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AstroSat observations of the dipping low-mass X-ray binary XB 1254–690

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ABSTRACT

XB 1254–690 is a neutron star low-mass X-ray binary with an orbital period of 3.88 h, and it exhibits energy-dependent intensity dips, thermonuclear bursts, and flares. We present the results of an analysis of a long observation of this source using the *AstroSat* satellite. The X-ray light curve gradually changed from a high-intensity flaring state to a low-intensity one with a few dips. The hardness–intensity diagram showed that the source is in a high-intensity banana state with a gradually changing flux. Based on this, we divide the observation into four flux levels for a flux-resolved spectral study. The X-ray spectra can be explained by a model consisting of absorption, thermal emission from the disc, and non-thermal emission from the corona. From our studies, we detect a correlation between the temperature of the thermal component and the flux and we examine the implications of our results for the accretion disc geometry of this source.

Key words: accretion, accretion discs – methods: data analysis – stars: neutron – X-rays: binaries – X-rays: bursts – X-rays: individual: XB 1254–690.

1 INTRODUCTION

Low-mass X-ray binary sources containing neutron stars (NS-LMXBs) are known for their variable nature. In X-rays, they exhibit dips, quasi-periodic oscillations (QPOs), bursts, flares, and coherent millisecond-period X-ray pulsations. Dips in soft X-rays are seen in a few NS-LMXBs (called the dippers), and in a few black hole LMXBs (D’Aì et al. 2014). These dips are thought to be caused by the periodic obscuration of X-rays by the accretion stream when it strikes the structures above the accretion disc. Such obscurations are possible only if the LMXBs are high inclination systems so that the line of sight passes through these structures (White & Swank 1982). The dips may recur at the system’s orbital period, and the change in the X-ray spectrum during a dip is complex. The structure and location of emitting and absorbing components in NS-LMXBs can be well-studied by modelling these spectral changes. The dippers sometimes exhibit low frequency (~ 1 Hz) QPOs, called ‘dipper QPOs’, at low intensities (Homan et al. 1999; Jonker, van der Klis & Wijnands 1999; Jonker et al. 2000; Bhattacharyya, Miller & Lamb 2006). Hence, dippers allow us to constrain the properties of the accretion discs and the polarized plasma above them (Jimenez-Garate, Schulz & Marshall 2003) and the QPOs help us understand the innermost region of the accretion disc (Jonker et al. 2000).

Another X-ray variability that is mainly observed in NS-LMXBs is X-ray bursts. X-ray bursts are characterized by an increase in

the intensity of the emission of X-rays with a short rise time of about a few seconds and a longer decay time. Unstable nuclear burning on the neutron star’s surface could lead to such X-ray bursts (Lewin & van der Klis 2010). In the past few years, burst oscillations have been observed from several X-ray sources. The discovery of burst oscillations at the spin frequencies of the accreting millisecond pulsars SAX J1808.4–3658 and XTE J1814–338 (Chakraborty et al. 2003; Strohmayer et al. 2003) has conclusively linked these oscillations to neutron star spin. Indeed, the detection of burst oscillations has facilitated the spin frequency measurements of neutron stars in more than a dozen NS-LMXBs. Detection of a low-spin frequency neutron star from NS-LMXBs can be beneficial. Besides, in addition to measuring spin rates, the modelling of burst oscillation light curves can be necessary for the measurements of stellar mass and radius (Bhattacharyya et al. 2005), and for understanding the thermonuclear flame spreading on neutron stars (Bhattacharyya & Strohmayer 2006).

X-ray flaring in NS-LMXBs has been known for many years. It was first observed in Sco X-1, which took place during both quiescent and active states of the source (Canizares et al. 1975). White, Peacock & Taylor (1985) observed a notable increase in the black body temperature during flaring along with an increase in the emitting area. Later it was observed that many other bright NS-LMXBs exhibit flares similar to Sco X-1. Nevertheless, not much work has been done to develop a physical understanding of the flaring phenomenon. The alteration between flaring in brighter sources and bursting in less bright sources is also not understood.

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Balucińska-Church et al. (2001) reported the study of flaring in the big dipper X 1624–490. They proposed that the flaring consists of the superposition of X-ray bursts which occurs rapidly because of the higher (~ 10 times) mass accretion rate.

XB 1254–690 is an NS-LMXB showing several of the above features. It is a dipping source and has a 19th magnitude blue star called GR Mus as an optical counterpart (Griffiths et al. 1978). The detection of Type I X-ray bursts confirmed that the compact object in this source is a neutron star (Mason et al. 1980). XB 1254–690 is known for exhibiting energy dependent X-ray dips with an orbital period of 3.88 ± 0.15 h (Courvoisier et al. 1986). Motch et al. (1987) reported the modulation in the optical light curve with the period same as the X-ray dips, with a temporal offset of 0.2 cycles after the X-ray dips. The presence of dips and the absence of eclipse in this source lead to constraining the inclination angle, i , to be between 65° and 73° (Courvoisier et al. 1986; Motch et al. 1987).

While studying the timing properties of XB 1254–690, Bhattacharyya (2007) established that it is an atoll source by calculating the colour–colour diagram using *Rossi X-ray Timing Explorer (RXTE)* observation and correlating the timing properties with the different sections of it. The authors also mentioned that the source was always found in the banana state and never found in low intensity spectrally hard island state. The first evidence of QPOs from XB 1254–690 was presented by Mukherjee & Bhattacharyya (2011) at frequencies 48.63 and 64.01 Hz. The suggestive evidence of 95 Hz oscillations from a thermonuclear burst from XB 1254–690 indicated that the central compact object is spinning with a frequency of 95 Hz (Bhattacharyya 2007). However, further confirmation of both QPOs and thermonuclear burst oscillations is yet to be done.

XB 1254–690 has shown a typical variation in the dip depth in the earlier observations, which makes it different from other dipping NS-LMXBs. *Ginga* observations of the source in 1990 showed deep dips in the light curve (Uno et al. 1997). However, dips were absent during the *BeppoSAX* observations in 1998 (Iaria et al. 2001) and in *RXTE* observations in 1997. In 1997 optical observations revealed that the amplitude of the optical variability was reduced by $\Delta V \sim 0.1$ mag with mean V magnitude unchanged (Smale & Wachter 1999). Non-detection of dips indicated that the angular size of the disc edge decreased to less than 10° from between 17° to 25° (Smale & Wachter 1999). The dips were detected again during the *XMM-Newton* observation in 2001 January and during *RXTE* observation in 2001 May and were again undetected in the 2001 December observation (Smale, Church & Balucińska-Church 2002), in 2002 February observation (Boirin & Parmar 2003), and in 2003 October observation (Iaria et al. 2007). Once again, the deep dipping was observed in the 2004 May *RXTE* observation of the source (Barnes et al. 2007).

Along with energy-dependent intensity dips and thermonuclear X-ray bursts, the source also exhibits flares. Smale et al. (2002) reported flaring along with dips (see fig. 1 of Smale et al. 2002) and bursts (see fig. 2 of Smale et al. 2002).

In this paper, we present the results of an analysis of a long observation of the dipping NS-LMXB XB 1254–690 using *AstroSat* carried out between 2018 May 03 and 2018 May 05. We observed flares and dips in the X-ray light curve during this observation. However, we did not detect any thermonuclear bursts. We studied the X-ray spectra of this dipping source using data from two instruments onboard *AstroSat*, namely Soft X-ray Telescope (SXT) and Large Area X-ray Proportional Counter (LAXPC), using detailed spectral models. The structure of this paper is as follows. In Section 2, we describe the data reduction procedure of both SXT and LAXPC instruments. In Section 2.4, we describe the HID generation and

Table 1. *AstroSat* observation details.

Obs ID	Obs. time (UT) (yyyy-mm-dd)	Exposure (s)
9000002074	2018-05-03	40700 (SXT) 99750 (LAXPC)

formation of four sections for flux resolved spectroscopy based on intensity. We present a detailed spectral analysis of *AstroSat* data in Section 3 along with details of constraining disc inner edge radius in Section 3.2. Finally, we epitomize the results and discuss their implications in Section 4.

2 OBSERVATION AND ANALYSIS

The Indian astronomical observatory *AstroSat* (Agrawal 2006; Singh et al. 2014) observed XB 1254–690 between 2018 May 03 and 2018 May 05 (ObsID: 9000002074). We analysed the data from two instruments onboard *AstroSat* namely SXT and LAXPC. The details of the observation with exposure time for both SXT and LAXPC are given in the Table 1.

2.1 SXT

The SXT (Singh et al. 2016, 2017) onboard *AstroSat* was the primary instrument for the observation, and the data were acquired in the photon counting (PC) mode. The source light curve and spectrum are extracted using the XSELECT tool in HEASOFT (version 6.26.1) from 14 arcmin circular region, which includes ~ 94 per cent of the total source photons and is suitable for the lowest possible systematic. For the background light curve, we consider a $14 - 16$ arcmin annular region. For spectral analysis, we use the response matrix file (RMF), deep blank sky background spectrum, and an auxiliary response file (ARF) provided by the SXT payload operation team.¹

2.2 LAXPC

The LAXPC (Yadav et al. 2016) data are analysed using the tools from LAXPCSOFT.² By the time of the present observation, LAXPC10 showed unforeseeable variations in high voltage (HV), and LAXPC30 suffered a gas leakage which caused gain instability. Hence, we are using only LAXPC20 data for spectral studies. However, we use both LAXPC10 and LAXPC20 for timing studies as the HV variations do not significantly affect the power density spectra (PDS). The background is dominating beyond 20.0 keV in LAXPC hence, we consider the 4.0–20.0 keV energy range and extract photons from the top layer of the unit to achieve a better signal-to-noise ratio (S/N).

2.3 Light curve

Fig. 1 shows the background-subtracted light curves with a bin size of 100 s in different energy ranges: 0.7–7.0 keV (SXT, top panel), 4.0–6.0 keV (LAXPC20, second panel), and 6.0–20.0 keV (LAXPC20, third panel). The fourth panel in the figure shows the hardness ratio (counts in the 6.0–20.0 keV energy range divided by those between the 4.0 and 6.0 keV band). The count rate in the SXT

¹https://www.tifr.res.in/~astrosat_sxt/dataanalysis.html

²http://astrosat-ssc.iucaa.in/uploads/laxpc/LAXPCsoftware_Aug4.zip

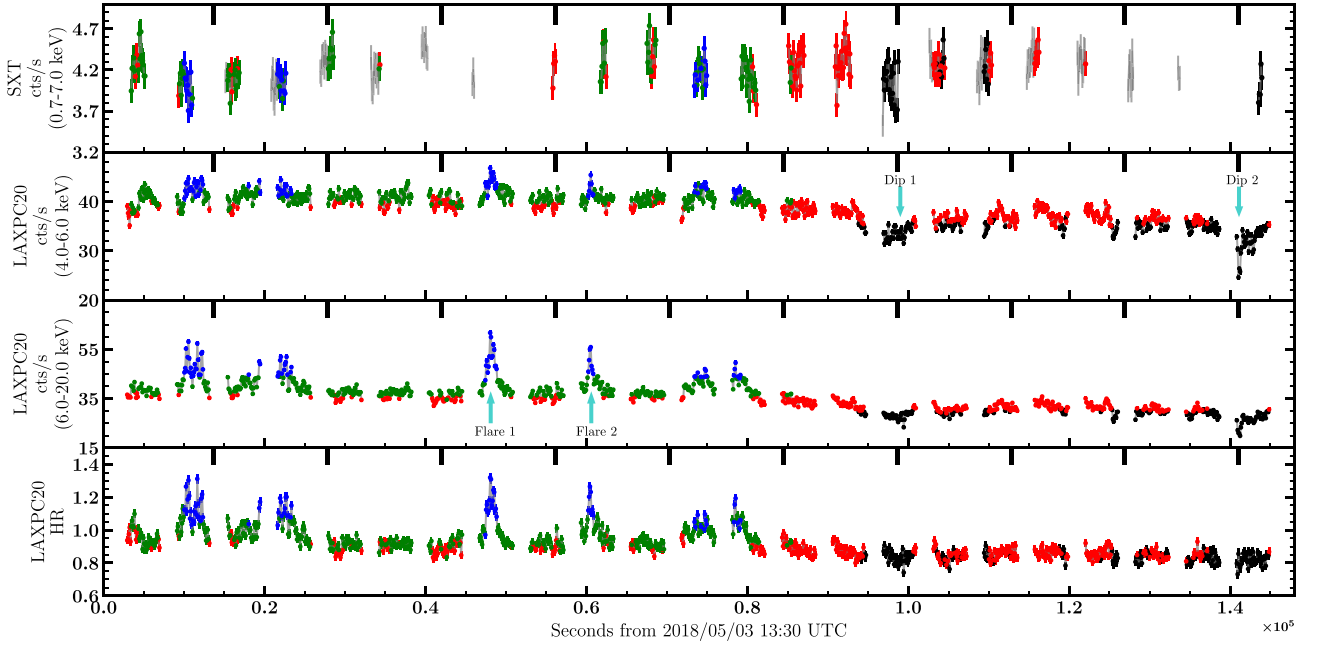


Figure 1. 0.7–7.0 keV *AstroSat*/SXT background-corrected light curve (first panel) followed by *AstroSat*/LAXPC20 background-corrected light curves from the top layer of the unit in two different energy bands (second panel: 4.0–6.0 keV, third panel: 6.0–20.0 keV) for XB 1254–690. The fourth panel is the hardness ratio using two energy bands of LAXPC20. All the light curves and hardness ratio are binned over 100 s. The colours black, red, green, and blue in the figure represent the four intensity-dependent sections we are considering for the flux resolved spectroscopy in this work (see Section 2.4 for details). The grey data points represent the total observation. The expected dip centres derived from the folding period and the corrected reference epoch are indicated with black thick vertical tick marks on the upper X-axis of all four panels (see Section 2.3 for details). The observed two dips are pointed with the arrows in the second panel, and two prominent flares are pointed with the arrows in the third panel.

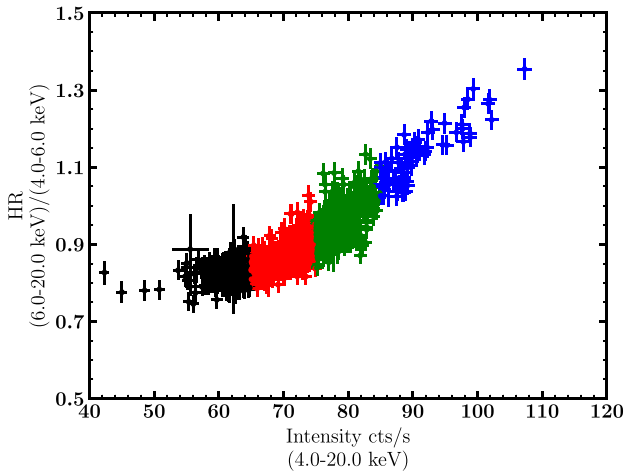


Figure 2. Hardness–intensity diagram (HID) of XB 1254–690 using *AstroSat*/LAXPC20 data from top layer with 100 s binning. The source was in the banana branch during the observation. HID is divided into four sections based on intensity to perform flux resolved spectroscopy. The flares belong to the blue section of HID, where both intensity and hardness ratio are high, and dips belong to the black section of HID, where intensity and hardness both are low.

light curve is normalized with respect to the detection area. The data points in the figure are coded in four different colours (black, red, green, and blue), representing the sections we are considering for flux-resolved spectroscopy. The grey data points represent the total observation. These intensity-dependent sections are discussed

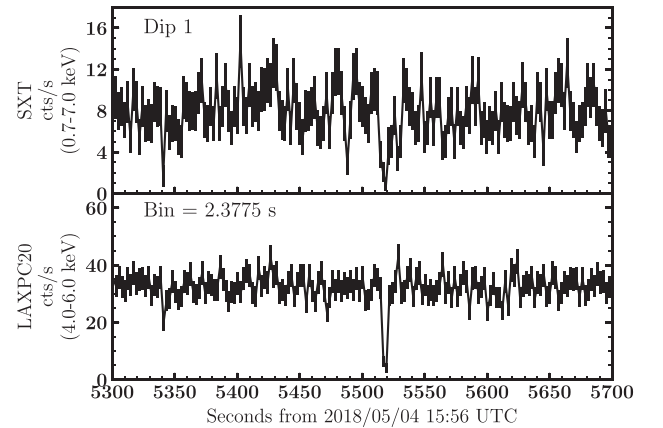


Figure 3. *AstroSat*/SXT 0.7–7.0 keV light curve (upper panel) and *AstroSat*/LAXPC20 4.0–6.0 keV light curve (lower panel) for dip 1 (shallow dip) observed in XB 1254–690 with time bin of 2.3775 s.

in Section 2.4 in detail. Gambino et al. (2017) reported the new linear orbital ephemeris (see equation 5 in Gambino et al. 2017) with 11931.8069(16) TJD as a newly corrected reference epoch and 14160.004(6) s orbital period. The thick vertical tick marks on the top X-axis of each panel represent the expected dip times using this ephemeris.

XB 1254–690 shows a decrease in its intensity during the present observation. Interestingly, several flare-like features are seen at the beginning of the observation, particularly in the first half. These flares are prominently seen in the 6.0–20.0 keV energy band of LAXPC20

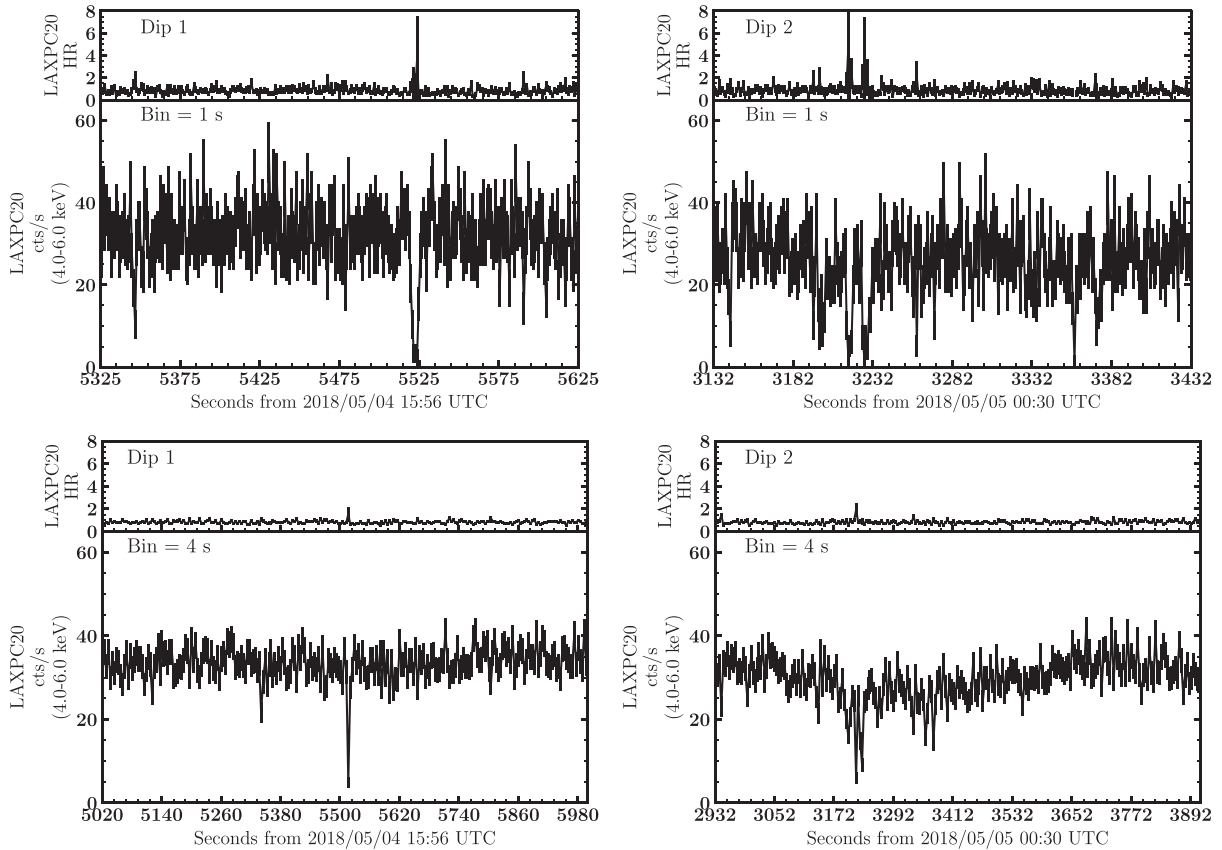


Figure 4. *AstroSat*/LAXPC20 4.0–6.0 keV light curve and hardness ratio (counts between 6.0 and 20.0 keV divided by counts between 4.0 and 6.0 keV) with a time bin of 1 s (upper panels) and 4 s (lower panels). The plots on the left side are for dip 1 (shallow dip) and on the right side are for dip 2 (deep dip) observed in XB 1254–690.

light curve (pointed with the arrows in the third panel of Fig. 1) and in the hardness ratio plot (fourth panel of Fig. 1). We detected two dips after the flaring episode towards the end of the observation. Both are evident in the 4.0–6.0 keV energy band of LAXPC20 (pointed with the arrows in the second panel of Fig. 1). To characterize dips, we followed the definition of ‘deep’, ‘shallow’, and ‘undetected’ dips given in Díaz Trigo et al. (2009). The *AstroSat* data have gaps due to Earth occultation and South Atlantic Anomaly (SAA). While calculating the reduction of the flux during dips compared to the persistent emission, we considered the light curves between these data gaps. The dip 1 is a ‘shallow’ dip (near 1.0×10^5 s) with 9.7 per cent reduction of 4.0–20.0 keV flux and the dip 2 is a ‘deep’ dip (near 1.4×10^5 s) with 15.9 per cent reduction in the flux when compared to the persistent emission. The appearance of these dips coincides with the expected dip times derived from the new linear orbital ephemeris given by Gambino et al. (2017).

2.4 Hardness–intensity diagram

The HID for XB 1254–690 is generated using LAXPC20 data from the top layer of the detector (Fig. 2). The hardness ratio is the ratio of background-corrected counts between 6.0 and 20.0 keV to the counts between 4.0 and 6.0 keV, and the intensity is the total background-corrected counts between 4.0 and 20.0 keV.

Based on the intensity, we divided the HID into four sections (marked in different colours in Fig. 2) to perform flux resolved spectroscopy of XB 1254–690. The selection of sections is made so

that each section will have at least 10 000 data points. We used *laxpc_fluxresl_gti* tool from LAXPCSOFT to generate Good Time Intervals (GTIs) for these sections. The GTIs generated from this tool are then used to generate both SXT and LAXPC20 spectra.

Fig. 2 distinctly indicates that both intensity and hardness are high during flaring (see the blue points in Fig. 1) as flaring is high energy phenomenon and are low during the dips (see the black points in Fig. 1) as dipping is a low energy phenomenon.

2.5 Dips and flares light curve

The shallow dip is observed in both SXT and LAXPC20, while the deep dip is observed only in the LAXPC20 data as SXT have a data gap during this time. Fig. 3 shows the SXT and LAXPC20 background-corrected light curve for the shallow dip with the time bin 2.3775 s (a minimum time resolution of SXT).

The LAXPC20 4.0–6.0 keV background-corrected light curve and the hardness ratio (counts between 6.0 and 20.0 keV energy band divided by the counts between 4.0 and 6.0 keV energy band) plot of a shallow dip with a time resolution of 1 s is shown in the upper left panel of Fig. 4. The part of the same dip with 4 s time resolution is shown in the lower left panel of the figure. Light curve and hardness ratio for the deep dip are shown in the right panel of Fig. 4 (upper right panel is with 1 s time resolution and the lower right panel is with 4 s time resolution). If we examine the plot of deep dip with 1 s time resolution, in the beginning, the intensity is decreasing slightly (known as the shoulder of the deep dip). In contrast, the

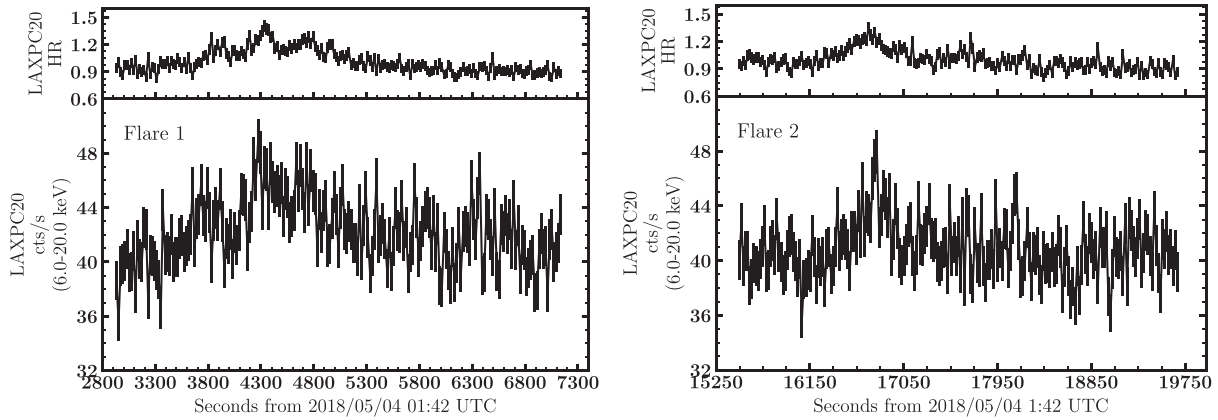


Figure 5. The 6.0–20.0 keV LAXPC20 light curve and the hardness ratio (counts between 6.0 and 20.0 keV divided by counts between 4.0 and 6.0 keV) for flare 1 (left panel) and flare 2 (right panel) observed in XB 1254–690 during this observation with a time bin of 20 s.

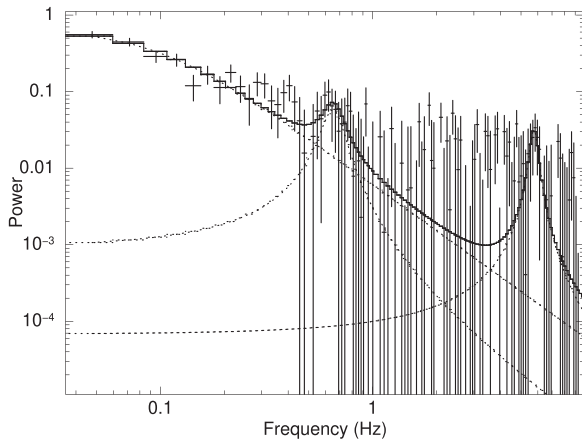


Figure 6. A QPO with significance $\sim 2\sigma$ and frequency 0.65 Hz seen in *AstroSat*/LAXPC observation of XB 1254–690. The PDS is extracted using the complete light curve in the 3.0–20.0 keV energy range of LAXPC10 and LAXPC20.

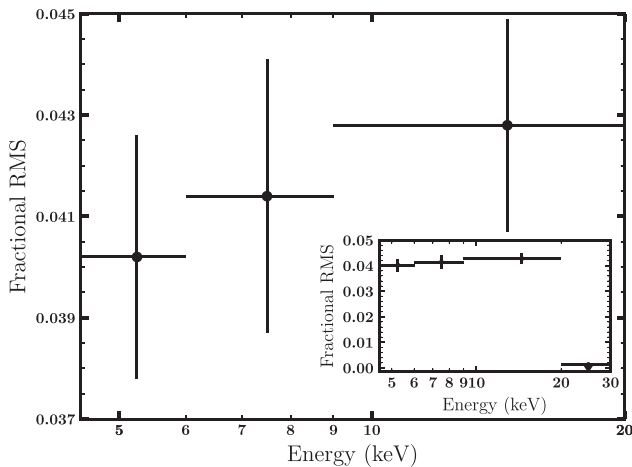


Figure 7. Fractional rms and energy correlation from the *AstroSat* observation of XB 1254–690. The rms was calculated from the PDS of the complete light curve in the 3.0–20.0 keV energy range of LAXPC10 and LAXPC20. The inset shows the relatively low rms estimated in the energy range beyond 20 keV.

hardness ratio is not varying much, and after some point, both light curve and hardness ratio vary extensively. The strongest hardening corresponds to the deepest segment of the dips. In these figures, we can observe that the shallow dip's depth and hardness ratio is similar to the deep dip, as it comprises many very short duration deep dips.

The two prominent flares observed in XB 1254–690 during this observation are shown in Fig. 5. The left panel is flare 1, and the right panel is flare 2. The lower section of each panel is the 6.0–20.0 keV LAXPC20 light curve, and the upper section is the hardness ratio (counts between 6.0 and 20.0 keV divided by counts between 4.0 and 6.0 keV). Both light curve and hardness ratio are binned over 20 s.

2.6 Power spectral density (PSD)

We used the LAXPC10 and LAXPC20 observations to extract the PDS, using the General High-energy Aperiodic Timing Software (GHATS).³ We extracted PDS in the energy range 3.0–20.0 keV with Nyquist frequency up to ~ 3000 Hz using intervals of ~ 10 s. Inspection of the PDS in various energy bands as well as the sections based on intensity (see Fig. 6) does not reveal the presence of high frequency candidate QPOs reported in Mukherjee & Bhattacharyya (2011). We also examined the dynamic PDS during the flares but did not detect any significant high frequency QPOs. To examine the low frequency variability, we extracted a PDS with Nyquist frequency extending up to 10 Hz using ~ 50 s intervals of the light curve and fit it using a zero centred Lorentzian and a Lorentzian for the QPO. The PDS of the complete light curve in the 3.0–20.0 keV energy range indicates the presence of a QPO with frequency 0.65 Hz (Fig. 6) with low statistical significance ($\sim 2\sigma$). Examination of the PDS in narrower energy bands indicates the presence of the feature but the statistical significance falls rapidly and there is no conclusive rms–energy relation due to the resulting large uncertainties. A correlation of rms and energy for the QPO can identify it as a 1 Hz QPO usually seen in dipping LMXBs (Homan 2012). Up to 20 keV the rms of the low frequency noise (LFN) and the energy have a Pearson correlation coefficient ~ 0.59 (Fig. 7). Beyond 20 keV the rms drops rapidly and we can only estimate upper limits, this is seen from the inset of Fig. 7.

³http://astrosat.iucaa.in/~astrosat/GHATS_Package/Home.html

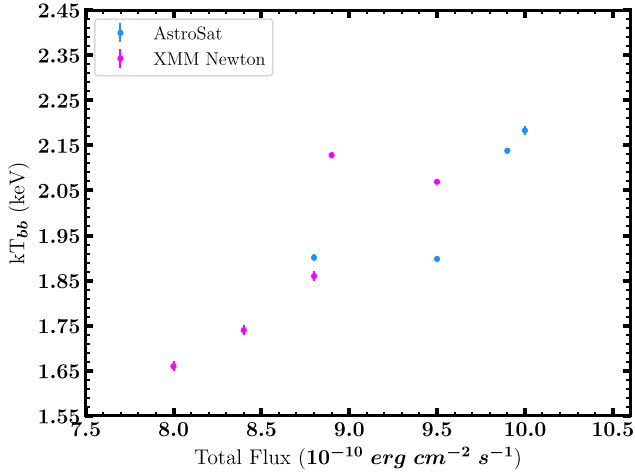


Figure 8. The disc blackbody component from model M1 (see Section 3.1.1) as a function of flux. The flux is calculated between 0.6 and 10.0 keV energy range to match the *XMM-Newton* range. The blue points are *AstroSat* results and the pink points are the *XMM-Newton* and *INTEGRAL* results reported in Díaz Trigo et al. (2009).

3 SPECTRAL ANALYSIS

The joint SXT and LAXPC20 spectral fitting for each of the four sections of the HID is carried out using XSPEC version 12.13.1 (Arnaud 1996). The energy ranges used for SXT and LAXPC20 spectra are between 0.7–7.0 keV and 4.0–20.0 keV, respectively. The counts below 0.7 keV and above 7.0 keV for SXT and above 20.0 keV for LAXPC20 are avoided to minimize the large systematic errors. Also, counts below 4.0 keV for LAXPC20 are ignored due

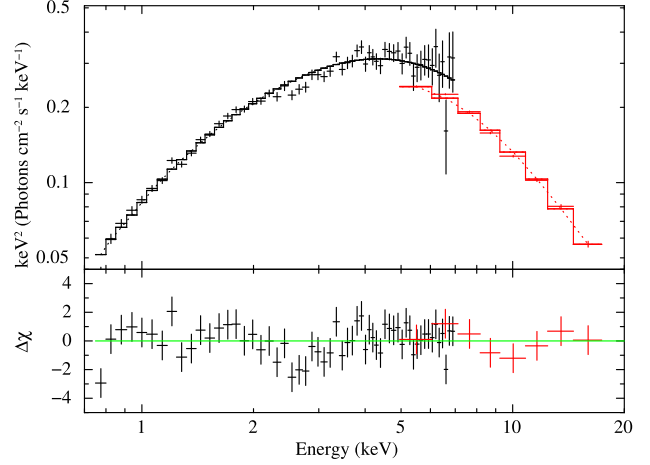


Figure 9. The results of 0.7–20.0 keV *AstroSat* spectral fitting of XB 1254–690 for the first section of the HID (see Section 2.4 for details on HID sections). *Top panel:* The SXT + LAXPC20 spectra. Black points indicate SXT (0.7–7.0 keV) data and red represents the LAXPC20 (4.0–20.0 keV) data. The spectra are fitted with model M2: `const*tbabs*cflux*simpl*diskbb`. *Bottom panel:* Residuals from the model fit.

to the uncertainty in the response matrix. For SXT the ARF file `sxt_pc_excl00_v04_20190608.arf`, RMF file `sxt_pc_mat_gto12.rmf`, and the background file `SkyBkg_comb_EL3p5-CL-Rd16p0-v01.pha` are used. The RMF file `lx20cshp01Lv1.0.rmf` is used for LAXPC20. All these files are obtained from the payload operation centre (POC)

Table 2. Spectral fitting parameters of XB 1254–690 spectra in the banana state observation with *AstroSat*. Joint SXT + LAXPC20 spectra for four sections are fitted with model M1: `const*(tbabs*warmabs*(diskbb+comptt) + tbabs*(gau1 + gau2))`. Errors represent 90 per cent confidence intervals.

HID section	<i>AstroSat</i>				<i>XMM-Newton</i> and <i>INTEGRAL</i> ^a
	1	2	3	4	
Parameter	Comp.				
kT_0 (keV)	comptt	0.222 ± 0.008	0.261 ± 0.015	0.216 ± 0.015	0.231 ± 0.013
kT_{comptt} (keV)		4.61 ± 0.06	3.34 ± 0.03	3.65 ± 0.04	3.28 ± 0.03
τ_p		4.42 ± 0.06	7.44 ± 0.10	7.09 ± 0.11	7.90 ± 0.10
k_{comptt}		0.0287 ± 0.0008	0.0191 ± 0.0006	0.0165 ± 0.0007	0.0325 ± 0.0009
kT_{bb} (keV)	dbb	1.901 ± 0.007	1.898 ± 0.005	2.138 ± 0.006	2.183 ± 0.009
$k_{\text{bb}} [(R_{\text{in}}/D_{10})^2 \cos\theta]$		2.78 ± 0.04	3.32 ± 0.04	2.29 ± 0.02	1.78 ± 0.03
E_{gau} (keV)	gau ₁	6.8 ± 0.3	7.0 ± 0.2	6.9 ± 0.3	7.0 ± 0.2
σ (keV)		0.53^f	0.53^f	0.53^f	0.53^f
k_{gau} (10^{-4} ph cm^{-2} s^{-1})		2.0 ± 0.5	2.2 ± 0.5	2.3 ± 0.6	2.9 ± 0.7
E_{gau} (keV)	gau ₂	0.85 ± 0.04	0.92 ± 0.09	<1.73	$0.84_{-0.10}^{+0.047}$
σ (keV)		0.1^f	0.1^f	0.1^f	0.1^f
k_{gau} (10^{-3} ph cm^{-2} s^{-1})		$1.2_{-0.2}^{+0.3}$	2.3 ± 0.1	<0.67	3.9 ± 0.2
$N_{\text{H}}^{\text{abs}}$ (10^{22} cm^{-2})	tbabs	0.20 ± 0.01	0.19 ± 0.01	0.15 ± 0.01	0.22 ± 0.01
$N_{\text{H}}^{\text{warmabs}}$ (10^{22} cm^{-2})	warmabs	2.0^f	2.0^f	2.0^f	2.0^f
$\log(\xi)$ (erg cm s^{-1})		3.95^f	3.95^f	3.95^f	3.95^f
σ_v (km s^{-1})		2600^f	2600^f	2600^f	2600_{-1300}^{+1700}
v (km s^{-1})					-1400 ± 780
χ^2_{ν} (degrees of freedom)		0.99 (53)	1.13 (56)	0.90 (56)	1.09 (56)
F (10^{-10} erg cm^{-2} s^{-1}) (0.6–10.0 keV)		8.8	9.5	9.9	10.0
F_{dbb} (10^{-10} erg cm^{-2} s^{-1}) (0.6–10.0 keV)		7.1	8.0	9.1	8.6
Exposure (ks)		$6.1^s/19.1^l$	$12.9^s/33.6^l$	$11.3^s/35.6^l$	$3.5^s/7.2^l$
r_{in} (km) ^b	True Inner Disc Radius	6.12 ± 0.04	6.69 ± 0.04	5.55 ± 0.02	4.90 ± 0.03

Notes. ^a Díaz Trigo et al. (2009). ^b $f = 1.7$, colour or correction factor. ^f represents that the parameters are fixed to the values reported in Díaz Trigo et al. (2009) while fitting SXT and LAXPC20 joint spectra. ^s and ^l denotes the exposure time for SXT and LAXPC20 corresponding to each HID section.

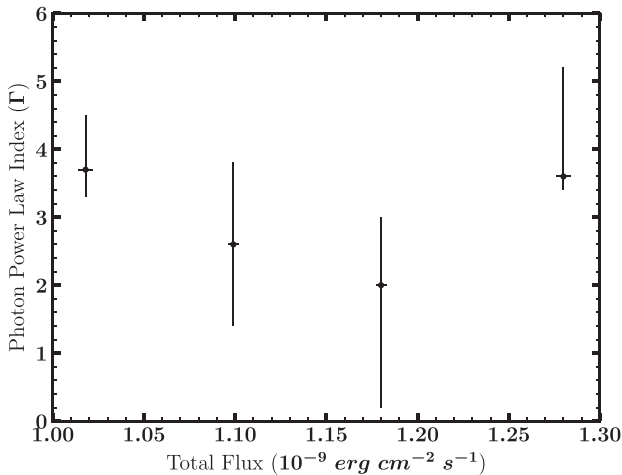


Figure 10. The results of 0.7–20.0 keV *AstroSat* spectral fitting of XB 1254–690 for the four HID sections (see Section 2.4 for details on HID sections). Spectral fitting parameter: photon power-law index (Γ) as a function of total flux. We do not observe a notable trend within the uncertainties.

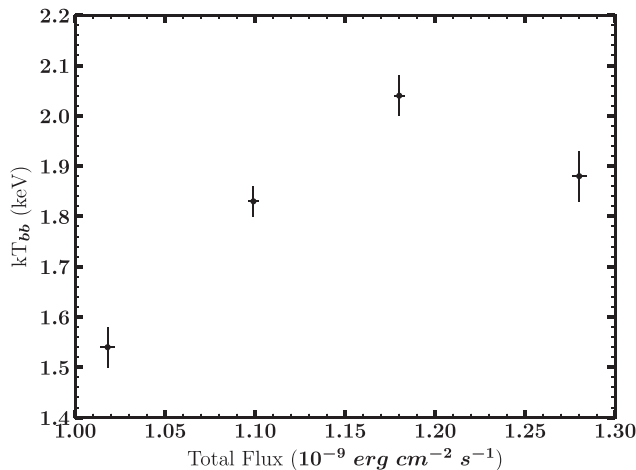


Figure 11. The results of 0.7–20.0 keV *AstroSat* spectral fitting of XB 1254–690 for the four HID sections (see Section 2.4 for details on HID sections). Spectral fitting parameter: Diskbb temperature (kT_{in}) as a function of total flux, found to be increasing as the source become harder.

of SXT⁴ and LAXPC.⁵ The background spectrum for LAXPC20 is generated using *laxpc_make_backspectra* tool of LAXPCSOFT. For the ease of χ^2 fitting in joint spectral analysis, the re-binning of the channels is performed to match the intrinsic spectral resolution of SXT⁶ and LAXPC⁷. A systematic uncertainty of 3 per cent is added while performing the spectral fitting. The SXT data are corrected for the gain; we used *gain_fit* command in XSPEC, keeping slope fixed to unity. We also included cross-normalization constant using *constant* model in XSPEC for the joint spectral fitting, considering it to be unity for SXT and allowing to vary for the LAXPC20 spectrum. This helps

⁴https://www.tifr.res.in/~astrosat_sxt/dataanalysis.html

⁵https://www.tifr.res.in/~astrosat_laxpc/LaxpcSoft.html

⁶Page 52 of *AstroSat* Handbook Ver: 1.11 http://www.iucaa.in/~astrosat/AstroSat_handbook.pdf

⁷Page 6 of *AstroSat* Handbook Ver: 1.11 http://www.iucaa.in/~astrosat/AstroSat_handbook.pdf

us to account for the cross-calibration normalization uncertainties in the fit. We also excluded dips while performing the spectral fitting of section 1 for the source.

The spectra from SXT and LAXPC20 data are jointly fitted with two sets of models. The first model [cons*(tbabs*warmabs*(diskbb+comptt) + tbabs*(gau₁ + gau₂))], called M1 here, is the one used by Díaz Trigo et al. (2009) to analyse the *XMM-Newton* and *INTEGRAL* data of XB 1254–690. Some of the parameters in this model, however, could not be constrained and had to be held constant to the values reported in Díaz Trigo et al. (2009). Hence, we also used a second more generic model [cons*tbabs*simpl*diskbb], called M2, to elicit the source behaviour.

3.1 Flux resolved spectroscopy

3.1.1 Model M1

The spectra are generated using GTIs for each of the HID sections (mentioned in Section 2.4). We fit the joint SXT + LAXPC20 spectra in the energy range 0.7–20.0 keV for all four intensity dependent sections for XB 1254–690 using the model M1, which is used by Díaz Trigo et al. (2009) to fit *XMM-Newton* and *INTEGRAL* data. The model M1 is consisting of a disc blackbody (diskbb) and a thermal Comptonization component (comptt). Both these components are modified by neutral photo-electric absorption ($N_{\text{H}}^{\text{abs}}$) and ionized photo-electric absorption using warmabs model, along with two Gaussian emission components. The warmabs model is consisting of column density of absorber ($N_{\text{H}}^{\text{warmabs}}$), ionization parameter $\xi = L/nR^2$ (L is the luminosity of the incident radiation, n is the gas density, and R is the distance from the radiation source), turbulent velocity broadening σ_v , and the average systematic velocity shift of the absorber v . The warmabs is used to model the photo-ionized plasma absorption in the line of sight. While fitting the SXT + LAXPC20 spectra we kept the warmabs and both Gaussian component parameters fixed to that of the *XMM-Newton* and *INTEGRAL* parameters reported in Díaz Trigo et al. (2009). Also to make a reasonable comparison between our results and *XMM-Newton* and *INTEGRAL* results, we calculated the flux between 0.6 and 10.0 keV range by standardizing the energy range using the *energies* command within XSPEC while fitting. A significant change in the disc blackbody component is observed when we fitted the spectra by keeping warmabs and Gaussian parameters consistent with the *XMM-Newton* and *INTEGRAL* results. The detailed best-fitting spectral parameters using M1 for HID sections 1 to 4 (sections given in Fig. 2) are given in Table 2. The disc blackbody temperature (kT_{bb}) as a function of flux is shown in Fig. 8, along with the *XMM-Newton* and *INTEGRAL* values reported in table 4 of Díaz Trigo et al. (2009). We found that the change in the disc blackbody temperature is consistent with that of the *XMM-Newton* and *INTEGRAL* values. We observe the shift in the flux values for *AstroSat* results as we are considering the entire observation for our study without excluding flares; though, we are not considering the dips while fitting the spectra. Note that Díaz Trigo et al. (2009) have considered only persistent emission from all five observations (two observations with deep dips, one with shallow dip, and two without dips) excluding dips and bursts.

3.1.2 Model M2

The joint spectra of SXT and LAXPC20 in the energy range of 0.7–20.0 keV are fitted with the model M2 consisting of a combination

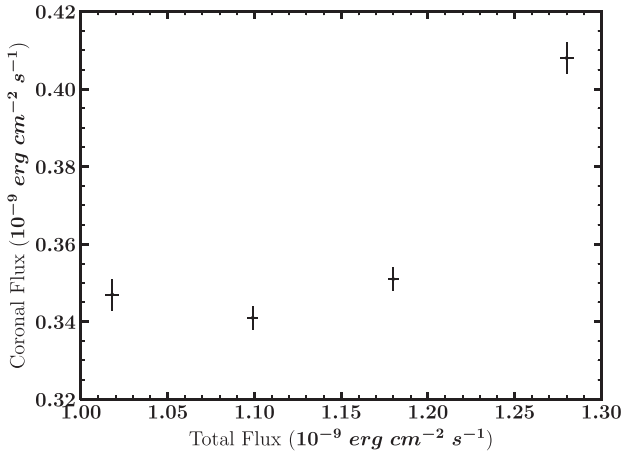


Figure 12. Coronal flux of XB 1254–690 as a function of total flux for the four sections of HID (see Section 2.4 for details on HID sections).

of Comptonization (`simpl`; Steiner et al. 2009) and a multicoloured disc blackbody (`diskbb`; Mitsuda et al. 1984; Makishima et al. 1986) along with Galactic absorption (`TBabs`). We implemented the convolution model `cflux` in this model, to estimate the total flux and disc flux for the energy range 0.7–20.0 keV and calculated the coronal flux of the source (Fig. 12). The best-fitting spectra for the first HID section (section 1, black given in Fig. 2) are shown in Fig. 9, along with the residuals. The detailed best-fitting spectral parameters for HID sections 1 to 4 are given in Table 2.

We observed the variations in the inner disc temperature (kT_{bb}) as a function of total flux (Fig. 11). We did not observe significant variations in the photon power-law index (Γ) (Fig. 10). The best-fitting offset values for the SXT gain fit were found to be 42.41, 34.26, 53.88, and 44.33 eV for sections 1, 2, 3, and 4, respectively. Furthermore, we did not observe improvement in the fitting parameter values by adding an iron line to the spectral model.

3.2 Constraining disc inner edge radius

The normalization parameter of `diskbb` model is defined as $(R_{\text{in}}/D_{10})^2 \cos \theta$, where R_{in} is the apparent inner disc radius in km, D_{10} is the distance to the source in 10 kpc units, and θ is the angle of the disc with respect to the observer. In our spectral fitting using M1 and M2, we observed the variation in the `diskbb` normalization (k_{bb}) for sections 1, 2, 3, and 4 of HID. We calculated the disc inner edge radius (r_{in}) using `diskbb` normalization from both M1 and M2 (Fig. 13). We considered distance to source as 7.6 ± 0.8 kpc (Gambino et al. 2017), inclination angle between 65° and 73° (Motch et al. 1987; Díaz Trigo et al. 2009), and a colour or a correction factor (f) as 1.7 (Shimura & Takahara 1995). The disc inner edge radius (r_{in}) is found to be decreasing as the source became harder from section 1 to section 4 (Fig. 13). The calculated values of r_{in} in km for each section are given in Table 3.

4 DISCUSSION

In this paper, we report the results of the flux resolved spectroscopy of XB 1254–690 data observed with *AstroSat* between 2018 May 03 and 2018 May 05. We have utilized the data from two pointing instruments (SXT and LAXPC) onboard *AstroSat*. The hardness ratio of the source is variable. XB 1254–690 is found to be exhibiting flares at the beginning of this observation. The flaring phenomenon

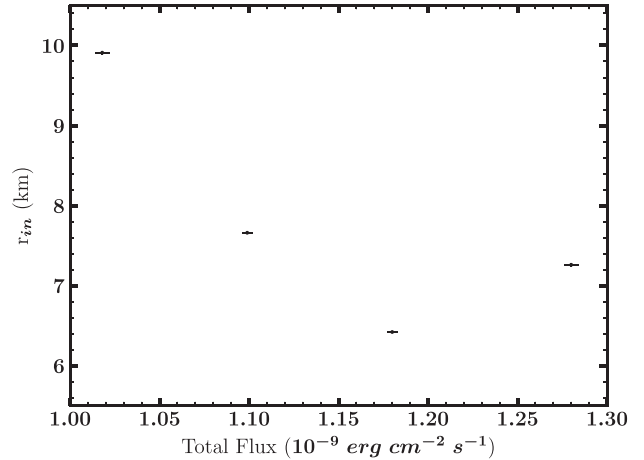


Figure 13. True inner disc radius (r_{in}) in km for XB 1254–690 as function of total flux for each HID section, calculated using `diskbb` normalization k_{bb} .

is a high energy phenomenon dominated by hard X-rays and hence were found to be associated with the hardness ratio and intensity. We observe two dips after the flaring episodes during this observation. The first dip we observed is a ‘shallow’ dip, and the second is a ‘deep’ dip. Dips are related to an increased absorption at low energies and, therefore, with an anticorrelation between hardness and intensity. The first dip with 100 s time resolution is identified as ‘shallow’, is consisting of a few rapid, deep variations with a time resolution of 1 s. The characteristics of dips are consistent with that observed in the earlier observations (Díaz Trigo et al. 2009). The presence of flares, along with dips and thermonuclear X-ray bursts, has been reported earlier (Smale et al. 2002; Mukherjee & Bhattacharyya 2011). This is the first time we observed strong flares in XB 1254–690 at the beginning, which is followed by two dips. The X-ray dipping properties of the source have been studied extensively in earlier observations (Iaria et al. 2001, 2007; Smale et al. 2002; Mukherjee & Bhattacharyya 2011). Most of the studies have reported the properties of persistent emission alone. Nevertheless, a detailed study of XB 1254–690 data inclusive of flares (and excluding dips) have not been done earlier.

XB 1254–690 was found to be in a banana state during this observation. Bhattacharyya (2007) established that XB 1254–690 is an atoll source. In the island state, an atoll source does not move up and down so fast, and the track is not as well-defined as in the banana state (see review by Lewin & van der Klis 2006). The shape of the track in the HID, after comparing with the HID tracks of atoll sources (e.g. in Lewin & van der Klis 2006), including the HID track of XB 1254–690 given in Bhattacharyya (2007), strongly indicates that the source is in the banana state during this observation.

We have performed a flux resolved spectroscopy on the spectra extracted at the different intensity levels with changing hardness. Mukherjee & Bhattacharyya (2011) reported the systematic continuum (excluding flares, dips, and bursts) spectral analysis of XB 1254–690 using *RXTE* observations. They performed analysis using 19 various combinations of continuum spectral models (see table 1 of Mukherjee & Bhattacharyya 2011) on the upper banana state and lower banana state of the source and suggested that the `bknpower` + `comptt` is the preferred model for the continuum. In our study, we considered the observation, which includes flares but excludes dips (note that thermonuclear bursts were not observed) and

extracted the spectra from four different sections of HID. The joint SXT and LAXPC20 spectra with total energy of 0.7 to 20.0 keV for each of the HID sections were well fitted with two sets of models – M1: `cons*tbabs*warmabs*(diskbb+comptt) + tbabs*(gau1 + gau2)` and M2: `cons*tbabs*cflux*simpl*diskbb`. Model M1 consists of a disc blackbody (`diskbb`) and thermal Comptonization component (`comptt`), along with neutral photo-electric absorption ($N_{\text{H}}^{\text{abs}}$) and ionized photo-electric absorption using `warmabs` model and two Gaussian emission components. Model M2 consists of Comptonization model and a multicoloured disc blackbody model along with Galactic absorption. In M2, we tried replacing `diskbb` model with the blackbody model, which resulted in a much higher reduced χ^2 (~ 3.4). Therefore, we suggest that `simpl*diskbb` is a non-complex model, suitable for the spectra (which includes flares) of XB 1254–690 in 0.7–20.0 keV energy range.

In model M1 (see Table 2), we have kept the `warmabs` parameters identical with *XMM-Newton* parameters (Díaz Trigo et al. 2009), to measure the disc blackbody temperature (kT_{bb}) and flux using the SXT. This allowed us to discover the kT_{bb} and flux correlation for XB 1254–690 for the first time. The disc blackbody temperature is lower for section 1 (1.883), increased gradually for the sections that do not have dips or flares (2.005 and 2.134), and highest for the section which has flares (2.386). The change in the disc blackbody temperature we observed is consistent with the trend observed in the Díaz Trigo et al. (2009). The significant increase in the blackbody temperature during the flares has been observed in the Z-source Sco X-1 (White et al. 1985) and the systematic increase in the inner disc temperature of the big dipper X 1624 – 490 has also been previously reported (Balucińska-Church et al. 2001).

In model M2 (see Table 3), the lower energy coverage of SXT allowed us to constrain Galactic column density for the source. The photon power-law index as a function of total flux (Fig. 10) does not show a significant trend given the uncertainties. In M2, the inner disc temperature (kT_{bb}) is found to increase from sections 1 to 3 (Fig. 11) with a minimum value of 1.54 ± 0.04 and a maximum value of 2.04 ± 0.04 . However, it decreases slightly for section 4. We computed the coronal flux for XB 1254–690 and plotted it as a function of the total flux (Fig. 12). The coronal flux was found to be increasing as the total source flux increased. The disc inner edge radius (r_{in}) (Fig.

13) calculated using the values of `diskbb` normalization (k_{bb}) and are given in Tables 2 and 3.

Although XB 1254–690 has been the target of many X-ray missions since its discovery in 1984, timing characteristics were not reported until 2011, in the *RXTE* observations of 2008 January 06 to March 13 (Mukherjee & Bhattacharyya 2011). In these observations Mukherjee & Bhattacharyya (2011) detected high-frequency QPOs ~ 96 Hz. In the *AstroSat* observations, we did not detect the ~ 96 Hz QPO or the high-frequency QPOs reported by Mukherjee & Bhattacharyya (2011). This is probably because the source was in the high-intensity upper banana state (UB), which is also indicated by the very low-frequency noise (VLFN) detected in the PDS (van der Klis 2004, 2006). The rms of the VLFN tends to increase with energy as seen in Fig. 7 where we show the relation up to the energy range 20 keV. Beyond 20 keV, the rms drops as shown in the inset of Fig. 7, indicating that the VLFN up to 20 keV is related to the unstable accretion dynamics of matter falling on to the neutron star. The presence of VLFN (~ 3 Hz) also indicates that the source was in the UB during this observation (van der Klis 2004, 2006; Bhattacharyya 2007). Low-Frequency Quasi-periodic Oscillations (LFQPOs), called 1 Hz QPOs, are usually seen in dipping LMXBs like XB 1254–690. These LFQPOs have not been reported so far in XB 1254–690 (Bhattacharyya 2007; Mukherjee & Bhattacharyya 2011; Homan 2012). In our analysis of the *AstroSat* observation, we detect a ~ 0.65 Hz signal with low significance ($\sim 2.7\sigma$) that can be confirmed with longer observations.

In summary, for the first time, we have found a kT_{bb} and flux correlation for NS-LMXB XB 1254–690. We have also given a constraint on the disc inner edge radius and tried to understand its evolution during flares using SXT and LAXPC onboard *AstroSat* data through the flux-resolved spectroscopy. Future observation of the source with *AstroSat*, simultaneously with *Nuclear Spectroscopic Telescope Array* (*NuSTAR*) (for the hard band) and *Neutron star Interior Composition Explorer* (*NICER*) (for the soft band), can be used to study the source in detail and to give better constraints to the parameters. Recurrent monitoring of the source can provide a distinctive opportunity to study the evolution of these parameters, and it will help us correlate them.

Table 3. Spectral fitting parameters of XB 1254–690 spectra in the banana state observation with *AstroSat*. Joint SXT + LAXPC20 spectra is fitted with model M2: `cons*tbabs*cflux*simpl*diskbb`. Errors represent 90 per cent confidence intervals. True inner disc radius for XB 1254–690 calculated using disc blackbody normalization for each HID section

HID section	Comp.	<i>AstroSat</i>			
		1	2	3	4
Parameter	Comp.				
$N_{\text{H}}^{\text{abs}}$ (10^{22} cm $^{-2}$)	tbabs	0.08 ± 0.02	0.10 ± 0.01	0.08 ± 0.01	0.09 ± 0.01
c_{flux} (10^{-9} erg cm $^{-2}$ s $^{-1}$)	Total Flux (0.7–20.0 keV)	1.018 ± 0.004	1.099 ± 0.003	1.180 ± 0.003	1.280 ± 0.004
Γ	simpl	$3.7^{+0.4}_{-0.8}$	2.6 ± 1.2	$2.0^{+1.8}_{-1.0}$	$3.6^{+0.2}_{-1.6}$
FracSctr		$0.46^{+0.07}_{-0.06}$	0.17 ± 0.02	0.10 ± 0.01	$0.61^{+0.19}_{-0.14}$
kT_{bb} (keV)	dbb	1.54 ± 0.04	1.83 ± 0.03	2.04 ± 0.04	1.88 ± 0.05
$k_{\text{bb}} [(R_{\text{in}}/D_{10})^2 \cos\theta]$		$7.3^{+1.9}_{-2.3}$	4.4 ± 0.7	$3.1^{+0.7}_{-1.0}$	$3.8^{+0.5}_{-0.8}$
c_{flux} (10^{-9} erg cm $^{-2}$ s $^{-1}$)	dbb Flux (0.7–20.0 keV)	0.671 ± 0.005	0.758 ± 0.001	0.829 ± 0.001	0.872 ± 0.001
c_{flux} (10^{-9} erg cm $^{-2}$ s $^{-1}$)	Coronal Flux (0.7–20.0 keV)	0.347 ± 0.004	0.341 ± 0.003	0.351 ± 0.003	0.408 ± 0.004
χ^2_{ν} (degrees of freedom)		1.16 (60)	1.15 (58)	1.16 (60)	1.13 (60)
r_{in} (km) ^a	True Inner Disc Radius	9.91 ± 0.02	7.66 ± 0.01	6.42 ± 0.01	7.26 ± 0.02

Notes. ^af = 1.7, colour or correction factor. Parameter 3: *UpScOnly* of the `simpl` model is frozen to unity during spectral fitting.

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DATA AVAILABILITY

The observational data utilized in this article are publicly available at ISRO's Science Data Archive for *AstroSat* Mission (https://astrorowse.issdc.gov.in/astro_archive/archive/Home.jsp). The additional information regarding data and data analysis will be available upon reasonable request.

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