Soft X-ray focusing Telescope aboard AstroSat: early results

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The Soft X-ray focusing Telescope (SXT) is a moderate-resolution X-ray imaging spectrometer supplementing the ultraviolet and hard X-ray payloads for broad-band studies of cosmic sources with AstroSat. Well suited for observing bright X-ray sources, SXT observations of nearby active galactic nuclei (AGN), binary star systems with compact companions, active stars, etc. are producing long soft X-ray light curves and high-quality spectra. The strong X-ray variability and multiple spectral components exhibited by SXT observations of nearby Seyfert 1 galaxies show excellent promise to probe accretion disks and central engines in AGN through multi-band variability and spectroscopy.

Keywords: Active galactic nuclei, stars, supernova remnants, X-ray astronomy.

Introduction

A Soft X-ray focusing Telescope (SXT), built in India for the first time, was launched aboard the country's first dedicated multi-wavelength astronomy satellite, AstroSat on 28 September 2015 (ref. 1). It was activated a few days after the launch in a sequence of operations culminating in the opening of its camera door on 26 October 2015, thus making its first observation of a cosmic X-ray source. SXT, one of the three co-aligned X-ray instruments aboard AstroSat, is based on the principle of doubly reflecting grazing incidence optics in approximate Wolter I geometry[2] consisting of a paraboloid surface followed by a hyperboloid surface. Forty concentric and co-axial shells consisting of 320 mirrors are nested and aligned together to increase the reflecting area. It carries a specially built focal plane camera having a cooled charge coupled device (CCD) for single-photon counting and spectroscopy. SXT is a modest size X-ray telescope with a short focal length of 2 m and provides soft X-ray (0.3–8.0 keV) images with a spatial resolution of a few minutes of arc and time resolution of 2.37 s (with a provision to go to 0.278 s). The on-axis effective collecting area of the telescope, a product of collecting area, the CCD quantum efficiency (QE; for isolated and bi-pixel events) and the transmission efficiency of the optical blocking filter has been simulated and is shown in Figure 1 as a function of energy. Unlike the large X-ray imaging telescopes XMM-Newton and Chandra, SXT is designed for undistorted view (free of pile-up) of bright X-ray sources. This, along with other hard X-ray detectors onboard AstroSat, allows simultaneous view of broad-band (0.2–80 keV) X-ray spectra of bright cosmic X-ray sources. Table 1 provides a summary of the main characteristics of the SXT. The energy resolution of 80–150 eV in the energy band 0.3–8.0 keV allows us to study line emission from some principal lines from elements like N, O, Ne, Mg, Si, S, Ar, Ca and Fe in collisionally ionized hot plasmas or photoinized plasmas.

A technical description of SXT and its early performance is given in Singh and co-workers[3,4]. Here, we present its scientific objectives and preliminary results of observations of various types of cosmic X-ray sources.

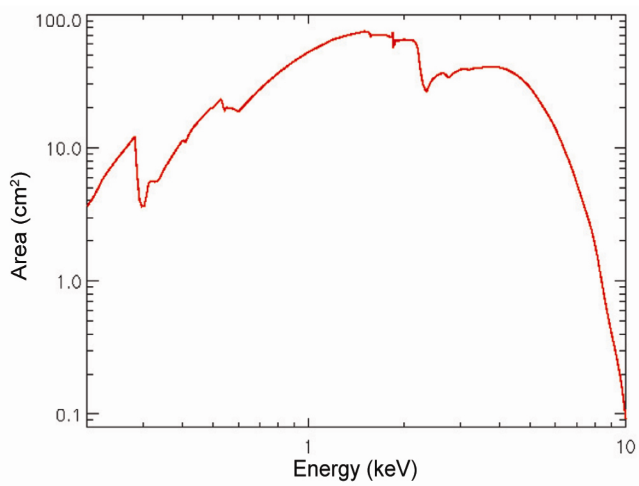

Figure 1. Effective area of the Soft X-ray Telescope (SXT) including the quantum efficiency (QE) of the charge coupled device (CCD).

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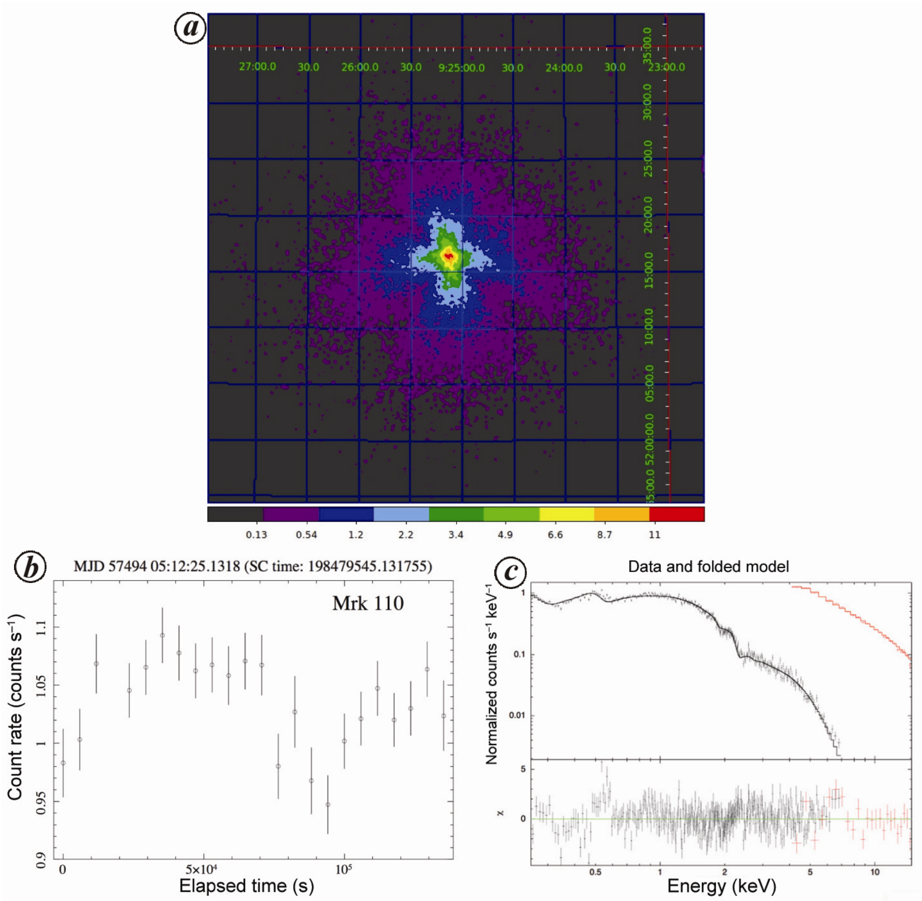

Figure 2. SXT observation of Mrk 110. (***a***) Soft X-ray image, (***b***) soft X-ray variability and (***c***) X-ray spectrum observed with SXT (black) and LAXPC (red).

Table 1. Main characteristics of the Soft X-ray focusing Telescope

Angular resolution	2′ (FWHM); 10′ (HPD)
Maximum effective area*	~90 sq. cm (1.5 keV)
Focal plane plate scale	4.0″/pixel (40 µm)
Field of view	40′ (dia.)
Energy resolution	140 eV (6 keV)
CCD temperature	–82° ± 2°C
Bandwidth	0.2–8.0 keV

*Includes transmission of the optical blocking filter and QE of the CCD.

SXT: scientific objectives

SXT provides high sensitivity for the detection of X-ray sources due to its low background resulting from its ability to focus X-rays onto a small detector plane. It can detect sources with an intensity as low as 20 µCrab (in about 10,000 s exposure). Its large field of view can provide X-ray images of extended diffuse sources like old supernova remnants and hot intracluster gas in clusters of galaxies and spatially resolved spectroscopy on the scale of several arcminutes. It can study X-ray variability on a timescale of more than 10 s. Specifically, the science goals of SXT are:

(a) Simultaneous wide-band spectral studies and time-resolved spectra of compact objects such as white dwarfs, neutron stars and black holes in X-ray binaries, supermassive black holes in active galactic nuclei (AGN) in the universe using the unprecedented combination with sensitive hard X-ray detectors.

(b) Soft X-ray line and continuum spectroscopy of hot, thin plasmas in clusters of galaxies, AGN, supernova remnants and stellar coronae, and in the gas photo-ionized by the strong X-ray continuum in accretion-powered X-ray sources (neutron stars, stellar mass black holes, supermassive black holes, etc.).

(c) Black hole spin measurement through accretion disk emission and broad iron line from black hole X-ray binaries.

(d) X-ray and ultraviolet (UV)/optical connection and the nature of accretion disks in radio-quiet AGN.

(e) Low energy absorption and the nature of absorbers, for example, whether these are cold (neutral) or warm (ionized), partially or fully covering.

(f) Origin of soft X-ray excesses in AGN, and in binary X-ray pulsars in conjunction with other higher energy X-ray instruments.

(g) Physics of shocks and accretion disks.

Early results from SXT observations

SXT has observed a variety of objects in the last one year of its operations, ranging from nearby active stars, X-ray binaries, supernova remnants (SNRs) to many types of distant active galaxies and clusters of galaxies. Active galaxies host supermassive black holes at their centres that accrete material from the surroundings and result in the most luminous, continuously emitting objects in the universe. The nuclei of radio-quiet active galaxies such as the Seyfert-type AGN provide a chance to probe the complex physics of accretion and the immediate environments very close to supermassive black holes. Our studies of radio-quiet AGN with AstroSat are aimed at understanding the nature of the accretion disks around supermassive black holes through the simultaneous measurement of X-ray and multi-band UV/optical variability, origin of soft X-ray excess and the role of complex absorption through broadband spectral variability.

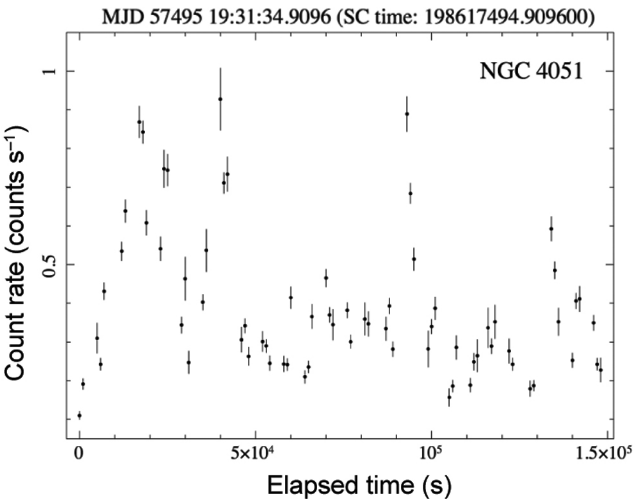

Figure 3. Rapid X-ray variability in NGC 4051 seen with SXT.

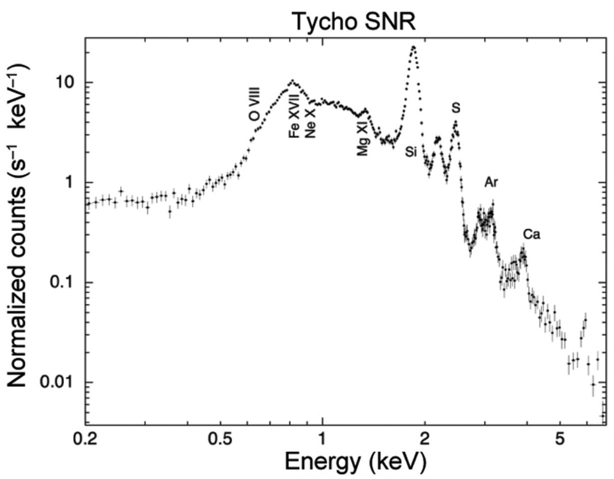

Figure 4. The soft X-ray spectrum of Tycho as observed with SXT.

Figure 2 *a* shows the image of a narrow line Seyfert I galaxy, Mrk 110 (redshift = 0.0355), in the soft 0.3–7.0 keV energy band. Figure 2 *b* shows the X-ray intensity variability of the source in the same energy band with bin time of 6000 s. Figure 2 *c* shows the average X-ray spectrum taken simultaneously with SXT and one of the large area X-ray proportional counter (LAXPC) units (LX20). In our preliminary analysis we have fitted a simple model consisting of low-energy galactic absorption (column density of $N_H = 5 \times 10^{20}$ cm^{-2}, a blackbody of 0.14 keV, a cut-off power law with photon index of 1.96 and cut-off energy of 18 keV). This model is shown as a histogram in the upper panel of Figure 2 *c* and is found to fit the data very well as can be seen from the residuals, i.e. the departure of observed data from the best-fit model in units of 1-sigma errors, as shown in the lower panel of Figure 2 *c*. More complex and realistic models are planned to be fitted to the spectra.

Very rapid and large X-ray variability on a timescale of 1000 s can be seen in another nearby (redshift = 0.0022) narrow line Seyfert galaxy, NGC 4051 (Figure 3) observed for about two days with SXT. The nature of variability of the soft X-ray emission in relation to optical/UV emission observed with the ultra violet imaging telescope payload and the hard X-ray emission observed with the LAXPC payload and its implications on the accretion disk is being studied in detail in Mrk 110 and NGC 4051, and will be published soon.

Figure 4 provides the energy spectrum obtained from an observation of Tycho supernova remnant showing emission lines from various elements – Mg, Si, S, Ar, Ca, Fe in the shock heated plasmas. The spectrum compares

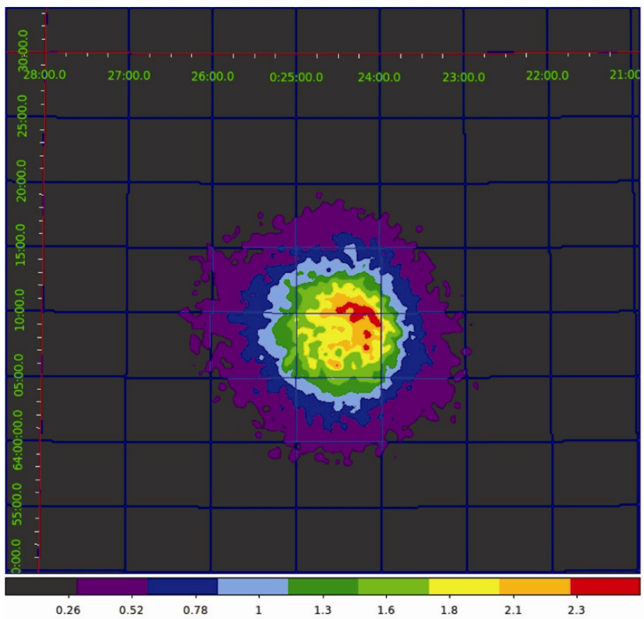

Figure 5. SXT image of Tycho in 0.3–1.6 keV energy band dominated by Fe-L emission.

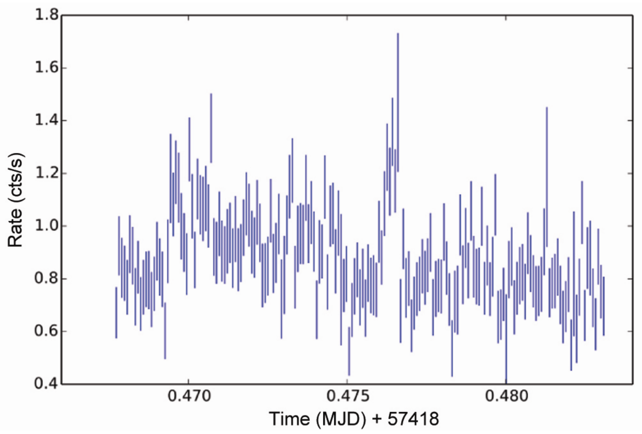

Figure 6. X-ray flaring activity of AB Dor observed with SXT.

very well with the previous observations by the XMM-Newton observatory[5]. Figure 5 is an image of the Tycho remnant derived in the energy band 0.3–1.6 keV, which is dominated by the Fe–L emission. The image shows that the Fe–L emission is mostly from the limb.

Figure 6 shows the X-ray light curve of a very rapidly rotating ($P_{rot} = 0.52d$) nearby ($d = 15$ pc) active star known as AB Dor in the energy band 0.3–7.0 keV observed with SXT on 31 January 2016. The time bin used here is 100 s and a lot of flaring activity can be seen in Figure 6. Its time behaviour and X-ray activity from several previous X-ray observations with other satellites have been presented in Lalitha and Schmitt[6], which shows that the rapid rotation is responsible for its rampant flaring.

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ACKNOWLEDGEMENTS. We acknowledge the dedication and devotion of the entire SXT team involved in building and testing of the instrument. In particular, we thank A. T. Kothare, I. Mirza, H. Shah, K. Mukerjee, S. L. Vishwakarma, V. M. Risbud, B. G. Bagade, V. Navalkar, V. J. Mhatre, S., A. Bajpai, N. Kamble, S. Kotak, J. P. Koyande (TIFR); A. F. Abbey, G. M. Hansford, A. P. Beardmore, T. Stevenson, late G. W. Fraser (University of Leicester, Leicester, UK); the staff of the Composites group at VSSC, the AstroSat project team at ISAC, the Integration group, the Thermal group, the Mission groups at ISSDC and ISAC, and G. S. Lodha (RRCAT, Indore). We also thank S. Lalitha (IIA, Bengaluru) for analysis of AB Dor data.

doi: 10.18520/cs/v113/i04/587-590