A broadband look of the Accreting Millisecond X-ray Pulsar SAX J1748.9-2021 using AstroSat and XMM-Newton

Rahul Sharma1, Aru Beri2,3, Andrea Sanna4 and Anjan Dutta1

1Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India
2DST-INSPIRE Faculty, IISER Mohali, Punjab, India 140306
3School of Physics and Astronomy, University of Southampton, Southampton, Hampshire, SO17 1BJ United Kingdom
4Università degli Studi di Cagliari, Dipartimento di Fisica, SP Monserrato-Sestu, KM 0.7, 09042 Monserrato, Italy

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ABSTRACT

SAX J1748.9-2021 is a transient accretion powered millisecond X-ray pulsar located in the Globular cluster NGC 6440. We report on the spectral and timing analysis of SAX J1748.9-2021 performed on AstroSat data taken during its faint and short outburst of 2017. We derived the best-fitting orbital solution for the 2017 outburst and obtained an average local spin frequency of 442.361098(3) Hz. The pulse profile obtained from 3–7 keV and 7–20 keV energy bands suggest constant fractional amplitude ∼0.5% for fundamental component, contrary to previously observed energy pulse profile dependence. Our AstroSat observations revealed the source to be in a hard spectral state. The 1–50 keV spectrum from SXT and LAXPC on-board AstroSat can be well described with a single temperature blackbody and thermal Comptonization. Moreover, we found that the combined spectra from XMM-Newton (EPIC-PN) and AstroSat (SXT+LAXPC) indicated the presence of reflection features in the form of iron (Fe Kα) line that we modeled with the reflection model xillvercp. One of the two X-ray burst observed during the AstroSat/LAXPC observation showed hard X-ray emission (>30 keV) due to Compton up-scattering of thermal photons by the hot corona. Time resolved analysis performed on the bursts revealed complex evolution in emission radius of blackbody for second burst suggestive of mild photospheric radius expansion.

Key words: accretion, accretion discs – stars: neutron – X-ray: binaries – X-rays: bursts – X-rays: individual (SAX J1748.9-2021)

1 INTRODUCTION

Low Mass X-ray Binaries (LMXBs) are composed of a compact object (a black hole or a neutron star) that accretes matter from a low mass companion star, ≤ 1M☉. In some neutron star (NS) LMXBs, X-ray pulsations of the order of millisecond have been detected (see e.g., Chakrabarty & Morgan 1998; Wijnands & van der Klis 1998; Galloway et al. 2002; Markwardt et al. 2002; Papitto et al. 2013b; Sanna et al. 2018c,d). These systems are called accretion powered millisecond X-ray pulsars (AMXPs) (see e.g., Patruno & Watts 2012; Campana & Di Salvo 2018, for reviews). The magnetic field estimated in these systems is of the order of 107 − 109 Gauss (see e.g., Cackett et al. 2009; Mukherjee et al. 2015; Ludlam et al. 2017; Sharma et al. 2019). Currently, 22 AMXPs are known and all of them are transient in nature, observed during outbursts in the past 21 years (Marino et al. 2019).

SAX J1748.9-2021 is an AMXP discovered with BeppoSAX during its 1998 outburst (in ’t Zand et al. 1999). It is located in the globular cluster NGC 6440 at a distance of ∼8.5 kpc (see e.g., Ortolani et al. 1994; Kuulkers et al. 2003; Valenti et al. 2007). The mass and radius of the companion star is estimated to be within the range of 0.70 – 0.83 M⊙ and 0.86 – 0.90 R⊙ (see, Cadelano et al. 2017). Since 1998 only six outbursts have been observed in SAX J1748.9-2021 (in ’t Zand et al. 1999; in ’t Zand et al. 2001; Markwardt & Swank 2005; Patruno et al. 2010; Pintore et al. 2016, 2018; Negoro et al. 2017; Sharma et al. 2019). SAX J1748.9-2021 showed intermittent pulsations at ~ 442.3 Hz during its
2001, 2005, 2010 and 2015 outbursts, from which the orbital period of $\sim 8.76$ h and projected semi-major axis of $\sim 0.4$ light-seconds was inferred (Gavriil et al. 2007; Altamirano et al. 2008; Patruno et al. 2009, 2010; Sanna et al. 2016).

The X-ray spectrum observed during the latest outburst of 2017 revealed the presence of hard spectral state (Pintore et al. 2018) similar to that observed during its 1998 outburst (in 't Zand et al. 1999). However, during other outbursts observed in this source spectral state transition (hard to soft) was found (Patruno et al. 2009; Li et al. 2018; Wu et al. 2018). SAX J1748.9-2021 shows the hard and soft spectral states (in 't Zand et al. 1999; Patruno et al. 2009; Pintore et al. 2016, 2018; Li et al. 2018; Wu et al. 2018; Sharma et al. 2019) as of the atoll sources (Hasinger & van der Klis 1989). The spectrum of SAX J1748.9-2021 has been described with a combination of following components: thermal emission from an accretion disc and/or NS surface, thermal Comptonization and the reflected emission from the accretion disc (in 't Zand et al. 1999; Pintore et al. 2016, 2018; Li et al. 2018; Wu et al. 2018; Sharma et al. 2019). An additional hard power-law tail was observed during the soft state of the 2015 outburst (Pintore et al. 2016).

Another interesting characteristic of SAX J1748.9-2021 is that it shows thermonuclear X-ray bursts (Type-I X-ray bursts) during its outbursts (in 't Zand et al. 1999; Kaaret et al. 2003; Galloway et al. 2008; Beri et al. 2016; Pintore et al. 2016, 2018; Li et al. 2018; Wu et al. 2018). Photospheric Radius Expansion (PRE) bursts have been observed in this source and were used to obtain mass and radius estimates of the NS (Güver & Özel 2013).

India’s first dedicated multi-wavelength astronomy satellite, AstroSat (Agrawal 2006; Singh et al. 2014), was launched in 2015. It has five principal payloads on-board: (i) the Soft X-ray Telescope (SXT), (ii) the Large Area X-ray Proportional Counters (LAXPCs), (iii) the Cadmium-Zinc-Telluride Imager (CZTI), (iv) the Ultra-Violet Imaging Telescope (UVIT), and (v) the Scanning Sky Monitor (SSM). Here, we have performed a broadband spectroscopy using simultaneous XMM-Newton and AstroSat (SXT and LAXPC) data of SAX J1748.9-2021 observed during its latest outburst of 2017. We also report results from the timing and burst analysis carried out with AstroSat/LAXPC data.

### 2 OBSERVATIONS AND DATA ANALYSIS

#### 2.1 AstroSat/LAXPC

LAXPC is one of the primary instrument aboard AstroSat. It consists of three co-aligned identical proportional counters (LAXPC10, LAXPC20 and LAXPC30) that work in the energy range of 3–80 keV. Each LAXPC detector independently record the arrival time of each photon with a time resolution of 10 $\mu$s and has five layers, each with 12 detector cells (for details see Yadav et al. 2016; Antia et al. 2017).

Table 1 gives the log of observations that have been used in this work. Due to the gain instability issue caused by gas leakage, we have not used LAXPC30 data. LAXPC data were collected in the Event mode (EA) which contains the information about the time, channel number and anodeID of each event. We have used LAXPC/Soft$¹$ software package to extract light curves and spectra. LAXPC detectors have dead-time of 42 $\mu$s and the extracted products are dead-time corrected. The background in LAXPC is estimated from the blank sky observations (see Antia et al. 2017, for details). We found that the source was detected up to 50 keV, therefore, to minimize the background we have performed spectroscopy using the data of top layer (L1, L2) of each detector (also see Beri et al. 2019, for details). We have used response files to obtain channel to energy conversion information while performing energy-resolved analysis.

We corrected the LAXPC photon arrival times to the Solar system barycentre by using the as1bary$²$ tool. We used the best available position of the source, R.A. (J2000) = $17^{h}48^{m}52.1^{s}$ and Dec. (J2000) = $−20^{\circ}21′32′′.40$ obtained with Chandra (Pooley et al. 2002). Timing analysis is performed on LAXPC10 and LAXPC20 data.

#### 2.2 AstroSat/SXT

The Soft X-ray Telescope (SXT) is a focusing X-ray telescope with CCD in the focal plane that can perform X-ray imaging and spectroscopy in the 0.3–7 keV energy range (Singh et al. 2014, 2016; Singh et al. 2017). SAX J1748.9-2021 was observed in the Photon Counting (PC) mode with SXT (Table 1). Level 1 data were processed with ASISXTevel12-1.4b pipeline software to produce level 2 clean event files and these files were merged using SXT Event Merger Tool (Julia Code$³$). This merged

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1. http://www.tifr.res.in/~astrosat_laxpc/LaxpcSoft.html
2. http://astrosat-ssc.iucaa.in/?q=data_and_analysis
3. http://www.tifr.res.in/~astrosat_sxt/dataanalysis.html
event file was used to extract image, light curves and spectra using the tool task xselect 2.4d, provided as part of HEASOFT version 6.22. A circular region with radius of 15 arcmin centered on the source was used. For spectral analysis, we have used the background spectrum (Sky-Bkg_comb_EL3p5_CL_Rd16p0_v01.pha), spectral redistribution matrix file (sxt_rma1_to12.rmf) and ancillary response file (sxt_rma1_to12.rmf) provided by the SXT team.

### 2.3 XMM-Newton/EPIC-PN

XMM-Newton has European Photon Imaging Camera (EPIC), Reflection Grating Spectrometer (RGS) and Optical Monitor (OM) on-board. The EPIC consists of one PN camera (Strüder et al. 2001) and two MOS detectors (Turner et al. 2001), sensitive in the 0.1–15 keV energy range. The XMM-Newton observation of SAX J1748.9-2021 has an overlap in time with the AstroSat observation (refer to Table 1 for details). For current analysis, we have used the EPIC-PN data which was operated in the timing mode. EPIC-PN data was reduced with SAS v16.1.0 with RDPHA corrections (Pintore et al. 2014). The spectra and light curves were extracted selecting single and double pixel events with PATTERN ≤ 4 and FLAG = 0, which retains events optimally calibrated for spectral analysis. Following Pintore et al. (2018), source and background events were extracted from RAWX=[32:44] and RAWX=[3:5], respectively. The spectra were rebinned with an oversample of 3 and minimum of 25 counts per bin using SPECGROUP task. To avoid the EPIC-pn (timing mode) calibration uncertainties at low energies, we analyzed the spectra in 1.3–10 keV energy range (Pintore et al. 2018).

### 3 RESULTS

#### 3.1 Light Curve

Figure 1 shows the light curve of SAX J1748.9-2021 during its 2017 outburst as observed with the X-ray telescope (XRT) on-board the Neil Gehrels Swift Observatory (Gehrels et al. 2004) and with Gas Slit Camera (GSC) on-board the Monitor of All-sky X-ray Image (MAXI; Matsumo et al. 2009; Mihara et al. 2011). Figure 2 shows the background corrected light curve extracted from LAXPC10 (upper panel) binned at 100 sec. The LAXPC light curves show the persistent emission separated by data gaps due to Earth occultation and South Atlantic Anomaly (SAA) passage. Two Type-I X-ray bursts are also observed in the LAXPC light curves (position marked with black arrows in Figure 2). However, these X-ray bursts were not seen in the SXT light curves (not plotted) as these times when X-ray bursts were observed have been filtered during the Good time filtering. The X-ray burst seen in the PN light curve has been reported earlier (Pintore et al. 2018). Therefore, we have excluded this X-ray burst from our analysis.

During the AstroSat observation, the 3–80 keV background subtracted count rate of persistent emission from LAXPC10 decreased to ∼half from 63 count s⁻¹ at the start of observation to 33 count s⁻¹ at the end of observation (Figure 2). Similar trend was observed with LAXPC20 also. However, we did not observe any change in the hardness ratio calculated using light curves in the two energy bands 3–10 keV and 10–30 keV during the observation (bottom panel of Figure 2), suggesting that source did not seem to change the spectral state with decay in the count rate. The 0.5–10 keV count rate of XMM-Newton decreased to 34 count s⁻¹ from 38 count s⁻¹, during the XMM-Newton observation.

#### 3.2 Timing analysis

We started by correcting the AstroSat/LAXPC time series for the binary orbital motion (see e.g. Burderi et al. 2007, for details on the method) through the available source
eclipsed orbital period.

Following Riggio et al. (2011); Sanna et al. (2016), we estimated the uncertainty on $T^*$ and $\bar{v}$ using Monte Carlo simulations (100 datasets to allow the $1\sigma$ error estimations), obtaining the values $T^*_2017 = T^*_2015 + \Delta T^* = 58034.28452(1)$ MJD(TDB) and $\bar{v} = 442.361098(3$ Hz.

Finally, in Figure 3 we report the best pulse profile obtained after correcting the updated orbital solution. The best-fitting model was the superposition of one and two sinusoidal functions with amplitudes of 0.45% and 0.15% for the fundamental and first overtone, respectively.

We also checked for burst oscillations during the two observed type-I bursts with LAXPC data, but no significant X-ray pulsation compatible with the spin frequency of the source seems to be present. Even after combining the two bursts, no significant pulsations were detected.

### 3.3 Burst Profiles

To understand the energy dependence of X-ray bursts, we extracted light curves in different energy bands namely, 3–6 keV, 6–12 keV, 12–18 keV, 18–24 keV, 24–30 keV and 30–40 keV. Figure 4 shows burst profiles created using the combined data of LAXPC10 and LAXPC20. Light curves are binned with a bin size of 1 sec. SAX J1748.9-2021 has exhibited a wide variety of burst profiles (Galloway et al. 2008; Beri et al. 2016; Pintore et al. 2016, 2018; Li et al. 2018). To quantify the behavior of observed bursts, decay times were measured by modeling the burst profiles using linear rise followed by an exponential decay. We measured the exponential decay time of both bursts in different energy bands. We found that the burst duration decreases with increasing energy. Figure 5 shows the gradual decrease in decay time with increasing energy due to cooling of the burst to lower temperature with the decay of burst (Degenaar et al. 2016; Beri et al. 2019). The first X-ray burst was detected up to 30 keV while the second was observed up to 40 keV (see inset in Fig. 4). Following Beri et al. (2019), we also checked for the presence of dips due to effect of X-ray burst on the hard X-ray emission in hard X-ray light curves during the observed bursts (30–80 keV for burst 1 and 40–80 keV for burst 2). No dip in the hard X-ray light curve was observed during any of the bursts.

### 3.4 Time-Resolved Burst Spectroscopy

To understand the spectral evolution during these X-ray bursts, we have performed time-resolved spectroscopy using spectra extracted with a duration of 1 sec. Spectra obtained from LAXPC10 and LAXPC20 were fitted simultaneously in the energy band of 3–30 keV. We added a cross-calibration constant between the two LAXPC instruments. For all burst intervals, a spectrum extracted from 90 s of data preceding the burst was extracted as the underlying accretion emission.

We fitted each spectrum with a blackbody function (tbbodyrad) in xspec v 12.9.1m (Arnaud 1996). Tbb was used to model interstellar absorption with abundances set to WLM (Wilms et al. 2000) and the cross-sections to VEH (Verner et al. 1996). We fixed the interstellar column density to $N_H = 0.58 \times 10^{22} \text{cm}^{-2}$ (Pintore et al. 2016).

The evolution of count rate in 3–30 keV, blackbody temperature ($kT_{BB}$) in keV, blackbody normalisation ($N_{BB}$), emission radius in km, absorbed flux in 3–30 keV in units of erg cm$^{-2}$ s$^{-1}$ and reduced $\chi^2$ during each burst are plotted in Figure 6 from top to bottom, respectively. Burst 2 was brighter than burst 1 and the temperature measured during the peak of this burst is $2.88 \pm 0.05$ keV. Moreover, the evolution of the blackbody radius indicates the presence of PRE phase. The peak temperature of burst 1 was observed to be $2.54 \pm 0.05$ keV. We calculated the bolometric flux ($F_{bol}$) using $F_{bol} = 1.076 N_{BB} (kT_{BB})^4 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$ (Galloway et al. 2008). At peak, bolometric flux was ob-
of energy.

served to be $2.09 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ and $2.57 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ for burst 1 and 2, respectively.

3.5 Broadband Spectral Analysis

We performed a broadband spectroscopy (1–50 keV) using the data during persistent emission obtained with SXT (1–7 keV) and LAXPC (3–50 keV) aboard AstroSat. Data below 1 keV was ignored due to low energy calibration issue of SXT. We used only LAXPC10 detector from LAXPC instrument for broadband spectral fitting, LAXPC20 was avoided due to instrument calibration issues at higher energies. The LAXPC10 spectra was regrouped as 0–99 by 2 channels, 100–199 by 4 channels and above 200 by 8 channels. A systematic uncertainty of 2% was added to LAXPC spectra (Antia et al. 2017; Sreehari et al. 2019). The SXT spectra was grouped using GRPPHA to have a minimum of 25 counts per bin. While performing spectral fitting, we added a multiplicative constant component to account for cross-calibration between two instruments. The parameter value of the constant was fixed to 1 for LAXPC10 and for SXT allowed to vary. We also allowed the gain of the response file of SXT to vary, with slope fixed to 1. We obtained a gain offset of $\sim 37$ eV. We have used tbabs to model interstellar neutral hydrogen absorption.

The X-ray spectral continuum of SAX J1748.9-2021 during its 2017 outburst was best fitted using a blackbody and Comptonization model (Pintore et al. 2018). However, we noticed that during its 1998 outburst, the X-ray spectral continuum was best fitted using a blackbody and neutral hydrogen absorption.

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The X-ray spectral continuum of SAX J1748.9-2021 during its 2017 outburst was best fitted using a blackbody and Comptonization model (Pintore et al. 2018). However, we noticed that during its 1998 outburst, the X-ray spectral continuum was best fitted using a single thermal Comptonized emission (in ’t Zand et al. 1999). Therefore, we began to model the combined spectra from SXT and LAXPC using a thermal Comptonized model nthcomp (Zdziarski et al. 1996; Życki et al. 1999). We found that tbabs*nthcomp gave an unsatisfactory fit, $\chi^2$/dof = 631/526. We also observed residuals around 30 keV which is due to the Xenon calibration edge (Antia et al. 2017) and modeled using a Gaussian. Addition of a second blackbody component (soft thermal component) improved the fit and we obtained a value of $\chi^2$/dof to be 599.8/524 (Figure 7). We would like to mention that we did not find any residuals around 6.4 keV (due

Table 2. The obtained best fit spectral parameters for SAX J1748.9-2021. Reported errors and limits are at 90% for one parameter.

| Model      | Parameters | SXT+LAXPC | SXT+XMM+LAXPC |
|------------|------------|-----------|---------------|
| Tbabs      | $N_H$ (10$^{22}$ cm$^{-2}$) | 0.67 ± 0.10 | 0.74 ± 0.08 |
| Bhobyrad   | $kT_{BB}$ (keV) | 1.12 ± 0.3 | 1.09 ± 0.04 |
|            | Norm       | 2.74$^{+1.8}_{-1.0}$ | 13.2 ± 1.5 |
| Nthcomp    | $\Gamma$ | 1.60 ± 0.04 | 1.719 ± 0.025 |
|            | $kT_{soft}$ (keV) | 0.35 ± 0.06 | $< kT_{BB}$ |
|            | $kT_{BB}$ (keV) | > 15.5 | > 14 |
|            | Norm       | 0.024$^{+0.004}_{-0.003}$ | 0.012 ± 0.003 |
| XillverCP  | log $\xi$ | 3.5 ± 0.3 | 1.5 ± 0.3 |
|            | $A_{Fe}$ | 1.5 ± 0.3 | 1.5 ± 0.3 |
|            | Norm (10$^{-4}$) | 1.1$^{+0.3}_{-0.2}$ |
| Constant   | $C_{LAXPC}$ | 1 (fixed) | 1 (fixed) |
|            | $C_{SXT}$ | 1.12 ± 0.04 | 1.19 ± 0.03 |
|            | $C_{XMM}$ | - | 1.01 ± 0.016 |
| Unabs. Flux| $F_{0.1-100}$ keV | $9.5 \times 10^{-10}$ | $7.73 \times 10^{-10}$ |
|           | (erg cm$^{-2}$ s$^{-1}$) | 509.8/524 | 527.5/493 |

Figure 4. AstroSat-LAXPC (LAXPC10+LAXPC20) background-corrected light curve of the two X-ray bursts in different energy bands. The inset shows light curves in two energy bands 24–30 keV and 30–40 keV.

Figure 5. The exponential decay time of two bursts as a function of energy.
We extracted the SXT and LAXPC spectra using data that was strictly simultaneous with the XMM-Newton observation. We removed the X-ray burst from the XMM-Newton data to obtain the spectrum during the persistent emission. These three spectra were simultaneously fitted with absorbed blackbody and Comptonized blackbody model. We fixed the value of calibration-constant to be 1 for LAXPC and let it free to vary for SXT and EPIC-PN. Gaussian models at $\sim 2.2$ keV and 30 keV were included to account for the Au-M calibration edge feature of XMM-Newton (Papitto et al. 2009; Ferrigno et al. 2014) and Xenon calibration edge of LAXPC (Antia et al. 2017), respectively, as seen in the residuals. We also found systematic residuals around 6.5 keV (see Fig-8b), arising due to the Fe K emission feature. This feature has also been reported by Pintore et al. (2018). Therefore, we added a Gaussian model component and obtained the emission line energy at 6.43$^{+0.22}_{-0.24}$ keV having a width of 0.77$^{+0.67}_{-0.54}$ keV. The equivalent width of this iron line feature is about 63 eV ($\chi^2$/dof = 532/493). With a fixed width of 0.13 keV, emission line energy found at 6.54$^{+0.06}_{-0.08}$ keV with equivalent width of 18.5 eV ($\chi^2$/dof = 533/494), consistent with Pintore et al. (2018). Next, we added the reflection component xillvercp (García & Kallman 2010; García et al. 2013) to account for the emission line, assuming it to be originating due to accretion disc reflection. The spectral shape of the xillvercp was assumed to be same as nthcomp. The inclination angle of the accretion disc was unconstrained during the fit, so we fixed it to 32$^{\circ.3}$ (Sharma et al. 2019). The free parameters of xillvercp were log\(\xi\), iron abundance (\(A_{Fe}\)) and normalization. After adding the reflection component, fit improved to $\chi^2$/dof = 527.5/493 with F-test probability of $\sim 5 \times 10^{-9}$. The disc was found to be highly ionized with ionization parameter of $\xi \sim 3200$ erg cm s$^{-1}$. The blackbody temperature was found to be $\sim 0.6$ keV and only lower limits of $> 14$ keV on the electron temperature of corona was obtained, consistent with Pintore et al. (2018). Additionally, we found lower value of SXT gain offset $\sim 17$ eV. The best fit parameter values are presented in Table 2 and best fit spectrum is shown in Figure 8a with residuals in 8c.

We report the average, unabsorbed 0.1–100 keV flux during AstroSat observation was $9.5 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, corresponds to unabsorbed luminosity of $L_X \sim 8.2 \times 10^{36}$ erg s$^{-1}$ for a distance of 8.5 kpc.

5.5.1 XMM-Newton+SXT+LAXPC spectrum

The 1–50 keV X-ray continuum of SAX J1748.9-2021 was observed in its sixth outburst in 2017. The AstroSat observed it for $\sim 2.5$ days, where the average LAXPC10 count rate decreased to 33 counts s$^{-1}$ from 63 counts s$^{-1}$. The LAXPC light curves also showed the presence of two type-I thermonuclear X-ray bursts.

The 1–50 keV X-ray continuum of SAX J1748.9-2021 can be well described with the blackbody and Comptonized...
blackbody. The best-fit spectral parameters showed that the source was in the hard spectral state during the AstroSat observations (Table 2). AMXPs show the hard spectrum with electron temperature of 30–50 keV (Falanga et al. 2005; Gierliński & Poutanen 2005; Papitto et al. 2010, 2013a; Wilkinson et al. 2011; Sanna et al. 2018a, b; Di Salvo et al. 2005; Gierliński & Poutanen 2005; Papitto et al. 2010, 2013a; Wilkinson et al. 2011; Sanna et al. 2018). Thus, it seems that the 2017 outburst of SAX J1748.9-2021 did not show any spectral state change as observed during its previous outbursts in 2001, 2005, 2010 and 2015 (Patruno et al. 2009; Li et al. 2018; Wu et al. 2018). Previously, SAX J1748.9-2021 was found to be only in the hard state during the 1998 outburst (in ’t Zand et al. 1999). However, we see that the 1998 outburst of SAX J1748.9-2021 also showed a similar behaviour, where peak luminosity reached ~ 10^{37} erg s^{-1} and the outburst lasted for ~ 10 days (in ’t Zand et al. 1999; Altamirano et al. 2008).

We also found that the combined spectra from EPIC-PN, SXT and LAXPC showed a best fit on adding the self-consistent reflection component to the model. The obtained value of the ionization parameter indicated the presence of strongly ionized accretion disc, ξ ~ 3200 erg cm s^{-1} (e.g., Papitto et al. 2010; Di Salvo et al. 2019). The iron abundance, A_Fe = 1.5^{+0.5}_{-0.8}, obtained from the fit is consistent with Solar values, although the uncertainty is large. The Comptonized emission associated to a hot corona or the accretion column is characterized by a photon index of 1.719 ± 0.025. The electron temperature was unconstrained, only lower limit of 14 keV was obtained. A thermal blackbody with temperature of 0.60 ± 0.04 keV and emission radius of ~ 3 km, likely originating from the neutron star surface is found.

X-ray coherent pulsations at ~ 442 Hz are significantly detected in the AstroSat dataset. Timing analysis of the collected events allowed us to obtain an updated orbital solution of the source, compatible within the errors with the solution obtained for the 2015 outburst of SAX J1748.9-2021 (Sanna et al. 2016). No X-ray pulsation has been detected on timescales shorter than the whole observation. The strength of the X-ray pulsation did not allow a detailed study of the signal as a function of energy. However, the pulse profiles obtained in the energy bands 3–7 keV and 7–20 keV suggest a constant fractional amplitude around 0.5% for the fundamental component. This result is in contrast with the pulse profile energy dependence reported for the previous outbursts (see e.g. Patruno et al. 2009; Sanna et al. 2016) where the fractional amplitude has been observed to increase from 0.1% at 0.5 keV to 4% at 20 keV.

In AMXPs, accretion taking place on the NS is guided by the magnetic field of the NS. This magnetically channelled accretion means that the accretion disc radius is outside the NS surface and smaller than the co-rotation radius (Pringle & Rees 1972; Illarionov & Sunyaev 1975). Mukherjee et al. (2015) estimated the upper limits on magnetic field strength of 14 AMXPs, by assuming that the inner edge of the disc can not be outside the co-rotation radius. As X-ray pulsations have been observed during AstroSat observation, imply on going magnetically channelled accretion on to the NS. At the lowest X-ray luminosity (accretion rate), the accretion disc cannot be outside the co-rotation radius. Using the above assumptions, we estimated the upper limit on the magnetic field strength of NS from the flux obtained with XMM+SXT+LAXPC data (F_{min} = 7.73 \times 10^{-16} erg cm^{-2} s^{-1}). Using equation (10) of Mukherjee et al. (2015), the upper limit on magnetic dipole moment estimated to be 1.6 \times 10^{37} G cm^{3}, consistent with the estimates of Sharma et al. (2019). This will give B < 1.6 \times 10^{9} G for SAX J1748.9-2021 which is nearly a factor of 2 lower than the previous estimate of Mukherjee et al. (2015).

4.1 Burst Analysis

We performed the time-resolved burst spectroscopy and energy-resolved burst analysis on the two X-ray bursts observed with AstroSat/LAXPC. From the time-resolved spectroscopy performed on the 1 sec bin of burst, a complex vari-

Figure 7. Best fitted time-averaged broadband spectra of SXT and LAXPC modeled with bbodyrad+nthcomp.

Figure 8. (a) Broadband spectra of SAX J1748.9-2021 from XMM-Newton, SXT and LAXPC fitted simultaneously. (b) Residuals (χ=(data-model)/error) with bbodyrad+nthcomp model. (c) Residuals with bbodyrad+nthcomp+xiillvercp model. The figure has been rebinned for the plotting purpose.
ation in emission radii of blackbody was found in burst 2, suggestive of mild PRE phase. The second burst was brighter than the first one. The burst 1 was detected up to 30 keV only, but burst 2 showed emission in 30–40 keV energy range also. The burst observed with Beppo-SAX during 1998 also showed the emission > 30 keV, where the burst emission is Compton up-scattered by the hot corona (in ‘t Zand et al. 1999). The bursts were also found to influence the hard to soft state transition time. The soft photons from the bursts cool the corona faster to push the state transition to the shorter time scale (Li et al. 2018). The burst decay time strongly depends on the energy and the decay time of burst 2 was lower than the burst 1. The peak temperature and bolometric flux of 2.88 keV and 2.57 × 10^{-8} erg cm^{-2} s^{-1}, respectively were obtained for burst 2. Previously, observed PRE bursts of SAX J1748.9-2021 showed the peak flux of ∼2.8 – 4 × 10^{-8} erg cm^{-2} s^{-1} (Galloway et al. 2008).

The local accretion rate per unit area onto the compact object can be estimated using $\dot{m} = L_{\text{per}}(1 + z)/(4\pi R^2/(GM/R))^{-1}$. Using the gravitational redshift of $1 + z = 1.31$ for a canonical NS with a mass $M = 1.4M_\odot$ and a radius of $R = 10$ km, we found $\dot{m} \approx 0.48 \times 10^8$ g cm^{-2} s^{-1}. The observed recurrence time depends on $\dot{m}$ as $\Delta t_{\text{rec}} \propto \dot{m}^{-8/2}$ measured from the burst observed during 2015 outburst (Li et al. 2018). From the estimated average accretion rate of 2017 outburst, the burst recurrence time estimated was ∼6 h. The shortest difference between the observed burst of 2017 was ∼8 h, consistent with above estimation. The three burst observed with wide field camera of BeppoSAX in 1998 outburst showed the recurrence time of ∼2.8 h (in ‘t Zand et al. 1999).

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REFERENCES

Agrawal P. C., 2006, Advances in Space Research, 38, 2989

Altamirano D., Casella P., Patruno A., Wijnands R., van der Klis M., 2008, ApJ, 674, L45

Antia H. M., et al., 2017, ApJS, 231, 10

Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17

Beri A., Paul B., Orlandini M., Maitra C., 2016, New Astron., 45, 48

Beri A., et al., 2019, MNRAS, 482, 4307

Burdere L., et al., 2007, ApJ, 657, 961

Cackett E. M., Altamirano D., Patruno A., Miller J. M., Reynolds M., Linares M., Wijnands R., 2009, ApJ, 694, L21

Cadelano M., Pallanca C., Ferraro F. R., Dalessandro E., Lanzoni B., Patruno A., 2017, ApJ, 844, 53

Campana S., Di Salvo T., 2018, in Rezaaoli L., Pizzocchero P., Jones D. L., Rea N., Vidaña L., eds, Astrophysics and Space Science Library Vol. 457, Astrophysics and Space Science Library. p. 149 (arXiv:1804.03422), doi:10.1007/978-3-319-97616-7_4

Chakrabarty D., Morgan E. H., 1998, Nature, 394, 346

Degenaar N., Koljonen K. I. I., Chakrabarty D., Kara E., Altamirano D., Miller J. M., Fabian A. C., 2016, MNRAS, 456, 3256

Di Salvo T., Sanna A., Burderi L., Papitto A., Iaria R., Gambino A. F. R., Riggi A., 2019, MNRAS, 483, 767

Evans P. A., et al., 2007, A& A, 469, 379

Falanga M., et al., 2005, A&A, 444, 15

Ferrigno C., et al., 2014, A& A, 567, A77

Galloway D. K., Chakrabarty D., Morgan E. H., Remillard R. A., 2002, ApJ, 576, L137

Galloway D. K., Muno M. P., Hartman J. M., Psaltis D., Chakrabarty D., 2008, ApJS, 179, 360

García J., Kallman T. R., 2010, ApJ, 718, 695

García J., Dausa T., Reynolds C. S., Kallman T. R., McClintock J. E., Wilms J., Eikmann W., 2013, ApJ, 768, 146

Gavriil F. P., Strohmayer T. E., Swank J. H., Markwardt C. B., 2007, ApJ, 669, L29

Gehrels N., et al., 2004, ApJ, 611, 1005

Gierliński M., Poutanen J., 2005, MNRAS, 359, 1261

Güver T., Özel F., 2013, ApJ, 765, L1

Haslinger G., van der Klis M., 1989, A& A, 225, 79

Ilarirovov A. F., Sunyaev R. A., 1975, A& A, 39, 185

Kaaret P., in ‘t Zand J. J. M., Heise J., Tomrick J. A., 2003, ApJ, 598, 481

Kuulkers E., den Hartog P. R., in’t Zand J. J. M., Verbunt F. W. M., Harris W. E., Cocchi M., 2003, A& A, 399, 663

Li Z., et al., 2018, A& A, 620, A114

Ludlam R. M., Miller J. M., Degenaar N., Sanna A., Cackett E. M., Altamirano D., King A. L., 2017, ApJ, 847, 135

Marino A., et al., 2019, A& A, 627, A125

Markwardt C. B., Swank J. H., 2005, The Astronomer’s Telegram, 495

Markwardt C. B., Swank J. H., Strohmayer T. E., in ‘t Zand J. J. M., Marshall F. E., 2002, ApJ, 575, L21

Matsuoka M., et al., 2009, PASJ, 61, 999

Mihara T., et al., 2011, PASJ, 63, S623

Matsuoka M., et al., 2009, PASJ, 61, 999

Mihara T., et al., 2011, PASJ, 63, S623

Mukherjee D., Bult P., van der Klis M., Bhattacharya D., 2015, MNRAS, 452, 3994

Negoro H., et al., 2017, The Astronomer’s Telegram, 10821

Ortolani S., Barbuy B., Ibarra R., Bica E., 1994, A&AS, 108, 653

Patruno A., Di Salvo T., D’Al A., Iaria R., Burderi L., Riggio A., Menna M. T., Robba N. R., 2009, A& A, 493, L39

Patrino A., Riggio A., di Salvo T., Burderi L., D’Al A., Iaria R., Bozzo E., Menna M. T., 2010, MNRAS, 407, 2575

Patrino A., et al., 2013a, MNRAS, 429, 3411

Patrino A., et al., 2013b, Nature, 501, 517

Patrino A., Watts A. L., 2012, preprint, (arXiv:1206.2727)
