein-Wolt et al. 2002, Hannikainen et al. 2005). Meanwhile, RXTE extensively observed both LFQPOs (Nandi et al. 2001; Vadawale et al. 2001; Ratti et al. 2012 and references therein) and HFQPOs (Morgan et al. 1997; Strohmayer 2001a; Belloni et al. 2006; Belloni & Altamirano 2013b; Méndez et al. 2013) in this source. Morgan et al. (1997) first detected 65 – 67 Hz HFQPO in GRS 1915 + 105 observed with RXTE. Belloni et al. (2006) reported the detection of HFQPO with frequency 170 Hz in $\theta$ class, whereas 63 – 71 Hz HFQPO is observed in $\kappa$, $\gamma$, $\mu$, $\delta$, $\omega$, $\rho$, and $\nu$ classes as well (Belloni & Altamirano 2013a). Simultaneous detection of 34 and 41 Hz features with the fundamental HFQPO at ~ 68 Hz was also reported with RXTE (Strohmayer 2001b; Belloni & Altamirano 2013b).

Recently, using AstroSat observations, Belloni et al. (2019) and Sreehari et al. (2020) observed HFQPO of frequencies 67.4 – 72.3 Hz and 67.96 – 70.62 Hz in GRS 1915+105, respectively. Belloni et al. (2019) studied the temporal properties of GRS 1915+105 considering only two variability classes from 2017 observations. They found a direct correlation between the centroid frequency of HFQPOs and hardness, including positive phase lags which were found to increase with energy and decrease with hardness. However, they did not investigate the spectral characteristics of the source. Further, Sreehari et al. (2020) observed the gradual decrease of the strength of the HFQPO features in $\delta$ class that eventually disappear with the increase of the count rate and the decrease of hardness ratio. They also infer that HFQPOs are present in the 6–25 keV energy range and ascertain that the HFQPOs in GRS 1915 + 105 seem to be yielded due to an oscillating Comptonized ‘compact’ corona surrounding the central source.

In this paper, for the first time to the best of our knowledge, we carry out in-depth analysis and modeling of wide-band AstroSat observations of eight variability classes ($\theta$, $\beta$, $\delta$, $\rho$, $\kappa$, $\omega$, $\gamma$ and $\chi$) of GRS 1915+105 during 2016 – 2021 to study the HFQPO features. While doing so, we examine the color-color diagram by defining the soft color (HR1, ratio of count rates in 6–15 keV to 3–6 keV) and hard color (HR2, ratio of count rates in 15–60 keV to 3–6 keV). Adopting the selection criteria for the ‘softer’ variability classes as $0.02 \lesssim HR2 \lesssim 0.11$ and $0.61 \lesssim HR1 \lesssim 0.90$, and ‘harder’ variability class with HR2 > 0.11 and HR1 $\gtrsim 0.7$, we find seven ‘softer’ variability classes, namely $\delta$, $\rho$, $\kappa$, $\omega$, $\gamma$, $\beta$ and $\theta$, respectively. Subsequently, we examine the light curves and study the energy dependent HFQPO features, percentage rms variabilities (rms%), and dynamic power spectra using LAXPC observations. We find HFQPO features in $\delta$, $\kappa$, $\omega$, and $\gamma$ variability classes, whereas no such HFQPO signatures are seen in $\theta$, $\beta$, $\rho$ and $\chi$ classes. We model the wide-band (0.7–50 keV) energy spectra by combining SXT and LAXPC data to understand the characteristics of the emission processes. Finally, we attempt to correlate the temporal and spectral parameters to explain the underlying mechanism responsible for the generation of HFQPO phenomena in the ‘softer’ variability classes of GRS 1915 + 105 observed with AstroSat.

The paper is organized as follows. In §2, we discuss the observations and data reduction procedures of the SXT and LAXPC instruments. In §3, we present the characteristics of different variability classes (i.e., $\theta$, $\beta$, $\delta$, $\rho$, $\kappa$, $\omega$, $\gamma$ and $\chi$) and discuss the results of both static and dynamic analyses of the power density spectra. Results from wide-band spectral analysis with and without HFQPO features are presented in §4. We discuss the results from spectro-temporal correlation in §5. In §6, we present a discussion based on the results from temporal and spectral studies in the context of the existing models of HFQPOs for BH-XRBs. Finally, we conclude in §7.

2 OBSERVATION AND DATA REDUCTION

India’s first multi-wavelength space-based observatory AstroSat (Agrawal 2006) provides a unique opportunity to ob-
Table 1. Observation details of the source GRS 1915+105 observed by AstroSat during 2016 to 2021 in seven ‘softer’ and one ‘harder’ variability classes. In the table, ObsID along with MJD, Orbit number and exposure time are mentioned. The detected (rdet) and incident (rin) count rate of the LAXPC detector along with hardness ratios are also tabulated. MJD 57451 corresponds to 4th March, 2016. See text for details.

| ObsID          | MJD  | Orbit | Effective Exposure (s) | rdet (cts/s) | rin (cts/s) | HR1 (B/A)*   | HR2 (C/A)*   | Variability Class | HFQPO |
|----------------|------|-------|------------------------|--------------|-------------|--------------|--------------|-------------------|-------|
| T01_030T01_9000000358 | 57451.89 | 2351 | 3459 | 7252 | 8573 | 0.68 | 0.07 | θ | No |
| 57452.82 | 2365 | 3148 | 4376 | 4825 | 0.69 | 0.09 | χ | No |
| G05_214T01_900000428 | 57549.55 | 3241 | 3233 | 7308 | 8651 | 0.76 | 0.04 | ω | Yes |
| G05_189T01_900000492 | 57522.56 | 3841 | 3027 | 7965 | 9588 | 0.75 | 0.03 | δ | No |
| G05_214T01_900000428 | 57553.88 | 3860 | 2381 | 6744 | 7872 | 0.87 | 0.06 | δ | Yes |
| G06_033T01_9000000792 | 57689.10 | 5862 | 2674 | 5359 | 6047 | 0.62 | 0.04 | β | No |
| G06_033T01_9000000792 | 57705.22 | 6102 | 3633 | 6712 | 7829 | 0.68 | 0.02 | δ | No |
| G07_028T01_900001232 | 57891.88 | 8683 | 3282 | 1431 | 1476 | 0.73 | 0.11 | ρ | No |
| G07_046T01_900001236 | 57892.74 | 8876 | 3627 | 1292 | 1328 | 0.61 | 0.09 | ρ | No |
| G07_028T01_900001370 | 57934.69 | 9629 | 977 | 2814 | 2993 | 0.76 | 0.04 | κ | No |
| G07_046T01_900001374 | 57946.10 | 9666 | 1093 | 3115 | 3335 | 0.79 | 0.04 | κ | Yes |
| G07_046T01_900001406 | 57961.39 | 9891 | 1323 | 3642 | 3947 | 0.86 | 0.07 | η | No |
| G07_046T01_900001408 | 57961.39 | 9894 | 2451 | 4415 | 4872 | 0.87 | 0.05 | κ | Yes |
| G07_046T01_900001500 | 57995.30 | 10394 | 3036 | 5719 | 6511 | 0.90 | 0.06 | ω | Yes |
| G07_046T01_900001506 | 57996.46 | 10411 | 3632 | 6160 | 7088 | 0.88 | 0.05 | ω | Yes |
| G07_046T01_900001534 | 58007.80 | 10579 | 1729 | 9685 | 8180 | 0.84 | 0.05 | ω | Yes |
| G07_046T01_900001534 | 58008.08 | 10583 | 1898 | 7392 | 8769 | 0.88 | 0.05 | γ | Yes |
| A04_180T01_900001622 | 58046.36 | 11154 | 2059 | 7312 | 8675 | 0.66 | 0.02 | δ | No |
| A04_180T01_900002000 | 58209.13 | 13559 | 2632 | 1403 | 1445 | 0.87 | 0.19 | χ | No |
| A05_173T01_900002812 | 58565.82 | 18839 | 3626 | 300 | 302 | 1.02 | 0.28 | χ | No |

* A, B and C are the count rates in 3 – 6 keV, 6 – 15 keV and 15 – 60 keV energy ranges, respectively (see Sreehari et al. 2020).

SXT is a Charged Coupled Device (CCD) based X-ray imaging instrument onboard AstroSat in the energy range of 0.3 – 8 keV, which operates both in Fast Window (FW) and Photon Counting (PC) modes. SXT data is analyzed following the guidelines provided by the SXT instrument team. We observe various astrophysical objects in the X-ray band of 0.3 – 100 keV energy range. It consists of three basic X-ray instruments, namely Soft X-ray Telescope (SXT) (Singh et al. 2017), Large Area X-ray Proportional Counter (LAXPC) (Yadav et al. 2016; Agrawal et al. 2017; Antia et al. 2017) and Cadmium Zinc Telluride Imager (CZTI) (Vadawale et al. 2016). The source GRS 1915+105 was observed by AstroSat for 47 pointed observations (termed as ObsID) during different time periods in between 2016 – 2021. In this work, we examine all 47 ObsIDs that include 38 Guaranteed Time (GT) data, 4 Announcement of Opportunity (AO) cycle data, and 5 Target of Opportunity (TOO) cycle data of LAXPC and SXT instruments. These observations exhibit all together seven ‘softer’ (θ, β, δ, ρ, κ, ω and γ) and one ‘harder’ (χ) variability classes, respectively. In order to avoid repetition of results from identical variability classes, we consider 24 Orbits from 17 ObsIDs as delineated in Table 1.

2 https://www.tifr.res.in/~astrosat_sxt/index.html

3 https://webapps.isssdc.gov.in/astro_archive/archive/Home.jsp.

4 http://www.lucas.in/~astrosat/AstroSat_handbook.pdf.
source spectra from LAXPC20 data only as it’s gain remain stable throughout the entire observational period (Antia et al. 2021).

3 TIMING ANALYSIS AND RESULTS

3.1 Variability Classes and Color-Color Diagram (CCD)

We generate 1 s binned light curve in the energy range 3–60 keV, after combining the data from LAXPC10 and LAXPC20 while studying the structured variability in different classes. Following Agrawal et al. (2018); Sreehari et al. (2019, 2020), we correct the dead-time effect in all the light curves and calculate the average incident and detected count rates in 3–60 keV energy ranges as tabulated in Table 1. The light curves are generated in 3–6 keV, 6–15 keV and 15–60 keV energy ranges to plot the CCDs. We define the soft color and hard color following Sreehari et al. (2020) as HR1 = B/A and HR2 = C/A, where A, B and C are the photon count rates in 3–6 keV, 6–15 keV and 15–60 keV energy bands, respectively. The CCDs are obtained by plotting HR1 against HR2. It may be noted that the combined LAXPC10 and LAXPC20 background count rate (∼225 cts/s) is negligible (∼2.5%) compared to the combined source count rate (∼10000 cts/s). Accordingly, we incorporate the background correction while carrying out the color-color and spectral analyses. However, power spectra are generated without background correction of light curves.

Following the classification scheme of Belloni et al. (2000), the light curves and CCDs indicate the presence of seven ‘softer’ variability classes as θ, β, δ, ρ, κ, ω and γ with an additional variant (ρ′) of ρ class (Athulya et al. 2021), and one ‘harder’ variability class (χ). The hardness ratios HR1 and HR2 for each class are tabulated in Table 1. It is clearly seen that the soft color HR1 and the hard color HR2 are generally less than 0.9 and 0.1, respectively, which imply the ‘softer’ variability classes. In Fig. 2, we present background subtracted and dead-time corrected LAXPC light curves of eight different variability classes (θ, β, δ, ρ, κ, ω, γ and χ) with the CCD at the top-left inset of each panel. Different structured variability patterns along with the variations in the CCDs are observed in various classes.

During the AstroSat campaign, the source was initially observed in θ variability class (see Banerjee et al. 2021), where the count rate went up to 20 kcts/s and both colors are softened as observed in the CCD. Further, the source was found in ω, δ and β variability classes (see Table 1). Subsequently, the source was found in a variability class ρ on MJD 57892.74. In this period, we see a ‘flare’ like nature in the light curve, and in the CCD, the points are distributed more towards the harder range. Next, the source displayed κ class variability, in which the count rates were high as 15 kcts/s and multiple ‘dips’ (low counts) of few tens to hundred seconds of duration are observed. In addition, small duration (∼few seconds) ‘non-dips’ (high counts) are also present between the two ‘dips’. The CCD shows a uniform C-shaped distribution of points. In ω class, the duration of ‘non-dips’ between two ‘dips’ increases up to a few hundred of seconds, and the CCD shows a similar pattern as observed in κ class. In γ class, the long duration ‘dips’ are absent instead of small ‘dips’ with a few seconds of duration are observed along with high counts.
Table 2. Details of the best fitted PDS parameters from LAXPC observations of GRS 1915+105 in 3 – 60 keV energy range in different variability classes. Results are obtained with combined data from LAXPC10 and LAXPC20. CO and L_o (i = 1, 2, 3, 4) denote the constant and multiple Lorentzians used to obtain the best fit. σ denotes the significance of HFQPOs. HFQPO\textsubscript{rms}% and Total\textsubscript{rms}% represent the rms percentage of the HFQPO feature and the entire PDS. The centroid energy (LC), FWHM (LW) and normalization (LN) of the detected HFQPOs are highlighted in bold font. All the errors are computed with 68% confidence level. See text for details.

| MJD (Orbit) | CO (10^-4) | L_1 | L_2 | L_3 | L_4 | y^2/df | σ | Estimated Parameters |
|-------------|-------------|-----|-----|-----|-----|--------|----|---------------------|
| 57545.89 (2351)^† | 5.83±0.01 | 0.0 | 5.95±0.01 | 1.09±0.02 | 0.0002±0.0001 | 170/229 | 17.96±6.78 | θ |
| 57545.89 (2351)^† | 6.33±0.01 | 0.0 | 6.41±0.01 | 1.06±0.02 | 0.0002±0.0001 | 170/229 | 17.96±6.78 | θ |
| 57553.88 (3860) | 1.36±0.01 | 0.0 | 1.39±0.01 | 1.37±0.02 | 0.0002±0.0001 | 143/235 | 20.00±4.43 | θ |
| 57569.10 (5862)^† | 1.72±0.01 | 0.0 | 1.34±0.01 | 1.34±0.02 | 0.0002±0.0001 | 129/231 | 26.30±6.12 | β |
| 57705.22 (6102) | 1.37±0.01 | 0.0 | 1.73±0.01 | 3.86±0.02 | 0.0002±0.0001 | 154/231 | 11.68±2.71 | θ |
| 57898.69 (9633) | 1.59±0.01 | 0.0 | 1.36±0.01 | 1.36±0.02 | 0.0002±0.0001 | 172/234 | 14.89±2.7 | θ |
| 57946.10 (9966) | 1.50±0.01 | 0.0 | 1.50±0.01 | 1.50±0.02 | 0.0002±0.0001 | 156/232 | 14.89±2.7 | θ |
| 57946.34 (9760) | 1.67±0.01 | 0.0 | 1.50±0.01 | 1.50±0.02 | 0.0002±0.0001 | 143/234 | 17.05±2.7 | θ |
| 57961.39 (9891)^† | 5.40±0.01 | 0.0 | 5.40±0.01 | 5.40±0.02 | 0.0002±0.0001 | 171/240 | 20.92±4.45 | θ |
| 57961.39 (9894) | 1.57±0.01 | 0.0 | 1.36±0.01 | 1.36±0.02 | 0.0002±0.0001 | 156/232 | 14.89±2.7 | θ |
| 57985.59 (1005) | 2.11±0.01 | 0.0 | 2.11±0.01 | 2.11±0.02 | 0.0002±0.0001 | 171/240 | 14.89±2.7 | θ |
| 57995.30 (10394) | 2.06±0.01 | 0.0 | 2.06±0.01 | 2.06±0.02 | 0.0002±0.0001 | 165/231 | 25.55±6.7 | θ |
| 57996.46 (10411) | 1.76±0.01 | 0.0 | 1.76±0.01 | 1.76±0.02 | 0.0002±0.0001 | 193/234 | 26.45±6.7 | θ |
| 58007.90 (10579) | 1.87±0.01 | 0.0 | 1.87±0.01 | 1.87±0.02 | 0.0002±0.0001 | 126/234 | 18.66±3.7 | θ |
| 58008.08 (10583) | 1.37±0.01 | 0.0 | 1.37±0.01 | 1.37±0.02 | 0.0002±0.0001 | 133/231 | 19.01±3.7 | θ |
| 58046.36 (11154)^† | 1.30±0.01 | 0.0 | 1.30±0.01 | 1.30±0.02 | 0.0002±0.0001 | 166/234 | 7.91±1.7 | θ |
| 58209.13 (14559)^† | 1.43±0.01 | 0.0 | 1.43±0.01 | 1.43±0.02 | 0.0002±0.0001 | 171/234 | 24.02±4.3 | θ |
| 58565.82 (18389)^† | 1.52±0.01 | 0.0 | 1.52±0.01 | 1.52±0.02 | 0.0002±0.0001 | 130/232 | 21.14±5.1 | θ |

† Non-detection of HFQPO.
A diagonally elongated distribution of points is found in the CCD. Finally, the source was found in ‘harder’ variability class ($\chi$) with count rate less than 1.5 kcts/s (Athulya et al. 2021). In each panel of Fig. 2, we show the SXT light curves of the same observations in the energy range of 0.5 – 7 keV at the top-middle inset. Similar structured variabilities are also observed in SXT light curves as seen in LAXPC observations.

Figure 2. Background subtracted and dead-time corrected 1 s binned light curves of GRS 1915+105 observed with AstroSat. Light curve corresponding to eight different variability classes, namely $\theta$, $\beta$, $\delta$, $\rho$, $\kappa$, $\omega$, $\gamma$ and $\chi$ are depicted from top to bottom panels. Each light curve is obtained by combining LAXPC10 and LAXPC20 data in 3 – 60 keV energy band. In every panel, the CCD and the SXT light curves (0.5 – 7 keV) are also shown at the top-left and top-middle insets, respectively. See text for details.

3.2 Static Power Spectra

We generate light curves of 1 ms resolution corresponding to each variability class with combined data from LAXPC10 and LAXPC20. We generate a power density spectrum (PDS) for each observation considering Nyquist frequency of 500 Hz with these light curves. We choose 32768 bins per interval for generating the respective PDS, which are further averaged to obtain the final PDS. A geometric binning factor of 1.4 is used for the power spectral analysis. Finally, the dead-time corrected power spectra are obtained following Agrawal et al. (2018); Sreehari et al. (2019, 2020).

Each PDS (in units of $(\text{rms}/\text{mean})^2/\text{Hz}$) is then modelled using multiple Lorentzians and a constant component in
the wide frequency range of 0.01 – 500 Hz. Each Lorentzian is represented by three parameters, namely centroid (LC), width (LW), and normalization (LN). In Fig. 3, we present the model fitted PDS of δ, κ, ω and γ variability classes with the detected HFQPO feature as depicted in the inset of each panel. The variability class and the observation details are marked in each panel. First, we begin with the modeling of the power spectrum of γ class observation using the model combination of a constant and four Lorentzians. Initially, two zero centroid Lorentzians and one Lorentzian with centroid frequency at 2.25 Hz along with a constant component are used to fit the entire PDS. The fit is resulted in a $\chi^2_{\text{red}}$ of 310/234 = 1.32. Further, to model the HFQPO feature, we include an additional Lorentzian with the centroid frequency of $\sim$ 72 Hz. We emphasize that while modeling the entire PDS and estimating the errors associated with the model parameters, all the model parameters are kept free. The best fit is obtained with a $\chi^2_{\text{red}}$ of 133/231 = 0.58 (see also Sreehari et al. 2020). We follow the above procedure to fit the PDS in the presence of HFQPO features for δ, κ and ω classes, and the best fitted model parameters along with errors are tabulated in Table 2. In addition, we also note the presence of a broad feature in the PDS of δ and γ class observations at $\sim$ 1 Hz and 2 Hz, respectively, which is absent in κ and ω classes.

The presence of a HFQPO feature in the power spectra is determined by means of quality factor ($Q = LC/LW \geq 3$) and significance ($\sigma = LN/err_{\text{neg}} \geq 3$), where $LC$, $LW$, $LN$ and $err_{\text{neg}}$ denote the centroid frequency, width, normalization, and negative error of normalization of the fitted Lorentzian function (Sreehari et al. 2020, and references therein). Best fitted PDS of γ class observation shows a strong signature of HFQPO feature of centroid frequency 72.32$^{+0.23}_{-0.21}$ Hz with significance of 11σ as shown in the inset of the bottom panel of Fig. 3. We calculate the percentage rms of the HFQPO by taking the square root of the definite integral $\int_0^{\omega_{\text{max}}}$ $\frac{\text{Power (rms)}}{\text{Power (mean)}}^2$ $\text{dHz}$ with significance of 11% in the presence of HFQPO feature as presented in Table 3. Further, for reconfirmation (Belloni et al. 2001; Sreehari et al. 2020), we include one additional Lorentzian in the PDS of Orbit 9629 (κ class, as an example) by freezing the centroid frequency at 69.76 Hz and width at 5.01 Hz, similar to the HFQPO characteristics obtained in Orbit 9666 (κ class) having similar exposure. The significance of the best fitted Lorentzian feature is found to be 1.21 at 1σ unit, which indicates the non-detection of HFQPO. All the model fitted parameters of the power spectra are presented in Table 2. In Fig. 4, we show the model fitted PDS corresponding to θ, β, δ, ρ, κ and χ classes, respectively. The power corresponding to θ, β, δ, ρ and κ class observations are scaled by multiplying 200000, 50000, 25000, 2000 and 100 for the purpose of clarity. See text for details.

### 3.3 Energy dependent Power Spectra

We study the energy dependent PDS for all the ‘softer’ variability classes to examine the HFQPO features. While doing
Figure 5. Energy dependent power density spectra depicted in 20–200 Hz frequency range. PDS corresponding to δ, κ, ω and γ class observations are presented in sequence from top to bottom panels. Energy ranges are marked in each panel including insets. The PDS corresponding to 3 – 6 keV and 25 – 60 keV energy ranges are modelled with a constant, whereas the PDS in 6 – 25 keV energy range is modelled using a constant and a Lorentzian. See text for details.

3.4 Dynamical Power Spectra

The power spectra in different variability classes reveal that HFQPOs are not persistent but rather sporadic in nature. Therefore, we examine the dynamic nature of the power spectrum, where we search for HFQPO in each segment of duration 32 s of the entire light curve of 1 ms resolution. The Leahy power spectrum (Leahy et al. 1983) for each segment of the light curve is computed and plotted as a vertical slice corresponding to each time bin using the stingray package (Huppenkothen et al. 2019). The frequency bin size is chosen as 2 Hz. We use bicubic interpolation (Huppenkothen et al. 2019) to improve clarity and smoothen the dynamic power spectrum. The power corresponding to each frequency is color coded such that yellow indicates minimum power and red indicates maximum power as shown in the colorbar of Fig. 6.

In the left side of Fig. 6, we present the light curve (top panel) of Orbit 10411, generated by combining LAXPC10 and LAXPC20 light curves along with the corresponding dynamic power spectrum (bottom panel). The light curve corresponds to the ω class variability (see Fig. 2). It is observed that the power at frequencies around 70 Hz is significant during ‘non-dips’ (high counts) and is insignificant during the ‘dips’ (low counts). The percentage rms amplitude of the HFQPO during high counts and low counts are obtained as 2.38 ± 0.29 and 0.67 ± 0.18 for ω class observation, respectively. This clearly suggests that the HFQPO of frequencies around 70 Hz are generated when the count rate is high. We also observe similar behavior during γ class observation. From the right side of Fig. 6, it is evident that the source emits at high count rate of about 9000 cts/s throughout the observation. As a result, HFQPO is seen to be present in almost every 32 s interval, although its power amplitude reduces during the narrow dips (500 – 700 s) present in the light curve. Overall, by analyzing the dynamic PDS, we infer that within the ‘softer’ variability classes (κ, ω and γ), high count rate (non-dips) seems to be associated with the generation of HFQPO features as illustrated in Appendix A.

4 SPECTRAL ANALYSIS AND RESULTS

For each variability class, we generate the corresponding wide-band energy spectra combining the SXT and LAXPC20 data. We consider 0.7 – 7 keV energy range for SXT spectra, whereas LAXPC spectra are extracted in the energy range of 3 – 50 keV (see Sreehari et al. 2019, 2020, for details). The dead-time corrections are applied to the LAXPC spectra while extracting with LaxpcSoftv3.4 software (Antia et al. 2017).
Table 3. Estimated percentage rms amplitudes of HFQPOs in different energy bands. All the errors are computed with 68% confidence level. See text for more details.

| MJD (Orbit) | HFQPO rms amplitude (%) | Non-detection of HFQPO | Detection of HFQPO |
|------------|-------------------------|------------------------|-------------------|
|            | energy band (3 – 6 keV) | energy band (6 – 25 keV) | energy band (25 – 60 keV) | rms% | HFQPO rms% | Class |
| 57451.89 (2351) | – | – | – | 0.54 ± 0.23 | – | θ |
| 57452.82 (2365) | – | – | – | 0.38 ± 0.11 | – | χ |
| 57453.35 (2373) | – | – | – | 0.43 ± 0.16 | – | θ |
| 57504.62 (3124) | 0.59 ± 0.11 | 2.33 ± 0.25 | 0.81 ± 0.32 | – | 1.48 ± 0.36 | δ |
| 57552.56 (3841) | – | – | – | 0.61 ± 0.23 | – | δ |
| 57553.88 (3860) | 0.79 ± 0.28 | 2.12 ± 0.22 | 0.88 ± 0.25 | – | 1.54 ± 0.48 | δ |
| 57609.10 (3862) | – | – | – | 0.16 ± 0.09 | – | β |
| 57607.22 (4012) | – | – | – | 0.86 ± 0.15 | – | ω |
| 57691.88 (3865) | – | – | – | 0.23 ± 0.12 | – | ρ |
| 57892.74 (8676) | – | – | – | 0.77 ± 0.26 | – | ρ |
| 57943.69 (9626) | – | – | – | 0.94 ± 0.15 | – | κ |
| 57943.69 (9633) | 0.38 ± 0.14 | 3.65 ± 0.31 | 0.56 ± 0.12 | – | 2.14 ± 0.50 | κ |
| 57946.10 (9666) | 0.75 ± 0.18 | 3.34 ± 0.48 | 0.62 ± 0.21 | – | 2.55 ± 0.71 | κ |
| 57946.34 (9670) | 0.83 ± 0.22 | 4.29 ± 0.54 | 0.71 ± 0.13 | – | 2.49 ± 0.37 | κ |
| 57961.39 (9881) | – | – | – | 0.82 ± 0.24 | – | κ |
| 57961.39 (9894) | 0.79 ± 0.15 | 2.86 ± 0.29 | 0.77 ± 0.11 | – | 2.28 ± 0.63 | κ |
| 57961.59 (9895) | 0.19 ± 0.07 | 3.12 ± 0.63 | 0.84 ± 0.33 | – | 1.98 ± 0.41 | κ |
| 57965.30 (10094) | 0.72 ± 0.21 | 3.03 ± 0.55 | 0.67 ± 0.12 | – | 2.25 ± 0.31 | θ |
| 57966.46 (10111) | 0.84 ± 0.24 | 4.01 ± 0.37 | 0.81 ± 0.15 | – | 2.66 ± 0.29 | ω |
| 58007.80 (10579) | 0.68 ± 0.12 | 3.21 ± 0.42 | 0.89 ± 0.19 | – | 1.86 ± 0.37 | ω |
| 58008.08 (10583) | 0.92 ± 0.16 | 3.64 ± 0.24 | 0.74 ± 0.21 | – | 2.46 ± 0.19 | γ |
| 58046.36 (11154) | – | – | – | 0.42 ± 0.14 | – | δ |
| 58209.93 (13593) | – | – | – | 0.76 ± 0.13 | – | χ |
| 58565.82 (18839) | – | – | – | 0.69 ± 0.11 | – | χ |

† Non-detection of HFQPO.
Figure 6. The light curves (3–60 keV) of ω and γ classes are depicted in the top panels of each plot. In the bottom panels of each plot, the dynamical power spectra generated from the high resolution (1 ms) light curve are presented. Here, 32 s segment size and 2 Hz frequency bin are used to represent the dynamical power spectra. The obtained results are presented using color code, where colorbars are marked in the right of the bottom panels. See text for details.

Figure 7. Unfolded wide-band (0.7 – 50 keV) energy spectra of the source GRS 1915 + 105. The spectra are modelled with $T_{\text{abs}} \times (\text{amegge} \times \text{nthComp} + \text{powerlaw}) \times \text{constant}$. The spectra of γ class observation on MJD 58008.08 (Orbit 10583) is presented in the left. Two best fitted spectra of κ class variabilities without (MJD 57961.39; Orbit 9891) and with (MJD 57961.59; Orbit 9895) HFQPO are depicted in the right. The bottom panels of each plot show the residuals in units of σ. See text for details.

We model the wide-band energy spectra using XSPEC V12.10.1f in HEASOFT V6.26.1 to understand the radiative emission processes active around the source. While modelling the energy spectra, we consider a systematic error of 2% for both SXT and LAXPC data (Antia et al. 2017; Leahy & Chen 2019; Sreehari et al. 2020). We use the gain fit command in XSPEC to take care of the instrumental features at 1.8 keV and 2.2 keV in SXT spectra. While applying gain fit, we allow the offset to vary and fix the slope at 1. The hydrogen column density (nH) is kept fixed at $6 \times 10^{22}$ atoms/cm$^2$ following Yadav et al. (2016); Sreehari et al. (2020).

To begin with, we adopt a model $T_{\text{abs}} \times \text{nthComp} \times \text{constant}$ to fit the wide-band energy spectrum of γ class observation (Orbit 10583) for which the strongest HFQPO feature is seen in the PDS (bottom panel of Fig. 3). Here, the model $T_{\text{abs}}$ (Wilms et al. 2000) takes care of the galactic absorption between the source and the observer. The model nthComp (Zdziarski et al. 1996) represents the thermally Comptonized continuum. A constant parameter is used to account for the offset between the spectra from two different instruments, SXT and LAXPC. The obtained fit is yielded a poor reduced $\chi^2$ ($\chi^2_{\text{red}} = \chi^2/\text{dof}$) of 2095/546 = 3.83 as there are large residuals left at the higher energies beyond 30 keV. Hence, we
include a powerlaw along with one Xenon edge component at 32 keV (Sreehari et al. 2019) to fit the high energy part of the spectrum. The Xenon edge is required for all the energy spectra to account for the instrumental absorption feature at 32 – 35 keV. Also, one smege component is used at ~ 9 keV to obtain the best fit. The model Tbabs×(smege×nthComp + powerlaw)×constant provides statistically acceptable fit with $\chi^2_{\text{red}} = \chi^2/\text{dof}$ of 563/533 = 1.08. In the left side of Fig. 7, we present the best fitted unfolded energy spectrum of γ class observation for representation.

The best fitted model parameters of the nthComp component for γ class observation (Orbit 10583) are obtained as electron temperature ($kT_e = 2.62_{-0.12}^{+0.10}$ keV, photon index ($\Gamma_{\text{nth}} = 2.02_{-0.07}^{+0.06}$) with normalization (norm$_{\text{nth}}$) = $15 \pm 2$. The seed photon temperature ($kT_{bb}$) is kept fixed at 0.1 keV during the fitting. The best fitted value for the powerlaw photon index ($\Gamma_{\text{PL}}$) is obtained as $\Gamma_{\text{PL}} = 3.00_{-0.06}^{+0.05}$ with powerlaw normalization norm$_{\text{PL}}$ = $21_{-4}^{+4}$. Following the same approach, we carry out the spectral modelling for all other observations of various variability classes (i.e., $\theta$, $\beta$, $\delta$, $\rho$, $\kappa$, $\omega$, $\gamma$ and $\chi$) irrespective to the presence or absence of HFQPOs. The best fitted model parameters are tabulated in Table 4. It is found that in all observations, the model Tbabs×(smege×nthComp + powerlaw)×constant satisfactorily describes the energy spectra except for $\rho$ and $\chi$ class observations. For $\rho$ class, the acceptable fit is obtained without powerlaw component, whereas in $\chi$ class observation, an additional diskbb component is required along with nthComp. Note that we are unable to constrain the electron temperature for the observations of $\rho$, $\rho'$ and two $\chi$ classes and hence we fix the electron temperature $kT_e = 10$ keV and 20 keV, respectively (see Table 4). In the right side of Fig. 7, we present the wide-band energy spectra of two $\kappa$ class observations on MJD 57961.39 (Orbit 9891) and MJD 57961.59 (Orbit 9895) without and with HFQPO feature, respectively. We point out that the best fitted energy spectrum of orbit 9891 (without HFQPO) has a weak nthComp contribution (norm$_{\text{nth}} \sim 7$), whereas in orbit 9895 (with HFQPO), the nthComp contribution (norm$_{\text{nth}} \sim 16$) is relatively higher. We also find relatively high electron temperatures in those observations that ascertain the detection of HFQPOs except one observation in $\theta$ class (Orbit 2351).

Further, we estimate the flux in the energy range 0.7 – 50 keV associated with different model components used for the spectral fitting. While doing so, the convolution model cflux in XSPEC is used. For γ class observation, the fluxes associated with nthComp and powerlaw components are estimated as 2.49 and 1.37 in units of $10^{-8}$ erg cm$^{-2}$ s$^{-1}$, respectively (see Table 4). We also calculate bolometric flux ($F_{\text{bol}}$) in the energy range 0.3 – 100 keV using the cflux model. Considering the mass ($M_{\text{BH}}$) and the distance ($d$) of the source as $M_{\text{BH}} = 12.4 M_\odot$ and $d = 8.6$ kpc (Reid et al. 2014), we calculate the bolometric luminosity in units of Eddington luminosity ($L_{\text{Edd}}$) as $L_{\text{bol}} = F_{\text{bol}} \times 4\pi d^2$. The luminosity is found to vary in the range of $3 - 34\%$ $L_{\text{Edd}}$. The calculated flux values and bolometric luminosities for all the observations are given in Table 4.

In order to understand the nature of the Comptonizing medium in the vicinity of the source, we calculate the optical depth ($\tau$) of the medium. Following Zdziarski et al. (1996); Chatterjee et al. (2021), the relation among the optical depth ($\tau$), nthComp spectral index ($\alpha = \Gamma_{\text{nth}} - 1$), and electron temperature ($kT_e$) is given by,

$$\alpha = \left[\frac{1}{4} + \frac{1}{(kT_e/c)^2} \tau (1 + \tau/3)\right]^{1/2} - \frac{3}{2},$$

where $\nu_c$ refers to the speed of light. Using equation (1), the optical depth ($\tau$) is calculated and found in the range $2 \lesssim \tau \lesssim 14$ for all the observations. This implies that an optically thick corona is present as a Comptonizing medium in the vicinity of the source. Moreover, we calculate the Compton y-parameter, which measures the degree of Compton up-scattering of soft photons in the underlying accretion flow by the Comptonizing medium. Following Agrawal et al. (2018); Chatterjee et al. (2021), the Compton y-parameter ($y = 4kT_e\tau^2/m_e c^2$) in the optically thick medium is found to be in the range of $0.63 \pm 0.08 - 3.12 \pm 0.35$. In Table 4, we tabulate the obtained optical depth ($\tau$) and Compton y-parameter values for all the observations.

5 SPECTRO-TEMPORAL CORRELATION

In this section, we examine the spectro-temporal correlation of the observed properties in different variability classes of GRS 1915+105. While doing so, we consider four variability classes, namely $\delta$, $\kappa$, $\omega$ and $\gamma$, and study the variation of the percentage rms amplitude (rms%) of HFQPO features as function of energy shown in the top panel of Fig. 8. The results corresponding to $\delta$, $\kappa$, $\omega$ and $\gamma$ classes are denoted by

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9 Eddington luminosity $L_{\text{Edd}} = 1.26 \times 10^{38} (M_{\text{BH}}/M_\odot)$ erg s$^{-1}$ for a compact object of mass $M_{\text{BH}}$ (Frank et al. 2002).
Figure 9. Variation of photon index ($\Gamma_{nth}$) as a function of Comptonized flux associated with nthComp (see Table 4) for $\delta$, $\rho$, $\kappa$, $\omega$, $\gamma$, $\theta$ and $\beta$ variability classes. The color codes denote the rms amplitudes (rms%) corresponding to the detection and non-detection of HFQPOs. Obtained results for different variability classes are presented using different symbols which are marked in the inset. See text for details.

In Fig. 9, we present the variation of photon index ($\Gamma_{nth}$) with the nthComp flux ($F_{nth}$) for observations in $\delta$, $\rho$, $\kappa$, $\omega$, $\gamma$, $\theta$ and $\beta$ variability classes. Here, the variation of the percentage rms amplitude (rms%) of the detected HFQPOs as well as the rms% of the non-detection of HFQPOs (see Table 3) are shown using color code. We find that rms% of HFQPOs lies in the range $\gtrsim 1.5\%$ and it drops below 1% when HFQPOs are not seen. Further, we notice that in $\omega$ class observations, $\Gamma_{nth}$ decreases with the increase of nthComp flux in the range $1.8 \times 10^{-8} \lesssim F_{nth}$ (erg cm$^{-2}$ s$^{-1}$) $\lesssim 4.5 \times 10^{-8}$. In $\kappa$ variability classes, marginal variations are observed in the nthComp flux unlike $\omega$ class observations although photon indices remain $\Gamma_{nth} \gtrsim 2$ when HFQPOs are present. For $\delta$ variability classes, we find $3.5 \times 10^{-8} \lesssim F_{nth}$ (erg cm$^{-2}$ s$^{-1}$) $\lesssim 4.58 \times 10^{-8}$ and $\Gamma_{nth} \gtrsim 1.9$ for HFQPOs. In addition, we point out that HFQPOs are not seen for $\theta$, $\beta$ and $\rho$ class observations although they belong to the ‘softer’ variability classes.

6 DISCUSSION

In this work, we carry out a comprehensive timing and spectral analyses of the BH-XRB source GRS 1915+105 using GT, AO and TOO data of entire AstroSat observations (2016 - 2021) in wide frequency (0.01 - 500 Hz) and energy (0.7 – 60 keV) bands. The variation of the hardness ratios in the CCDs and the nature of the light curves confirm the presence of seven ‘softer’ variability classes, namely $\theta$, $\beta$, $\delta$, $\rho$, $\kappa$, $\omega$, and $\gamma$ along with one additional variant of $\rho$ class ($\rho'$) of the source (Athulya et al. 2021). The LAXPC count rates are found to vary in the range of 1328 – 10997 cts/s, and the hardness ratios are seen to vary as $0.61 \lesssim HR1 \lesssim 0.90$ and $0.02 \lesssim HR2 \lesssim 0.11$. We observe similar variabilities in the low energy (0.7 – 7 keV) SXT light curves as well.

We examine the origin of the HFQPO features and find its presence only in four ‘softer’ variability classes ($\delta$, $\omega$, $\kappa$, $\gamma$). The centroid frequency and the percentage rms amplitude of the HFQPOs are found to vary in the range of 68.14 – 72.32 Hz and 1.48 – 2.66 per cent, respectively (see Table 2 and 3). The present findings are consistent with the earlier results reported using RXTE observations (Belloni & Altamirano 2013a) as well as AstroSat observations (Belloni et al. 2019; Sreehari et al. 2020). It may be noted that the presence of additional peaks in the frequency range 27 – 41 Hz along with HFQPOs at 67 – 69 Hz was also observed (Belloni et al. 2001; Strohmayer 2001b) in GRS 1915+105. However, we do not find any signature of additional peak in our analysis. Meanwhile, Morgan et al. (1997); Strohmayer (2001b) noticed the evolution of frequency from $\sim 67$ Hz to $\sim 69$ Hz in $\gamma$ class which is found to evolve further to $72.39\pm0.22$ Hz as seen in our observations (see Table 2 and 3). This perhaps indicates an unique characteristics of the evolution of HFQPO in a given variability class that requires further investigation.

Next, we investigate the energy dependent PDS to ascertain the photons that are responsible for the origin of the HFQPOs (see Fig. 5). We observe that HFQPO features are present in 6 – 25 keV energy band in four variability classes (see Fig. 5 and Table 3). However, we do not find HFQPO signature in $\theta$, $\beta$, $\rho$ and $\chi$ variability classes (see Fig. 4 and Table 3). We find that the significance and percentage rms amplitudes of the HFQPOs are higher in 6 – 25 keV energy band compared to 3–60 keV energy band (see Table 3). Further, we study the variation of percentage rms amplitude and nthComp flux as function of energy, shown in Fig. 8. These findings are in agreement with the previous studies which were carried out considering energy bands of 2 – 13 keV and 13 – 30 keV only (Belloni et al. 2001). It is also found that the nthComp flux gradually decreases with energy (see Fig. 8) and beyond $\sim 25$ keV, the flux contribution becomes negligible (see Fig. 7).

We notice that $\kappa$ and $\omega$ class variabilities exhibit different duration of ‘non-dips’ (high counts $\sim 9600$ cts/s) and ‘dips’ (low counts $\sim 1250$ cts/s) features. While studying the dynamic PDS, we find that the HFQPO is generally present during ‘non-dips’ period with relatively higher rms amplitude (2.38 $\pm$ 0.29 and 2.35 $\pm$ 0.22 for $\omega$ and $\kappa$ classes). We do not find the signature of HFQPO during the ‘dips’ period as seen in Fig. 6 (see also appendix A). Similar findings are also observed for $\gamma$ class variability where the HFQPO is persistently seen during the entire high count duration (see also Belloni et al. 2001).

We find that the wide-band spectra (0.7 – 50 keV) of $\theta$, $\beta$, $\delta$, $\kappa$, $\omega$ and $\gamma$ class observations are satisfactorily described by the thermal Comptonization nthComp along with a powerlaw component (see Fig. 7 and Table 4). On the contrary, the nthComp component seems to be adequate to fit the energy spectra of $\rho$ class observations. From the spec-
eral modelling, we obtain the range of $\text{nthComp}$ photon index as $1.83 \lesssim \Gamma_{\text{nth}} \lesssim 2.89$, and electron temperature as $1.82 \lesssim kT_e \lesssim 3.66$ keV (see Table 4). In addition, we obtain a steep powerlaw photon index ($\Gamma_{\text{PL}}$) as $2.59 - 3.27$ for all the variability classes under consideration. Similar steep $\Gamma_{\text{PL}}$ is also reported in the previous studies carried out for $\theta$ (Belloni et al. 2006) and $\delta$ (Sreehari et al. 2020) variability classes of the source. We estimate the optical depth ($\tau$) of the surrounding medium and obtain its value as $2 \lesssim \tau \lesssim 14$. This evidently indicates the presence of a cool and optically thick corona around the source, which presumably acts as a Comptonizing medium that reprocesses the soft seed photons. The Compton $\gamma$-parameter is obtained in the range $0.63 \pm 0.08 - 3.12 \pm 0.35$ which infers that the soft photons are substantially reprocessed via Comptonization at the optically thick corona. Further, we calculate the bolometric luminosity in $0.3 - 100$ keV energy range for all the variability classes and find its value in the range $3 - 34\% L_{\text{Edd}}$. These findings suggest that the source possibly emits in sub-Eddington limit during the observations under consideration.

In Fig. 8, we examine the energy dependent ($6 - 25$ keV) $\text{rms\%}$ of HFQPOs in $\delta$, $\kappa$, $\omega$, and $\gamma$ variability classes, and find that $\text{rms\%}$ increases ($1 - 8\%$) with energy up to $\sim 17$ keV and then decreases. Subsequently, we observe that the Comptonize flux ($\text{Flux}_{\text{nth}}$) decreases with energy which tends to become negligible beyond $25$ keV. This possibly happens when the soft photons emitted from the disc are Comptonized by the ‘hot’ electrons from an optically thick corona ($8 \lesssim \tau \lesssim 12$) and produce the aforementioned Comptonized continuum. In order to elucidate the spectra above $\sim 25$ keV, an additional powerlaw component with photon index $\Gamma_{\text{PL}} \sim 3$ is required. This eventually indicates that there could be an extended corona present surrounding the central corona, which is responsible for this high energy emissions (Sreehari et al. 2020). We further notice that for intermediate range of $\text{nthComp}$ photon index ($1.97 \leq \Gamma_{\text{nth}} \leq 2.44$) along with the large variation of $\text{nthComp}$ flux ($1.06 \times 10^{-8} \leq \text{Flux}_{\text{nth}}$ (erg cm$^{-2}$ s$^{-1}$) $\lesssim 4.46 \times 10^{-8}$) generally yields HFQPO signature in $\delta$, $\kappa$, $\omega$ and $\gamma$ variability classes (see Fig. 9). With this, we argue that Comptonization process plays a viable role in exhibiting HFQPO. Overall, based on the findings presented in Fig. 8 and Fig. 9, we conjecture that HFQPOs in GRS 1915+105 are perhaps manifested due to the modulation of the ‘Comptonizing corona’ surrounding the central source (Méndez et al. 2013; Aktar et al. 2017, 2018; Dihingia et al. 2019; Sreehari et al. 2020).

Meanwhile, several theoretical models are put forwarded to explain the HFQPO features occasionally observed in BH-XRBs. Morgan et al. (1997) first attempted to elucidate the HFQPO features with Keplerian frequency associated with the motion of hot gas at the innermost stable circular orbit (ISCO). This model yielded high source mass as $\sim 30 M_\odot$, which is in disagreement with the dynamical mass measurement of GRS 1915+105 (Greiner et al. 2001; Reid et al. 2014) and hence dissented (Belloni & Altamirano 2013a). Nowak et al. (1997) interpreted the origin of 67 Hz QPO in GRS 1915+105 as the resulting frequency of the lowest radial g-mode oscillation in the accretion disc. However, this model lacks cogency for those BH-XRBs that generally manifest $> 10\%$ rms amplitude variability. Further, there were alternative attempts to address the origin of HFQPO without dwelling much on observational features (Chen & Taam 1995; Rezzolla et al. 2003; Stuchlik et al. 2007). Noticing significant hard lag in GRS 1915+105, Cui (1999) infer that a Comptonizing region is responsible for the HFQPOs. Remillard et al. (2002) further stressed on the presence of ‘Compton corona’ that reprocesses the disk photons and yields HFQPO features. In addition, Aktar et al. (2017, 2018) reported that the HFQPO features of GRO J1655−40 at 300 Hz and 450 Hz perhaps resulted due to the modulations of the post-shock corona (PSC) that radiates Comptonized emissions (Chakrabarti & Titarchuk 1995). Recently, Dihingia et al. (2019) ascertained that the shock induced relativistic accretion solutions are potentially viable to explain the HFQPOs in well studied BH-XRB sources, namely GRS 1915+105 and GRO J1655−40. With this, we affirm that the HFQPO models proposed based on the ‘Comptonizing corona’ fervently favor our observational findings delineated in this work.

7 CONCLUSIONS

In this paper, we perform in-depth temporal and spectral analyses in the wide-band ($0.7 - 60$ keV) energy range of the BH-XRB source GRS 1915+105 using entire AstroSat observations (2016 – 2021) in seven ‘softer’ variability classes, namely $\theta$, $\beta$, $\delta$, $\rho$, $\kappa$, $\omega$ and $\gamma$, and one ‘harder’ variability class ($\chi$), respectively. The overall findings of this work are summarized below:

- We find HFQPO feature in $\delta$, $\kappa$, $\omega$ and $\gamma$ classes of GRS 1915 + 105 having frequency in the range 68.14 – 72.32 Hz. However, we did not find the signature of HFQPO features in $\theta$, $\beta$, $\rho$, and $\chi$ class observations.
- Energy dependent PDS study indicates that the emergent photons in the energy range 6 – 25 keV seem to be responsible for generating the HFQPO features. Beyond this energy range, the HFQPO signature is not detected. We notice that percentage rms amplitude ($\text{rms\%}$) of HFQPOs increases ($1 – 8\%$) with energy up to $\sim 17$ keV and then decreases.
- Dynamical PDS of $\kappa$ and $\omega$ classes reveal that the ‘nondips’ (high count) features of the light curve are possibly linked with the generation of HFQPOs.
- The wide-band spectral modelling indicates that in presence of HFQPO, the thermal Comptonization components ($1.06 \times 10^{-8} \lesssim F_{\text{nth}}$ (erg cm$^{-2}$ s$^{-1}$) $\lesssim 4.46 \times 10^{-8}$) having $\Gamma_{\text{nth}}$ of $1.97 - 2.44$ dominate (up to $\sim 25$ keV) over the additional powerlaw component ($0.52 \times 10^{-8} \lesssim F_{\text{PL}}$ (erg cm$^{-2}$ s$^{-1}$) $\lesssim 1.37 \times 10^{-8}$) with $\Gamma_{\text{PL}} \sim 3$ (above $\sim 25$ keV).

With the above findings, we argue that the variability produced during the ‘softer’ classes of GRS 1915+105 is possibly due to the modulation of the Comptonizing corona that manifests the HFQPO features.

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DATA AVAILABILITY

Data used for this publication are currently available at the Astrobrowse (AstroSat archive) website (https://astrobrowse.issdc.gov.in/astro_archive/archive) of the Indian Space Science Data Center (ISSDC).

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Figure A1. Top: Power density spectrum (PDS) corresponding to one ‘non-dip’ (high counts) duration (red segment of the light curve) of ω class observation (Orbit 10411) in a wide frequency range of 0.01 – 500 Hz. Bottom: PDS corresponding to one ‘dip’ (low counts) duration (red segment of the light curve). Both PDS are obtained for the energy band of 3 – 60 keV with LAXPC10 and LAXPC20 combined observations. In each panel, zoomed view of the high frequency region of the PDS is depicted at the inset.

APPENDIX A: INTENSITY DEPENDENT POWER SPECTRA

The power spectra are generated separately considering both ‘non-dips’ (high counts) and ‘dips’ (low counts) duration of the light curve (Orbit 10411, ω class). In the top panel of Figure A1, we show the power spectrum corresponding to the ‘non-dip’ segment of the light curve shown at the bottom-left inset using red color. The HFQPO signature around 67.08 ± 1.05 Hz is distinctly visible (rms% = 2.38 ± 0.29) at the top-right inset. In the lower panel, we plot the power spectrum obtained for the ‘dip’ segment of the light curve which is indicated in red color at the bottom-left inset. The HFQPO feature is not seen (rms% = 0.67 ± 0.18) as shown at the top-right inset. We further confirm that similar findings are observed during κ class observation (Orbit 9895) as well, where rms% of the HFQPO feature for ‘non-dips’ and ‘dips’ duration are obtained as 2.35 ± 0.22 and 0.26 ± 0.10, respectively.