J. Astrophys. Astr. (2021)42:17
https://doi.org/10.1007/s12036-020-09678-z

PAYLOAD REVIEW

Science with the AstroSat Soft X-ray telescope: An overview

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MS received 6 November 2020; accepted 4 December 2020

Abstract. The Soft X-ray Telescope (SXT) aboard the AstroSat satellite is the first Indian X-ray telescope in space. It is a modest size X-ray telescope with a charge coupled device (CCD) camera in the focal plane, which provides X-ray images in the $\sim$0.3–8.0 keV band. A forte of SXT is in providing undistorted spectra of relatively bright X-ray sources, in which it excels over some current large CCD-based X-ray telescopes. Here, we highlight some of the published spectral and timing results obtained using the SXT data to demonstrate the capabilities and overall performance of this telescope.

Keywords. Galaxies: active—novae, cataclysmic variables—space vehicles: instruments—telescopes—X-rays: binaries—X-rays: stars.

1. Introduction

The AstroSat Observatory is the first dedicated Indian astronomy satellite (Agrawal 2006; Singh *et al*. 2014; Seetha & Megala 2017; Singh & Bhattacharya 2017), with the Soft X-ray Telescope (SXT[1]), which is the first Indian X-ray telescope in space, on board (Singh *et al*. 2016, 2017a).

Cosmic X-rays are reflected by two sets of co-axial nested mirrors in SXT. The first set has conically approximated paraboloid surfaces and the second set has conically approximated hyperboloid surfaces. This is an approximate Wolter I geometry (Wolter 1952), with a cooled charge coupled device (CCD) camera at the focal plane. Multiple instruments/telescopes of AstroSat can simultaneously observe a source in a wide energy range from optical to hard X-rays (up to $\sim$100 keV; Seetha & Megala 2017), and SXT covers the crucial soft X-ray band ($\sim$0.3–8.0 keV; Singh *et al*. 2017b) in this range. This telescope has the following modest capabilities (Singh & Bhattacharya 2017; Singh

This article is part of the Special Issue on "AstroSat: Five Years in Orbit".

[1]https://www.tifr.res.in/~astrosat_sxt/index.html.

Published online: 25 May 2021

et al. 2017a, b): (1) the maximum effective area of ~ 90 cm^2 at ~ 1.5 keV; (2) an energy resolution of 80–150 eV in the 0.3–8.0 keV range; (3) time resolutions of 2.37 s in the Photon Counting (PC) mode and of 0.278 s in the Fast Window (FW) mode; (4) the field-of-view of 40 arcmin square; and (5) the Point Spread Function (PSF) having a full-width half-maximum of ~ 100 arcsec and the half encircled energy radius of ~ 5.5 arcmin. However, SXT has a much smaller pile-up compared to current large soft X-ray imaging telescopes, and hence is ideal to observe bright X-ray point sources.

These make SXT capable, as an independent telescope, to study continuum spectra, broad and somewhat narrow spectral lines and variations with timescales of seconds and above of various types of cosmic sources. Furthermore, this telescope, jointly with the Large Area X-ray Proportional Counters (LAXPC) and the Cadmium–Zinc–Telluride Imager (CZTI) aboard AstroSat, or jointly with any other hard X-ray instrument or telescope, such as *NuSTAR*, can observe the broadband X-ray spectrum of cosmic sources, and can uniquely contribute to the estimation of the hydrogen column density, and the characterization of the soft X-ray spectra. Its good energy resolution and signal-to-noise ratio can be particularly useful for broadband spectral modeling.

In this paper, we give an overview of some notable scientific results which required a significant role of SXT. In Sections 2–8, we mention results on black hole X-ray binaries (BHXBs), neutron star low-mass X-ray binaries (LMXBs), neutron star high-mass X-ray binaries (HMXBs), ultra-luminous X-ray pulsars (ULPs), cataclysmic variables (CVs), active galactic nuclei (AGNs) and stars, respectively. In Section 9, we make concluding remarks.

2. Black hole X-ray binaries

Astronomical black holes are characterized by two parameters, mass and spin, and hence the measurement of these parameters is essential to probe the fundamental physics of these objects (e.g., Middleton 2016). A black hole X-ray binary, i.e., a stellar-mass black hole accreting matter from a companion star, is particularly useful for this purpose, as well as to test a theory of gravitation and to probe the inflow and outflow of matter and its emission in an extremely strong gravitational field.

AstroSat SXT can be very useful to study soft X-ray continuum spectra and spectral lines from BHXBs, to measure their temporal variations and to track their evolution through various states. This telescope is particularly capable to characterize the accretion disk and reflection spectra, which can be used to estimate black hole parameter values. Here, we will give a few examples.

A transient BHXB 4U 1630–47 was observed with AstroSat during its 2016 outburst. The source was found in a very soft state with an accretion disk contribution of $\sim 97\%$ to the total flux. Such a source state is ideal to measure the black hole spin from the disk inner edge radius estimated from the disk spectral component. SXT was particularly useful to characterize the disk spectrum, having covered its peak and both sides better than other instruments (see Fig. 1). Using the XSPEC[2] `kerrbb` model for the relativistic disk blackbody to fit AstroSat SXT+LAXPC and contemporaneous *Chandra* High Energy Grating (HEG) spectra, the dimensionless black hole spin parameter was measured to be 0.92 ± 0.04 with 99.7% confidence (Pahari *et al.* 2018a). Similarly, a characterization of the thermal disk spectrum of the persistent BHXB LMC X–1 with SXT led to a measurement of the black hole spin parameter of ~ 0.93 (Mudambi *et al.* 2020a).

The ability of SXT to characterize both the disk blackbody spectral component and the relativistic Fe Kα emission line of the reflection spectral component was crucial to measure mass and spin parameters of the transient BHXB MAXI J1535–571 (see Fig. 2; Sridhar *et al.* 2019). More recently, AstroSat (SXT+LAXPC+CZTI) and contemporaneous *NuSTAR* data were used to characterize another transient BHXB MAXI J1820+070. The black hole mass was estimated to be 6.7–13.9$M_{\odot}$, and SXT, being the only instrument in this work providing <3 keV data and hence being able to reliably fit the disk spectral component, was crucial for this estimation (Chakraborty *et al.* 2020). Note that this mass range derived from the spectral fitting is consistent with the results obtained from dynamical measurements (Torres *et al.* 2019, 2020).

In addition to the above examples, several other publications have reported the characterization of BHXB spectral and timing properties with AstroSat science instruments, including SXT (e.g., Maqbool *et al.* 2019; Bhargava *et al.* 2019; Sreehari *et al.* 2019, 2020; Mudambi *et al.* 2020b; Baby *et al.* 2020). SXT was also useful to probe the formation of a giant

[2]https://heasarc.gsfc.nasa.gov/xanadu/xspec/.

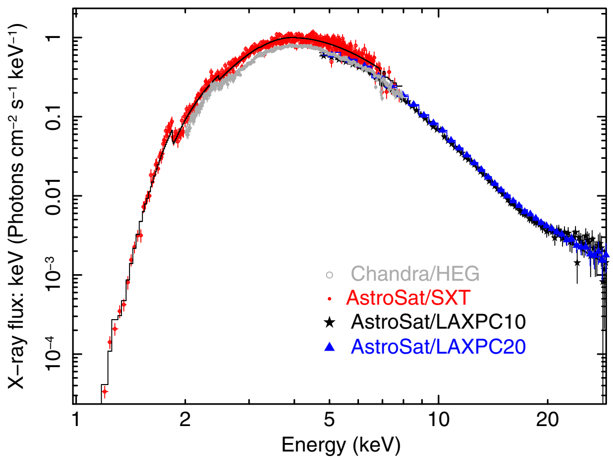

Figure 1. Joint fitting of X-ray spectra of the BHXB 4U 1630–47 from AstroSat SXT, two LAXPC detectors (LAXPC10 and LAXPC20) and *Chandra* High Energy Grating (HEG). An absorbed, relativistic, disk blackbody model with Gaussian absorption features and convolved with a Comptonization model is used for fitting. The source was in a soft state with a disk flux fraction of $\sim$0.97. It can be seen that SXT covers the spectrum and its peak better than other instruments, which was particularly useful to measure the black hole spin (see Section 2; figure courtesy: Mayukh Pahari; Pahari *et al*. 2018a).

radio jet base and to measure the orbital period parameters of the X-ray binary Cygnus X–3, for which the nature of the compact object is not yet confirmed (Pahari *et al*. 2018b; Bhargava *et al*. 2017).

3. Neutron star low-mass X-ray binaries

A neutron star LMXB is a binary system in which the neutron star accretes matter from a low-mass star. In such a system, the magnetic field of the neutron star is typically low ($\sim 10^{7-9}$ G), and hence the accretion disk can extend almost up to the stellar surface. Consequently, a number of features, such as thermonuclear X-ray bursts, high-frequency quasi-periodic oscillations, accretion-powered millisecond period pulsations, etc., are sometimes observed from these sources, which can be useful to probe the strong gravity regime and the superdense degenerate core matter of neutron stars (Bhattacharyya 2010).

AstroSat science instruments, including SXT, are ideal to study various spectral and timing properties of neutron star LMXBs, and their evolution. For example, the combined spectra from AstroSat (SXT+LAXPC) and *XMM-Newton* (EPIC-PN) observations of the neutron star LMXB SAX J1748.9–2021 suggested the presence of reflection features (Sharma *et al*. 2020). Figure 3 shows that the spectra measured with SXT and *XMM-Newton* EPIC-PN match well with each other. Another work on the neutron star LMXB GX 17+2 demonstrated that SXT not only is suitable for spectral and timing studies in soft X-rays, but also can be used for spectro-timing analyses (Malu *et al*. 2020). In this paper, the cross-correlation studies using SXT and LAXPC light curves showed time lags of the order of a hundred seconds.

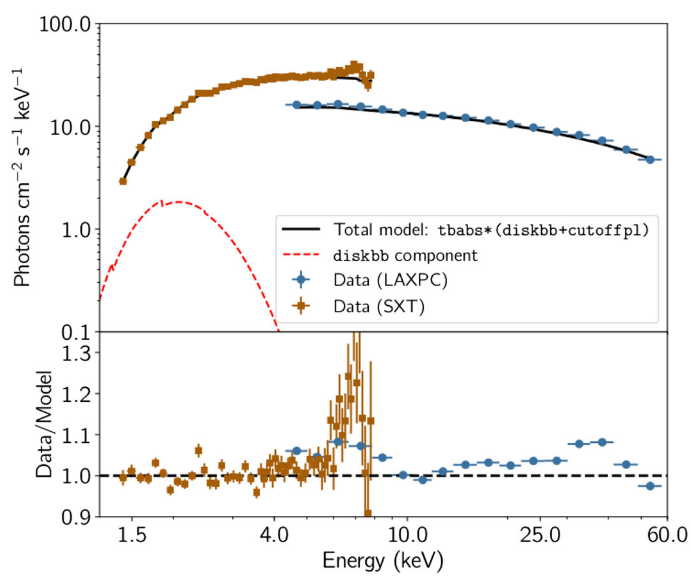

Figure 2. AstroSat SXT and LAXPC joint spectrum from the BHXB MAXI J1535–571. The model used to fit is an absorbed disk blackbody plus cut-off power-law, the latter representing a Comptonization component (*upper panel*). This brings out two prominent features – Fe $K\alpha$ emission line and Compton hump – of the reflection component of the spectrum in the data-to-model ratio plot (*lower panel*). It is clearly seen that both the disk blackbody and the asymmetry of the Fe $K\alpha$ line due to relativistic effects can be measured only with SXT, which are crucial to estimate the black hole mass and spin (see Section 2; figure courtesy: Navin Sridhar; Sridhar *et al*. 2019).

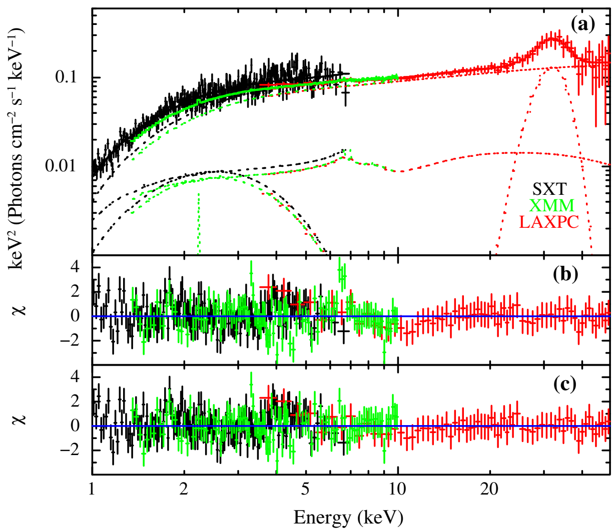

Figure 3. AstroSat SXT and LAXPC, and *XMM-Newton* EPIC-PN joint spectrum of the neutron star LMXB and accretion-powered millisecond X-ray pulsar SAX J1748.9–2021 **(a)**. Panels **(b)** and **(c)** show the residuals for the XSPEC models `tbabs(bbodyrad+nthcomp)` and `tbabs(bbodyrad+nthcomp+xillvercp)`, respectively. This figure shows that SXT and *XMM-Newton* EPIC-PN residuals match well with each other, with the SXT spectrum extending farther in lower energies (see Section 3; figure courtesy: Aru Beri; Sharma *et al.* 2020).

4. Neutron star high-mass X-ray binaries

A neutron star HMXB is a binary system in which the neutron star accretes matter from a high-mass star (e.g., Walter *et al.* 2015). In such a system, the magnetic field of the neutron star is usually high ($\sim 10^{12}$ G), and hence the accretion disk is typically truncated far from the star. As a result, the accreted matter is channeled on to the magnetic polar caps, making the source a pulsar. These systems are ideal to study an interaction between the accreted matter and the strong stellar magnetic field. Several neutron star HMXBs, for example, 4U 0728–25, GRO J2058+42, 4U 1909+07, have been observed with AstroSat, and SXT was used to characterize the broadband spectra and pulse profiles in soft X-rays (Roy *et al.* 2020; Mukerjee *et al.* 2020; Jaisawal *et al.* 2020).

5. Ultra-luminous X-ray pulsars

Ultra-luminous X-ray sources (ULXs), given their luminosities typically exceeding 10^{39} erg s^{-1}, could be accreting intermediate-mass black holes, or neutron stars or stellar-mass black holes having accretion with super-Eddington rates. A subset of ULXs have been confirmed to be accreting neutron stars from the observed spin-induced brightness pulsations, and they are known as ultra-luminous X-ray pulsars (ULPs; e.g., King *et al.* 2017).

The characterization of the first Galactic ULP, Swift J0243.6+6124, can therefore be extremely useful to understand this important class of sources. AstroSat observed the 2017–2018 outburst of Swift J0243.6+6124, and characterized its broadband spectrum, as well as energy-dependent and luminosity-dependent pulse profiles in the energy range of 0.3–150 keV (Beri *et al.* 2021). SXT was particularly useful to measure the continuum spectrum, as well as pulse profiles (see Fig. 4), in soft X-rays. Besides, recent observations of the Be X-ray binary and pulsar RX J0209.6–7427 with AstroSat SXT and LAXPC have indicated that its spectral and timing properties are remarkably similar to those of ULXs, suggesting that this source could be a ULP (Chandra *et al.* 2020).

6. Cataclysmic variables

AstroSat SXT can characterize spectral and temporal properties of cataclysmic variables (CVs), i.e., accreting white dwarfs. A sub-type of such binary systems, in which the white dwarf accretes matter from a red giant donor star via an accretion disk, can have explosive thermonuclear burning of the accumulated hydrogen rich material. This may lead to an outburst with a massive ejection of the material at velocities ≥ 300 km s^{-1}. These are known as Symbiotic Recurrent Novae, and only four such objects are currently known to exist (Schaefer 2010).

AstroSat SXT observed one such nova, V3890 Sgr, in two long observations in 2019 from 5th September to 16th September, just ~ 8 days after its third recorded outburst, with the highest cadence monitoring from a low-Earth orbit satellite (Singh *et al.* 2021). The observations caught the first appearance of Super Soft Source (SSS) emission (<1 keV) on day 8.57 after the outburst, revealing the presence of a very high mass white dwarf. Rapid and highly variable evolution of the SSS, that included its complete vanishing during days 8.6–8.9 and subsequent appearance, followed by another extremely low flux state during days 16.8–17.8, and rising again were observed. A detailed spectral modeling, using white dwarf emission models for the SSS and plasma models for higher energy (1–7 keV) emission, to study the source spectral evolution has been carried out. The rapid spectral evolution (see

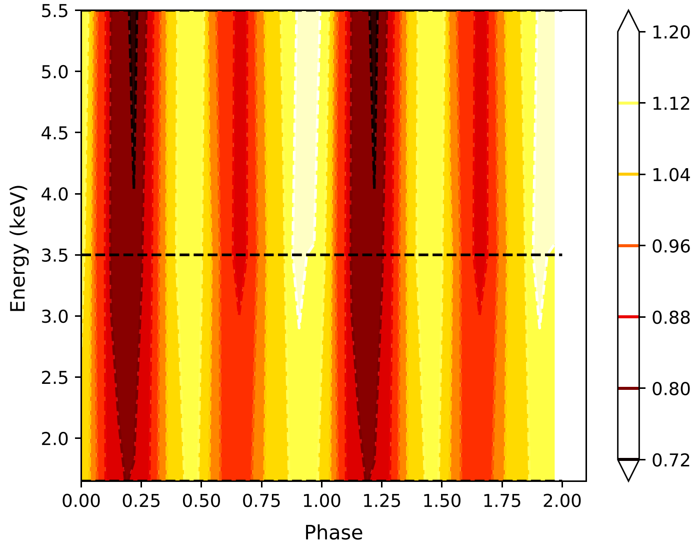

Figure 4. Energy-resolved pulse profile of the first Galactic ultra-luminous X-ray pulsar Swift J0243.6+6124, using the AstroSat SXT data. This figure shows that SXT could sufficiently resolve the X-ray pulsation period of $\sim$9.85 s in its FW mode (see Section 5; figure courtesy: Aru Beri; Beri *et al.* 2021).

Fig. 5) on nearly hourly time scales is not explained by evolutionary models of accretion and ejecta.

7. Active galactic nuclei

Active galactic nuclei (AGNs) are supermassive black holes, which accrete gas from the surrounding medium near the centres of galaxies. AGNs can radiate prominently in a wide energy range – from radio to γ-rays, and are rich in observational features in multiple wavebands. Based on these features, these objects have been divided into several subclasses, such as Seyfert galaxies and Blazars. AGNs are extremely important to study the strong gravity regime, accretion/ejection mechanisms, the feedback to the host galaxy and the intergalactic medium, and cosmology (e.g., Netzer 2015).

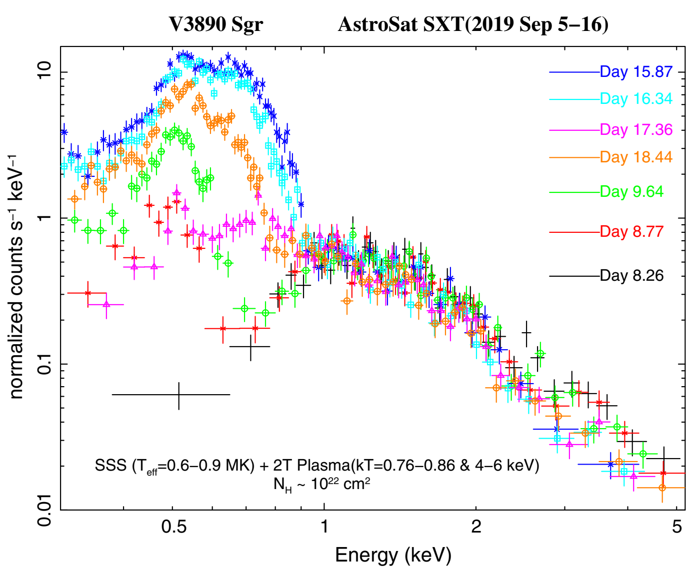

Figure 5. Evolution of AstroSat SXT spectrum of the symbiotic recurrent nova V3890 Sgr. The figure includes 7 of the 79 individual SXT spectra during its 2019 outburst, showing rapid variations. The days indicate the days after the beginning of the outburst. A Super Soft Source (SSS) emission component (with the best-fit effective temperature $\sim$0.6–0.9 MK) and a two temperature plasma emission component (with best-fit temperatures $\sim$0.76–0.86 keV and $\sim$4–6 keV), with a best-fit hydrogen column density of $\sim 10^{22}$ cm^{-2}, were used to describe the spectra (see Section 6; Singh *et al.* 2021).

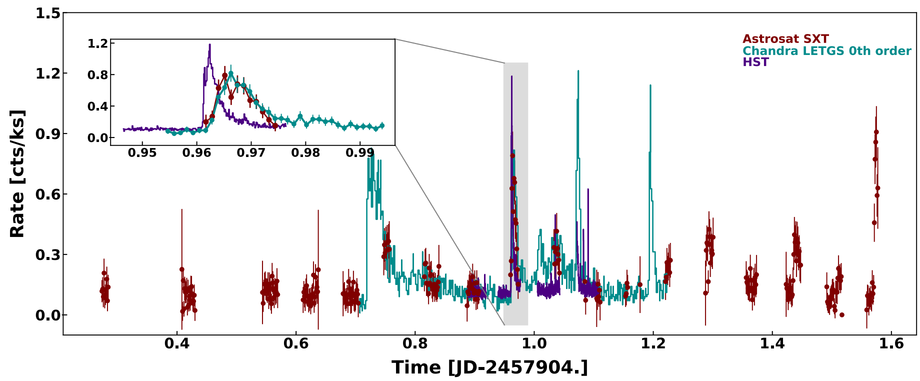

Figure 6. AstroSat SXT, *Chandra* LETGS 0th order and *HST* light curves of the nearest star Proxima Centauri, which hosts an Earth-like planet in its habitable zone. This figure shows flares and quiet periods of the star, which may affect the habitability of the planet. SXT observations were particularly useful to track the stellar activity throughout the observing campaign, with a flare observed simultaneously with all three instruments (see Section 8; figure courtesy: Lalitha Sairam; Lalitha *et al.* 2020).

AstroSat has observed several AGNs, and SXT has significantly contributed to the spectral and timing characterization of some of them. For example, SXT has measured the broadband spectrum and variability of the narrow-line Seyfert 1 galaxy RE J1034+396 in soft X-rays, and contributed to the source power spectrum, which, when compared with the power spectrum of the BHXB GRS 1915+105, indicated a supermassive black hole mass of $\sim 3 \times 10^6 M_\odot$ (Chaudhury *et al.* 2018). In another work, the variability of a Blazar, Mrk 421, was measured with AstroSat SXT and LAXPC, as well as with *Swift*, which was very promising to establish a way to probe the disk-jet connection (Chatterjee *et al.* 2018). Besides, SXT was useful to characterize the soft X-ray spectrum of another Blazar, RGB J0710+591 (Goswami *et al.* 2020).

Simultaneous UV/X-ray observations of a Seyfert galaxy with AstroSat can be useful to probe the thermal Comptonization responsible for the broadband X-ray emission. Joint X-ray spectral analyses of five sets of SXT and LAXPC spectra revealed a steepening and brightening X-ray power-law component with increasing intrinsic UV emission for the Seyfert 1.2 AGN IC 4329A (Tripathi *et al.*, to be submitted). These observations implied that UV emission from the disk indeed provides the primary seed photons for the Thermal Comptonization process, and the X-ray spectral variability is caused by either cooling of the hot corona or increasing optical depth of the corona, each with increasing UV flux.

8. Stars

Coronal activity in stars can be studied by observing the variation of its high-energy radiation, including occasional flares (Gudel & Naze 2009). Such a study can be useful not only to probe the stellar physics and the surrounding environment, but also to understand the impact of the ejected particles and radiation on the plausible planets, including their habitability. AstroSat SXT is capable of tracking the stellar soft X-ray intensity variation, which was demonstrated by an observational campaign on our nearest star Proxima Centauri with SXT, *Chandra* Low Energy Transmission Grating Spectrometer (LETGS) and *Hubble Space Telescope* (*HST*). Proxima Centauri is an M-dwarf with an Earth-like planet within its habitable zone, and several flares and the non-flare emission observed from the star were useful to probe the coronal temperatures, abundance, etc. (see Fig. 6; Lalitha *et al.* 2020). Particularly, one flare was observed with all three instruments, and showed the Neupert effect, that is the UV emission preceding the soft X-ray emission.

9. Conclusions

Recent publications in refereed journals have confirmed that SXT can successfully study spectral and timing properties of a variety of cosmic sources, as a standalone telescope, as well as in combination with other AstroSat science instruments and other satellites, such as *Chandra*, *XMM-Newton*, *NuSTAR*, and even *HST*. Since the launch of AstroSat in late 2015, SXT has been performing as expected, without any significant degradation of its capabilities. If this continues, SXT can be very useful for deep observations, as well as to track the evolution of relatively bright X-ray transients in a more dedicated manner in the future.

Acknowledgements

The publications mentioned here used the data from the AstroSat mission of the Indian Space Research Organisation (ISRO), archived at the Indian Space Science Data Centre (ISSDC). The works mentioned here were performed utilizing the calibration databases and auxiliary analysis tools developed, maintained and distributed by the AstroSat-SXT team with members from various institutions in India and abroad, and the SXT Payload Operation Center (POC) at the TIFR, Mumbai (https://www.tifr.res.in/∼astrosat_sxt/index.html). SXT data were processed and verified by the SXT POC. The authors thank Mayukh Pahari, Navin Sridhar, Aru Beri and Lalitha Sairam for providing some of the figures.

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