Large Area X-ray Proportional Counter instrument on AstroSat

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Large Area X-ray Proportional Counter (LAXPC) is one of the major AstroSat payloads. The instrument will provide high time-resolution X-ray observations in 3–80 keV energy band with moderate energy resolution. A cluster of three co-aligned identical LAXPC detectors is used in AstroSat to provide large collection area of more than 6000 sq. cm. The large detection volume (15 cm depth) filled with xenon gas at ~2 atm pressure, results in detection efficiency greater than 50% above 30 keV. With its broad energy range and fine-time resolution (10 μs), LAXPC instrument is well suited for timing and spectral studies of a wide variety of known and transient X-ray sources in the sky. We have done extensive calibration of all LAXPC detectors using radioactive sources as well as GEANT4 simulation of LAXPC detectors. We describe in brief some of the results obtained during the payload verification phase along with LAXPC capabilities.

Keywords: Energy- and time-resolution, payloads, space observatory, X-ray sources.

Introduction

ASTROSAT is India's first space observatory for simultaneous multi-wavelength studies with five science payloads. There are four X-ray instruments on-board AstroSat which cover a wide energy band. These include: (i) Large Area X-ray Proportional Counter (LAXPC) instrument covering 3–80 keV region, (ii) a Cadmium–Zinc–Telluride Imager (CZTI) array covering 20–100 keV, (iii) a Soft X-ray Imaging Telescope (SXT) covering 0.3–8 keV and (iv) a Scanning Sky Monitor (SSM) with energy range 2–10 keV (ref. 1). The main objective of LAXPC instrument is to study X-ray timing and wide band spectral properties of stellar and galactic systems containing compact objects.

The LAXPC instrument uses a cluster of three co-aligned identical LAXPC detectors to achieve large area of collection in excess of 6000 sq. cm. The deep detection volume (15 cm depth) filled with xenon gas at ~2 atm pressure, results in detection efficiency greater than 50% above 30 keV. The LAXPC instrument consists of three identical units, each with its own independent front-end electronics, high voltage (HV) supply and signal processing electronics. The system-based time generator (STBG) is common for all the three LAXPC detectors to provide time stamp with accuracy of 10 μs for all the accepted events. Each LAXPC detector consists of 60 anode cells of 3 cm × 3 cm cross-section and 100 cm length, arranged in five layers providing a 15 cm deep X-ray detection volume. The Veto layer consisting of 1.5 cm × 1.5 cm × 100 cm anode cells, is divided in three parts (left side, right side and bottom) providing three Veto layer outputs[2,3]. Data from all the LAXPC detectors are independently acquired preserving the identity of each unit.

The LAXPC is a large and complex X-ray instrument (eleven flight packages with about 150 electronic cards, including spare model) which has been designed and developed indigenously at Tata Institute of Fundamental Research (TIFR), Mumbai. We have done extensive calibration of LAXPC detectors in the laboratory with radioactive sources as well as using GEANT4 simulation. AstroSat was launched successfully on 28 September 2015. The STBG unit, processing electronics and low-voltage detector electronics were switched on during the second and third days after the launch. The LAXPC payload became fully functional on 19 October 2015, when HV of all three LAXPC detectors was switched on. On-board LAXPC detector gas purification system was operated during 20–22 October and 23–24 November 2015. LAXPC observation of Cas A supernova remnant is shown in Figure 1, which suggests around 20% energy resolution at 6.4 keV iron line[2]. At higher energy (>20 keV), the energy resolution is found to be in the range 10%–14% (ref. 4).

In the performance verification (PV) phase, AstroSat observed the black hole system, GRS 1915+105 during

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5–7 March 2016, which was in the steep power law (SPL) state. To test the timing characteristics of the detector, event mode data which give the energy of each photon and its arrival time with a time-resolution of 10 μs were used to calculate the power density spectrum (PDS) up to the Nyquist frequency of 50 kHz (Figure 2). The resulting PDS does not show any instrumental effect other than peaks beyond 10 kHz due to the dead-time of the detector (42.3 μs). The green line in Figure 2 shows the expected peak power of a quasi-periodic oscillation (QPO) with quality factor $Q = 4$ and rms of 5%. This LAXPC instrument can detect QPOs of such strength easily till 3000 Hz. Energy-dependent power spectra reveal a strong low-frequency (2–8 Hz) QPO and its harmonic along with broadband noise[5]. At the QPO frequencies, the time lag as a function of energy has a non-monotonic behaviour such that the lags decrease with energy till about 15–20 keV and then increase for higher energies.

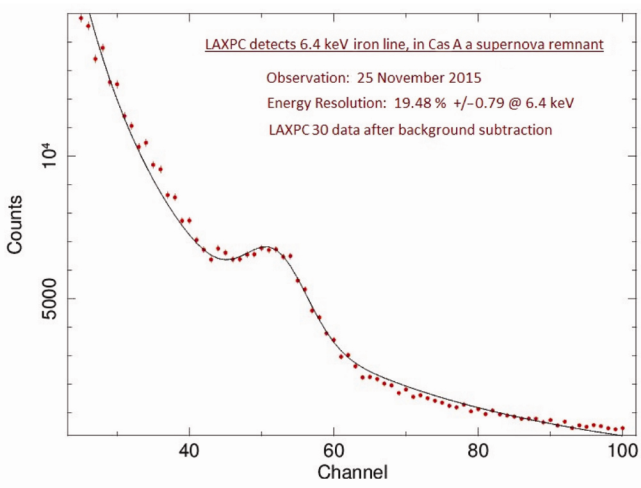

Figure 1. Cas A (supernova remnant) observation of LAXPC30 showing ~20% energy resolution at 6.4 keV.

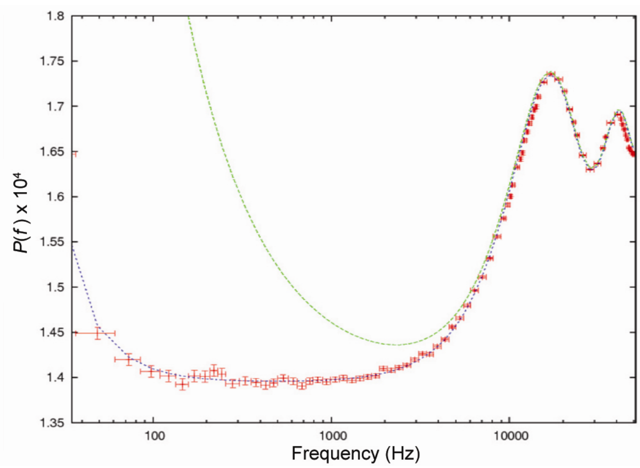

Figure 2. High-frequency rebinned power density spectrum of GRS 1915+105 in the steep power law class observed during 5–7 March 2016. The power spectrum matches well with the predicted Poisson noise level with a dead time of $t = 42.3$ μs and a low-frequency power-law component. The green line shows the expected peak power of a quasi-periodic oscillation with quality factor $Q = 4$ and rms of 5% (ref. 5).

LAXPC detectors have been extensively studied for effective area, detector response and background using GEANT4 simulation and compared to match with the laboratory calibration[4]. AstroSat observed another black hole system, Cygnus X-1 in the low hard state which shows prominent thermal Comptonization component. The power spectrum can be characterized by two broad Lorentzian functions centred at ~0.4 and ~3 Hz (ref. 6). During the PV phase, the neutron star X-ray binary 4U 1728–34 was observed with AstroSat/LAXPC on 8 March 2016. We have detected typical type-1 thermonuclear bursts in this source. Dynamical power spectrum of the data in the 3–20 keV band, reveals the presence of a kHz QPO whose frequency drifted from ~815 Hz at the beginning of the observation to about 850 Hz just before the burst[7]. This kHz QPO was also detected in the 10–20 keV band, which was not detected in earlier Rossi X-ray timing experiment/proportional counter array (RXTE/PCA) observations of this source.

Among the recent X-ray space missions, NASA's RXTE/PCA has been one of the most successful missions[8]. The LAXPC instrument provides several advantages compared to RXTE/PCA. The effective area of the LAXPC instrument at energies greater than 30 keV is significantly larger than PCA[4,5]. The event mode data allow for an energy-dependent analysis of any choice of energy and time bins. Simultaneous observations with other instruments on-board AstroSat, especially SXT, can provide critical spectral coverage below 3 keV. The results discussed above demonstrate that LAXPC has advantage in the study of QPOs and their associated characteristics over RXTE/PCA, specially in case of high frequency QPOs. With largest effective area in the hard X-rays for any X-ray astronomy instrument ever flown, the LAXPC instrument will be particularly suited to exploit the timing and broadband spectroscopy in the 3–80 keV band. Here we highlight some key scientific topics that can be probed particularly well with the LAXPC instrument.

Accretion disk and relativistic jets are integral parts of black holes on all mass scales. Stellar mass black hole X-ray binaries, often referred to as microquasars, provide favourable observational conditions like fast variability and a clear view of the inner accretion disk where most of high-energy processes are supposed to take place. Many of these are transient in nature. One of the key questions is how does energy flow during an outburst in a transient system which results in different X-ray states at different stages of an outburst and how are relativistic transient radio jets produced? The fast transitions between the low hard state and the high soft state has been so far seen only in two sources – GRS 1915+105 and IGR J17091-3624 (refs 9 and 10). These fast transitions are attributed to

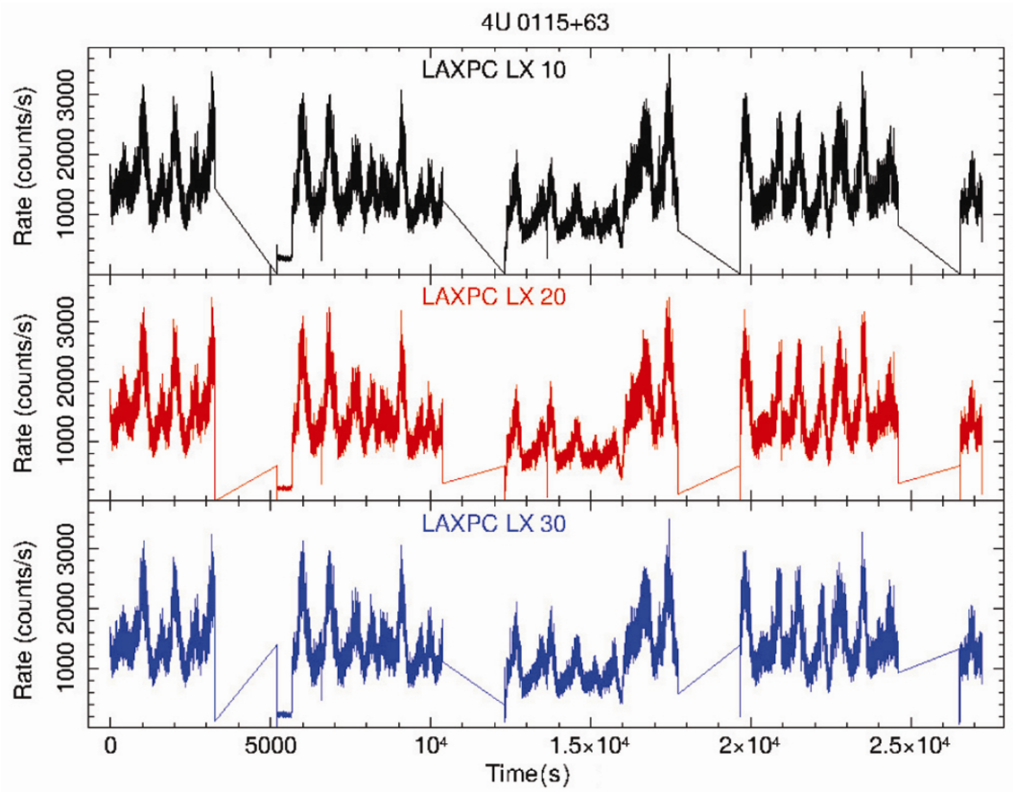

Figure 3. AstroSat/LAXPC instrument observed 4U 0115+63 during an outburst on the fifth day of its operation (24 October 2015). The X-ray light curves are shown here as observed by three LAXPC detectors in 3–80 keV energy band.

thermal instability in the accretion disk, but what causes this instability is not clear. The LAXPC instrument can help in understanding evolution of outbursts in microquasars, evolution of different X-ray states and their connection with transient radio jets. Black hole systems are associated with intense gravitational fields and X-ray observations are a probe to test the theories of gravity. The mass and spin of a black hole are factors which determine the nature of the gravitational field. The black hole spin can be measured independently using spectroscopy by modelling the X-ray spectrum and the relativistic broadening of the iron line. The QPOs observed in the power density spectra of such systems arising from Keplerian period of the inner most stable orbit, can also be used to estimate the black hole spin.

The accreting X-ray pulsars are neutron stars with very high magnetic field that accrete matter from a companion star and produce X-rays with a lighthouse effect. These are X-ray sources with a large fraction of their X-ray flux emitted in the hard X-ray band (>10 keV), and are particularly suited for observations with the LAXPC instrument. The X-rays, having been produced in the polar regions of an assumed dipolar magnet, pass through the magnetosphere of the neutron star that is teeming with electrons and ions. Resonance scattering of the X-ray photons from these electrons in a strong magnetic field produces absorption features in the X-ray spectrum, called cyclotron lines. It is a tell-tale signature of the extremely high magnetic field of the neutron stars, a few times 10^{12} gauss or more than a million times stronger than the strongest manmade magnetic field. The LAXPC instrument, with very large effective area, will enable the study of variation of cyclotron line at different viewing angles and thus provide important clues regarding the structure of the magnetic field of the neutron stars, hitherto assumed to be dipole.

During the first week of operation when the LAXPC instrument became fully functional for the first time in orbit, the Be X-ray Binary 4U 0115+63 underwent a huge type II outburst, reaching a peak flux value of about 0.8 Crab. This binary has a neutron star as the X-ray source from which 3.61 s pulsations have been detected. The LAXPC instrument made pointed-mode observations of this binary on 24 October 2015, when the source intensity was near its peak. The light curves of the three LAXPC detectors show strong-intensity oscillations with a period of ~1000 s (or 1 mHz QPO; Figure 3). The oscillations arise from accretion disk instability.

Some low-magnetic-field neutron stars, when accreting at a modest rate, show spectacular thermonuclear bursts. X-ray temperature and flux variation during these bursts is the most commonly used method for measurement of the radius of a neutron star. Such studies have so far been carried out in limited energy band and with the assumption of simple blackbody-type emission during the bursts. However, the non-burst emissions from such neutron stars are known to suffer from reprocessing in the surrounding medium. With a wide energy band of the LAXPC instrument and a large photon collection area, thermonuclear burst spectroscopy will be performed to investigate the signatures of reprocessing, thus critically examining the prevailing method of neutron star radius measurement. LAXPC has already observed thermonuclear bursts in two neutron star X-ray binaries – 4U 1728–34 and 4U 1636-536 (ref. 7). Along with the ultraviolet telescope on-board AstroSat, it will also be possible to investigate the reprocessing of the thermonuclear bursts in multiple optical and visible bands, a task that has been achieved only once in the past.

A class of binary X-ray sources, named supergiant fast X-ray transients (SFXTs), has puzzled astronomers for over a decade. In spite of having binary components identical to a well-known class of sources, the high-mass X-ray binaries, they are less luminous by 2–4 orders of magnitude and show occasional X-ray flares that last a few minutes to a few hours. Different models, accretion from dense clumps in the winds of the companion star, gated accretion onto neutron stars with strong magnetic field, etc. have been proposed to explain the SFXT phenomenon. The LAXPC instrument, along with the SXT of AstroSat will allow deep search for pulsation and/or cyclotron line from these objects, and thus provide definitive information about the compact objects in them. If found, X-ray pulsations will be useful to measure the binary parameters of the SFXTs with up to a few days orbital period.

Accreting neutron stars are potential sources of continuous gravitational wave (GW) emission. An accretion mound on a neutron star with spin frequency of several hundred hertz can be a potential candidate for detection of continuous GW. However, to carry out a search for GW in a long observation period of a few months or years, spin and orbital parameters of the neutron star and their changes must be known over the entire period. Dedicated LAXPC observations could be utilized to search for pulsation of the neutron star and then determine the orbital parameters in some of the brightest accreting neutron stars in low-mass X-ray binary systems that will aid in the search for continuous GW from them.

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