Estimation of the black hole spin in LMC X-1 using AstroSat

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ABSTRACT
LMC X-1, a persistent, rapidly rotating, extra-galactic, black hole X-ray binary (BHXB) discovered in 1969, has always been observed in its high soft state. Unlike many other BHXBs, the black hole mass, source distance and binary orbital inclination are well established. In this work, we report the results of simultaneous broadband spectral studies of LMC X-1 carried out using the data from Soft X-ray Telescope and Large Area X-ray Proportional Counter aboard AstroSat as observed on 2016 November 26th and 2017 August 28th. The combined spectrum was modelled with a multicolour blackbody emission (diskbb), a Gaussian along with a Comptonization component (simpl) in the energy range 0.7–30.0 keV. The spectral analysis revealed that the source was in its high soft state ($\Gamma = 2.67^{+0.24}_{-0.24}$ and $\Gamma = 2.12^{+0.19}_{-0.20}$) with a hot disc ($kT_{in} = 0.86^{+0.01}_{-0.01}$ and $kT_{in} = 0.87^{+0.02}_{-0.02}$). Thermal disc emission was fit with a relativistic model (kerrbb) and spin of the black hole was estimated to be $0.93^{+0.01}_{-0.01}$ and $0.93^{+0.04}_{-0.03}$ (statistical errors) for the two epochs through X-ray continuum-fitting, which agrees with the previous results.

Key words: accretion, accretion disks — black hole physics — X-rays: binaries, persistent, high-mass — X-rays: individual: LMC X-1

1 INTRODUCTION
LMC X-1, the first catalogued extra-galactic X-ray source in the Large Magellanic Cloud, was discovered in 1969 by Uhuru (Mark et al. 1969; Price et al. 1971). Since then, the source has been observed by most of the leading X-ray missions including the AstroSat and NICER which agree with the previous results. In the last two decades, there have been a few attempts to accurately determine spin of the black hole in LMC X-1. Indeed, such efforts are significant as the spin carries valuable information about the black hole formation mechanism and its growth history (Moderski et al. 1998; Volonteri et al. 2005). X-ray reflection spectroscopy (analysis of the Fe-K line) (Brenneman & Reynolds 2006; Miller 2007; Reynolds 2014) and X-ray continuum-fitting (analysis of the disc continuum) (Zhang et al. 1997; McClintock et al. 2014) are the two methods mostly used to estimate black hole spins as they are straightforward and involve very few parameters. Gierliński et al. (2001) developed a general relativistic accretion disc model and applied it to constrain spin of the black hole in LMC X-1 by fitting X-ray continuum using soft X-ray data from ASCA (0.7–10.0 keV). For the high-energy tail beyond the disc spectrum they chose a thermal Comptonization model (Zdziarski et al. 1996). However, they could not give a good constraint on the black hole spin as the mass

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and disc inclination angle of LMC X-1 were evaluated rather poorly at that time. Gou et al. (2009) determined the spin of the black hole in LMC X-1 to be $0.97^{+0.05}_{-0.02}$ using eighteen thermal dominant spectra from RXTE/PCA (3.0–30.0 keV) adopting X-ray continuum-fitting technique. They invoked the convolution model (simpl) (Steiner et al. 2009) to fit the Comptonization component, relativistic model (kerrbb) (Li et al. 2005) to account for the thermal disc continuum emission and phabs to correct for the interstellar absorption. Steiner et al. (2012) used 11 coordinated observations from RXTE/PCA-2 and Suzaku (0.8–10.0 keV) to constrain the spin of the black hole in LMC X-1 adopting X-ray reflection spectroscopy. The spectrum was modelled using two different types of reflection models (reflbb) (Ross & Fabian 2005; Reis et al. 2008), and ireflect (Magdziarz & Zdziarski 1995) and a narrow Gaussian (Magdziarz & Zdziarski 1995) to account for the broad relativistic reflection features. Models kerrbb2 (Li et al. 2005; Davis & Hubeny 2006), simpl and tbvabs (Wilms et al. 2000) were used in both the cases. The spin was found to be $0.97^{+0.01}_{-0.13}$ and $0.97^{+0.02}_{-0.25}$ for models involving reflbb and ireflect+Gaussian respectively at 68 per cent confidence. Tripathi et al. (2020) analysed seventeen observations from RXTE/PCA-2 for determining spin of the black hole in LMC X-1 employing the new model nkbb developed by Zhou et al. (2019). The spectra were modelled using a combination of nkbb (thermal component), simpl (Comptonization) and tbabs (Galactic absorption). The black hole mass, distance and disc inclination angle were taken from Orosz et al. (2009) and spectral hardening factor was fixed to 1.55. The spin was constrained to be $0.988_{-0.004}$ at 90 per cent confidence using X-ray continuum-fitting.

LMC X-1 is one of the few BH XBs whose mass, distance and binary orbital inclination angle are well constrained now. Many of the inferences of its black hole spin are primarily obtained from RXTE/PCA-2 data, which is limited by its low energy coverage (3.0–30.0 keV). However, as LMC X-1 has a characteristic temperature of $\sim 0.9$ keV (Ruhlen et al. 2011) it is crucial to have a broadband coverage especially in the lower energy range (<3 keV) to obtain precise estimate of spin through spectral fitting. The Soft X-ray Telescope (SXT) (Singh et al. 2016, 2017) and Large Area X-ray Proportional Counter (LAXPC) (Yadav et al. 2016; Agrawal 2017) aboard the Indian Space Observatory AstroSat (Singh et al. 2014) is ideally suited for this as it provides simultaneous broadband coverage (0.3–80.0 keV). In the recent work on the spectral evolution of GRS 1915+105 using simultaneous broadband (1.0–50.0 keV) data from AstroSat by Misra et al. (2020), the importance of low energy coverage (<3 keV, SXT data) to constrain the inner disc radii and the use of convolution model simpl to model the Comptonization component instead of commonly used power-law are well emphasised. Here, we report the detailed simultaneous broadband spectral analysis of the observations of LMC X-1 by SXT and LAXPC aboard AstroSat and estimation of spin of the black hole.

2 DATA REDUCTION

LMC X-1 was observed in its high soft state (HSS) by SXT and LAXPC on board AstroSat on two occasions, separated by 9 months (Table 1). Level 2 clean event files for all the orbits were obtained using ASISXSTLevel2-1.4b version of the official SXT pipeline from Level 1 photon counting mode data files of SXT. A single, exposure corrected, merged Level 2 clean event file was created using SXT event merger tool2 by merging data from different orbits for each of the Epochs separately and was used for the analysis.

The SXT spectrum was extracted using HEAsoft version-6.24 tool XSELECT for a circular region of 16’ radius which includes $\sim 97$ per cent of the total source photons. The response matrix file (RMF) “sxt_pc_mat_v012.rmf” and an off-axis auxiliary response file (ARF) generated using SXT ARF generation tool3 appropriate for the source location on the charged coupled device (CCD) were used for the analysis. The blank sky observation(s): “SkyBkg_comb_EL3p5_Cr1_Rd16p0_v01.pha” provided by the SXT POC team was used for background subtraction.

Level 2 event files were obtained from Level 1 event mode data of LAXPC using the latest version of LAXPC software4, LAXPC subroutine ‘laxpc_make_stdgti’ (Antia et al. 2017) was used to generate good time interval (GTI) file to remove the Earth occultation of the source and South Atlantic Anomaly passes of the satellite. Total spectrum along with RMF for LAXPC10, LAXPC20 and LAXPC30 was obtained using “laxpc_make_spectra”. LAXPC background spectrum was extracted by employing the faint background model of LAXPC as the source has very low count rate in the energy range $>30$ keV. A lightcurve generated at 10 s time bin using data from all the three LAXPCs revealed that LAXPC30 was off for sometime during the observation. Therefore, data from LAXPC30 was not used in this work. Since LAXPC20 had lower background compared to LAXPC10, we used LAXPC20 data for the analysis.

3 SPECTRAL ANALYSIS

Combined spectral fittings of SXT–LAXPC20 observations in the energy range 0.7–30.0 keV were carried out using XSPEC version-12.10.0c (Arnaud 1996) with a combination of suitable models. While the higher energy regime (>30.0 keV) was ignored due to high background, the lower energy regime (<0.7 keV) was also not considered due to the uncertainties in effective area and response of the CCD of SXT. A systematic error of 3 per cent to account for uncertainties in response calibration and background uncertainty of 3 per cent were incorporated at the time of spectral fitting.

3.1 Modelling for the disc temperature and inner disc radius

The combined spectra having thermal and Comptonization components were fit with a combination of multicolour

1 http://www.tifr.res.in/~astrosat$_$sxt/sxtpipeline. html
2 http://www.tifr.res.in/~astrosat$_$sxt/dataanalysis. html
3 http://www.tifr.res.in/~astrosat$_$sxt/dataanalysis. html
4 http://astrosat-ssc.iucaa.in/?q=laxpcData
blackbody (diskbb) (Mitsuda et al. 1984; Makishima et al. 1986) and Comptonization (simpl) models along with Galactic absorption (tbabs). The relative normalization was allowed to vary between SXT and LAXPC20 spectra. The model showed some residuals at around 6.5 keV, suggesting the presence of an Iron line feature. Hence, we included a Gaussian component with its centroid fixed at 6.5 keV allowing the width and normalization to vary. The additional component led to a $\Delta x^2 \sim 5$ and $\sim 11$ for Epoch 1 and 2 respectively. Since SXT’s effective area is relatively small at energies greater than 6 keV and LAXPC spectral resolution is limited with 3 per cent systematics, we refrained from using more complex relativistic models for the Iron line feature.

In Epoch 1, the asymptotic power-law index, $\Gamma = 2.67^{+0.24}_{-0.24}$ indicated that the source was in its HSS. Modelling the disc component revealed the disc temperature ($kT_{\text{disc}}$) and normalization ($N_{\text{disc}}$) to be $0.86^{+0.01}_{-0.01}$ keV and $60.26^{+4.84}_{-4.44}$ respectively. The best fit spectrum is shown in Figure 1 (Top panel) and the best fit parameters are summarised in Table 2. An offset gain correction of 32.6 eV determined using XSPEC command gainfit with the slope fixed at unity was applied to the SXT data. The total flux and disc flux in the 0.7–30.0 keV energy band were estimated using the convolution model cflux and the disc fraction was found to be $\sim 77$ per cent of the total flux.

Hardness intensity diagram (HID) was generated from the background subtracted LAXPC20 lightcurve at 10 s binning. We define the hardness as the ratio of count rate in the energy bands 4.5–15.0 keV and 3.0–4.5 keV and the intensity as the count rate in the energy band 3.0–15.0 keV. Four regions (A, B, C and D as shown in Figure 2) were selected from the HID such that each region had sufficient intensity. The hardness ratio was found to vary between 0.4–1.2 from region A to D. The GTI file appropriate for each region was retrieved using the LAXPC subroutine “laxpc_fluxreslgti”. The corresponding SXT and LAXPC spectra were then extracted using these GTI files. The resulting spectra were modelled using the same combination of models as before. A fixed offset gain correction of 32.6 eV was applied to the SXT data and the relative normalization between SXT and LAXPC was fixed at 1.17$^{+0.05}_{-0.05}$. The hydrogen column density was fixed at $0.46\times10^{22}$ cm$^{-2}$. The Gaussian line energy, width and normalization were frozen at 6.5 keV, 1.0 keV and $2.33\times10^{-4}$ respectively. The best fit parameters with errors are listed in Table 3. As shown in Figure 3, the disc normalization at these four regions of the HID were almost a constant within the uncertainties, indicating no substantial change in the inner disc radius of the accretion disc. Thus, we fitted these four normalization values to a constant function and obtained a best fit value of 61.64. We subsequently fixed the disc normalization for all four spectra to this value and refitted the spectra. The resultant variation of the asymptotic power-law index, fractional scattering and inner disc temperature ($kT_{\text{disc}}$) with total flux are plotted in Figure 4.

The Epoch 2 best fit spectrum is shown in Figure 1 (Bottom panel) and the best fit parameters are given in Table 2. An offset gain correction of 36.8 eV was applied to the SXT data. The disc temperature and normalization were found to be $0.87^{+0.02}_{-0.02}$ keV and $66.76^{+10.88}_{-9.30}$ respectively. The disc flux was found to be $\sim 84$ per cent of the total flux. The HID for Epoch 2 did not show any variations.

3.2 Modelling for the black hole spin

The combined spectrum of SXT–LAXPC20 (0.7–30.0 keV) was modelled using the combination of tbabs, simpl, Gaussian and relativistic (kerrbb) models to determine the spin of the black hole. The black hole mass (10.91 M$_{\odot}$) and source distance (48.10 kpc) were taken from Orosz et al. (2007, 2009). Furthermore, we assumed the disc inclination (i) to be same as the binary orbital inclination (36.38°). The spectral hardening factor was frozen at 1.7 (Shimura & Takahara 1995) and the kerrbb normalization was fixed at 1. The Gaussian line energy was fixed at 6.5 keV for both the

| Table 1. Observations of LMC X-1 |
|----------------------------------|
| Obs. ID | Obs. Start Date | Obs. Start Time | Exposure Time |
| yyyy-mm-dd | hh:mm:ss | SXT | LAXPC |
| 9000000926 | 2016-11-26 | 13:39:42 | 29.86 | 44. |
| 9000001496 | 2017-08-28 | 19:56:23 | 3.14 | 15. |

Figure 1. SXT (0.7–5.0 keV) (black) and LAXPC20 (4.0–30.0 keV) (red) combined spectra with residuals for Epoch 1 (Top panel) and Epoch 2 (Bottom panel) fit with diskbb, simpl, Gaussian and tbabs models. The expected background spectra for SXT and LAXPC20 are also shown.
Table 2. The best fit parameters of SXT and LAXPC20 spectra - disc temperature and inner disc radius.

| Epoch | constant $N_H$ ($10^{22}$ cm$^{-2}$) | Gamma ($\Gamma$) | FractScrr | Width (keV) | $N_{Gaussian}$ ($10^{-4}$) | $kT_{in}$ (keV) | $N_{disc}$ | $\chi^2$/dof |
|-------|-----------------------------------|-----------------|----------|-----------|-----------------|----------------|----------|-------------|
|       | Relative normalization Hydrogen column density | Asymptotic power-law index | Scattered fraction of the seed photons | Gaussian width | Gaussian normalization | Temperature at inner disc radius | Disc normalization |            |
| 1    | $1.22^{+0.06}_{-0.05}$ | $0.40^{+0.01}_{-0.01}$ | $2.67^{+0.24}_{-0.24}$ | $0.079^{+0.029}_{-0.022}$ | $<1.56$ | $2.33^{+2.31}_{-1.94}$ | $0.86^{+0.01}_{-0.01}$ | $60.26^{+4.84}_{-4.41}$ | 362/364 |
| 2    | $1.28^{+0.08}_{-0.08}$ | $0.40^{+0.02}_{-0.02}$ | $2.12^{+0.19}_{-0.20}$ | $0.054^{+0.016}_{-0.014}$ | $1.25^{+0.42}_{-0.44}$ | $6.57^{+3.09}_{-2.82}$ | $0.87^{+0.02}_{-0.02}$ | $66.76^{+10.88}_{-9.30}$ | 172/202 |

Table 3. Spectral fit parameters of four selected regions on the HID of the Epoch 1

| HID regions | A | B | C | D |
|-------------|---|---|---|---|
| Total flux ($10^{-9}$ erg cm$^{-2}$ s$^{-1}$) | $0.444^{+0.005}_{-0.005}$ | $0.471^{+0.004}_{-0.003}$ | $0.490^{+0.005}_{-0.005}$ | $0.517^{+0.007}_{-0.007}$ |
| SXT exposure time (s) | $2792$ | $8906$ | $2594$ | $1020$ |
| LAXPC exposure time (s) | $8200$ | $17000$ | $8300$ | $3400$ |
| Gamma ($\Gamma$) | $2.51^{+0.30}_{-0.28}$ | $2.54^{+0.19}_{-0.19}$ | $2.62^{+0.21}_{-0.21}$ | $2.80^{+0.24}_{-0.23}$ |
| FractScrr | $0.045^{+0.009}_{-0.009}$ | $0.057^{+0.015}_{-0.011}$ | $0.087^{+0.025}_{-0.019}$ | $0.125^{+0.042}_{-0.031}$ |
| $kT_{in}$ (keV) | $0.84^{+0.14}_{-0.15}$ | $0.86^{+0.01}_{-0.01}$ | $0.87^{+0.02}_{-0.02}$ | $0.88^{+0.02}_{-0.03}$ |
| $N_{disc}$ | $67.03^{+4.72}_{-4.12}$ | $64.61^{+3.20}_{-2.92}$ | $59.96^{+4.87}_{-4.21}$ | $57.29^{+7.17}_{-7.78}$ |
| $\chi^2$/dof | $167/167$ | $273/280$ | $151/165$ | $82/84$ |

Table 4. The best fit parameters of SXT and LAXPC20 spectra - spin of the black hole.

| Epoch | constant $N_H$ ($10^{22}$ cm$^{-2}$) | Gamma ($\Gamma$) | FractScrr | Width (keV) | $N_{Gaussian}$ ($10^{-4}$) | $a$ | $M$ (10$^{18}$ g s$^{-1}$) | L$^{(a)}$ | $\chi^2$/dof |
|-------|-----------------------------------|-----------------|----------|-----------|-----------------|-----|--------------------|--------|-------------|
|       | Relative normalization Hydrogen column density | Asymptotic power-law index | Scattered fraction of the seed photons | Gaussian width | Gaussian normalization | spin of the black hole | Rate of accretion | Eddington ratio |            |
| 1    | $1.22^{+0.04}_{-0.04}$ | $0.50^{+0.01}_{-0.01}$ | $2.40^{+0.20}_{-0.19}$ | $0.049^{+0.015}_{-0.011}$ | $1.0^{(f)}$ | $<0.87$ | $0.93^{+0.01}_{-0.01}$ | $1.17^{+0.08}_{-0.08}$ | $0.13^{+0.01}_{-0.01}$ | 367/363 |
| 2    | $1.30^{+0.06}_{-0.06}$ | $0.53^{+0.02}_{-0.02}$ | $2.03^{+0.17}_{-0.10}$ | $0.044^{+0.012}_{-0.011}$ | $1.35^{+0.51}_{-0.58}$ | $3.98^{+2.56}_{-2.29}$ | $0.93^{+0.04}_{-0.03}$ | $1.39^{+0.20}_{-0.17}$ | $0.15^{+0.02}_{-0.02}$ | 214/203 |

$^{(f)}$ Parameter frozen during the fitting.
$^{(a)}$ L = $L_{acc}/L_{Edd}$, where $L_{acc} = \eta M c^2$ with $\eta \sim 0.17$ for $a = 0.93$ and $L_{Edd} = 1.3 \times 10^{38} (M_{BH}/M_\odot)$ erg s$^{-1}$, $M_{BH} = 10.91 \pm 1.41 M_\odot$

Epochs. The Gaussian normalization for Epoch 1 was fixed at 1 whereas the width was allowed to vary. Meanwhile, for Epoch 2 both the Gaussian normalization and width were treated as variables.

SXT data required an offset gain of 43.4 eV (Epoch 1) and 33.9 eV (Epoch 2) to be added during the analysis. The best fit values of the spin and other parameters in both the Epochs are presented in Table 4. The hydrogen column density and rate of accretion in Epoch 2 was found to be slightly higher than that in Epoch 1, whereas the fractional scattering was found to be slightly lower in Epoch 2.

4 TIMING ANALYSIS

The complete event mode data of LAXPC in the energy range 4.0–30.0 keV was considered for the temporal analysis for the longer observation Epoch 1. The lightcurve from LAXPC10 and LAXPC20 in the energy range 4.0–30.0 keV,
Figure 2. HID of Epoch 1 binned at 10 s. Vertical lines indicate the regions A, B, C and D selected on the HID and horizontal line indicates the mean value of the hardness ratios.

Figure 3. Normalization of diskbb at the regions A, B, C and D on HID of Epoch 1. It should be noted that the number 1 on the X-axis corresponds to A, 2 corresponds to B and so on. The plot is fitted by a function f(x) = constant.

with a time resolution of 0.05 s was divided into three segments of 1639.34 s each. The power spectra of the three segments were averaged to give a mean power density spectrum (PDS). The PDS was generated in the frequency range 0.6 mHz–10 Hz. Gaps in the data set prevented using larger time segments and hence the analysis was restricted to >0.6 mHz. The PDS binned logarithmically in frequency is shown in Figure 5. At high frequencies the power is a constant due to Poisson noise, while some excess is detected at low frequencies, but no QPO like features are visible. Fitting the PDS with a power-law (to model the low frequency excess) and a constant (for the Poisson noise) yielded a $\chi^2/\text{dof}$ of 9/12 and the best fit power-law index was found to be $2.01_{-0.68}^{+1.61}$. 

5 SUMMARY

In this work, we have performed a comprehensive spectral analysis of LMC X-1, a persistent X-ray source hosting a Kerr black hole and an O III companion star, using the AstroSat data, observed on 2016 November 26th (Epoch 1) and 2017 August 28th (Epoch 2) from SXT and LAXPC20 instruments.

The combined SXT–LAXPC20 spectra were modelled with a combination of diskbb, simpl, Gaussian and tbabs models. Asymptotic power-law index for Epoch 1 ($\Gamma = 2.67_{-0.24}^{+0.34}$) was slightly higher than Epoch 2 ($\Gamma = 2.12_{-0.20}^{+0.19}$), whereas the disc temperature ($0.86_{-0.01}^{+0.02}$ keV) estimated at the inner disc radius of Epoch 1 was found to be slightly lower than that of Epoch 2 ($0.87_{-0.02}^{+0.02}$ keV). The hydrogen column density ($N_H$) increases slightly from Epoch 1 to Epoch 2 and $N_H$ determined at Epoch 1 agrees with the values of Alam et al. (2014) and Cui et al. (2002).

Flux resolved spectroscopy performed for Epoch 1 revealed that the diskbb normalization remained almost a constant across the four regions (A, B, C, and D) on the HID. The fractional scattering increased from region A to D with a maximum value of ~0.145 and a minimum of ~0.032. The inner disc temperature varied from ~0.863 keV (A) to ~0.870 keV (D).

We invoked the relativistic model (kerrbb) along with Gaussian and tbabs to fit the joint spectra of SXT and LAXPC20 and estimated the spin of the black hole ($0.93_{-0.01}^{+0.02}$ and $0.93_{-0.02}^{+0.04}$ for Epoch 1 and Epoch 2 respectively). These values agree with the literature values (Gou et al. 2009; Steiner et al. 2012). The uncertainties in the spin value reflect only the statistical errors during spectral fitting and do not include uncertainty in the distance and inclination measurements. If we allow distance and inclination to vary within their errors during spectral fitting, the spin parameter values have a larger allowed range i.e. 0.95_{-0.13}^{+0.03} (Epoch 1) and 0.9_{-0.04}^{+0.05} (Epoch 2). The relativistic accretion disc model, “kerrbb” assumes that the disc is geometrically thin, which is valid when the luminosity is less than 0.3 times the Eddington value $L_{\text{Edd}}$ (McClintock et al. 2006). As shown by Gou et al. (2009), the luminosity of LMC X-1 is indeed sub–Eddington. Here for Epoch 1 and Epoch 2, we obtain the luminosity to be ~0.13 $L_{\text{Edd}}$ and ~0.15 $L_{\text{Edd}}$ thereby validating the use of “kerrbb” to model the spectra.

Figure 6 shows the variation of $\chi^2$ as a function of the black hole spin parameter (a). Low values of spin parameter (a <0.8) are statistically rejected with high significance. We note again, that the spin parameter has been well determined because of the tight estimates on the mass of the black hole and binary orbital inclination angle. We illustrate this by showing the confidence levels for the spin parameter in the middle panel of Figure 7, if the inclination angle was not known, the spin parameter would not have been constrained at all. In this work, we have assumed the spectral hardening factor to be the expected theoretical...
value, $f = 1.7$ (Shimura & Takahara 1995). We investigated the influence of varying this parameter on the spin measurement. The bottom panel of Figure 7 shows the confidence contours for $f$ parameter and black hole spin by keeping the black hole mass and inclination angle fixed. We note that the data restricts $f$ to be within $1.4 - 2.1$ at 1-$\sigma$ level, which includes the expected value of 1.7. Moreover, the spin parameter is constrained to be greater than 0.7, if the spectral hardening factor is less than 2.0.

The LAXPC10 and LAXPC20 lightcurve in energy range 4.0–30.0 keV, with a time resolution of 0.05 s was generated from the complete event mode data of LAXPC. The lightcurve was divided into three segments of 1639.34 s each. The power spectra of the three segments were averaged to give a mean PDS. The PDS was generated in the frequency range 0.6 mHz–10 Hz. We noticed that the power remained constant due to Poisson noise at higher frequencies and showed some excess at lower frequencies. However, no QPO like features were seen.

In summary, we have estimated the spin of the persistent black hole binary LMC X-1 using SXT and LAXPC data of AstroSat through X-ray continuum-fitting. Future observations of the source by AstroSat and simultaneous observations by NICER in the soft band and NuSTAR in the hard band, can be used to confirm the results presented here and provide perhaps more stringent constraints on the spin parameters. With spin and other non varying parameters of the system well constrained, spectral modelling will provide a good measure of the accretion rate and parameters of the thermal plasma producing the Comptonized component. Frequent monitoring of the source would provide a unique opportunity to study how these parameters evolve with time and the relation between them.

Figure 4. The spectral fit parameters: Asymptotic power-law index (Top panel), Fractional scattering (Middle panel) and inner disc temperature ($kT_{\text{in}}$) (Bottom panel) as a function of total flux for the four regions on the HID with the disc normalization frozen at 61.64.
Figure 5. Power density spectrum in the energy range 4.0–30.0 keV (Top panel) and residuals (Bottom panel) fitted by a power-law to model the low frequency excess and a constant to model the Poisson noise.

Figure 6. Variation of $\chi^2$ for different values of spin parameter (a), corresponding to the model parameters listed in Table 4. Free parameters listed in Table 4 were allowed to vary while computing $\chi^2$. Spin parameter values of <0.8 are rejected with high significance.

Figure 7. Contour plot of spin and mass of the black hole (Top panel), spin and disc inclination angle ($i$) (Middle panel) and spin and spectral hardening factor ($f$) (Bottom panel). The 68, 90 and 99 per cent contours are shown. The plus mark corresponds to the local minima (best fit) found by the fit.
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DATA AVAILABILITY

The data utilised in this article are available at AstroSat—ISSDC website (http://astrobrowse.issdc.gov.in/astro$\_$archive/archive/Home.jsp). The software used for data analysis is available at NASA’s HEASARC website (https://heasarc.gsfc.nasa.gov/lheasoft/download.html).

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