AstroSat View of the Newly Discovered X-Ray Transient MAXI J1803–298 in the Hard-intermediate State

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Abstract
We perform comprehensive temporal and spectral analysis of the newly discovered X-ray transient MAXI J1803–298 using an AstroSat target of opportunity observation on 2021 May 11 during its outburst. The source was found to be in the hard-intermediate state. We detect type C quasi-periodic oscillations (QPOs) at the frequencies of ∼5.4 and ∼6.3 Hz along with a subharmonic at ∼2.8 Hz in the 3–15 keV band. The frequency and fractional rms amplitude of the QPO in the 15–30 keV band are found to be higher than those in the 3–15 keV band. We find soft lags of ∼3.8 and ∼6.8 ms for the respective QPOs at ∼5.4 and ∼6.3 Hz, whereas a soft lag of ∼4.7 ms is found at the subharmonic frequency. The increase in the soft lags at the QPO frequencies with energy is also observed in other black hole transients and attributed to the inclination dependence of the lags. The rms energy spectra indicate the power-law component to be more variable than the disk and reflection components. We find a broad iron line with an equivalent width of ∼0.17–0.19 keV and a reflection hump above ∼12 keV in the energy spectrum. Based on the X-ray spectroscopy and considering the distance to the source as 8 kpc, the estimated mass of the black hole suggest that the source is likely to be a stellar mass Kerr black hole X-ray binary.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); Black hole physics (159); Stellar mass black holes (1611); Stellar accretion disks (1579); X-ray transient sources (1852); X-ray sources (1822); X-ray binary stars (1811)

1. Introduction
Black hole X-ray transients (BHTs) are accreting systems that show intermittent outbursts after a prolonged period of quiescence due to abrupt changes in their mass accretion rate. A sudden increase in the luminosity by several orders of magnitude during such an outburst leads to the discovery of these kind of systems (Tanaka & Shibazaki 1996; Shidatsu et al. 2014; Plant et al. 2015). The evolution of an usual outburst takes place through the state transition of the BHTs from the low/soft state (LHS) to the high/soft state (HSS) via the hard and soft intermediate states (HIMS and SIMS; Belloni et al. 2005; Belloni 2010). These states can be identified on the hardness intensity diagram (Belloni et al. 2005; Homan & Belloni 2005; Gierliński & Newton 2006; Fender et al. 2009; Belloni 2010) based on the definite spectral and timing properties exhibited by the BHTs in the respective states. The HSS is mainly characterized by the thermal emission from an optically thick and geometrically thin accretion disk and associated with a weak fractional rms variability of a few percent. In this state, the accretion disk is usually extended close to the innermost stable circular orbit (ISCO; Gierliński & Done 2004; Steiner et al. 2010; Belloni et al. 2011). Contrarily, the LHS is dominated by the hard power-law emission, originated through the Comptonization process, having a high-energy cutoff at ~100 keV. The power density spectra (PDSs) in this state are associated with a strong fractional rms variability of ~30% (McClintock & Remillard 2006; Belloni et al. 2011; Zhou et al. 2013; Shidatsu et al. 2014; Ingram et al. 2017). The true extent of the inner accretion disk in the LHS is still a matter of debate. Esin et al. (1997) proposed that the optically thick and geometrically thin accretion disk is replaced by a hot advection-dominated accretion flow in the LHS, and thus the accretion disk appears to be truncated away from the ISCO (see McClintock et al. 1995, 2001, 2003; Narayan & Yi 1995; Narayan et al. 1996; Esin et al. 2001; Ingram et al. 2009; Fürst et al. 2015; Plant et al. 2015; García et al. 2015; Ingram et al. 2016). However, the controversy still remains, as it is suggested by some of the previous results that the inner accretion disk may appear to be truncated due to the photon pileup issue present in the data (Done & Díaz Trigo 2010; Miller et al. 2010). The inner disk radius can be estimated by modeling either the thermal emission from the disk (Zhang et al. 1997) or the fluorescent iron emission line arising due to the reflection of the hard coronal X-rays from the accretion disk (Fabian et al. 1989). However, the properties of the BHTs in the intermediate states are not clear enough until now, and the energy spectrum is found to be associated with both the power-law component and contribution from the accretion disk.

The transition of BHTs from one state to another is also associated with certain changes in the timing properties of such systems. Among these, the appearance of low-frequency quasi-periodic oscillations (LFQPOs) at the frequency range of 0.05–30 Hz is very common in the intermediate states and LHS. The LFQPOs are classified as type A, B, and C depending on certain characteristics exhibited by them. Type C QPOs generally appear in the HIMS and LHS as narrow and...
variable peaks at the frequency ranging from a few mHz to several Hz and depict a strong fractional rms ($\geq 10\%$). On the other hand, type B QPOs are found in the SIMS at the frequency range of 4–6 Hz and show a relatively weaker fractional rms ($\sim 4\%$). Type A QPOs are rarely seen and appear as broad and weak peaks (with a few percent of fractional rms) in the frequency range of 6–8 Hz (Wijnands & van der Klis 1999; Remillard et al. 2002; Casella et al. 2005; Homan & Belloni 2005; Motta et al. 2011; Motta 2016; Stevens & Uttley 2016; Gao et al. 2017; Stevens et al. 2018; Belloni et al. 2020). The study of the LFQPOs and the change in their properties, such as time lags and fractional rms amplitude with energy, allow one to understand the mechanism of the variability occurring on a timescale of seconds to days and also provide a connection to the spectral component responsible for the origin of such energy-dependent variability in BHTs.

MAXI J1803–298 is a newly detected bright uncataloged X-ray transient discovered by the Monitor of All-sky X-Ray Image (MAXI; Matsuoka et al. 2009) with a 4–10 keV flux level of 46 $\pm$ 18 mcrab on 2021 May 1. The source was found to be located at R.A. = 18$^{h}$39$^{m}$41$^{s}$ and decl. = $-29^{\circ}48^{\prime}14^{\prime\prime}$, estimated with an elliptical error region of long and short radii of 0.2$^\prime$–7.5$^\prime$ in the frequency range of 4 $-$ 298 Hz. The optical spectroscopy, carried out with the Southern African Large Telescope on 2021 May 2, suggested the source to be a low-mass black hole X-ray binary (BHXRB) system (Buckley et al. 2021). The radio counterpart was also detected by Espinasse et al. (2021) on 2021 May 4. Further follow-up observations of the source with several other telescopes in the X-ray band reveal the detection of LFQPOs and an iron line in the source. Moreover, the follow-up observation by MAXI/GSC on 2021 May 12 indicated the hard-to-soft transition of the source, where the spectral parameters indicate that the system is likely to be a BHXRB (Shidatsu et al. 2021). In this work, we perform a detailed spectral and temporal analysis of the newly discovered X-ray transient source MAXI J1803–298 using an AstroSat target-of-opportunity (ToO) observation. We detect LFQPOs, which exhibit a similar nature to type C QPOs. We have also studied the energy-dependent variability of the QPO properties. Moreover, we find the presence of a broad iron line when the source was in the HIMS. The spectral modeling of the time-averaged X-ray energy spectra is performed with three model combinations, including the blurred reflection model. The remainder of the paper is organized as follows. We present the observation and data reduction in Section 2, and Section 3 contains the analysis and results of our temporal and spectral study. Finally, Section 4 is devoted to discussion and concluding remarks.

2. Observation and Data Reduction

We proposed a ToO observation of the X-ray transient MAXI J1803–298 with India’s first multiwavelength satellite, AstroSat. The follow-up observation (ObsID: T04_003T01_9000004368) of the source was carried out by AstroSat on May 11 at 01:09 UTC (MJD 59,345) and lasted up to May 11 at 11:59 UTC. We obtained the level 2 data of the Soft X-Ray Telescope (SXT; Singh et al. 2016, 2017) from the ISSDC website. The data from individual orbits were merged using the SXT event merger tool to produce an exposure-corrected merged clean event file. Using this merged clean file, we first extracted the source count rate from a circular region of 15′ radius centered at the source position using the XSELECT V2.6d tool. The source count rate was significantly larger than the threshold value for pileup (i.e., $>40$ counts s$^{-1}$) in photon counting mode, which gives a hint about the presence of possible pileup in the energy spectrum. To mitigate the pileup effect, we excluded the source counts from the center region of the point-spread function (PSF) until the source count rate became below the threshold rate for the pileup. We found that for an annulus region with an inner radius of 7.5′ and outer radius of 15′, the source count rate becomes lower than the abovementioned threshold value. Therefore, we used this aperture size to extract the source spectrum. The large PSF (FWHM $\sim 2′$) and half-power diameter ($\sim 10′$) of the SXT and the calibration sources present at the corners of the CCD do not leave the source-free regions to extract the background spectrum. Because of this, we used the blank sky background file (SkyBkg_comb_b_EL3p5_CL_Rd16p0_v01.pha) provided by the SXT payload operation center (POC). We also used the response matrix file sxt_pc_mat_g0to12.rmf, provided by the SXT POC. The SXT off-axis auxiliary response file in accordance with the location of the source on the CCD was derived using the sxtARFMODULE tool. After the launch of AstroSat, the gain of the onboard SXT instrument is shifted, and a correction corresponding to this gain shift has not been incorporated in the current version of the SXTPIPELINE. Hence, per the recommendation by the SXT team, we corrected the gain shift in the SXT spectrum within the Interactive Spectral Interpretation System (ISIS v.1.6.2–40; Houck & Denicola 2000) by considering the slope fixed at unity and making the offset variable.

We also used the data observed by the Large Area X-Ray Proportional Counter (LAXPC; Yadav et al. 2016a, 2016b; Agrawal et al. 2017; Antia et al. 2017). We processed the LAXPC level 1 data of the source using the LAXPC software (Laxpcsoft) and obtained the level 2 data. We generated the light curves and energy spectrum using the standard task within the Interactive Spectral Interpretation System (ISIS) and the calibration sources present at the corners of the CCD do not leave the source-free regions to extract the background spectrum. To mitigate the pileup effect, we excluded the source counts from the center region of the point-spread function (PSF) until the source count rate became below the threshold rate for the pileup. We found that for an annulus region with an inner radius of 7.5′ and outer radius of 15′, the source count rate becomes lower than the abovementioned threshold value. Therefore, we used this aperture size to extract the source spectrum. The large PSF (FWHM $\sim 2′$) and half-power diameter ($\sim 10′$) of the SXT and the calibration sources present at the corners of the CCD do not leave the source-free regions to extract the background spectrum. Because of this, we used the blank sky background file (SkyBkg_comb_b_EL3p5_CL_Rd16p0_v01.pha) provided by the SXT payload operation center (POC). We also used the response matrix file sxt_pc_mat_g0to12.rmf, provided by the SXT POC. The SXT off-axis auxiliary response file in accordance with the location of the source on the CCD was derived using the sxtARFMODULE tool. After the launch of AstroSat, the gain of the onboard SXT instrument is shifted, and a correction corresponding to this gain shift has not been incorporated in the current version of the SXTPIPELINE. Hence, per the recommendation by the SXT team, we corrected the gain shift in the SXT spectrum within the Interactive Spectral Interpretation System (ISIS) by considering the slope fixed at unity and making the offset variable.

3. Analysis and Results

3.1. Timing Analysis

We extracted the source and background light curves from the LAXPC20 data in the 3–60 keV band. In the upper panel of Figure 1, we show the background-subtracted source light curve with a time bin size of 10 s derived in the same energy band. The source intensity remains almost constant over the
between the 3–7 and 7–15 keV bands as shown in the lower panel of Figure 1, does not indicate any significant variation in the light curve throughout this particular observation.

We derived PDSs in the 3–15 and 15–30 keV bands using light curves binned with 0.02 s corresponding to a Nyquist frequency of 50 Hz. We did not use the poor-quality data above 30 keV. We considered intervals of 16,384 bins and obtained rms-normalized PDSs in each interval by dividing the Leahy-normalized power spectra by an average rate (Leahy et al. 1983; Belloni and Hasinger 1990). We computed the final PDS by averaging all of the rms-normalized PDSs for different intervals and propagated the error bars appropriately. We rebinned the final PDS in the frequency space using a geometric binning factor of 1.05. Further, we subtracted the dead time–corrected Poisson noise level from each PDS (see Zhang et al. 1995; Yadav et al. 2016b; Agrawal et al. 2018). Since LAXPC has a dead time of 43 μs that can affect the true source rms, we followed the prescription given by Bachetti et al. (2015) in order to correct the effect of dead time on the source rms using the formula \( \text{rms}_{\text{det}} = \text{rms}_{\text{det}} \left( 1 + \tau_d r_{\text{det}} / N \right) \). Here \( \text{rms}_{\text{det}} \) is the dead time–corrected rms, \( \text{rms}_{\text{det}} \) is the instrument-detected rms, \( \tau_d \) is the dead time, \( r_{\text{det}} \) is the detected count rate, and \( N \) is the number of proportional counter units (van der Klis 1988; Zhang et al. 1995; Sreehari et al. 2020). In addition, all of the PDSs are corrected for the corresponding background rates (Yadav et al. 2016b; Rawat et al. 2019). Figure 2 shows the PDSs derived using the full LAXPC exposure time in the 3–15 and 15–30 keV bands in the left and right panels, respectively. We modeled the PDS in the 3–15 keV band with a power law and five Lorentzians and detected an LFQPO at ∼5.4 Hz along with a subharmonic at ∼2.8 Hz with a detection significance of 16σ and 12.5σ, respectively. However, it is noted here that since we could not fit the broad QPO feature at ∼5.4 Hz with a single Lorentzian component, an additional Lorentzian component centered at ∼6.3 Hz was used. The detection significance level of the QPO at ∼6.3 Hz is found to be 6.8σ, which is relatively lower than that of the QPO at ∼5.4 Hz. On the other hand, the PDS in the 15–30 keV band is fitted with only two Lorentzian components. In this band, we also detected the QPO at a frequency of ∼5.6 Hz with a significance of 16.4σ. It appears that the QPO in this band is found to be shifted to a slightly higher frequency than that of the 3–15 keV band. However, the subharmonic was absent in this band. The best-fit parameters are listed in Table 1, where all of the errors are quoted at the 90% confidence level. In the 3–15 keV band, the quality factors \( Q = v_{\text{centroid}} / \text{FWHM} \) are ∼7.3 (for the QPO at ∼5.4 Hz) and ∼4.3 (for the QPO at ∼6.3 Hz), whereas it is found to be ∼2.1 for the subharmonic. Moreover, the estimated \( Q \)-value of the QPO at ∼5.5 Hz in the 15–30 keV band is ∼3.3, which is comparatively lower than that found in the 3–15 keV band. The fractional rms amplitudes are ∼9% (for the QPO at ∼5.4 Hz) and ∼7.3% (for the QPO at ∼6.3 Hz), whereas it is ∼7% for the subharmonic. However, the fractional rms variability amplitude of the QPO in the 15–30 keV band is ∼20%, which appears to be higher than that obtained in the 3–15 keV band.

Moreover, to check the time-dependent behavior of the QPO, we derived the dynamic power spectrum (DPS) in the frequency range of 0.1–10 Hz for both the 3–15 and 15–30 keV bands using the LAXPC tool laxpc_dynpower\(^{11}\) over the full exposure time of the LAXPC20 data (Jithesh et al. 2019; 2022 July 1 Chand et al.

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\(^{11}\) http://astrosat-ssc.iucaa.in/laxpcData
Rawat et al. 2019). The DPS derived in the 3–15 keV band is depicted in Figure 3, where a clear change in the QPO frequency in the interval of ∼5.4–6.4 Hz can be seen over time. Thus, we divided the 3–15 keV band light curve into three time segments: (i) seg 1: up to 21.5 ks; (ii) seg 2: 21.5–34 ks; and (iii) seg 3: 34–40 ks (see Figure 1). Following this, we derived rms-normalized and Poisson noise (dead time–corrected)—subtracted PDS for each segment. The QPO frequency is found at ∼5.4 Hz in seg 1, increases to ∼6.4 Hz in seg 2, and finally moves down to ∼5.5 Hz in seg 3. However, no significant systematic variation in the fractional rms amplitude of the QPO between these three segments is noticed. The segmentwise PDSs are shown Figure 4, and the corresponding best-fit parameters are listed in Table 2. No change in the frequency of the QPO is observed in the 15–30 keV band.

In addition to the above, we investigated the energy dependence of the fractional rms amplitude variability of both the QPOs and the subharmonic using the full LAXPC exposure time. In this regard, we divided the 3–30 keV band into seven energy bands (i.e., 3–5, 5–7, 7–10, 10–15, 15–20, 20–25, and 25–30 keV) and derived the fractional rms variability at the QPOs and subharmonic frequencies from the PDSs of each energy band. The variation in fractional rms variability as a function of energy is depicted in Figure 5. It is clear that the fractional rms amplitudes of both the QPOs first increase from the disk emission–dominated band (3–5 keV) to the power law–dominated band (10–15 keV) and then either decrease or become flat, most likely due to the presence of a less variable reflection continuum (see Figure 5). A similar trend is found in the rms energy spectrum of the subharmonic, where the amplitude of the variability is slightly lower than those of the QPOs. It is noted here that the error bars in the last few data points at the high energy bands are very large for the rms energy spectra of both the QPOs and the subharmonic.

To investigate the nature of the variability, we computed time lags at the QPOs and subharmonic frequencies by performing a cross-spectral analysis (Vaughan & Nowak 1997; Nowak et al. 1999) over the full LAXPC exposure time. For two evenly sampled time series x(t) and y(t), the complex-valued Fourier transforms X(f) and Y(f) were calculated, where t is the time bin in seconds and f is the Fourier frequency in Hz. From these, the cross-spectrum as $C_{XY}(f) = X^*(f)Y(f) = |X(f)||Y(f)|\exp(-i\phi_X(f) - \phi_Y(f))$ was calculated, where $X^*(f)$ is the complex conjugate of X(f), and $\phi_X(f)$ and $\phi_Y(f)$ are the phase angles. After this, the cross-spectrum was averaged over M nonoverlapping light-curve segments and K frequency bins. Using the averaged cross-spectrum $\overline{C}_{XY}(f)$, the phase lags were obtained as $\phi(f) = \text{arg}(\overline{C}_{XY}(f))$, and it was then

![Figure 2](image-url) The PDS derived in the 3–15 (left panel) and 15–30 (right panel) keV bands. Black data points represent the PDS, and the black dotted lines indicate the model.
Figure 3. The DPS, derived in the 3–15 keV band, shows a clear change in the QPO frequency during the observation. The observation starts on MJD 59,345.

Figure 4. The PDS derived in the 3–15 keV band for seg 1 (left panel), seg 2 (middle panel), and seg 3 (right panel).

Figure 5. Fractional rms variability as a function of energy for the QPOs at ∼5.4 Hz (left panel) and ∼6.3 Hz (middle panel) and the subharmonic at ∼2.8 Hz (right panel).

Table 2

| Segment | ν_{qpo} (Hz) | 24 \( \pm \) 0.01 | 0.84 \( \pm \) 0.04 | 12.4 \( \pm \) 0.4 | 2.64 \( \pm \) 0.05 | 1.07 \( \pm \) 0.13 | 7.2 \( \pm \) 2.7 | 136.1/79 |
|---------|--------------|-------------------|------------------|----------------|------------------|------------------|----------------|----------------|
| 1       | 5.36 \( \pm \) 0.01 | 0.84 \( \pm \) 0.04 | 12.4 \( \pm \) 0.4 | 2.64 \( \pm \) 0.05 | 1.07 \( \pm \) 0.13 | 7.2 \( \pm \) 2.7 | 136.1/79 |
| 2       | 6.37 \( \pm \) 0.03 | 1.2 \( \pm \) 0.1 | 10.1 \( \pm \) 0.6 | 3.14 \( \pm \) 0.08 | 1.2 \( \pm \) 0.3 | 6 \( \pm \) 3 | 77.6/73 |
| 3       | 5.54 \( \pm \) 0.02 | 0.52 \( \pm \) 0.07 | 11 \( \pm \) 3 | 2.8 \( \pm \) 0.1 | 1.1 \( \pm \) 0.3 | 7 \( \pm \) 4 | 69.2/55 |

Note. 1,2,3 Centroid frequency, width, and fractional rms of QPO. 4,5,6 Centroid frequency, width, and fractional rms of subharmonic.
transformed into the time lags as $\tau(f) = \phi(f)/2\pi f$. The error on the time lag was calculated using the prescription given in Nowak et al. (1999). To derive the time lags from the LAXPC20 data, we used the LAXPC subroutine laxpc_find_freqlag, which uses the method described in Vaughan & Nowak (1997) and Nowak et al. (1999). In order to study the time lags as a function of frequency, two light curves were extracted in the 3–5 and 9–12 keV bands, which are dominated by thermal emission of the accretion disk and X-ray power-law continuum, respectively. Each light curve was then divided into 4682 segments of length 3.2 ks, and the Fourier frequency was binned to an interval of 0.28 Hz. The variation of time lags as a function of Fourier frequency is shown in Figure 6, where the negative lag represents the soft lag. This suggests that the photons from the soft energy band lag behind the ones from the hard energy band. We have marked the time lags at the QPOs and the subharmonic frequencies with the three dotted vertical lines in hard energy band. We have marked the time lags at the QPOs and where the negative lag represents the soft lag. This suggests that the subharmonic frequencies across the 3–5 energy dependence of the time lags observed at the QPOs and energy bands. However, the trend of the lag energy spectra is found that the soft lag for both of the QPOs first increases (negatively) up to $\sim$12 keV and then almost becomes flat or starts decreasing. The error bars are large at the higher energy bands. However, the trend of the lag energy spectra is found to be similar to the rms energy spectra of the QPOs, where both the soft lag and fractional rms increase with energy up to $\sim$12 keV, and then become almost flat, or start decreasing. A similar trend between the time lags and fractional rms variability has also been found for the subharmonic. However, a mismatch in the last data point of the time lags and rms spectra is present with large error bars.

### 3.2. Broadband Spectral Analysis

We carried out the broadband X-ray spectral analysis by simultaneously fitting the SXT (0.7–6 keV) and LAXPC20 (3–50 keV) spectral data in the 0.7–50 keV band. All of the spectral modeling was performed using ISIS (v.1.6.2-40; Houck & Denicola 2000), and the uncertainties are quoted at a 90% confidence level. We grouped the SXT spectral data into a minimum signal-to-noise ratio ($S/N$) of 5 and a minimum of three channels per bin, whereas the LAXPC20 spectral data were grouped into a minimum $S/N$ of 3 and a minimum of one channel per bin. Initially, we fitted both spectra simultaneously with a power-law component modified by the Galactic absorption model TBabs, considering the abundances and cross sections of the interstellar medium from Wilms et al. (2000) and Verner et al. (1996), respectively. A constant component was also multiplied to the model to take care of the relative normalization between the two different instruments. We fixed the constant factor to 1 for the SXT spectral data and kept it free to vary for the LAXPC20 spectral data. Moreover, we added the multicolor disk blackbody model (diskbb; Mitsuda et al. 1984) to address the spectrum originating from the accretion disk and incorporated a 3% systematic error into both the SXT and LAXPC20 spectral data to account for the calibration uncertainty, as suggested by the instrumentation team. However, this model setup $tbabs*(powerlaw +diskbb)$ left significant residuals in the 5–9 and above $\sim$12 keV bands, implying the presence of the iron line and the reflection hump, respectively (see Figure 8). Hence, we have incorporated a gaussian component for the iron line and convolved disk spectrum from the diskbb model with the thcomp model (Zdziarski et al. 2020) to account for the Comptonization of the seed photons by the thermal electrons. Since the thcomp model is a convolution model that redistributes a fraction of the seed photons to higher energies, the sampled energy range was extended to 1000 keV. The model $constant*tbabs*(thcomp+diskbb+gaussian)$ (hereafter model 1) provides an admissible fit with $\chi^2/dof = 338/239$. The best-fit spectral parameters are listed in Table 3, whereas the best-fit model is shown in Figure 9. We found the absorption column density ($N_H$) to be $\sim 0.2 \times 10^{22}$ cm$^{-2}$. The inner disk temperature ($kT_{in}$) and the photon index ($\Gamma$) are found to be $\sim 0.8$ keV and $\sim 2.2$, respectively. We could not constrain the value of the electron temperature ($kT_{e}$) and only found the lowest value to be 23 keV, whereas the covering fraction (cov$_{molec}$) is found to be $\sim 0.4$. Furthermore, we kept the centroid line energy of the iron line fixed at 6.5 keV and varied the line width along with the normalization. The best-fit value of the line width is $\sim 1.2$ keV, whereas the estimated equivalent width (EW) of the iron line is found to be $0.17 \pm 0.02$ keV.

In order to calculate the physical parameters, such as the mass and spin of the black hole, as well as the mass accretion rate, we replaced the diskbb model with the relativistic accretion disk model kerrbb (Li et al. 2005) in model 1. Here we convolved the disk spectrum originating from the kerrbb model with thcomp and thus the model setup becomes $constant*tbabs*(thcomp+kerrbb+gaussian)$, termed model 2. This model provides a better fit in comparison with model 1 with $\chi^2/dof = 235.5/237$. In addition, we have followed Chakraborty et al. (2021) and derived an Akaike information criterion (AIC; Akaike 1974) and a Bayesian information criterion (BIC; Schwarz 1978).

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12 [https://www.tifr.res.in/~astrosat_sxt/dataanalysis.html](https://www.tifr.res.in/~astrosat_sxt/dataanalysis.html)
Figure 7. Time lags derived as a function of energy for the QPOs at ~5.4 Hz (left panel) and ~6.3 Hz (middle panel) and the subharmonic at ~2.8 Hz (right panel).

Figure 8. The residuals of LAXPC20 spectral data, fitted with the model constant*tabs(powerlaw+diskbb). The presence of the iron line excess in the 5–9 keV region and the reflection hump above the ~12 keV region are clearly visible.

to show which of these two models (1 and 2) represents the data well. The AIC is defined as 
\[ \text{AIC} = -2 \ln L + P \]
where \( L \) is the likelihood of the best-fitting model, and \( P \) is the number of free parameters. On the other hand, the BIC can be calculated as 
\[ \text{BIC} = -2 \ln L + \frac{1}{2} N \ln P \]
where \( N \) is the total number of data points. Here the likelihood \( L \) can be calculated as 
\[ -2 \ln \text{likelihood} = \chi^2 \]
where \( \chi^2 \) is the value of \( \chi^2 \) for the best-fitting model. The model having the lowest values of AIC and BIC is considered as the most plausible model representing the data. The respective estimated values of AIC and BIC are 356.6 and 405.7 for model 1, whereas those of model 2 are found to be 202.6 and 296.1. From these calculated values of AIC and BIC, it is clear that model 2 fits the data better than model 1. The best-fit spectral parameters obtained using model 2 are given in Table 3, and the best-fit model is shown in Figure 9. Here we fixed the normalization parameter of the kerrbb component at unity and the spectral hardening factor at 1.7 (Shimura & Takahara 1995). We also fixed the distance of the source \( (D) \) at 8 kpc, considering the source to be at the Galactic center (Shidatsu et al. 2021). The

Galactic absorption column density found from this model is ~0.3 \( \times \) 10^{22} cm^{-2}. We found the 90% lower limit on the spin parameter \( (a) \) of the black hole to be 0.95. The mass of the black hole is well constrained and found to be \( M_{BH} = 14 \pm 2 M_{\odot} \). From this model, we found the inclination angle \( i = 48^\circ \pm 4^\circ \), and the rate of mass accretion by the compact object from the companion star is \( M = 0.35^{+0.05}_{-0.03} \times 10^{18} g s^{-1} \). The estimated value of the photon index is \( \Gamma \sim 2 \). Moreover, the temperature of the electron cloud
and the covering fraction are found to be \( kT_e \sim 17 \text{ keV} \) and \( \text{cov}_{\text{line}} \sim 0.20 \), respectively. Here we also kept the centroid line energy of the iron line fixed at 6.5 keV and the line width free to vary. The best-fit value of the line width and the estimated EW of the iron line using model 2 are found to be \( 1.4 \pm 0.2 \) and \( 0.19^{+0.04}_{-0.05} \) keV, respectively.

Further, we attempted to model the full reflection spectrum using the relativistic reflection model relxillCp. The model relxillCp is a part of the blurred reflection model relxill (García et al. 2014), which internally includes a physical Comptonization continuum. In this regard, we replaced the gaussian component in model 2 with relxillCp; thus, the full model setup becomes constant*tbabs*(thcomp*kerrbb+relxillCp), which is referred to as model 3. Here the X-ray continuum is fitted with kerrbb, whereas relxillCp is considered only as a reflection component by keeping the \( R_{\text{ref}} \) parameter fixed at \(-1\). The spin and inclination parameters were tied across relxillCp and kerrbb and kept free. In addition, the photon index (\( \Gamma \)) was tied between relxillCp and thcomp and also kept free. We considered a single emissivity profile \( \varepsilon \propto q^{-\eta} \), where \( q \) is the emissivity index) throughout the accretion disk and therefore tied the break radius with the outer disk radius at \( 400 r_g \). We tried to vary \( q \) freely but found that it was pegging to the lowest defined value of 3 and hence kept it fixed at 3. We also fixed the value of the iron abundance \( (A_{\text{Fe}}) \) to the solar value. Since model 3 appears to be slightly overfitted with the use of a 3% systematic error on both the SXT and LAXPC20 spectral data, we considered 2% systematic for each spectrum for this model. This provides a fit with \( \chi^2/\text{dof} = 256.6/236 \). However, no significant changes in the parameter values are found over the change of this systematic error. The best-fit spectral parameters obtained using model 3 are listed in Table 3, and the best-fit model is depicted in Figure 9. The AIC and BIC values obtained for model 3 are 268 and 323, respectively. We found the best-fit value of the Galactic absorption column density \( (N_{\text{HI}}) \) to be \( \sim 0.45 \times 10^{22} \text{ cm}^{-2} \). The photon index (\( \Gamma \)), estimated from thcomp, is found to be \( \sim 2.13 \). However, the temperature of the electron cloud could not be constrained, and its 90% lower limit is found to be 95 keV. The spin and inclination parameters, estimated by considering both the reflection and continuum components, are found to be \( 0.94^{+0.03}_{-0.28} \) and \( i = 57^{+17}_{-16} \), respectively. Using model 3, the estimated mass of the black hole is \( M_{\text{BH}} = 10.5 \pm 2.0 \ M_\odot \). The measured inner radius of the accretion disk from relxillCp is \( R_{\text{in}} = 3.0^{+2.0}_{-2.0} R_{\text{isco}} \). Moreover, we found the ionization parameter of the disk to be high with \( \log \xi \sim 4 \).

Since time-dependent QPO properties and a slight change in the HR from seg 1 to seg 2 have been observed in this source (see Figure 1), we extracted both SXT and LAXPC20 spectral data in these two time segments and performed broadband spectral analysis using models 2 and 3. Similar to the above, we have incorporated a 3% systematic for model 2 and 2% in model 3. The spectral modeling indicates that the best-fit model parameters obtained from models 2 and 3 do not show any significant segmentwise variations (see Table 4). Moreover, we have not noticed any clear variation in the unabsorbed source flux derived in the 0.7–50 keV band over the segments.

### 4. Discussion and Concluding Remarks

In this work, we have carried out comprehensive spectral and timing analysis of the newly discovered X-ray transient MAXI J1803–298 using an AstroSat observation (on MJD 59,345) during its outburst in 2021 May, when the source was in the HIMS.

We have detected LFQPOs along with a subharmonic in the 3–15 keV band. Both the frequency and the fractional rms amplitude of the QPO are found to be increased in the 15–30 keV band in comparison to those found in the 3–15 keV band, implying an energy-dependent nature of the QPO (see Table 1). The absence of the subharmonic in this band may be due to the low S/N of the data. The shape of the PDS, quality factor, and fractional rms amplitude of both QPOs are found to be similar to the characteristics of the type C QPOs (Casella et al. 2005; Motta et al. 2011; Belloni et al. 2020). As we found an increase in the fractional rms amplitude of the QPO with energy in the HIMS, a similar increase in the fractional rms amplitude of the LFQPO at \( \sim 0.16 \text{ Hz} \) with energy was also reported in the LHS of the source by Wang et al. (2021) using an Insight-HXMT observation on MJD 59,337. However, unlike the energy-dependent nature of the QPO observed in this work, they found the QPO to be energy-independent. NICER also observed the source in the LHS on MJD 59,336 and
detected an LFQPO at \( \sim 0.13 \) Hz, which was found to be drifted to a higher frequency of \( \sim 0.23 \) Hz in the interval of 2 days on MJD 59,338 (Bult et al. 2021). An LFQPO at a comparatively higher frequency of \( \sim 0.4 \) Hz was also detected by a NuSTAR observation on MJD 59,340, when the source was in LHS (Xu & Harrison 2021). Following this, we observed the source on MJD 59,345 in the HIMS and detected the QPOs at comparatively higher frequencies of \( \sim 5.4 \) and \( \sim 6.3 \) Hz along with a subharmonic at \( \sim 2.8 \) Hz. Again, the NICER follow-up observations of MAXI J1803–298 over the period of MJD 59,353–59,359 detected the type B QPO at \( \sim 6 \) Hz along with a broad subharmonic at \( \sim 3 \) Hz, when the source stepped into the intermediate steep power-law state (Ubach et al. 2021). During this period, the QPO frequency moved between \( \sim 5.6 \) and \( \sim 5 \) Hz. It is clear that the QPO moved from low to high frequency and also changed its nature, as the source made a state transition during this particular outburst. As discussed above, the intermittent presence of the QPOs and the change in their frequencies with time and energy indicate the evolution in the source geometry from the rising phase of the outburst to the decaying phase. Along with the energy-dependent nature, the QPO also shows a time-dependent variation. The DPS derived over the full exposure time of this particular AstroSat observation (see Figure 3) suggests that the change in the QPO frequency may have a connection with the slight drop in the count rate observed in seg 2 of the light curve (see Figure 1). This can also be confirmed from Table 2, where the QPO frequency goes up from \( \sim 5.4 \) to \( \sim 6.4 \) Hz and finally goes down to \( \sim 5.5 \) Hz. Although periodic dips at an interval of \( \sim 7 \) hr have been reported in a few follow-up observations during the 2021 outburst (Homan et al. 2021; Xu & Harrison 2021; Jana et al. 2021, 2022), it was not noticed in the time span of our observation.

The study of the energy-dependent timing properties in the BHTs provides important insights to differentiate the properties of the intermediate states from those of the soft states. The appearance of the type C QPOs is one of the most salient features seen in the HIMS; therefore, the study of these QPOs acts as an important tool to further investigate the characteristics of BHTs in the HIMS (Bu et al. 2021). Although the exact physical origin of these QPOs is still not clear, sufficient indications have been found in support of the geometric origin of the type C QPOs (Gilfanov 2010). The Lense–Thirring precession of a radially extended region of the hot inner flow in the truncated disk models is usually thought to be responsible for the appearance of the LFQPOs in the PDSs of the BHTs, suggesting the geometric origin of the type C QPOs (Stella & Vietri 1998; Ingram et al. 2009). Moreover, a number of studies have been carried out in support of the geometric origin of the type C QPOs by probing the dependence of the timing properties on the orbital inclination angle (Schnittman et al. 2006; Motta et al. 2015). As in Figure 5, the fractional rms variability amplitudes of both QPOs initially increase with photon energy up to \( \sim 12 \) keV and then either become flat or decrease slightly, which may be due to the large variability of the power-law component with respect to the disk emission and reflection component. In this regard, it is noted here that a large number of studies have been conducted on the energy dependence of the fractional rms variability amplitude of type C QPOs for several BHXRBs, such as GX 339-4.
(Belloni et al. 2011), Cyg X-1, XTE 1752–223 (Muñoz-Darias et al. 2010), GRS 1915+105 (Rodriguez et al. 2004; Yan et al. 2012; Yadav et al. 2016b; Rawat et al. 2019; Zhang et al. 2020; Karpouzas et al. 2021), XTE J1650–500 (Gierliński & Zdziarski 2005), XTE J1859+226 (Casella et al. 2004), H1743–322 (Li et al. 2013a), XTE J1550–564 (Li et al. 2013b), and MAXI J1631–479 (Bu et al. 2021), where an increase in the amplitude of the fractional variability up to ≈10 keV and then a flattening or decrease has been found. This increase in the fractional rms of the QPOs with photon energy (positive correlation) is usually found in the intermediate states, and the positive correlation implies the origin of the QPOs from the coronal region (see Li et al. 2013a, 2013b). Apart from this, You et al. (2018) performed the simulation of the fractional rms amplitudes of the type C QPOs using the Lense–Thirring precession model and suggested that the flattening above ≈10 keV is caused by the effect of a high orbital inclination angle. Feng et al. (2021) also suggested that the source MAXI J1803–298 has a high disk orbital inclination angle, i ≈ 70°. The value of the disk orbital inclination estimated from model 3 (see Table 3) hints that this source may be a highly inclined system. Moreover, a flat and decreasing nature in the fractional rms variability with energy (inverted correlation) of the type C QPOs is observed in the LHS of some of the BHXBs (Rodriguez et al. 2004; Gierliński & Zdziarski 2005; Sobolewska 2006; Li et al. 2013a, 2013b; Chand et al. 2020). A few more studies of the energy-dependent fractional rms variability above 30 keV have been performed for the BHXBs GRS 1915+105 (Tomsick & Kaaret 2001), MAXI J1535–571 (Huang et al. 2018), and MAXI J1820 +070 (Ma et al. 2021), which also indicate the geometric origin of the type C QPOs.

With respect to the 3–5 keV band, the decreasing trend in the time lags with energy estimated at the QPOs and the subharmonic frequencies (see Figure 4) implies the presence of a soft or negative lag, where the hard photons arrive before the soft ones. The presence of a soft lag is also supported by lag-frequency spectra, where negative lags are observed at both the QPOs and the subharmonic frequencies (see Figure 6). The systematic study of the 15 BHXBs using RXTE archival data by van den Eijnden et al. (2017) revealed that the sign of the energy-dependent lags strongly depends on the orbital inclination. Besides, the change in the behavior of the time lag properties with inclination was studied by Dutta & Chakrabarti (2016) for the BHXB sources GX 339-4 and XTE J1550–564, and they suggested that the soft or negative lag may appear in the high-inclination sources due to reflection and focusing effects. Moreover, considering the 3–4 keV band as the reference band, Yadav et al. (2016b) found a decreasing trend in the time lags up to ≈20 keV and then an upturn in the lag energy spectrum of GRS 1915+105 using AstroSat observations. Based on this result, they suggested the precession of the inner disk due to the Lense–Thirring effect to be responsible for the origin of the QPO, and the observed time lag is due to the light travel time effects of the irradiation by the inner disk on the nonprecessing outer one. In this case, the upturn in the time lags above ≈20 keV is suggested to be due to the time delay of the reflected photons with respect to the continuum at ≈20 keV.

We have modeled the time-averaged X-ray energy spectra from both SXT and LAXPC20 jointly using three model combinations (see Table 3). Based on the statistics, we have found that model 2 describes the spectra in a better way than the other two models. The photon index (Γ) obtained from the thcomp component from the best-fit model 2 indicates that the source was in the HIMS during this particular observation. Moreover, its values obtained from the other two models are found to be nearly similar. It is worth mentioning here that Jana et al. (2022) also observed the same source immediately after our observation and similarly found the source to be in the HIMS. The Galactic absorption column density (N_H) derived from models 1 to 3 is found to be in the range of (0.22–0.45)×10^{22} cm^{-2}. These values are almost consistent with the values reported by Bult et al. (2021), Feng et al. (2021), and Jana et al. (2022). However, the larger value of the absorption column density obtained from model 3 may be due to the soft excess introduced by the relxillCp model at low energies. The inner disk temperature (kT_{in}) obtained from the diskbb model suggests that the accretion disk is hot. The line width of the iron line estimated from models 1 and 2 is similar within the errors (see Table 3), and the presence of such a broad iron line suggests its origin in the innermost regions of the accretion disk, where the relativistic effects play the role of distorting the shape of the line (Fabian et al. 2000). In addition, we find that the X-ray spectrum is dominated by the power-law component with a power-law fraction of ~60%, whereas the accretion disk contributes only ~30%. The slight discrepancy in the values of the same parameters derived from the chosen models may arise from the different assumptions made in the model components. In this regard, it is worth mentioning here that kerrbb represents a relativistic accretion disk, which considers the disk to be extended close to the ISCO. Moreover, kerrbb also accounts for the effect of self-irradiation and either zero or nonzero torque at the inner boundary of the disk (Li et al. 2005). On the other hand, diskbb neglects the relativistic effects and represents a thin Newtonian disk (Mitsuda et al. 1984; Makishima et al. 1986). Apart from this, diskbb does not consider the effect of irradiation and zero torque at the inner boundary of the disk (Stiele & Kong 2017). We have found a black hole mass of 14 ± 2 M_☉, spin (a) > 0.95 (90% confidence level), and an inclination angle (i) of 48.4° based on the kerrbb model, which only uses the disk continuum. Similar parameters have also been estimated from model 3 by considering both the disk continuum (kerrbb) and the reflection spectrum (relxilCp). We find that parameters such as the mass and spin of the black hole and the disk inclination angle are consistent within the errors with those values estimated from model 2. From models 2 and 3, the estimated black hole mass ranges from ~8.5 to 16 M_☉ and the spin parameter is >0.7. In addition, the disk inclination angle derived from the abovementioned two models ranges from ~43° to 74°. These values are consistent with the recent works by Feng et al. (2021) and Jana et al. (2022), where the authors also detected the presence of significant periodic dips in the light curves. We note that the estimated mass and spin of the black hole are completely based on the X-ray spectroscopy and depend on the distance of the source, which is assumed to be 8 kpc. The measured radius of the inner accretion disk (see Table 3) by modeling the reflection features suggests that the accretion disk is extended close to the ISCO. A small inner disk radius in the HIMS for MAXI J1535–571 and GX 339–4 was also reported by Sridhar et al. (2019, 2020) using RXTE and AstroSat observations. The disk is found to be highly ionized. To understand the dependency of the mass and spin parameter...
of the black hole on the distance to the source, we have varied the distance in the range of 6–10 kpc in both model 2 and model 3. However, we find that the best-fit values of the black hole mass and spin obtained from models 2 and 3 are consistent within the errors with those derived by assuming the distance to be 8 kpc for the respective models. Similarly, no significant variation is observed in the mass accretion rate. Moreover, unlike the time-dependent behavior of the QPO properties, we do not find any significant changes in the spectral parameters over time (see Table 4). All of the above results obtained through temporal and spectral analysis indicate that the newly discovered X-ray transient source MAXI J1803–298 is possibly a BHXR B hosting a stellar mass Kerr black hole.

We thank the anonymous referee for the useful comments and suggestions that have improved the quality of the paper. The authors acknowledge the financial support of ISRO under the AstroSat archival data utilization program (No. DS-2B-13013(2)/8/2019-Sec.2). This publication uses data from the AstroSat mission of the Indian Space Research Organisation (ISRO), archived at the Indian Space Science Data Centre (ISSDC). This work has used data from the SXT and LAXPC instruments on board AstroSat. The LAXPC data were processed by the Payload Operation Center (POC) at TIFR, Mumbai. This work has been performed utilizing the calibration databases and auxiliary analysis tools developed, maintained, and distributed by the AstroSat-SXT team with members from various institutions in India and abroad and the SXT POC at the TIFR, Mumbai (https://www.tifr.res.in/~astrosat_sxt/index.html). The SXT data were processed and verified by the SXT POC. S.C. expresses his sincere thanks to David P. Huememoer for his help. V.K.A. thanks GH, SAG; DD, PDMSA and Director, URSC for encouragement and suggestions that have improved the quality of the paper. Belloni, T. M. 2010, in Lecture Notes in Physics, Vol. 794 ed. T. Belloni (Berlin: Springer), 53
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