Broadband ‘spectro-temporal’ features of extragalactic black hole binaries LMC X-1 and LMC X-3: An AstroSat perspective

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ABSTRACT
We present the first results of extragalactic black hole X-ray binaries LMC X-1 and LMC X-3 using all the archival and legacy observations by AstroSat during the period of 2016 − 2020. Broadband energy spectra (0.5−20 keV) of both sources obtained from the SXT and LAXPC onboard AstroSat are characterized by strong thermal disc blackbody component (kT_in ~ 1 keV, \( f_{\text{disc}} > 79\% \)) along with a steep power-law (\( \Gamma \approx 2.4 \) − 3.2). Bolometric luminosity of LMC X-1 varies from 7% to 10% of Eddington luminosity (\( \mathcal{L}_{\text{E,edd}} \)) and for LMC X-3 is in the range 7%−13% of \( \mathcal{L}_{\text{E,edd}} \). We study the long-term variation of light curve using MAXI data and find the fractional variance to be \( \sim 25\% \) for LMC X-1 and \( \sim 53\% \) for LMC X-3. We examine the temporal properties of both sources and obtain fractional rms variability of PDS in the frequency range 0.002 − 10 Hz to be \( \sim 9\% \) − 17% for LMC X-1, and \( \sim 7\% \) − 11% for LMC X-3. The ‘spectro-temporal’ properties indicate both sources are in thermally dominated soft state. By modelling the spectra with relativistic accretion disc model, we determine the mass of LMC X-1 and LMC X-3 in the range \( 7.64 \) − \( 10.00 \) \( M_\odot \) and \( 5.35 \) − \( 6.22 \) \( M_\odot \) respectively. We also constrain the spin of LMC X-1 to be in the range 0.82 − 0.92 and that of LMC X-3 in 0.22 − 0.41 with 90% confidence. We discuss the implications of our results in the context of accretion dynamics around the black hole binaries and compare it with the previous findings of both sources.

Key words: X-ray binaries – accretion, accretion discs – black hole physics – stars: black holes – radiation mechanisms: general – stars: individual: LMC X-1 – stars: individual: LMC X-3

1 INTRODUCTION

Black Hole X-ray Binaries (BH-XRBs) consist of a black hole (BH) along with a normal companion star which are gravitationally bound to each other. Highly compact BH accretes matter from the companion star and forms an accretion disc around it. The accretion disc gets heated up due to the geometrical compression in the accretion process and gives out energy in different wavebands, mainly in X-rays. Based on the type of X-ray emission, XRBs are classified either as persistent sources or as transients (Chen et al. 1997; Tetarenko et al. 2016; Corral-Santana et al. 2016). Persistent sources are the ones that radiate X-ray luminosity consistently for a long period of time (Tanaka & Shibazaki 1996). Transients, on the other hand, undergo outburst emitting large X-ray flux (Tsunemi et al. 1989) once in a while. Generally, XRBs exist either in intermediate state (SIMS) and high/soft state (HSS) (Remillard & McClintock 2006) depending on the mass of the companion star. Most of the observed transient sources typically exist in LMXBs whereas persistent sources are found in HMXBs.

To study the accretion dynamics around the black holes, it is necessary to understand the X-ray spectrum of the source. The radiation spectrum of BH-XRBs generally consists of thermal and non-thermal components. While thermal radiation comes from different radii of accretion disc (Shakura & Sunyaev 1973), non-thermal emission is due to the Comptonization of photons from the disc by hot corona (Tanaka & Lewin 1995; Chakrabarti & Titarchuk 1995). Thermal radiation from the disc forms the low energy soft X-ray flux in the energy spectra and non-thermal radiation contributes to the high energy. The emitted radiation varies with respect to energy and time, resulting in different spectral states. These spectral states are usually classified as low/hard state (LHS), hard-intermediate state (HIMS), soft-intermediate state (SIMS) and high/soft state (HSS) (Homan et al. 2001; Belloni 2005; Remillard & McClintock 2006; Nandi et al. 2012; Radhika & Nandi 2014; Radhika et al. 2016b; Nandi et al. 2018; Sreehari et al. 2019; Baby et al. 2020; Kat0 et al. 2020 (under review) and references therein). Persistent BH-XRBs mainly ex-
hibit HSS and LHS (Shapiro 1973; McClintock & Remillard 1986; Main et al. 1999; Zdziarski et al. 2002; Remillard & McClintock 2006). During HSS, the X-ray energy spectrum of the source consists of a strong disc component and a weak power-law component. While the source is in LHS, the spectrum consists of a hard power-law component (Chakrabarti & Titarchuk 1995; Tanaka & Lewin 1995; Chen & Taam 1996; Haardt et al. 2001; Zdziarski et al. 2002; Nandi et al. 2012; Sreehari et al. 2018; Aneesh et al. 2019).

In addition to the spectral variability exhibited at different states, BH-XRBs show timing variability. This variability can be understood by studying the source light curve and Power Density Spectrum (PDS) which allows us to investigate the variation in power at different frequencies. During LHS, the PDS can be described by a flat-top noise with a broken power-law, and sometimes have signatures of Quasi-periodic Oscillations (QPOs) (Casella et al. 2005; Remillard & McClintock 2006; Belloni et al. 2011). PDS during HSS is characterized by a weak power-law component. Narrow frequency features are rarely seen during this state. The fractional rms amplitude in the source light curve is seen to be high (>10%) during LHS (Belloni & Hasinger 1990; Tanaka & Lewin 1995; Nowak 1995; Nandi et al. 2012) and it decreases (<10%) as the source moves towards the HSS.

During HSS, the inner edge of the disc moves towards the BH and it is predicted to be very close to the radius of innermost stable circular orbit i.e. ISCO (Shapiro & Teukolsky 1983). Most of the thermal emission during this state comes from the innermost region of the disc where there is a strong gravitational effect and these soft X-rays gives us information on specific angular momentum of the BH. Angular momentum of the BH can be expressed in terms of a dimensionless parameter called spin as $a = cJ/2M_{BH}^2$, whose magnitude varies between 0 and 1 (Zhang et al. 1997a; Shafee et al. 2006; McClintock et al. 2006, 2014). Here, $J$ represents the angular momentum, $c$ is the speed of light, $G$ is gravitational constant and $M_{BH}$ is mass of the BH. Thus by studying the disc component during thermal dominated spectra of a BH, $J$ can be calculated which in turn gives the spin parameter if $M_{BH}$ is known. This method of determining the spin of BH by modelling the broadband energy spectrum is known as the continuum-fitting method (Zhang et al. 1997b; McClintock et al. 2011; Steiner et al. 2014).

LMC X-1 is the first extragalactic X-ray source found in the Large Magellanic Cloud (LMC) (Mark et al. 1969). The system is a HMXB containing an O7 III star along with a black hole, which are orbiting with a period of ~3.9 days (Cowley et al. 1995). The mass of black hole, inclination angle of the system and distance to the source are estimated to be $10.91 \pm 1.41 M_\odot$, $36.38 \pm 1.92^\circ$ and $48.1 \pm 2.22$ kpc respectively (Orosz et al. 2009). Continuum fitting of energy spectra during the thermal dominated states has shown that it is a rapidly spinning black hole (see also Tripathi et al. 2020) with spin parameter $a = 0.95^{+0.05}_{-0.05}$ (Gou et al. 2009). The X-ray emissivity of the source is always found to be in thermal dominated state (Ebisawa et al. 1989, 1993; Schmidke et al. 1999) with a power-law tail component above 10 keV. X-ray flux of the source is moderately variable in short period (< 1 ks) (Nowak et al. 2001) whereas very stable on long time-scale (Orosz et al. 2009). The temporal properties of LMC X-1 are similar to that of typical HSS with its PDS approximately following a power-law ($\propto f^{-1}$). QPOs of frequency ~ 26 – 29 mHz have been reported earlier and seems to be peculiar since such type of QPOs are usually found in hard state (Alam et al. 2014).

LMC X-3 is another persistent, bright, X-ray source in LMC consisting of a Roche lobe filling HMXB (Orosz et al. 2014) with a BH of mass $6.98 \pm 0.56 M_\odot$ (Soria et al. 2001; Orosz et al. 2014). Studies done on this object show that LMC X-3 is spinning at a very low rate with $a = 0.25^{+0.23}_{-0.20}$ (Steiner et al. 2010) and the disc inclination angle is $69.24 \pm 0.72^\circ$ (Orosz et al. 2014). The source is mostly found in thermal dominated state (Nowak et al. 2001) with the occasional transition to LHS (Boyd et al. 2000; Wilms et al. 2001; Smale & Boyd 2012). LMC X-3 is also found to have undergone an Anomalous Low/Hard State (ALS) repeatedly where the X-ray flux drops to a very low value (~ 1 x 10$^{-3}$ erg/s) in lower energy (Torpin et al. 2017). The long term variability of the source has a high amplitude of the factor of ~ 4 on a 100 – 200 day time scale (Cowley et al. 1991). However, the variability in the short term scale is very less of only a few percentages (Nowak et al. 2001). Temporal studies done on the source show that the LHS consists of a strong broadband variability with fractional rms of ~20% along with a QPO at 0.4 Hz (Boyd et al. 2000) and HSS has less variability with no QPOs (Treves et al. 1988). Despite having large flux variation in long term scale, the inner disc radius is found to remain constant over a long period of time (Steiner et al. 2010).

In this work, we present the first results of the broadband spectral and temporal study of the extragalactic BH-XRBs LMC X-1 and LMC X-3 carried out using all the AstroSat (Agrawal 2001) archival and legacy observations. AstroSat with its unprecedented spectral and timing resolution along with its broadband coverage forms an excellent observatory to carry out studies on XRBs. Therefore in this study, we make use of the remarkable characteristics of AstroSat to perform the spectral and temporal studies of the sources. Source properties during different epochs which are separated by a time gap of a few months spanning over ~ 4.5 years of the AstroSat era are explored. We look into the evolution of the source light curve on long term and short term in order to understand the evolution of fractional variance. While long term variability of the source light curve is studied using MAXI data, LAXPC observations are used to study the short term variability. We also investigate the nature of the PDS to estimate the fractional rms amplitude and look for the presence of any QPOs by means of temporal analysis. Further, we attempt to constrain the BH mass, spin and accretion rate by applying the relativistic disc model to the broadband energy spectra using continuum fitting method.

This paper is organized as follows. In section 2, we present the observation and data reduction method of AstroSat data. In section 3, we discuss the methods of timing analysis and spectral modeling. The results of temporal properties, spectral properties along with the estimation of physical parameters are presented in section 4. Finally in section 5, we discuss and conclude the results of our study of LMC X-1 and LMC X-3 using AstroSat observations.

### 2 OBSERVATION AND DATA REDUCTION

Persistent X-ray binaries LMC X-1 and LMC X-3 are observed by AstroSat during the period of 2016–2020 with its X-ray instruments Soft X-ray Telescope (SXT) (Singh et al. 2017) and Large Area X-ray Proportional Counter (LAXPC) (Yadav et al. 2016; Antia et al. 2017) in the energy range 0.3 – 8 keV and 3 – 80 keV respectively. We make use of its broadband energy coverage and excellent timing resolution (10 µs) of LAXPC instrument in our study. We obtain all the archival and legacy observation data of these sources from the AstroSat-Indian Space Science Data Centre (ISSDC)\(^1\) (see Table...
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Figure 1. *AstroSat* - SXT images of the sources LMC X-1 and LMC X-3 obtained using PC and FW modes are shown respectively in the left and right panels. These two images represent observations during MJD 57717 and MJD 58155 respectively. We consider a circular region of 10′ for LMC X-1 and 5′ for LMC X-3 as marked in the images from which the spectrum and light curve are extracted (see section 2.1 for details). The bright spots in the corner of PC mode image are from the calibration sources.

Table 1. The log of LMC X-1 and LMC X-3 observations by *AstroSat*.

| Observation Id | Date (MJD) | Epoch | Exposure (s) |
|----------------|------------|-------|--------------|
| A02_118T01_9000000826 | 57717 | 1 | 62210 |
| A03_119T02_9000001496 | 57993 | 2 | 14554 |
| A08_008T01_9000003414 | 58854 | 3 | 62074 |
| A08_008T01_9000003596 | 58939 | 4 | 4573 |
| A08_008T01_9000003596 | 58940 | 5 | 53504 |

| Observation Id | Date (MJD) | Epoch | Exposure (s) |
|----------------|------------|-------|--------------|
| G05_212T01_9000000600 | 57814 | 1 | 25712 |
| G05_212T01_9000000672 | 57650 | 2 | 21423 |
| A03_106T01_9000001130 | 57846 | 3 | 19408 |
| A03_106T01_9000001190 | 57862 | 4 | 28600 |
| A04_112T01_9000001698 | 58074 | 5 | 28905 |
| A04_112T01_9000001778 | 58104 | 6 | 42962 |
| A04_112T01_9000001884 | 58155 | 7 | 32550 |
| A04_112T01_9000001908 | 58169 | 8 | 32738 |
| A08_008T02_9000003430 | 58860 | 9 | 56862 |

1. We also make use of MAXI data obtained from “MAXI/GSC on-demand web interface”\(^2\) to plot the long term light curve and hardness ratio.

2. \(XSELECT\) v2.5g. SXT image of the source has count rate < 40 counts/s and we did not find any effect of pile-up (following the criteria given in *AstroSat* handbook\(^4\)). Therefore, a circular region of radius 10′ (left panel of Figure 1) and 5′ (right panel of Figure 1) are chosen for PC and FW modes respectively. From this region, the spectrum and light curve for further analysis are extracted. SXT background file and response matrix file (rmf) provided by the SXT instrument team are used. The auxiliary response file (ARF) for the selected source extraction region is obtained using \(\text{sxtarfmodule}\). In the energy spectrum, data is grouped with 20 counts in a single bin. A gain fit correction is applied for SXT spectrum using the \text{gain fit} command to account for instrumental features at low energy values of 1.8 keV and 2.2 – 2.4 keV for absorption edges of Si & Au respectively (see also Singh et al. 2017 and SWIFT-XRT website\(^5\)).

2.1 SXT Data Reduction

X-ray imaging instrument SXT operates in the energy range of 0.3 – 8 keV. For the analysis of SXT data, we follow the guidelines provided by SXT team\(^6\) (see also Sreehari et al. 2019; Baby et al. 2020 for details). SXT has observed both sources LMC X-1 and LMC X-3 in Photon Counting (PC) mode and some of the LMC X-3 observations in Fast Window (FW) mode. Level-2 SXT data for all the observations are obtained from the ISSDC data archive. Individual orbit data are merged into a single event file with the SXT event merger tool using *Julia* v1.1. The resultant cleaned event file is used to extract the spectrum and light curve in 0.3 – 8 keV energy range using \(XSELECT\) v2.5g. SXT image of the source has count rate < 40 counts/s and we did not find any effect of pile-up (following the criteria given in *AstroSat* handbook\(^4\)). Therefore, a circular region of radius 10′ (left panel of Figure 1) and 5′ (right panel of Figure 1) are chosen for PC and FW modes respectively. From this region, the spectrum and light curve for further analysis are extracted. SXT background file and response matrix file (rmf) provided by the SXT instrument team are used. The auxiliary response file (ARF) for the selected source extraction region is obtained using \(\text{sxtarfmodule}\). In the energy spectrum, data is grouped with 20 counts in a single bin. A gain fit correction is applied for SXT spectrum using the \text{gain fit} command to account for instrumental features at low energy values of 1.8 keV and 2.2 – 2.4 keV for absorption edges of Si & Au respectively (see also Singh et al. 2017 and SWIFT-XRT website\(^5\)).

2.2 LAXPC Data Reduction

LAXPC Level-1 data is downloaded from the ISSDC data archive. Level-1 data is processed to Level-2 by using the LAXPC pipeline software (LaxpcSoft\(^6\)). We make use of the data from LAXPC 20 only for the uniform study of observations during 2016-2020, due to gain instability reported in LAXPC 10 and LAXPC 30 detectors \(^7\) (see also Baby et al. 2020). Observation specific response and background files generated by the software following Antia et al. 2017 are used. The software routine creates the Good Time Interval (GTI) file consisting of timing information during Earth occultation and South Atlantic Anomaly (SAA). LAXPC data is obtained by considering the single events and top layer of the detector unit (see also Sreehari et al. 2019; Katoch et al. 2020 (under review)). The analysis and modelling methods of the reduced data are presented in the next section.

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\(^1\) https://www.tifr.res.in/~astrosat_sxt/dataanalysis.html

\(^2\) http://maxi.riken.jp/mxondem/

\(^3\) https://www.issdc.gov.in/docs/ast/1/AstroSat-Handbook-v1.1.0.pdf

\(^4\) https://www.swift.ac.uk/analysis/xrt/digest_cal.php#res

\(^5\) https://www.tifr.res.in/~astrosat_laxpc/LaxpcSoft.html

\(^6\) http://astrosat-ssc.iucaa.in/
3 ANALYSIS AND MODELLING

3.1 Temporal Analysis

Source light curves with a time-bin of 1 day, obtained from MAXI observations in the energy range of 2 – 20 keV, 2 – 6 keV and 6 – 20 keV are used to study the long term variance of the sources. The hardness ratio (HR) is obtained by dividing the source flux (in units of photons/cm²/s) of the two light curves (i.e. flux of 6 – 20/2 – 6 keV). We estimate the fractional variance of the light curve for the period of 2016 – 2020 using $F_{\text{var}} = \sqrt{\overline{s^2} - \overline{s_{\text{err}}^2}}$

$\overline{s^2}$ is the total variance of the light curve and $\overline{s_{\text{err}}^2}$ is the error associated with measurement and $\overline{s}$ is the mean count rate of the light curve.

We generate the LAXPC light curves with 1 sec time-bin to study the short term variability of the sources in the energy range of 3 – 20 keV. LAXPC light curves of 50 ms time-bin in the energy range of 3 – 20 keV are also considered to study the nature of the PDS. Each light curve is divided into intervals of 8192 time bins and the PDS is constructed for each of these bins. The average of these PDS is obtained and is binned logarithmically by a factor of 1.05 in the frequency space. The resultant binned PDS are normalized to get the fractional rms spectra ($P_{\text{DS}}$ is obtained and is binned logarithmically by a factor of 1).

We also estimate the fractional rms amplitude in the frequency range 0.002 – 10 Hz using the rectangle rule integration method given by $rms = \sqrt{\overline{P^2} - \overline{P}\overline{P}} \times 100$ (in %)$^9$ (see also Radhika et al. 2016a,b, 2018 for details), where $P$ is the power in the units of rms²/Hz and $\Delta f$ is the frequency in Hz. We follow the above mentioned procedures for both sources and obtained timing results are presented in section 4.1.

3.2 Spectral Analysis

As the energy spectra of both sources have no significant flux above 20 keV, we consider the SXT spectrum in the energy range of 0.5 – 7 keV and that of LAXPC in 4 – 20 keV. Broadband energy spectra (0.5 – 20 keV) are analyzed and modeled using Xspec v12.10 tool (Arnaud 1996) of HEAsoft v6.26.1.

We use TBabs model to represent the hydrogen column density ($n_H$) along the line of sight. Since much of the absorption of X-ray from LMC X-1 and LMC X-3 is due to the metallic abundance in the host galaxy (Hanke et al. 2010), we consider the LMC abundance following Hanke et al. (2010) in our calculation of $n_H$. These abundance values are adapted by using the abund file command in XSpec during the spectral fit. Initially, we model the broadband spectral data using a single powerlaw along with an absorption model by keeping the parameters of powerlaw in both data set independent of each other. It is observed that the unfolded spectrum with respect to powerlaw along-with the ratio of data by powerlaw model shows instrumental smearing (Vaughan et al. 1999; Boller et al. 2002; Fabian et al. 2002; Fabian & Vaughan 2003) as well as the need for disc component in the lower energy range. Then, in order to study the spectral properties of the source, we model the broadband (0.5 – 20 keV) energy spectrum of LMC X-1 for all the epochs with the phenomenological model $\text{TBabs} (\text{diskbb} + \text{powerlaw})$. This model combination is referred as Model-1. An overall systematic error of 1% is incorporated into all the fits to account for uncertainty in the response matrix. For LMC X-3, energy spectra of all the epochs are found to be very soft with significant data till 10 keV. Therefore, we use Model-1 for spectral modeling of LMC X-3 without powerlaw component for all observations except Epochs 1 and 4. However, a smudge is included to account for the reflection seen above 7 keV for most of the epochs. We also made an attempt to model the spectra with physical model mbhcomp (Zycki et al. 1999) of Xspec but the fit did not give meaningful physical parameter values and $\chi^2_{\text{red}}$ obtained was > 2. From the broadband energy spectra, we calculate the unabsorbed bolometric source flux (in 0.1 – 100 keV) as well contribution of disc flux (in 0.5 – 20 keV) over the total unabsorbed flux using the cflux model. The hardness ratio (HR) is calculated by estimating the ratio of flux in the energy range 6 – 20 keV and 3 – 6 keV. Errors for all the parameters are obtained at 90% confidence interval, and relevant error propagation formulae are also implemented based on Bevington & Robinson 2003.

Further, we model the broadband energy spectra using several relativistic accretion disc models in order to constrain the physical parameters of the BHs. In this regard, we consider the kerrbb model (Li et al. 2005), which assumes a thin, relativistic accretion disc around a Kerr black holes. Therefore, we model the broadband energy spectra using the continuum model combination of kerrbb and simp1 (Steiner et al. 2009) in order to constrain the mass ($M_{\text{BH}}$), spin ($a$) and mass accretion rate ($\dot{M}$) of the system. We refer to the model combination: $\text{TBabs(kerrbb*simp1)}$ as Model-2 hereafter. While kerrbb takes into account of the relativistic effect on soft X-ray from the accretion disc, simp1 model considers the Comptonization process of the disc photons. While using Model-2 for both sources, we consider the known values of inclination angle and distance (see section 1). The detailed results obtained from timing and spectral modeling are presented in section 4.

4 RESULTS

4.1 Temporal Properties

In this section, we present the temporal properties and lightcurve variability of LMC X-1 and LMC X-3 using LAXPC data. Along with this, we present the long-term light curve variability of the sources as observed by MAXI for a period of ~ 4.5 years (MJD 57400 – MJD 59000) within the duration of AstroSat observations. In the left side of Figure 2, we show the variability of the light curve in 2 – 6 keV (top panel), 6 – 20 keV (middle panel) and HR (bottom panel) of LMC X-1. In the right side of Figure 2, we plot the same for LMC X-3. It is observed that LMC X-1 does not show significant variability and the average HR of this source is ~ 0.2. The fractional variance $F_{\text{var}}$ of the light curve in the energy range 2 – 20 keV, is calculated using the method mentioned in section 3.1 is found to be 24.9% for LMC X-1. On the other hand, LMC X-3 shows significant intensity variation with HR in the range 0.01 – 2.0. The $F_{\text{var}}$ calculated for LMC X-3 considering the entire time period is found to be 52.9%. The light curve periodicity during the initial 700 days is ~ 100 – 200 days and beyond that, the source has a random variability pattern (see top right panel of Figure 2 for LMC X-3). Short term variability of the source is studied using LAXPC light
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4.2 Spectral Properties

4.2.1 LMC X-1

AstroSat has observed the source LMC X-1 during five epochs (see Table 1) with a time gap of several months. From the spectral fit, we get the $n_H$ value of $1.22 \pm 0.02 - 1.48 \pm 0.04 \times 10^{22}$ atoms cm$^{-2}$. We note that the Epoch-1 spectrum requires an additional cut-off at 6.29$^{+0.08}_{-0.09}$ keV which is taken into account with a single power law model ($\chi^2_{\text{red}}$ improves from 1.94 to 1.32). During the different epochs, the value of disc temperature ($T_d$) varies from 0.86$ \pm 0.01$ to 0.98$ \pm 0.01$ keV, while the photon index (\(\Gamma\)) is in the range 2.46$ \pm 0.04$ – 3.29$ \pm 0.04$. The bolometric luminosity calculated (0.1 – 100 keV) is in the range of $8.4 \times 10^{37}$ erg/s ($\approx 0.07 L_{\text{Edd}}$) to $1.17 \times 10^{38}$ erg/s ($\approx 0.10 L_{\text{Edd}}$). Total flux is found to be contributed mainly from the disc with 79% - 94% contribution. Also, the value of the hardness ratio is observed to vary from 0.16 to 0.34. We do not observe any feature of Fe line emission in any of the epochs, but a reflection edge exists in the range of 7 keV during Epochs 1 and 2. The folded spectrum of Epoch-4 of LMC X-1 is shown in the left plot of Figure 4. In Table 3, we summarize the values obtained for the parameters using Model-1.

The observed inner disc radius of the accretion disc $r_{\text{in}}$ is calculated using the normalization ($N_{\text{diskb}}$) value of diskbb. $N_{\text{diskb}}$ and disc radius are related as $N_{\text{diskb}} = (r_{\text{in}}/D_0)^2 \times \cos \theta$, where $r_{\text{in}}$ is the observed inner disc radius, $D_0$ is the distance to the source in 10 kpc and $\theta$ is the inclination angle of the disc. However, since $r_{\text{in}}$ is the apparent radius we estimate the ‘true’ radius following Kubota et al. 1998. ‘True’ radius is given as $R_{\text{in}} = \xi^2 r_{\text{in}}$ where $\kappa$ is taken to be 1.55 (see section 4.3 for details) and $\xi = 0.412$ as given by Kubota et al. 1998. We obtain the value of ‘true’ radius $R_{\text{in}}$ to be varying from 29.65$ \pm 0.71$ km to 39.17$ \pm 0.71$ km during the different epochs of LMC X-1.

4.2.2 LMC X-3

LMC X-3 has been observed by AstroSat during nine epochs with a time gap of several months (see Table 1). The $n_H$ value obtained during different epochs is in the range of 0.03$ \pm 0.01$ – 0.07$ \pm 0.02 \times 10^{22}$ atoms cm$^{-2}$. Its average value is slightly higher than that obtained by considering only the Galactic abundance ($\approx 0.04 \times 10^{22}$). During the different epochs, the value of disc temperature is $\sim 1$ keV while the norm varies from 16.18$^{+0.97}_{-0.90}$ to 21.35$^{+0.30}_{-1.7}$. No Fe line features are observed in any of the spectra. Unabsorbed bolometric luminosity (0.1 – 100 keV) is found to vary between 5.1$ \times 10^{37}$ – 1.02$ \times 10^{38}$ erg/s ($\approx 0.07$ – 0.13 $L_{\text{Edd}}$). The disc flux contribution and hardness ratio calculated are $> 96\%$ and 0.10 – 0.19 respectively throughout the different observational epochs. Modified inner disc radius $R_{\text{in}}$ is found to be in the range 32.40$ \pm 0.95$ – 37.21$ \pm 0.95$ km, considering $\kappa = 1.7$. We plot the folded spectrum of Epoch-5 data of LMC X-3 in Figure 4. The spectral parameters of best-fit values are mentioned in Table 3.

Figure 2. MAXI light-curve of LMC X-1 (left panel) and LMC X-3 (right panel) during the period of 2016 – 2020 in the energy band of 2 – 6 keV (top panel) and 6 – 20 keV (middle panel). Ratio of the flux in hard energy and soft energy bands (6–20/2–6 keV) is plotted in bottom panel. All the AstroSat observations considered for these sources have been marked in black vertical lines along with corresponding Epoch numbers.
that both sources have a soft energy spectrum dominated by the contribution from the disc component flux. Hence we attempt to estimate the source mass and spin using the broadband continuum fitting method. For this purpose, we model the spectra with Model-2.

The important model parameters obtained are $M$, $a$, $M_{BH}$ in units of $M_\odot$, photon index ($\Gamma$) and scattering fraction ($\text{FracScat}$). We estimate $M$ of LMC X-1 to be of $1.24^{+0.10}_{-0.09} - 2.16^{+0.39}_{-0.25} \times 10^{18}$ g/s. We find that this value of accretion rate is 0.29 – 0.51 of the Eddington rate ($M_{Edd}$). Gou et al. 2009 estimated the spectral hardening factor for this source to be 1.55 using RXTE observations during which the source existed in a thermal dominated state. Since all the AstroSat observations considered in this paper also have thermal disc dominated spectra with almost constant luminosity, we choose the same value for the hardening factor. To confirm the consistency of this value, we fit the spectral data by keeping the $\Gamma$ value fixed. To confirm the hardening factor to be 1.55 for all the epochs of LMC X-1. We note that the resultant parameters using the $\text{simpl}$ model i.e. $\Gamma = 2.61^{+0.15}_{-0.16}$ and the $\text{FracScat}$ is in the range $0.03^{+0.01}_{-0.02}$ for different epochs of LMC X-1. The $M$ of LMC X-3 is in the range $2.02^{+0.09}_{-0.08} - 4.03^{+0.17}_{-0.14} \times 10^{18}$ g/s which corresponds to $0.14 - 0.29$ of $M_{Edd}$. Spectral hardening factor of 1.7 is considered for these fits of LMC X-3.

We obtain the source mass for LMC X-1 to be in the range of $7.64^{+0.92}_{-0.25} M_\odot$ to $10.00^{+0.52}_{-1.22} M_\odot$ during the different epochs. The...
spin parameter is found to be varying from $0.82^{+0.10}_{-0.02}$ to $0.92^{+0.03}_{-0.04}$. During the nine observation epochs of LMC X-3, we find the source mass to be varying from $5.35^{+0.32}_{-0.22} M_{\odot}$ to $6.22^{+0.48}_{-1.24} M_{\odot}$. The value of spin is estimated to be in the range of $0.22^{+0.02}_{-0.01} - 0.41^{+0.02}_{-0.02}$. The model fitted parameters along-with the values of spin and mass are tabulated in Table 4. In order to get a better estimation of the error of the mass and spin parameters, we have performed Markov Chain Monte Carlo (MCMC) chain simulation using Goodman-Weare algorithm (Goodman & Weare 2010). This is incorporated using XSpec where the walkers parameter is set to 32, initial chain length is taken to be 15,000 with a burn length of 5,000. In Figure 5, we show the contour plots of mass versus spin values and their probability distributions for the Epoch-4 and Epoch-7 observations of LMC X-1 and LMC X-3 respectively. This is plotted by adapting the MCMC Hammer algorithm (Foreman-Mackey et al. 2013). The contours are plotted for the 68% and 90% confidence intervals (see also Sreehari et al. 2020), showing the range of spin and mass values.

### Table 3. Spectral parameter values obtained from the best-fit of Model-1 for both LMC X-1 and LMC X-3. $T_{in}$ (in units of keV) corresponds to disc temperature, $N_{diskbb}$ is disc norm. The parameters of powerlaw are denoted by the photon index $\Gamma$ and norm $N_{PL}$. The value of $edgeE$ is the energy component from the smedge model. $L_{bol}$ is the bolometric luminosity for the energy range $0.1 - 100$ keV in units of $10^{38}$ erg/s estimated by incorporating the known values of mass quoted in section 1. $f_{disk}$ and $f_{total}$ are unabsoerd disc flux and total flux calculated in the energy range $0.5 - 20$ keV. $HR$ corresponds to the hardness ratio estimated for ratio of flux in $6 - 20$ keV and $3 - 6$ keV. Error for all the parameters are calculated with 90% confidence, and by also considering the error propagation method wherever appropriate.

| Epoch | $T_{in}$ (keV) | $N_{diskbb}$ | $\Gamma$ | $N_{PL}$ | $edgeE$ (keV) | $L_{bol}$ ($\times 10^{38}$ erg/s) | $f_{disk}$/f_{total} (%) | $HR$ | $\chi^2/df$ |
|-------|---------------|--------------|----------|---------|---------------|------------------------------|------------------------|------|----------|
| 1     | 0.86 ± 0.01   | 53.41^{+2.16}_{-1.29} | 2.63 ± 0.02 | 0.10^2 | 7.54^{+0.93}_{-0.30} | 0.94 | 84 | 0.21 ± 0.02 | 700.39/529 = 1.32 |
| 2     | 0.90^{+0.02}_{-0.01} | 46.17^{+4.35}_{-2.77} | 2.46 ± 0.04 | 0.16 ± 0.01 | 8.28^{+0.79}_{-0.35} | 1.17 | 84 | 0.34 ± 0.02 | 582.95/417 = 1.39 |
| 3     | 0.96 ± 0.01   | 35.02^{+1.78}_{-1.78} | 3.29 ± 0.04 | 0.10^2 | - | 0.84 | 84 | 0.16 ± 0.02 | 670.77/506 = 1.32 |
| 4     | 0.98 ± 0.02   | 30.96^{+0.91}_{-0.71} | 3.03^{+0.13}_{-0.05} | 0.09^2 | - | 1.02 | 79 | 0.24 ± 0.03 | 393.08/338 = 1.16 |
| 5     | 0.98 ± 0.01   | 30.74^{+0.29}_{-0.17} | 3.19^{+0.10}_{-0.04} | 0.15 ± 0.01 | - | 0.95 | 94 | 0.19 ± 0.02 | 540.27/480 = 1.12 |

\* - includes a high energy cut off at 6.29 keV (see section 4.2.1 for details).
\* - only disc contribution.
\* - error is insignificant.

5 DISCUSSION AND CONCLUSIONS

In this paper, we have studied the broadband spectral and temporal variability of the BH sources LMC X-1 and LMC X-3 using AstroSat archival and legacy data. For LMC X-1 we study the source characteristics during five different observation epochs and for LMC X-3 nine observations have been looked into; all spanning a 5 years period. Applying the same procedure as discussed in section 3.1 to the entire RXTE-

Figure 4. Broadband spectral fitting performed for Epoch-4 observation of LMC X-1 (left) in 0.5 – 20 keV and Epoch-5 observation of LMC X-3 (right) in 0.5 – 10 keV. Combined SXT and LAXPC spectrum is modelled with Model-1 for LMC X-1 and diskbb along with smedge for LMC X-3.
ASM light curve\footnote{http://xte.mit.edu/asmlc/One-Day.html} for ~15 years in 3 – 12 keV band, we obtain the fractional variance as 34% and 76% for LMC X-1 and LMC X-3 respectively. On comparing this with the results we obtained using MAXI data, it agrees that variability of LMC X-1 on large time scale is less whereas that of LMC X-3 is very high.

We note that the short term LAXPC light curve variability varies from 7.41% to 15.89% for LMC X-1, while it is in the range 9.7% - 23.9% for LMC X-3 (see Table 2). We observe that on long time-scales the value of HR remains constant for LMC X-1, while it has a significant variation with a periodic pattern for LMC X-3. From Figure 2 we find that LMC X-1 does not show any periodic nature in its light curve, while LMC X-3 does. The light curve periodicity of LMC X-3 during the initial 700 days is ~ 100 – 200 days, which is similar to that reported earlier by Cowley et al. 1991; Nowak et al. 2001; Smale & Boyd 2012. However, since MJD 58100 the variability pattern becomes random and do not follow the periodic nature (see right panel of Figure 2).

We explored the temporal properties of the source by generating the PDS. For all epochs of LMC X-1 and LMC X-3, the PDS shows only weak power-law nature as evident from the left and right panels of Figure 3. The fractional rms amplitude varies in

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Epoch & $M$ & $\Gamma^\ast$ & FracScat$^\ast$ & $a$ & $M_{BH}$ & $\chi^2/dof$
\hline
1 & 1.60$^{+0.03}_{-0.02}$ & 4.46$^{+0.24}_{-0.21}$ & 0.20$^{+0.03}_{-0.02}$ & 0.86$^{+0.08}_{-0.07}$ & 9.39$^{+0.50}_{-0.46}$ & 744.50/529 = 1.40
2 & 2.16$^{+0.10}_{-0.10}$ & 2.61$^{+0.13}_{-0.12}$ & 0.13$^{+0.03}_{-0.02}$ & 0.82$^{+0.10}_{-0.09}$ & 10.00$^{+0.95}_{-0.92}$ & 682.18/417 = 1.50
3 & 1.24$^{+0.10}_{-0.09}$ & 3.04$^{+0.11}_{-0.11}$ & 0.03$^{+0.01}_{-0.01}$ & 0.90$^{+0.03}_{-0.03}$ & 7.64$^{+0.95}_{-0.92}$ & 631.94/510 = 1.24
4 & 1.48$^{+0.24}_{-0.15}$ & 3.31$^{+0.57}_{-0.36}$ & 0.09$^{+0.05}_{-0.05}$ & 0.91$^{+0.03}_{-0.03}$ & 8.92$^{+1.22}_{-1.11}$ & 397.53/338 = 1.18
5 & 1.29$^{+0.12}_{-0.12}$ & 4.50$^{+0.03}_{-0.03}$ & 0.09$^{+0.04}_{-0.04}$ & 0.92$^{+0.03}_{-0.03}$ & 7.99$^{+0.73}_{-0.71}$ & 545.63/490 = 1.11
\hline
\end{tabular}
\caption{Best-fit parameters obtained by fitting Model-2 for continuum-fitting of broadband energy spectra. The value of $d$ is frozen to 48.1 kpc, while $i$ is considered as $36.38 \pm 1.92^\circ$ for LMC X-1 and $69.24 \pm 0.72^\circ$ for LMC X-3 (see section 1). BH mass $M_{BH}$ is constrained to be in the range of $7.0 - 12.0 M_{\odot}$ and 5.0 – 8.0$M_{\odot}$ for LMC X-1 and LMC X-3 respectively. Spectral hardening factor of 1.35 and 1.7 has been considered for this fitting of LMC X-1 and LMC X-3 respectively. Parameter $M$ is the accretion rate in units of $10^{18}$ g/s, $\Gamma$ is the photon index, FracScat is the scattering fraction, $a$ represents the source spin and $M_{BH}$ is the mass in units of $M_{\odot}$. Error of all the parameters are estimated at 90% confidence.}
\end{table}
between 9% and 16.7% for LMC X-1 and 7.16% – 10.9% for LMC X-3 (see Table 2). We also did not observe any QPOs during the different epochs, even though previous publications have reported presence of mHz QPOs in LMC X-1 (Alam et al. 2014) and LMC X-3 (Boyd et al. 2000) in LHS. The weak power-law nature of the PDS, fractional rms and absence of QPOs support the fact that the sources have characteristics of a soft state. Thus from both spectral and temporal characteristics, we understand that the sources remain in a thermal emission dominated spectral state.

The spectral fits performed for the broadband AstroSat observations of the sources are very well described by a thermal disc emission, with presence of occasional steep power-law of photon index $\sim 2.4 – 3.2$ (see Figure 4 and Table 3). From Table 3, we find that the disc temperature remains around 1 keV and the fractional disc flux contribution is observed to change between 79% and 94% during the different epochs for LMC X-1. We also find that the hardness ratio varies from 0.16 to 0.34 during the epochs. This suggests that source spectra are dominated by thermal disc component during all the five epochs. For LMC X-3, we observe that the disc temperature is $\sim 1$ keV, fractional disc flux is $> 96\%$ and HR is 0.10 – 0.19 (Table 3) during the different epochs. These variations in the spectral parameters indicate that the source LMC X-3 occupied a disc dominated high soft state during the AstroSat observations. The values of disc parameters obtained are consistent with that obtained by the BeppoSAX (Treves et al. 2000; Haardt et al. 2001) and RXTE observations (Nowak et al. 2001). The bolometric luminosity estimated of 0.07 – 0.10 $L_{\text{Edd}}$ and 0.06 – 0.14 $L_{\text{Edd}}$ suggests that the sources LMC X-1 and LMC X-3 are emitting in sub-Eddington.

We also did attempt to find the ‘true’ radius of the accretion disc following Kabota et al. 1998 and got a value of 29.65 – 39.17 km for LMC X-1 and 32.40 – 37.2 km for LMC X-3, which are within $\pm 3$ km of the mean value. We understand that the radius varies over a long time period for both sources. It has to be noted that these estimations of radius do not follow in sync\(^{11}\) with the source mass estimated (see section 4.3) and reported earlier (Orosz et al. 2009, 2014). We did not observe any strong Fe Kα line in both sources. But a reflection edge was seen which possibly has a minimal contribution to the total unabsorbed flux.

Further, we attempt to constrain the source parameters: mass and spin. Since there were no Fe Kα emission line detected, we have chosen the continuum fitting method over the entire broadband AstroSat energy range considered. By using the kerr video model, we were able to get acceptable spectral fit parameters (mass of 12.64 – 13.00 $M_\odot$) during the different epochs of LMC X-1 but not for any of the observations of LMC X-3. This suggests that the source LMC X-1 belongs to the category of extremely rotating BHs, while LMC X-3 is a weakly rotating source. Using the kerrbb and simpl model combination, we were able to constrain both sources’ mass, spin and accretion rate. In order to get better estimations on errors of these parameters, we have performed MCMC chain simulation using Goodman-Weare algorithm (Goodman & Weare 2010) within XSpec. Errors estimated with 90% confidence using this chain yielded a better estimation. We cross-check these error values with the error estimation using MCMC hammer algorithm (Figure 5). We find that the mass for LMC X-1 to be in the range of $7.64^{+0.99}_{-0.25} M_\odot$ to $10.00^{+0.52}_{-1.22} M_\odot$ and for LMC X-3 it is $5.35^{+0.34}_{-0.34} M_\odot$ to $6.22^{+0.48}_{-1.74} M_\odot$. All these estimates are in close agreement with the dynamical mass estimate of 10.91 ± 1.41 $M_\odot$ and 6.98 ± 0.56 $M_\odot$ reported by (Orosz et al. 2009, 2014) for LMC X-1 and LMC X-3 respectively. Similarly, the spin estimate of 0.82$^{+0.10}_{-0.02}$ – 0.92$^{+0.04}_{-0.05}$ for LMC X-1 agrees with the previous report by Gou et al. 2009; Tripathi et al. 2020, Mudambi et al. (2020) has recently reported a spin value of 0.93 by analyzing the first two AstroSat observations of LMC X-1, but by considering only the Galactic abundance and a higher spectral hardening factor (1.7). For LMC X-3, the spin estimated is 0.22 ± 0.03 – 0.41 ± 0.02 within 90% confidence interval (see section 4.3, Figure 5 and Table 4), which is better constrained w.r.t. that already reported (0.25$^{+0.29}_{-0.20}$, Steiner et al. 2010). We also check the rotating nature of the sources following Makishima et al. 2000, which expresses the source mass as $M = R_{\text{BH}}/8.86\sigma$. Here, $\alpha$ is the positive parameter which has a value of $1$ for non-rotating BHs and $1/6$ for BHs with extreme rotation. Considering the value of the ‘true’ radius of the accretion disc and the average source mass estimated (see section 4.2.1, 4.2.2, 4.3), we find the value of $\alpha$ to be 0.37 – 0.50 for LMC X-1 and 0.63 – 0.73 for LMC X-3. These estimates of $\alpha$ suggest that the source LMC X-1 probably is a maximally rotating ‘hole’, which is also supported by the spin estimation of 0.82 – 0.92. Also, the value of $\alpha$ being close to 1 for LMC X-3 suggests that the compact object could be a weakly rotating BH. This fact is consistent with the estimate of spin using continuum fitting method as 0.22 – 0.41.

LMC X-1 and LMC X-3 are peculiar when compared to other persistent BH-XRBs in terms of the spectral behavior. Based on the study of spectral and temporal evolution of the sources using AstroSat observations discussed in this paper, we observe the sources remain in a thermally dominated state over a long duration. We observe that LMC X-3 exists in a HSS during all the AstroSat observations conducted till date. Previous publications have mentioned a state transition to LHS, which probably suggest frequent monitoring observations of the source are required to probe the accretion dynamics. Similar kind of spectral state transitions over long time scales have been observed for other persistent sources like Cyg X-1 (Gierliński et al. 1999), GRS 1758-298 and 1E 1740.7-2942 (Main et al. 1999) using RXTE observations.

Based on the spectral and temporal studies for the sources LMC X-1 and LMC X-3 using AstroSat observations, we summarize our results with the following conclusions:

- The study of MAXI light curves over a duration of 4.5 years show that LMC X-1 has a long term fractional variability of 25%, while LMC X-3 has a higher variability of 53%.
- Long term light curve periodicity of ~ 100 – 200 days seen for LMC X-3 during the initial 700 days, while the variability pattern becomes random later without having any periodic nature.
- LMC X-1 is moderately variable from 7.4% – 16% over short time scale, while LMC X-3 has variability ranging from 9.7% – 24% during the different observation epochs.
- The spectral characteristics suggest the sources have a thermal disc dominated energy spectra.
- The weak power-law nature of PDS and evolution of fractional rms amplitude with the absence of low-frequency QPOs supports that sources remained in the thermally dominated soft state.
- We constrain the source mass in the range of 7.64 – 10.00 $M_\odot$ for LMC X-1, and 5.35 – 6.22 $M_\odot$ for LMC X-3, which are in close agreement with that already reported.
- The spin parameter is estimated to be 0.82 – 0.92 for LMC X-1 and is consistent with previous publications. In case of LMC

\(^{11}\) Considering $R_{\text{ISCO}} = 9 \text{ km}$ for a non-rotating BH of mass $1 M_\odot$ and 3 km for an extremely rotating BH with same mass, where $R_{\text{ISCO}}$ is the radius of innermost stable circular orbit (Shapiro & Teukolsky 1983; Remillard & McClintock 2006)
X-3, we could obtain a better constrain of the spin as 0.22 – 0.41 in contrast with that reported earlier.

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Facilities: AstroSat, MAXI.

DATA AVAILABILITY

The data used for analysis in this article are available in AstroSat-ISSDC website ([https://astrobrowse.issdc.gov.in/astro_archive/archive/Home.jsp](https://astrobrowse.issdc.gov.in/astro_archive/archive/Home.jsp)) and MAXI website ([http://maxi.riken.jp/top/index.html](http://maxi.riken.jp/top/index.html)).

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