AstroSat view of GRS 1915+105 during the Soft State: Detection of HFQPOs and estimation of Mass and Spin

Sreehari H.1,2, Anuj Nandi1,†, Santabrata Das3,‡, V. K. Agrawal1, Samir Mandal4,§, M. C. Ramadevi1, Tilak Katoch5

1. Space Astronomy Group, ISITE Campus, U. R. Rao Satellite Centre, Outer Ring Road, Marathahalli, Bangalore, 560037, India.
2. Indian Institute of Astrophysics, Bangalore, 560004, India.
3. Indian Institute of Technology Guwahati, Guwahati, 781039, India.
4. Indian Institute of Space Science and Technology, Thiruvananthapuram, 695547, India.
5. DAA, Tata Institute of Fundamental Research, Colaba, Mumbai, 400005, India.

ABSTRACT

We report the results of AstroSat observations of GRS 1915+105 obtained using 100 ks guaranteed-time (GT) during the soft state. The Color-Color Diagram (CCD) indicates a variability class of δ with the detection of High Frequency QPO (HFQPO) in the power density spectra (PDS). The HFQPO is seen to vary in the frequency range of 67.96 – 70.62 Hz with percentage rms ~ 0.83 – 1.90 % and significance varying from 1.63 – 7.75. The energy dependent power spectra show that the HFQPO features are dominant only in 6 – 25 keV energy band. The broadband energy spectra (0.7 – 50 keV) of SXT (Soft X-ray Telescope) and LAXPC (Large Area X-ray Proportional Counter) modelled with nthComp and powerlaw imply that the source has an extended corona in addition to a compact ‘Comptonizing corona’ that produces high energy emission and exhibits HFQPOs. The broadband spectral modelling indicates that the source spectra are well described by thermal Comptonization with electron temperature (kT_e) of 2.07 – 2.43 keV and photon-index (Γ_{nth}) between 1.73 – 2.45 with an additional powerlaw component of photon-index (Γ_{PL}) between 2.94 – 3.28. The norm of nthComp component is high (~ 8) during the presence of strong HFQPO and low (~ 3) during the absence of HFQPO. Further, we model the energy spectra with the xirbb model to estimate the accretion rate, mass and spin of the source. Our findings indicate that the source accretes at super-Eddington rate of 1.17 – 1.31 Ṁ_{Edd}. Moreover, we find the mass and spin of the source as 12.44 – 13.09 M_⊙ and 0.990 – 0.997 with 90% confidence suggesting that GRS 1915+105 is a maximally rotating stellar mass X-ray binary black hole source.

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

1 INTRODUCTION

The astrophysical compact objects like white dwarf (WD), neutron star (NS) and black hole (BH) are often seen to exist along with its companion star. These binary sources are usually X-ray bright and referred as X-ray binaries (XRBs, Seward & Charles 2010). The high energy X-ray emission from black hole XRBs (BH-XRBs) is attributed to the accretion processes that are involved in the mass transfer from the companion star to the black hole. Detailed study of the X-ray emission from BH-XRBs is essential to understand the accretion dynamics as well as the effect of strong gravity in the vicinity of the black holes.

XRBs are known to exhibit excess power in certain frequencies called Quasi-periodic Oscillations (QPOs) which are evident from the power density spectrum (PDS) of these sources (van der Klis et al. 1985; Belloni et al. 2005; Remillard & McClintock 2006; Nandi et al. 2012; Belloni & Motta 2016; Sreehari et al. 2019, and references therein). The QPOs in BH-XRBs lie in a wide range of frequencies ~ 0.1 – 450 Hz and they have been classified into two general categories: (a) low-frequency QPOs (LFQPOs) in the range < 40 Hz and (b) high-frequency QPOs (HFQPOs) in the range ~ 40 – 450 Hz (Remillard & McClintock 2006). The origin of HFQPOs is of great interest as these oscillations are transient as well as subtle. Moreover, HFQPOs possibly are the manifestations of various relativistic effects in the orbits close to the black hole and it can be used as an important tool to probe general relativity in the strong gravity limit (Stella & Vietri 1998; Rebusco 2008; Merloni et al. 1999; Vincent et al. 2013; Stefanov 2014, and references therein). However, the conclusive consensus on the origin of HFQPOs is not reached yet.

Some BH-XRBs like GRS 1915+105 and IGR J17091–3624 also exhibit visually identifiable variabilities in their light curves. These variabilities are also associated with changes in the corresponding energy spectra and are categorized into several variability classes using Color-Color Diagrams (CCDs), light curve profiles (Belloni et al. 2013).
Energy spectral modelling of various BH-XRBs indicates that the emission from these sources are in general thermal as well as non-thermal in nature. The multi-temperature disc black body emission represents the Keplerian accretion disc (Shakura & Sunyaev 1973), whereas the high energy emission from the source is attributed to the inverse-Comptonisation (Sunyaev & Titarchuk 1980; Tanaka & Lewin 1995; Chakrabarti & Titarchuk 1995) of seed photons by the hot corona located at the inner part of the disc surrounding the black hole. Several other models along with the additional features like elemental abundance and relativistic-reflection (Garcia et al. 2014, and references therein) have been introduced to explain overall emission features. However, these models are phenomenological in nature as they do not directly provide the physical properties (namely, mass and spin) of the accreting BH source. Keeping this in mind, in this paper, we attempt to model the broadband energy spectra of GRS 1915+105 using the xspec model (Li et al. 2005) model. This model deals with rotating black hole and is used to estimate the mass and spin of the sources.

Since detection, the source GRS 1915+105 has remained active in X-rays (Castro-Tirado et al. 1992). However, the source underwent into the non-active phase in the recent past although some flickering activities in X-rays were occasionally seen. It is noteworthy that GRS 1915+105 exhibits fourteen different structured X-ray variability classes (Belloni et al. 2000; Klein-Wolt et al. 2002; Hannikainen et al. 2005). In a classical effort, Greiner et al. (2001) estimated the mass of the source to be $M_{BH} = 14 \pm 4 ~M_\odot$ considering the orbital period of $\sim 33.5$ days. Recently, Reid et al. (2014) estimated the black hole mass as $12.4^{+2.0}_{-1.8} ~M_\odot$ and the distance as $8.6^{+2.9}_{-1.6} ~kpc$ using parallax method. Zdziarski (2014) calculated the inclination of GRS 1915+105 to be $\sim 65^\circ$ based on kinematic constraints from the mass ejections. On the other hand, several papers have been made to estimate the spin of the source. The estimation of spin of GRS 1915+105 is reported to be $\alpha_k = 0.98_{-0.01}^{+0.01}$ (Blum et al. 2009; Miller et al. 2013).

GRS 1915+105 exhibited LFQPOs during the RXTE era (Ratti et al. 2012, and references therein). Besides this, Yadav et al. (2016) detected LFQPOs from GRS 1915+105 using AstroSat/LAXPC data. GRS 1915+105 has also exhibited 67 Hz and 40 Hz HFQPOs during the RXTE era (Morgan et al. 1997; Strohmayer 2001b). Belloni et al. (2006) reported the detection of a 170 Hz HFQPO in the C-State of GRS 1915+105. Moreover, Belloni & Altamirano (2013) detected HFQPOs with frequencies varying from 63 – 71 Hz using RXTE data. Méndez et al. (2013) showed a detailed comparison of the lag spectra for 35 Hz and 67 Hz HFQPOs of GRS 1915+105. Recently, Belloni et al. (2019) reported HFQPOs of frequencies between 67.4 – 72.3 Hz in the $\omega$ and $\mu$ variability classes of GRS 1915+105 from the AstroSat observations of July 2016. They also studied the phase lags and their relation with hardness ratio, although they ignored the dead-time effect while carrying out power spectral analysis and detection of QPOs. Moreover, they did not carry out the broadband spectral modelling to understand the emission processes. Meanwhile, several models were proposed to explain the origin of the HFQPOs observed in GRS 1915+105. Morgan et al. (1997) first proposed that the HFQPOs are associated with the Keplerian frequency at the inner-most stable circular orbit (ISCO). Cui et al. (1998) suggested that the HFQPOs possibly arise due to the relativistic Lense-Thirring precession around a highly spinning black hole. Nowak et al. (1997) proposed a model based on disko-seismic g-modes of oscillation for explaining the HFQPOs of this source. However, these models bear the limitations of revealing the inherent properties of the source under consideration including the relevant radiative emission processes.

Indeed, the broadband X-ray spectra of GRS 1915+105 was studied (Grove et al. 1998; Zdziarski et al. 2001) with combined observations from CGRO/OSSE and RXTE. The spectra from few keV to 10 MeV showed a single powerlaw with no high energy cut-off up to 500 keV, unlike other BH-XRBs. RXTE spectra of the source was modelled with just a thermal Comptonization component (Vilhu et al. 2001). BeppoSAX spectra of B and C states were found to have a definite high-energy cut-off, varying from 45 to 100 keV (Feroci et al. 1999).

Keeping all these in mind, in this paper, we use Guaranteed Time (GT) AstroSat data of June 2016 to identify the variability class and characterize the detected HFQPOs of GRS 1915+105. We carry out the energy dependent study of power spectral features to understand the HFQPO properties. Combining the data from both imaging (SXT) and the proportional counter units (LAXPC) on board AstroSat, we generate and fit the broadband energy spectra with phenomenological as well as physical models in order to get an insight of the disc emission processes. Moreover, we attempt to constrain the mass and spin of the source using broadband spectral modelling and finally compute the mass accretion rate as well.

We organize the paper as follows. In §2, we present the reduction and extraction procedures of AstroSat data. In §3, we discuss the methods of timing analysis and present the results. In §4, we carry out the spectral analysis and present the results of broadband spectral modelling with AstroSat data. In §5, we attempt to constrain the mass and spin of the black hole including the accretion rate. Finally, in §6, we discuss the results of our spectro-temporal studies of the BH source GRS 1915+105 and conclude.

2 OBSERVATION AND DATA REDUCTION

The source GRS 1915+105 was observed during the period of June 11, 2016 (MJD 57550) to June 15, 2016 (MJD 57554) using Guaranteed Time (GT) of AstroSat (Agrawal et al. 2017) for 100 ks (Observation ID: G05_189T01_9000000492). In this paper, we make use of the data from the imaging instrument SXT and the proportional counter LAXPC on board AstroSat. SXT (Singh et al. 2017) operates in the 0.3 – 8 keV energy range. LAXPC (Antia et al. 2017) consists of three proportional counters (LAXPC10, LAXPC20 and LAXPC30) operating in the energy range of 3 – 80 keV with a high temporal resolution of 10 $\mu$s (Yadav et al. 2016).

SXT data reduction is carried out using the software provided by SXT-POC1 at TIFR. Once the cleaned event files are generated using the pipeline, we use XSELECT tool to extract images, light curves and spectra. However, as the SXT time resolution is poor (0.28 s), we do not use it for temporal analysis. For spectral modelling, we use the redistribution matrix files (rmfs), ancillary response files (arfs) and the background spectral files provided by the SXT instrument team at TIFR2.

We use the software available at the AstroSat science support cell3 for the extraction of light curves of source as well as background from the LAXPC data. The response files and software for data extraction are provided by LAXPC instrument team of TIFR4. Further,
we follow the procedures as described in Agrawal et al. (2018) and Sreehari et al. (2019) to extract energy spectra from both SXT and LAXPC observations. Once the light curves and energy spectra are generated, we carry out temporal and spectral modelling as detailed in §3 and §4.

3 TIMING ANALYSIS AND RESULTS

We generate the light curves by combining data from LAXPC10 and LAXPC20 with 1 s binning for generating CCDs. CCDs are used to understand the hardness ratio variation and variability class of the source. Following this, we generate 1 ms binned light curves for generating the power spectra. The modelling of power spectra and the obtained results are presented in §3.2.

3.1 Color-Color Diagram

As mentioned before, we use light curves with 1 s binning for generating CCDs. The CCD is the variation of $HR_1 = B/A$ versus $HR_2 = C/A$, where $A$, $B$ and $C$ are the count rates in $3 – 6$ keV, $6 – 15$ keV and $15 – 60$ keV energy bands, respectively. The background subtracted and dead-time corrected (see equation 1) light curves in the energy band $3 – 60$ keV for the LAXPC observations on MJD 57551.04 (Orbit 3819) and MJD 57552.56 (Orbit 3841) are shown in Figure 1. The background count rate is in the range of 100 to 140 counts/sec. The CCDs are provided as inset in each panel which indicate that the maximum values of $HR_1$ and $HR_2$ for both the observations are less than 1.1 and 0.12, respectively. Comparing the CCDs and X-ray variability with RXTE observations (Belloni et al. 2000), we classify that the source is in its δ class during our observational campaign. However, both $HR_1$ and $HR_2$ values are seen to decrease as the source count rate increases whereas the reverse trend is observed towards the end (see Fig. 4 and Table 1). These findings indicate the signature of soft state (see Table 2 for spectral parameters). In addition, we do not find HFQPOs in those observations where mean values of $HR_1 \leq 0.76$ and $HR_2 \leq 0.04$ (see Table 1 and §3.2). In all the remaining observations, we detect HFQPOs.

3.2 Temporal Properties

We generate power spectrum for each LAXPC observation considering a Nyquist frequency of 500 Hz in order to search for the presence of HFQPOs. We use intervals of 32768 bins and compute the power spectrum for each interval, which is then averaged to obtain the final power spectrum. A geometric binning factor of 1.03 is used for representing the power spectrum in frequency space. After generating the Leahy power spectrum (Leahy et al. 1983), we carry out dead-time ($\tau_d$) corrected Poisson noise subtraction following Agrawal et al. (2018); Sreehari et al. (2019). Dead-time corresponds to the time interval between the successive photon detection by the detector. This effectively affects the Poisson noise level yielding the reduction of actual rms in the power spectrum. LAXPC has a dead-time of 42.5 $\mu$s (Yadav et al. 2016). Following van der Klis (1988), we calculate the incident count rate ($r_{in}$) as

$$r_{in} = \frac{r_{det}}{1 - \tau_d \frac{r_{det}}{N}},$$

(1)

where $r_{det}$ refers to the detected count rate and $N$ is the number of proportional counter units used.

Thereafter, following Zhang et al. (1995, and references therein), we compute the dead-time affected Poisson noise power ($P_n$). Besides affecting the noise level, dead-time also modulates the source rms. So, after subtracting $P_n$ level from the power spectrum, we correct for the dead-time effects on rms amplitude by scaling it using the relation given by,

$$rms_{in} = rms_{det} \left(1 + \tau_d r_{in}/N\right) = \frac{rms_{det}}{1 - \tau_d r_{det}/N},$$

(2)

where $rms_{in}$ is the dead-time corrected rms and $rms_{det}$ is the rms detected by the instrument (see Bachetti et al. 2015; Sreehari et al. 2019, for details).

We model the power density spectrum (PDS) using a combination of constant and Lorentzian features, and illustrate it in frequency (Hz) versus $rms^2$/Hz plane. The Lorentzian has three parameters namely centroid frequency ($\nu$), full width at half maximum (FWHM) and normalization (norm). Here, a Lorentzian feature is adopted to define QPO, based on the values of its Quality factor (Q = $\nu$/FWHM), significance and rms (see Sreehari et al. 2019, and references therein). The QPO rms is computed by finding the square root of the definite integral of the Lorentzian representing the QPO in Frequency-power space. The QPO significance is computed as the ratio of Lorentzian normalization to its negative error (see Alam et al. 2014; Sreehari et al. 2019, and references therein).

Figure 2 presents the PDS from combined LAXPC10 and LAXPC20 data corresponding to the Orbit 3860 in the frequency range from 0.06 Hz to 500 Hz. The PDS is modelled with multiple Lorentzians and a constant that yields $\chi^2_{red} = 135.2/208 = 0.65$. Since the detected HFQPOs are seen to lie within a narrow range of frequencies, for the purpose of representation, we model the power spectra in the frequency range $20 – 200$ Hz for all the observations.

Following the above consideration, we fit the PDS in the said fre-
The energy dependent PDS for Morgan et al. (2020) shows the correlation of QPO frequency with count rate (top panel), HFQPO frequency (middle panel) and QPO rms with count rate. It is evident that as the source count rate increases and HR value decreases (see Table 1), the HFQPO rms reduces and eventually disappears. The vertical green bars indicate the observations during Orbits 3819, 3841 and 3860 that we present in Figure 3. From Table 1, we find that the percentage rms of HFQPO lies in the range of 0.83% to 1.90%. The dead-time correction factor for rms is obtained in the range 1.17 to 1.21. The HFQPO is weak or below the significance level of detection, when the source count rate peaks.

The $\chi^2_{\text{red}}$ values for power spectral modelling are provided in Table 1. Modelling the PDS (Orbit 3860) in the frequency range $20-200\text{ Hz}$ with only a constant yields a $\chi^2_{\text{red}}$ of 97.68/78 = 1.25. However, the presence of excess power above the constant level around 69 Hz indicates the presence of a QPO. This feature is further modelled with a Lorentzian apart from the constant resulting in an overall $\chi^2_{\text{red}}$ of 45/75 = 0.6. The decrease of $\chi^2_{\text{red}}$ from 1.25 to 0.6 suggests that HFQPO feature is significant and requires modelling. Moreover, we detect the Lorentzian feature at 69 Hz in several observations which indicates that it is not a random increase in amplitude and hence we argue that it is not a case of over-fitting.

Since HFQPOs are detected in several observations, we intend to carry out energy dependent behaviour of these oscillations. For this purpose, we generate PDS from light curves in the energy range of $3-6\text{ keV}$, $6-25\text{ keV}$ and $25-60\text{ keV}$ and model them in the frequency range of $20-200\text{ Hz}$. Figure 5 shows the energy dependent PDS for MJD 57551.04 (Orbit 3819). It is evident that the HFQPO is present only in the $6-25\text{ keV}$ energy band (middle panel) and not in the lower ($3-6\text{ keV}$) and higher ($25-60\text{ keV}$) energy bands. We find that the upper limit of the significance in the energy range $3-6\text{ keV}$ and $25-60\text{ keV}$ are 1.69 and 0.44, respectively. The strong HFQPO feature (Q-factor $\sim 46$, significance of 6.45 $\sigma$ and rms of 2.15 $\pm$ 0.23$\%$) in the $6-25\text{ keV}$ energy band is found at $68.75^{+0.12}_{-0.12}\text{ Hz}$. All LAXPC observations of GRS 1915+105 have similar power spectral features (non-detection of HFQPO signals) in the $3-6\text{ keV}$ and $25-60\text{ keV}$ bands. However, the HFQPO strength (rms) and significance varies over the observations as can be seen from Table 1. The absence of HFQPO feature in $3-6\text{ keV}$ energy band indicates that the QPOs are

Figure 2. Power spectrum for the observation of Orbit 3860 from combined LAXPC10 and LAXPC20 data in the broad frequency range from 0.06 – 500 Hz. PDS is modelled with multiple Lorentzians and a constant component.

Figure 3. Combined power spectra of LAXPC10 and LAXPC20 in 3 – 25 keV energy band, for three orbits of AstroSat observations. HFQPOs are detected during Orbits 3819 and 3860, whereas no such detection is seen during Orbit 3841 (middle panel). See text for details.
Table 1. Details of HFQPO parameters from LAXPC observations of GRS 1915+105 in 3−25 keV energy band. These results are obtained from the observational data of LAXPC10 and LAXPC20 during \( \delta \) class variability of the source. Errors corresponding to 68% confidence are quoted for each parameter. See text for details.

| MJD    | Orbit | Exposure | \( r_{\text{det}} \) (cts/s) | \( r_{\text{in}} \) (cts/s) | QPO (Hz) | FWHM (Hz) | Significance (\( \sigma \)) | rms (%) | HR1 | HR2 | \( \chi^2/dof \) |
|--------|-------|----------|----------------|----------------|----------|-----------|----------------|---------|-----|-----|----------------|
| 57550.97 | 3818  | 1982     | 6835            | 7996          | 68.02±0.20 | 2.82±0.54 | 7.75          | 1.90 ± 0.23 | 0.92 | 0.08 | 48/74 |
| 57551.04 | 3819  | 1590     | 6919            | 8112          | 69.18±0.14 | 1.49 fixed | 6.94          | 1.56 ± 0.11 | 0.91 | 0.08 | 43/75 |
| 57551.12 | 3820  | 1030     | 6954            | 8159          | 68.26±0.17 | 2.33±0.11 | 3.45          | 2.31 ± 0.04 | 0.91 | 0.08 | 34/75 |
| 57551.19 | 3821  | 0791     | 7214            | 8520          | 69.46±0.12 | 2.17±0.08 | 4.17          | 1.18 ± 0.17 | 0.88 | 0.07 | 50/75 |
| 57551.25 | 3822  | 1215     | 7223            | 8533          | 69.37±0.09 | 1.72±0.04 | 3.19          | 0.98 ± 0.20 | 0.86 | 0.06 | 32/75 |
| 57551.33 | 3823  | 1638     | 7095            | 8352          | 69.64±0.06 | 1.72 fixed | 2.06          | 0.89 ± 0.21 | 0.85 | 0.06 | 43/75 |
| 57551.40 | 3824  | 2063     | 7095            | 8355          | 69.78±0.26 | 1.67±0.50 | 2.16          | 1.00 ± 0.27 | 0.83 | 0.06 | 32/75 |
| 57551.47 | 3825  | 2516     | 7162            | 8448          | 69.63±0.24 | 1.84±0.41 | 2.94          | 0.86 ± 0.20 | 0.84 | 0.06 | 39/75 |
| 57551.53 | 3826  | 2941     | 7153            | 8435          | 69.37±0.32 | 2.75±0.10 | 3.86          | 1.12 ± 0.25 | 0.84 | 0.06 | 46/75 |
| 57551.61 | 3827  | 3364     | 7224            | 8534          | 70.62±0.93 | 2.31±1.18 | 4.26          | 0.85 ± 0.23 | 0.83 | 0.06 | 50/75 |
| 57551.84 | 3830  | 2953     | 7405            | 8787          | 70.38±0.64 | 2.04±0.94 | 3.84          | 0.83 ± 0.21 | 0.82 | 0.05 | 34/75 |
| 57552.25 | 3838  | 1116     | 7586            | 9045          | 69.83±0.27 | 1.88 fixed | 1.63          | 0.91 ± 0.28 | 0.77 | 0.04 | 42/75 |
| 57552.41 | 3839  | 2180     | 7793            | 9339          | 69.46±0.34 | 1.46 fixed | 2.49          | 0.83 ± 0.16 | 0.77 | 0.04 | 26/75 |
| 57552.47 | 3840  | 2603     | 8089            | 9768          | 67.96±1.99 | 5.37±2.27 | 2.95          | 1.01 ± 0.26 | 0.76 | 0.04 | 47/77 |
| 57552.56 | 3841  | 3027     | 8155            | 9865          | -1.14      | -         | -            | -         | -    | -   | 0.75  |
| 57552.63 | 3843  | 2154     | 8076            | 9749          | -         | -         | -            | -         | -    | -   | 0.75  |
| 57552.86 | 3845  | 2402     | 7867            | 9446          | -         | -         | -            | -         | -    | -   | 0.76  |
| 57553.00 | 3848  | 1939     | 7738            | 9260          | 69.96±1.08 | 2.57±2.32 | 2.49          | 0.84 ± 0.35 | 0.77 | 0.04 | 36/75 |
| 57553.88 | 3860  | 2381     | 6813            | 7966          | 69.22±0.17 | 2.53±1.18 | 3.74          | 1.42 ± 0.44 | 0.88 | 0.07 | 45/75 |
| 57553.95 | 3862  | 2042     | 6918            | 8110          | 68.98±0.39 | 3.78±1.22 | 5.36          | 1.45 ± 0.25 | 0.88 | 0.07 | 34/75 |
| 57554.02 | 3863  | 1755     | 6965            | 8176          | 69.03±0.29 | 3.35±1.04 | 5.23          | 1.50 ± 0.29 | 0.88 | 0.07 | 38/75 |
| 57554.09 | 3864  | 1170     | 6888            | 8070          | 69.20±0.12 | 2.00±0.27 | 7.43          | 1.49 ± 0.14 | 0.89 | 0.07 | 41/75 |
| 57554.16 | 3865  | 1156     | 6638            | 7728          | 69.01±0.24 | 2.55±0.87 | 4.61          | 1.63 ± 0.39 | 0.90 | 0.08 | 36/75 |

Figure 4. LHS: Top panel depicts the dead-time corrected source count rate for each observation. The red asterisks indicate observations where HFQPO is absent. The middle panel shows the frequency of all detected HFQPOs and the ones above 3 \( \sigma \) significance are presented in blue colour. The bottom panel shows the corresponding HFQPO rms. The vertical green shades represent the observations for which the power spectra are presented in Figure 3. RHS: The variation of QPO frequency with count rate is shown in the top panel and the dependence of QPO rms on count rate is presented in the bottom panel.

likely to be the result of an oscillating corona located in the vicinity of the black hole and it emits in 6−25 keV energy band. In order to have better clarity on the energy dependence of HFQPOs and understand the emission processes, we carry out the broadband energy spectral modelling of AstroSat view of GRS 1915+105 and present the results in §4.

4 SPECTRAL ANALYSIS AND RESULTS

To carry out the spectral analysis, we use simultaneous data from both SXT and LAXPC. The latest calibration files are provided by
Table 2. Broadband spectral modelling parameters from the model $T_{\text{bb}}(n\text{thComp} + \text{powerlaw})$. Observations in which HFQPOs are absent are tabulated separately. Errors are computed with 90\% confidence.

| MJD (Orbit) | $kT_{\text{bb}}$ (keV) | $kT_{e}$ (keV) | $\Gamma_{\text{nth}}$ | norm$_{\text{nth}}$ | $\Gamma_{\text{PL}}$ | norm$_{\text{PL}}$ | Flux (ergs/cm$^2$/s) | $\chi^2$/dof |
|-------------|----------------|--------------|----------------|----------------|----------------|----------------|-----------------|-------------|
| Detection of HFQPOs |
| 57551.33 (3823) | 0.3 | 2.25 ± 0.08 | 1.79 ± 0.07 | 8.1 | 2.94 ± 0.12 | 15.8 | 3.09 × 10$^{-8}$ | 440/415 = 1.06 |
| 57551.53 (3826) | 0.19 ± 0.02 | 2.32 ± 0.03 | 1.76 ± 0.01 | 8.6 | 3.04 ± 0.01 | 17.6 | 3.11 × 10$^{-8}$ | 655/551 = 1.18 |
| 57551.84 (3830) | 0.1 | 2.23 ± 0.02 | 1.73 ± 0.03 | 8.9 | 3.04 ± 0.04 | 15.5 | 3.22 × 10$^{-8}$ | 737/628 = 1.17 |
| 57552.41 (3839)$^\dagger$ | 0.1 | 2.07 ± 0.18 | 2.24 ± 0.86 | 3.9 | 3.28 ± 0.03 | 34.9 | 3.34 × 10$^{-8}$ | 441/339 = 1.30 |
| 57553.88 (3860) | 0.1 | 2.43 ± 0.13 | 1.74 ± 0.06 | 7.0 | 3.09 ± 0.04 | 25.5 | 3.07 × 10$^{-8}$ | 615/547 = 1.12 |
| Non-detection of HFQPOs |
| 57552.56 (3841) | 0.1 | 2.09 ± 0.15 | 2.45 ± 0.84 | 3.01 | 3.28 ± 0.02 | 30 | 3.55 × 10$^{-8}$ | 729/636 = 1.14 |

$^\dagger$: Weakest HFQPO

Figure 5. The energy dependent power spectra for the observation corresponding to Orbit 3819 are shown. Top panel indicates that there is no signature of QPO in the 3 – 6 keV energy band. The middle panel corresponding to 6 – 25 keV energy band shows significant detection of HFQPO. Bottom panel is for 25 – 60 keV energy band where power spectrum is noise dominated without any detection of QPO. See text for details.

AstroSat mission team$^5$. A systematic of 2\% is added per spectral bin as suggested by Antia et al. (2017); Leahy & Chen (2019).

SXT spectra are extracted in the 0.7 – 7 keV band, whereas deadtime corrected LAXPC spectra (Antia et al. 2017) are extracted in the energy range of 3 – 50 keV (see Agrawal et al. 2018; Sreehari et al. 2019, for details). As there are only a few good quality data available from SXT in the database$^6$, we are able to generate broadband spectra only for those observations. Modelling of the SXT spectra indicates an nH column density (in 10$^{22}$ atoms/cm$^2$) in the range 5.93 ± 1.01 to 6.07 ± 1.19. We model the energy spectra with fixed nH of 6 × 10$^{22}$ atoms/cm$^2$ and the obtained spectral parameters are quoted in Table 2. The change in parameters due to the variation of nH is within the error bars of the values obtained by freezing nH at 6 × 10$^{22}$ atoms/cm$^2$. Gain correction is applied using gain fit routine of XSPEC on all the SXT spectra to account for the instrumental features peaks at 1.8 and 2.2 keV. Initially, we model the broadband spectra with phenomenological model combination $T_{\text{bb}}(\text{diskbb} + \text{powerlaw} \times \text{smedge})$ that yields a disc temperature of $2.57 \pm 0.05$ keV, photon index of $3.11 \pm 0.06$ for the observation on MJD 57551.33 (Orbit 3823) with a $\chi^2$/dof = 438/418 = 1.04. Using cflux model, we estimate the disc contribution which is found to be 69.7\% of the total flux. This indicates that the source is in thermally dominated soft state. This also corroborates the CCDs representing the light curve (i.e., $\delta$ class) as a softer state of GRS 1915+105.

In order to understand the physical processes leading to the emission from the source, we fit the broadband energy spectrum of Orbit 3823 with the thermal Comptonization model ($n\text{thComp} + \text{powerlaw}$). The fitted parameters due to the variation of nH is within the error bars of the values obtained by freezing nH at 6 × 10$^{22}$ atoms/cm$^2$. Gain correction is applied using gain fit routine of XSPEC on all the SXT spectra to account for the instrumental features peaks at 1.8 and 2.2 keV. Initially, we model the broadband spectra with phenomenological model combination $T_{\text{bb}}(\text{diskbb} + \text{powerlaw} \times \text{smedge})$ that yields a disc temperature of $2.57 \pm 0.05$ keV, photon index of $3.11 \pm 0.06$ for the observation on MJD 57551.33 (Orbit 3823) with a $\chi^2$/dof = 438/418 = 1.04. Using cflux model, we estimate the disc contribution which is found to be 69.7\% of the total flux. This indicates that the source is in thermally dominated soft state. This also corroborates the CCDs representing the light curve (i.e., $\delta$ class) as a softer state of GRS 1915+105.

In the left panel of Figure 6, we depict the unfolded spectrum of an observation (MJD 57552.56, Orbit 3841) for which HFQPO feature is not seen in the PDS (middle panel of Figure 3). The fitted parameters are obtained as $kT_e \sim 2.09$ keV and $\Gamma_{\text{nth}} = 2.45 \pm 0.84$, respectively. The powerlaw index in this case is obtained as $\Gamma_{\text{PL}} \sim 3.28$. Further, we model the broadband energy spectrum for the observation on MJD 57553.88 (Orbit 3860) which shows a significant (3.74σ) detection of HFQPO in the PDS (bottom panel of Figure 3). In the right panel of Figure 6, we present the unfolded spectrum modelled with $T_{\text{bb}}(n\text{thComp} \times \text{smedge} + \text{powerlaw})$. The $n\text{thComp}$ component yields $\Gamma_{\text{nth}} = 1.74 \pm 0.06$ and $kT_e \sim 2.43$ keV. The powerlaw component is seen to be strong with a steep photon index of

---

$^5$ http://astrosat-ssc.iucaa.in/?q=laxpcData

$^6$ https://astrobrowse.insdc.gov.in/astro_archive/archive/Home.jsp

MNRA 000, 1–11 (2020)
5 ESTIMATION OF MASS, SPIN AND ACCRETION RATE

In this section, we present the results of broadband spectral modelling (Orbits 3826, 3830, 3841, 3860) to constrain the mass and spin of the source. While doing this, we use the kerrbb model (Li et al. 2005) along with the simpl model (Steiner et al. 2009) of XSPEC (Arnaud 1996) to fit the spectra. The kerrbb model represents a thin, general relativistic multi temperature blackbody disc around a rotating black hole whereas the simpl is a Comptonization model in which a fraction of the seed photons is scattered into a power-law distribution. Following the spectral analysis method discussed in the previous section, we model the broadband observations with a combination of models as Tbabs(simpl * kerrbb * smege) constant that results into an acceptable fit with $\chi^2_{\text{red}} \approx 1$ (see Table 3). The model fitted energy spectra for Orbits 3841 and 3860 are shown in Figure 7. We find that the model fitted parameters of black hole mass $M_{\text{BH}} = 12.92 \pm 0.17 M_\odot$, accretion rate $\dot{M} \approx 7.89 \times 10^{18} \text{ g/s}$ and spin $a_k = 0.991 \pm 0.001$ for the observation of Orbit 3841. Similarly, we obtain $M_{\text{BH}} = 12.85 \pm 0.24 M_\odot$, $\dot{M} \approx 7.05 \times 10^{18} \text{ g/s}$ and $a_k = 0.995 \pm 0.001$ for the observation of Orbit 3860. Interestingly, the accretion rate corresponding to non-detection of HFQPO (Orbit 3841) is higher than that in observations where HFQPO is detected. It is to be noted that two additional gaussians are used at 1.8 keV and 2.2 keV to account for the instrumental peaks at these energies, instead of using gain fit.

In Table 3, we present the spectral fit parameters for all broadband observations, where column 1 – 8 represent observation date with Orbit number, photon index ($\Gamma$), scattered fraction ($F_{\text{sca}}$), accretion rate ($\dot{M}$), black hole mass ($M_{\text{BH}}$) in solar mass unit ($M_\odot$), spin ($a_k$), smege energy ($E_{\text{smege}}$) and $\chi^2_{\text{red}}$ ($\chi^2$/dof), respectively. The index ($\Gamma$) varies from 3.08 – 4.80, whereas scattered fraction of seed photons is minimum ($F_{\text{sca}} \sim 0.05$) when the HFQPO is absent and maximum ($F_{\text{sca}} \sim 0.55$) when the HFQPO signal is most significant. Adopting the source mass as obtained from the spectral fitting (see Table 3), and considering the source distance as $\approx$ 8.6 kpc (Reid et al. 2014), we find that GRS 1915+105 accretes at super-Eddington rate of $1.17 - 1.31 \dot{M}_{\text{Edd}}$ during the GT phase AstroSat observations under consideration.

Further, we examine the dependence of accretion rate and spin on the mass of the source. Figure 8 (left) shows the confidence contours obtained for mass of the black hole and the accretion rate for the Orbit 3860. Similarly, in Figure 8 (right), we depict the confidence contours of mass and spin of the source for the same observation. It indicates that the black hole mass ($M_{\text{BH}}$) lies in the range $12.85 \pm 0.24 M_\odot$ and spin ($a_k$) lies in the range $0.993 - 0.996$. The red, green and blue curves represent contours of 68%, 90% and 99% confidence, respectively.

Since our goal is to estimate black hole parameters, we have also attempted with the kerrd model (Ebisawa et al. 2003). The spectral fits yields a mass range of $11.66 - 12.69 M_\odot$ and accretion rate of $7.05$ to $7.75 \times 10^{18} \text{ g/s}$. The mass estimate from kerrd model is marginally lower than the estimates from kerrbb, while the accretion rate estimate from both models are consistent. It may be noted that kerrd model assumes fixed spin value as 0.998, whereas the spin is treated as free parameter in kerrbb model, besides accretion rate and mass. Because of that we prefer kerrbb model over kerrd model and quote the parameters from kerrbb model as our final result.

6 DISCUSSION AND CONCLUSION

In this paper, we study the spectro-temporal properties of GRS 1915+105 using GT phase observations of the AstroSat data. The CCDs indicate that the source exhibits $\delta$ class variability (Belloni et al. 2000) with small hardness ratios (HR1 < 1.1, HR2 < 0.12). During our observational campaign, GRS 1915+105 was in the soft state and significant variations in the count rate (7728 - 9865...
Figure 7. The best fit unfolded energy spectra (0.7 – 50 keV) of GRS 1915+105 observed on MJD 57552.56 (Orbit 3841) and MJD 57553.88 (Orbit 3860) with AstroSat. The spectra are modelled with Tbabs(simpl × kerrbb × smedge)constant. The bottom panel of each figure shows residuals in units of $\sigma$.

Table 3. Broadband spectral modelling parameters from Tbabs(simpl × kerrbb × smedge)constant. Errors are computed with 90% confidence.

| MJD (Orbit) | $\Gamma$ | Frac. Scattered ($F_{\text{sc}}$) | $M$ ($10^{18}$ g/s) | $\alpha_k$ | $E_{\text{smedge}}$ (keV) | $\chi^2$/dof |
|-------------|--------|-----------------|-----------------|----------|-----------------|-------------|
| 57551.53 (3826) | 3.92 ± 0.01 | 0.13 ± 0.01 | 7.65 ± 0.11 | 0.996 ± 0.001 | 6.41 ± 0.42 | (657/564=1.16) |
| 57551.84 (3830) | 3.83 ± 0.01 | 0.09 ± 0.01 | 7.73 ± 0.07 | 0.996 ± 0.001 | 6.44 ± 0.40 | (733/629=1.16) |
| 57552.56 (3841) | 3.09 ± 0.01 | 0.05 ± 0.01 | 7.89 ± 0.07 | 0.991 ± 0.001 | 7.88 ± 0.86 | (717/639=1.12) |
| 57553.88 (3860) | 4.80 ± 0.01 | 0.55 ± 0.01 | 7.05 ± 0.10 | 0.995 ± 0.001 | 5.08 ± 0.70 | (662/559=1.18) |

Figure 8. The confidence contours of two parameters namely accretion rate ($M$) and mass of the black hole ($M_{\text{BH}}$) for the observation during Orbit 3860 is shown on the left panel. On the right panel, we show the confidence contours for the mass ($M_{\text{BH}}$) and spin ($a_k$). The red, green and blue contours show delta fit statistic of 2.30 (68%), 4.61 (90%) and 9.21 (99%), respectively.
of the energy spectra (Radhika et al. 2016). During our observations, the hardness ratios of the source (see Table 1) also indicate that the source becomes relatively softer when the HFQPOs are absent. From the energy dependent power spectra, it is evident that the HFQPOs are present only in the 6–25 keV (see Figure 5) but not in the 3–6 keV and 25–60 keV energy bands. Following Belloni et al. (2001), we calculate the upper limit of the QPO significance in 3–6 keV as 1.69 and in 25–60 keV as 0.44. The rms amplitude of the HFQPOs in our observations is found to vary within 0.83–1.90 % and the frequencies of these HFQPOs lie in the range of 67.96–70.62 Hz. Belloni & Altamirano (2013) also reported HFQPO of frequency 67.4 ± 2.0 Hz, using RXTE data of the same source. Recently, Belloni et al. (2019) reported a variable HFQPO in the range between 67.4–72.3 Hz, where higher phase lags are observed in harder regions.

HFQPOs are detected in other BH-XRB sources, such as GRO J1655–40, XTE J1550–564 and H 1743–322 (Remillard & McClintock 2006). Phase-lag studies of the 67 Hz QPO in GRS 1915+105 (Cui 1999; Méndez et al. 2013) indicates that the hard photons lag the soft photons. This is consistent with our scenario where soft radiation from the accretion disc is inverse-Comptonized within a compact corona around the black hole. A 66 Hz HFQPO was detected in the black hole binary source IGR J17091–3624 by Altamirano & Belloni (2012). They have discussed the possibility that this HFQPO (≈ 67 Hz) detected in both GRS 1915+105 and IGR J17091–3624 is linked to the physical processes that produce low-frequency structured variability exhibited by these two sources.

Several models have been proposed to explain the origin of these QPOs. The relativistic precession model by Stella & Vietri (1998) considers that HFQPOs are associated to the orbital frequency as well as the nodal and the periastron precession frequencies. Rezzolla et al. (2003) proposed a model where HFQPOs are attributed to the pressure mode oscillations of an accretion torus orbiting the black hole. Recently, in a theoretical attempt, Dihingia et al. (2019) showed that shock induced accretion solutions around a rapidly rotating stellar mass black hole are viable to account for such an HFQPO phenomenon. Interestingly, Varniere et al. (2020) explored the possibility of HFQPO generation resulting from vortices formed due to Rossby wave instability (RWI) at the inner edge of the accretion disc. As the centroid frequencies of the HFQPOs do not vary beyond a few percent, we conjecture that it perhaps originated from the vicinity of the source and therefore carries the imprint of the effect of strong gravity, namely the mass and spin of the black hole.

In order to explain the radiative properties of the accretion flow around the source, we carry out the broadband energy spectral modelling using combined SXT and LAXPC data in the 0.7–50 keV energy
range. Modelling of spectra with a multi-temperature disc blackbody (diskbb) along with a powerlaw indicates high disc contribution (51 − 69.7%) to the total emitted radiative flux. We find relatively steeper photon index (∼3) and high disc temperature (∼2.5 keV) that eventually indicate the source belongs to the soft state.

Next, to examine the physical processes and the spectral parameters, we model the spectra using nthComp and powerlaw. The photon index (Γth) is seen to be small and remain nearly constant (Γth ∼ 1.7) during the HFQPO observations whereas Γth becomes large (Γth ∼ 2.45) when HFQPO is not detected (see Table 2). It may be noted that the seed photon temperature does not change appreciably (kTeb ∼ 0.1 − 0.3 keV) in these observations. We find electron temperature kTe in the range 2.07 − 2.43 keV (i.e., an exponential roll over energy ∼7.3 keV) and 1.73 < Γth < 2.45 for broadband spectra. In addition, an extended corona seems to be present as well, because an additional powerlaw component with higher photon index (ΓPL ∼ 3) is required to model the higher energy part of the spectrum (above 25 keV). Indeed, it may be plausible that the accretion flow harbours a cool and compact central corona that not only exhibits HFQPOs, but also emits high energy photons till ∼25 keV (see Figures 5 and 6). Also, surrounding the inner compact corona, a diffuse but relatively hot extended ‘Compton’ corona may be present which is likely to produce hard X-ray photons up to ∼50 keV. The existence of such an extended coronal structure around GRS 1915+105 would be possible as the source may not swallow all the matter accreted at super-Eddington rate (Done et al. 2004; Punsly & Rodríguez 2013).

The broadband spectra of observations with relatively higher rms of HFQPOs indicate a weaker extended corona (15.5 < normPL < 25.5) in comparison to those spectral observations where HFQPOs are absent (normPL ∼ 30). Besides this, we notice from Table 2 that the observations with significant HFQPOs have a stronger (normnth ∼ 8.0) and harder (Γth ∼ 1.73 − 1.79) ‘compact corona’ than the observation (Orbit 3841) without an HFQPO. This is an indication that the origin of the HFQPO is due to the oscillations of the ‘compact corona’ that is represented by the nthComp model. The fact that the powerlaw is strong (normPL ∼ 34.9) and nthComp is comparatively weak (normnth ∼ 3.9) for Orbit 3839 which has the HFQPO with lowest rms (0.83%) also supports our argument that the HFQPO is the result of a compact oscillating corona represented by the nthComp. Dihingia et al. (2019) indicated that HFQPOs at ∼67 Hz in GRS 1915+105 possibly originated due to the quasi-periodic modulation of a very compact inner region of the disc. It is noteworthy that the energy spectra of the source GRO J1655−40 corresponding to the HFQPOs of frequency 300 Hz (Remillard et al. 1999) and 450 Hz (Strohmayer 2001a) possess strong Comptonized contribution extending beyond 100 keV (Aktar et al. 2018). Meanwhile, Remillard et al. (2002) also pointed out that the HFQPOs perhaps originated because of the modulation of the compact Compton corona. Overall, we conjecture that the observed HFQPOs are the manifestation of the oscillations of a ‘hot’ and compact post-shock corona (Aktar et al. 2018; Dihingia et al. 2019).

In addition, we model the broadband energy spectra of all the observations using kerrbb model and estimate mass and spin of the source along with the flow accretion rate. Our findings reveal that the mass of the source (Mbh) lies in the range 12.44 − 13.09 M⊙ (see Table 3). This estimate is consistent and better constrained compared to the earlier estimates (Greiner et al. 2001; Reid et al. 2014). We find the spin of the source (aK) in the range 0.990 − 0.997 with 90% confidence whereas the previous estimate of spin value was reported as aK = 0.98±0.01 (Shahée et al. 2006; Blum et al. 2009; Miller et al. 2013). The fraction of Compton up-scattering (F sca) is found to be as high as ∼0.55 when a strong HFQPO is detected (Orbit 3860), whereas F sca is low (0.05) during the absence of HFQPO (Orbit 3841). The index of the simplify convolution model is the lowest (∼3.09) during the non-detection of HFQPO and highest (4.80) during the detection of a strong HFQPO (Orbit 3860). Our results also indicate that the source accretes at super-Eddington rate in the range 1.17−1.31 Medd during GT phase of AstroSat observations.

In order to improve the error estimation, we have carried out Markov Chain Monte Carlo (MCMC) simulations. We use the Goodman-Weare chain algorithm (Goodman & Weare 2010) in xspec (Arnaud 1996) with walker parameter set to 32. The chain length is taken as 15,000 and burn length is fixed to 5,000. However, there is no significant improvement in the error estimations. We also cross-check our error estimations using the MCMC hammer algorithm (emcee7) based on Foreman-Mackey et al. (2013). These results are limited by the unavailability of an analytical approximation for kerrbb model. The results from emcee estimation of spin and mass parameters for Orbit 3860 are shown in Figure 9. The estimate of mass of the black hole for this observation is 12.47 − 13.23 M⊙ and the spin is estimated to be 0.993 − 0.996 at 90% confidence level. It is to be noted that the errors quoted in this paper are purely statistical and systematics are not accounted for. The top and right panels show mass and spin distribution respectively, whereas the corner panel shows the confidence contours considering both mass and spin. The contour plot from MCMC simulations and the contour generated from xspec (see right panel of Figure 8) using steppar functions are consistent.

Finally, we emphasize that GRS 1915+105 is a maximally rotating, comparatively higher mass X-ray binary source accreting at super-Eddington rate and exhibiting HFQPO features. In addition, we point out that for the first time to the best of our knowledge, the mass, spin, accretion rate and HFQPOs of GRS 1915+105 are concurrently examined and reported using AstroSat observations.

ACKNOWLEDGMENTS

We thank the anonymous reviewer for his/her suggestions and comments that helped us to improve the quality of this manuscript. AN, VKA, MCR thank DD, PDMSA and Director, URSC for encouragement and continuous support to carry out this research. SH thanks Department of Physics, IIT Guwahati for providing the facilities to complete part of this work. This research made use of the data obtained through GT phase of AstroSat observations. The authors thank the SXT-POC of TIFR and the LAXPC team of IUCAA and TIFR for providing the data extraction software for the respective instruments.

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).

REFERENCES

Agrawal P. C., et al., 2017, Journal of Astrophysics and Astronomy, 38, 30

7 https://emcee.readthedocs.io/en/stable/#
