

AstroSat: India's First Multi-wavelength Astronomy Satellite

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AstroSat launched on September 28, 2015 is India's first Space Observatory. It is designed to observe the universe simultaneously in multi-wave bands spanning a very broad range of wavelengths in the visible, ultraviolet, and X-rays. All the scientific instruments on-board were made operational in a sequential manner starting on October 1st, 2015. The performance parameters of the various scientific instruments and some results from the first observations carried out after their commissioning are presented here.

1. Introduction

It has become increasingly clear over the past few decades that understanding the nature of cosmic objects and their emission processes in different wavelength regions requires observing them simultaneously in as many wave-bands as possible. This has, hitherto, been possible in only a very few space missions for various technical reasons as the requirements and environments vary. Multi-wave band observations are extremely important for understanding the physics of regions with strong gravity, e.g., accretion disks and columns around White Dwarfs as in Cataclysmic Variables, Neutron Star Binaries and galactic binaries with a few solar mass Black Holes as well as supermassive black-holes in extragalactic sources like active galactic nuclei (AGN). Such observations are also very important to unravel the physics of highly accelerated streams of particles in astronomical jets as seen in Blazars and mini-quasars. Strong Magnetic fields that are responsible for Cyclotron lines seen around accreting neutron stars, and physics of very hot coronal plasmas in active stars, supernova remnants and clusters of galaxies are other areas of research requiring simultaneous multi-wave observations.

AstroSat, weighing 1513 Kg, was launched from the Satish Dhawan Space Centre in Shriharikota (SHAR) by an augmented Polar Satellite Launch Vehicle (PSLV) on 28th September 2015 at 10 AM (IST) into a circular orbit 650 kms above Earth with an inclination of 6 degrees north. There are five principal instruments for observations onboard AstroSat. Four of these are co-aligned to within a few arc mins to look at the same source in the sky and observe it simultaneously in the wave-bands of visible, near ultra-violet (NUV), far ultra-violet (FUV), soft X-rays and hard X-rays. In addition there is Charge Particle Monitor (CPM) to monitor the charged particle background and is used for the safety of certain instruments and to screen the X-ray events. Fig.1 shows the complete AstroSat. The pointing towards a cosmic source is controlled by gyros and star sensors, while ensuring the safety of all the instruments. Three X-ray instruments together give an unprecedented large X-ray bandwidth, with hard X-ray sensitivity that is better than the previous NASA mission known as Rossi X-ray Timing Explorer (RXTE). The imaging capability in the NUV and FUV is better than in the older UV mission of NASA known as GALEX. The near Equatorial launch of the satellite ensures low background hard X-ray detectors. The main characteristics of the five instruments are briefly described below, followed by the first light results. For a more detailed description of all the instruments, the reader is referred to [1] and references therein. *At the time of this presentation, only the X-ray instruments had been switched on, therefore the first light results from only the X-ray payloads are given here. Subsequently the UVIT was switched on and is working perfectly.*

2. X-ray Instruments

2.1 Soft X-ray imaging Telescope (SXT)

SXT, based on the principle of grazing incidence, consists of a set of nested coaxial and con-focal shells of conical mirrors approximating paraboloidal and hyperboloidal shapes in Wolter I geometry. X-rays are incident on a conical mirror representing a paraboloidal (1α) surface. The reflected X-rays are further reflected by a second conical mirror representing a hyperboloid (α) surface which focuses the X-rays onto a charge coupled device (CCD). The conical surfaces made of aluminium foils have a smooth gold surface replicated on them giving a smoothness in the range of 7 – 10 Angstroms (FWHM). The focal length of the telescope is 2 meters and the on-axis point spread function (PSF) in the focal plane has a FWHM of ~ 20 . The CCD (CCD-22 with 600×600 pixels

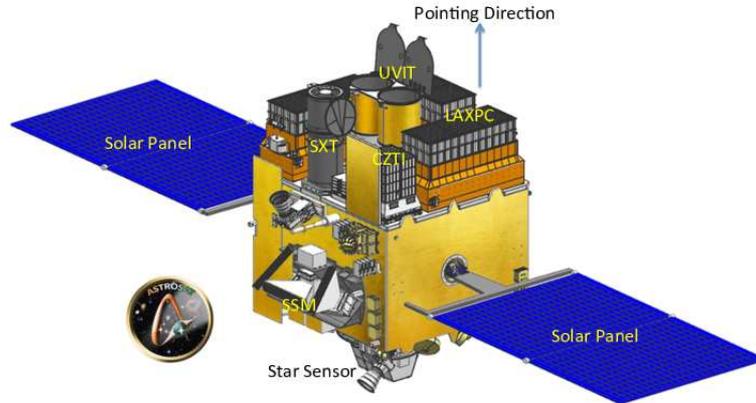


Figure 1. A 3D view of the fully assembled AstroSat showing the main instruments.

used in Swift XRT and XMM-Newton MOS) at the focus is housed in a Focal Plane Camera Assembly (FPCA). The FPCA built in collaboration with the University of Leicester, U.K., provides protection from energetic protons via a shield surrounding the CCD inside the FPCA. The CCD is cooled to 191^0K (-82^0C) by a thermo-electric cooler (TEC) and a radiator plate assembly. A very thin optical blocking filter is similar to the XMM-Newton thin filter is kept above the CCD. The CCD is illuminated permanently by four individual Fe^{55} radioactive calibration sources shining on the four corners (outside the field of view) of the CCD, and used for in-flight calibration at two principal line energies of ~ 5.9 keV and 6.5 keV. There is a provision for reading the CCD using six data modes: "Photon Counting" (PC) mode, "Photon Counting Window" (PCW) mode, "Fast Windowed Photon Counting" (FW) mode, "Bias Map" (BM) mode, "Calibration" (Cal) mode and "House Keeping" (HK) mode. In the PC mode, data from the entire CCD will be collected but only those events that are above a specified threshold energy only will be transmitted. The PCW mode is similar to the PC mode, but the data are collected from one of the predefined smaller square windows on the CCD chosen by the user and uploaded by a tele-command. The readout time in the PC and PCW modes is ~ 2.4 s. In the FW mode, a fixed window of 150×150 pixels centred on the CCD will be used. The readout time of this mode will be approximately 278 ms. The Cal mode will be used to check the calibration of SXT using data from four corner windows of the CCD, with a small central window on the source. In the BM mode, the entire CCD frame will be sent without any threshold. The energy bandwidth of the SXT is 0.3 – 8 keV. The effective area of the telescope, after taking into account the efficiency of the filter and the CCD, is ~ 128 cm² at 1.5 keV, and ~ 22 cm² at 6 keV. The field of view (fov) of the SXT is ~ 40 arcmin (dia). The spectral resolution is $\sim 5\text{-}6\%$ at 1.5 keV, and $\sim 2.5\%$ at 6 keV. The SXT can detect sources as faint as $\sim 10^{-13}$ ergs cm⁻² s⁻¹ at 5σ in an exposure of ~ 20000 s. SXT will be instrumental in doing X-ray spectroscopy and measuring the low energy absorption. With a psf of 2 arcmin, SXT is less susceptible to pile-up effects in the CCD and provides capability to observe bright sources in soft X-rays.

2.2 Large Area Xenon Proportional Counters (LAXPCs)

LAXPCs are 3 identical proportional counters each with its own independent front-end electronics, HV supply, and signal processing electronics. Each unit consists of 60 anode cells of size $3 \times 3 \times 100$ cm³ arranged in 5 layers providing a 15 cm deep X-ray detection volume filled with a mixture of 90% Xenon + 10% Methane at a pressure of 1520 torr. A Veto layer surrounds the main X-ray detection volume on 3 sides to reject events due to charged particles and interaction of high energy photons in the detector thus reducing the background. The alternate anode cells of each layer are linked together and operated in mutual anti-coincidence, and so are the outputs from different layers, to further reduce the non-cosmic X-ray background. An aluminised Mylar film of 50 microns thickness serves to seal the gas inside and act as the entrance window for X-rays into the detector. A gas purifier system will

recycle the gas regularly in each LAXPC. The Mylar window is supported against the gas pressure by a honeycomb shaped collimator made of aluminium cells in a square geometry. The fov of the LAXPC is $1^\circ \times 1^\circ$ defined by a multilayer collimator of tin, copper and aluminium placed in a collimator housing and aligned with the openings in the aluminium collimator below. A 1 mm thick tin sheet coated with copper surrounds each LAXPC unit and shields from high energy X-rays entering the detector from the sidewalls. In normal mode of operation, LAXPC has two modes running simultaneously: (a) Broad Band Counting (BBC) that records the event rates in various energy bands in a selectable time bin (8 ms to 1024 ms; default value 64 ms), and (b) Event Mode Data that records the arrival time of each event with an accuracy of 10 micro sec, its energy and identity. The energy bandwidth for each LAXPC is 3 – 80 keV, and the total effective area is 8000 cm² in the energy band of 5 – 20 keV. The energy resolution is 12% at 22 keV. It has the best time resolution of all the instruments. LAXPC has no spatial resolution except when it is scanning mode where it can reach a resolution of 1–5 arcmin. With its large area and low background it is expected to detect a 0.1 mCrab source in ~ 1000 s at 3σ level.

2.3 Cadmium-Zinc-Telluride Imager (CZTI)

CZTI with a detection area of 976 cm² consists of 64 modules of CZT each of area 15.25 cm², arranged in four identical and independent quadrants. A passive collimator (fov = $4.6^\circ \times 4.6^\circ$ FWHM for energies ≤ 100 keV) helps in allowing nearly parallel X-rays to enter the detector. A Coded Aperture Mask (CAM) made of 0.5 mm thick Tantalum plate is of the same size as the detector is positioned above the collimator. CAM has a pre-determined pattern of open and closed squares/rectangles matching the size of the detector pixels. The patterns are based on 255-element pseudo-noise Hadamard Set Uniformly Redundant Arrays. Seven types of patterns, with some repeats, were placed in the form of a 4×4 matrix to generate the CAM for one quadrant. This same pattern is placed on other quadrants, rotated by 90° , 180° and 270° respectively. At energies > 100 keV the collimator slats and the coded mask become progressively transparent. For Gamma Ray Bursts, the instrument behaves like an all-sky open detector. The CZT detectors are operated at temperature of $\sim 0^\circ\text{C}$ by passive cooling provided by a radiator plate. A Cesium Iodide (TI) based scintillator detector (20 mm thickness) located just under the CZT detector modules and viewed by a photomultiplier tube is used for vetoing background events. A radioactive (Am^{241}) calibration source module is mounted in a gap between the base of the collimator slats and the detector plane in each quadrant and illuminates the CZT detector with alpha-tagged 60 keV photons for calibration of the energy response. Each individual pixel is connected to a pre-amplifier, which is embedded in an Application Specific Integrated Circuit (ASIC). The X-ray detector has a detection efficiency of 95% within 10 – 120 keV and an energy resolution ($\sim 8\%$ at 100 keV). The processing electronics carries out reading, analysing, storing and/or transferring of detector data to the satellite via data formatter, and responding to tele-commands, just like all the other X-ray instruments. The CZTI can operate in 16 modes. It has the capability to measure polarisation in the 100 – 300 keV region.

2.4 Scanning Sky Monitor (SSM)

SSM operating in 2.5 – 10 keV bandwidth consists of three identical units of position sensitive gas-filled proportional counters with a coded-mask and associated electronics mounted on a rotating platform to scan the sky. Each unit scans the sky in one dimension over a fov of $\sim 22^\circ \times 100^\circ$. The effective area of SSM is 53 cm² at 5 keV (11 cm² at 2.5 keV). An aluminised Mylar window, 50 μm thick seals the gas and is supported by a collimator and coded mask. Six different coded mask patterns with 50% transparency, provide position resolution of ~ 1 mm at 6 keV with corresponding angular resolution ~ 12 arc min on the sky in the coding direction (2.5° in a direction perpendicular to the coding direction). The energy resolution is $\sim 25\%$ at 6 keV, and the 3σ detection sensitivity is ~ 28 mCrab for 10 minutes integration. The time resolution is 1 ms.

3. Ultra-Violet Imaging Telescopes (UVIT)

The twin telescopes of UVIT image the sky simultaneously in three broad wavebands: FUV (130-180 nm), NUV (200-300 nm), and VIS (320-550 nm). The optics configuration is Ritchey-Chretien (R–C 2), with a hyperbolic primary ($f/4.5$) mirror with effective diameter of 375 mm and focal length of 4.750 m. The fov is ~ 28 arc min (dia), and the spatial resolution (FWHM) is < 1.8 arc sec for the FUV and NUV channels, and ~ 2.2 arc sec for the VIS

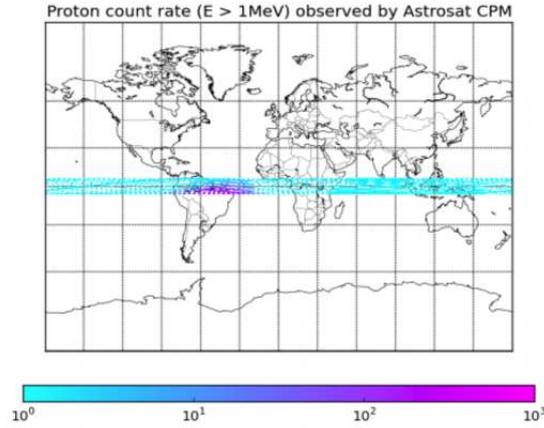


Figure 2. The map of SAA as measured by the CPM. Courtesy: the SSM team.

channel. Several filters are mounted in filter-wheels in front of detectors for selecting narrower wavelength bands. In the FUV and NUV channels, gratings are also provided for low-resolution (~ 100) slit-less spectroscopy. The detectors used in the focal planes are intensified CMOS type with an aperture of ~ 40 mm (dia). The UV detectors are used in photon counting mode and the visible detector in integration mode. The entire array of 512×512 pixels covering the entire fov or a part of it in a "window" mode can be read at rates up to $600 \text{ frames s}^{-1}$, depending on the area of the window. The effective areas as a function of the wavelengths have been estimated for all the filter and telescope combinations and varies from $8 - 50 \text{ cm}^2$ depending on the combination used, The time resolution is 1.7 ms. The detection sensitivity is 20 mag in FUV in a 200 sec observation at 5σ level.

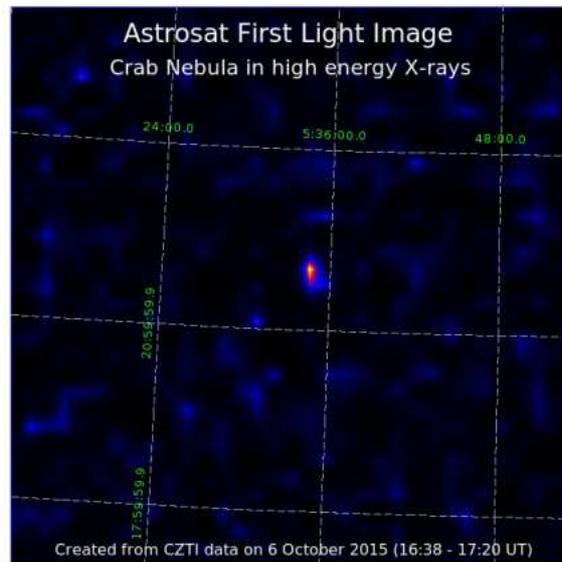


Figure 3. The first light image of the Crab with the CZTI (right). Courtesy: the CZTI team.

4. First light results from X-ray instruments

The first scientific instrument to be switched on was the CPM, and it resulted in the scan of the South Atlantic Anomaly giving a map of the high energy protons (Fig.2). The CZTI was switched on next and obtained an image of the Crab in hard X-rays, shown in Fig.3. This was followed by the operationalisation of the SSM (Fig.4), and

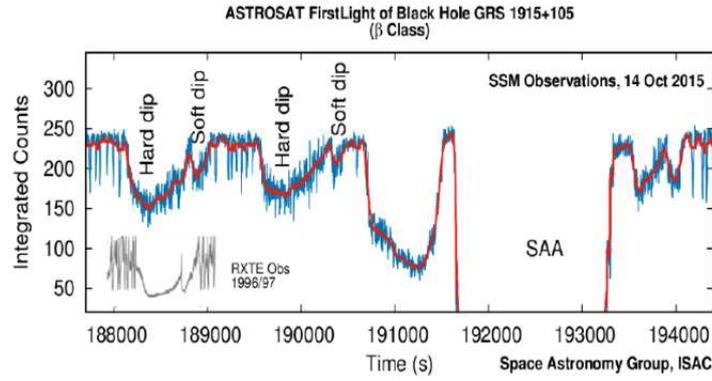


Figure 4. X-ray light curve of a black-hole X-ray binary GRS1915+105 seen with the SSM. Courtesy: the SSM team.

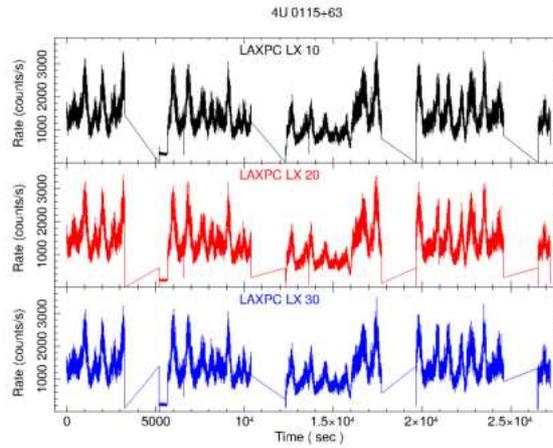


Figure 5. X-ray light curves, as seen with all the 3 units of LAXPC, from a High Mass X-ray Binary (4U0115+63) with a pulsating neutron star (high magnetic field) companion. Courtesy: the LAXPC team.

the three units of LAXPC (Fig.5). The SSM observation of GRS1915+105 shows that the comparison with an earlier observation with RXTE, is excellent. The LAXPC observation showed that all the 3 units are working equally well and are similar in their performance as per the design. LAXPC units also detected the 3.6 s pulsations from 4U0115+63. The camera door of the SXT was opened on October 26, 2015 and an X-ray images of a blazar (PKS2155-304) was recorded (Fig.6). The image and the number of counts recorded established that SXT has a point spread function of ~ 2 arc min (FWHM) and can reach the designed detection sensitivity. Detailed analysis of these and other similar observations and the characterisation of all the instruments will be completed during the Performance Verification phase of the satellite ending on March 31, 2016. This will be followed by 6 months of guaranteed time observations by the instrument teams, after which the satellite will be open to public for observations, based on the peer review process.

5. Acknowledgements

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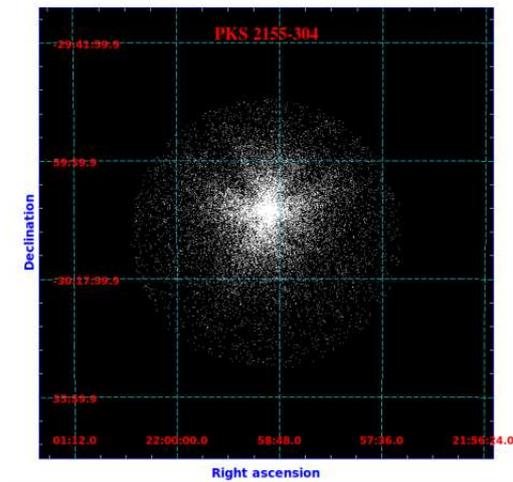


Figure 6. First light image of soft X-rays from a blazar, PKS2155-304, at a redshift of 0.116, with the SXT.

Trivandrum, SAC, Ahmedabad, the mission team at SHAR and at ISTRAC and ISSDC, Bengaluru, who worked tirelessly for AstroSat.

References

- [1] KulinderPal Singh et al., SPIE, 9144-63 (2014).