Cadmium–Zinc–Telluride Imager on-board AstroSat: a multi-faceted hard X-ray instrument

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The AstroSat satellite is designed to make multi-waveband observations of astronomical sources and the Cadmium–Zinc–Telluride Imager (CZTI) instrument of AstroSat covers the hard X-ray band. CZTI has a large area position-sensitive hard X-ray detector equipped with a coded aperture mask, thus enabling simultaneous background measurements. Ability to record simultaneous detection of ionizing interactions in multiple detector elements is a special feature of the instrument, and this is exploited to provide polarization information in the 100–380 keV region. CZTI provides sensitive spectroscopic measurements in the 20–100 keV region, and acts as an all-sky hard X-ray monitor and polarimeter above 100 keV. During the first year of operation, CZTI has recorded several gamma-ray bursts, measured the phase-resolved hard X-ray polarization of the Crab pulsar, and the hard X-ray spectra of many bright galactic X-ray binaries. The excellent timing capability of the instrument has been demonstrated with simultaneous observation of the Crab pulsar with radio telescopes like Gaint Metrewave Radio Telescope and Ooty Radio Telescope.

Keywords: All-sky hard X-ray monitor, gamma-ray bursts, neutron stars, X-ray polarization.

Introduction

THE prime emphasis of the AstroSat satellite is the X-ray timing instrument Large Area X-ray Proportional Counter (LAXPC) coupled with a sensitive wide-field Ultraviolet Imaging Telescope (UVIT)[1]. The LAXPC instrument is expected to extend the rich legacy of X-ray timing measurement pioneered by the Rossi X-ray Timing Explorer (RXTE) in an improved manner due to the phenomenally large effective area in the hard X-ray (20–80 keV) band. It was, however, realized from the RXTE experience that a simultaneous sensitive wide-band X-ray spectroscopic measurement would prove extremely crucial for understanding the timing behaviour of many astrophysical sources. A sensitive Soft X-ray Telescope (SXT) to cover the lower energy part of the spectrum and Cadmium–Zinc–Telluride Imager (CZTI) to extend the bandwidth above 80 keV were included in the AstroSat configuration.

CZTI uses the large bandgap semiconductor device, i.e. Cadmium–Zinc–Telluride (CZT), which can be operated at near-room temperatures. CZT provides high stopping power, low thermal noise, very good energy and spatial resolution. CZTI has a geometric area of 976 sq. cm and this is achieved using 64 detector modules divided into four quadrants, each quadrant containing a 4×4 matrix of detector modules mounted on a special thermal conductive board (Figure 1, left). Each module consists of 256 pixelated contacts arranged in a 16×16 array and a digital readout system. The readout includes the energy of incident photon and address of the pixel where it was measured. CZTI also consists of a veto detector for background rejection and an alpha-tagged source for in-orbit calibration. Coarse imaging is achieved using a coded aperture mask which consists of closed and open patterns of squares/rectangles matching the size of the detector

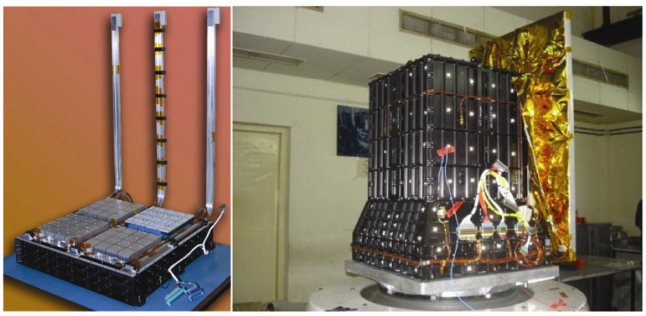

Figure 1. (Left) The 64 detector modules assembled in four quadrants, along with the heat pipes for efficient cooling. (Right) The assembled Cadmium–Zinc–Telluride Imager (CZTI) instrument on the vibration table.

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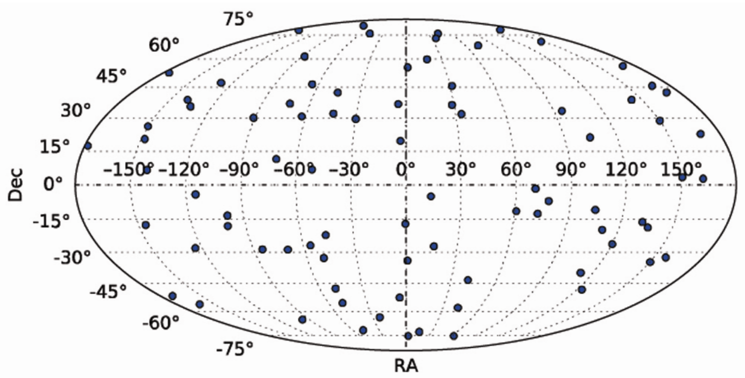

Figure 2. Gamma-ray bursts detected by AstroSat CZTI from 10 October 2015 to 27 January 2017.

pixels. The patterns are based on 255-element pseudo-noise Hadamard set uniformly redundant arrays. Figure 1 (right) shows the assembled CZTI in the vibration table. The configuration of CZTI is discussed in detail in Bhalerao *et al.*[2]. CZTI has an angular resolution of 17′ in the field of view of 4.6°× 4.6° (FWHM) and an energy resolution of 6.5 keV (~11% at 60 keV).

The primary scientific objective of CZTI is to measure the hard X-ray spectrum of bright X-ray sources in the energy range 20–100 keV. Crab nebula is used as a spectral calibrator and it is found that a canonical power law could be fit from 20 to 150 keV. The cross-calibration of CZTI with the other AstroSat instruments is on-going. Here we discuss the capability of CZTI as a transient monitor, and the timing and polarization features.

CZTI as a transient monitor

The coded aperture mask and other support structures of CZTI have been designed for the primary energy range and thus become increasingly transparent at energies above 100 keV. However, the 5 mm thick CZT detectors do have significant detection efficiency up to about 400 keV. This gives rise to a unique capability of CZTI as a transient monitor at energies above 100 keV. It enables CZTI to act as a wide-field monitor for gamma-ray bursts (GRBs). The two-layer detector system of CZTI consisting of the primary detector plane of CZT detectors along with the veto detector also provides wide-band measurements of GRB spectra in the extended energy range 100–800 keV. By extending the technique of the coded mask imaging to the shadows generated by CZTI support structure as well as satellite support structure, the Imager also provides modest localization capability for GRBs.

The hard X-ray monitoring capability of CZTI has been well established with in-flight operations. CZTI was the first scientific instrument to be switched ON after the launch of AstroSat, and on the first day of science observation CZTI detected GRB151006A (refs 3, 4). CZTI has now detected over 96 GRBs in 16 months of operation (Figure 2). Detected GRBs are published as GCN (Gamma Ray Coordinate Network) circulars, and also published online at http://astrosat.iucaa.in/czti/?q=grb.

Another important application of the transient detection capability is the search for electromagnetic (EM) counterparts of gravitational wave (GW) sources. CZTI has put competitive limits on X-ray emission from GW151226 (ref. 5), and will continue to be used for X-ray counterpart search, localization and analysis along with current and future GW observations.

The satellite and CZTI structure are not uniformly transparent to high-energy X-rays, and partially obscure sources in different directions. This creates distinct direction-dependent shadows on the detectors. By analysing these shadow patterns, one can effectively use the entire satellite as a coded aperture for localizing the sources on the sky. This has been demonstrated for two sources so far – by verifying the position of GRB151006A (ref. 4), and independently localizing GRB170105A on the sky[6]. For such sources, scattering from different elements of the satellite also becomes an important factor. Hence, detailed simulations of the satellite in GEANT4 have been carried out to calculate expected responses for transients in different directions. Apart from source localization, results from these simulations are also used to calculate spectra of the transient sources.

Hard X-ray polarization

Another fascinating capability of CZTI is to measure polarization of incident X-rays in the energy range 100–380 keV. This arises from the pixelated nature of the CZTI detector plane and the significant detection efficiency of the 5 mm CZT thick detectors beyond the primary spectroscopic energy range of CZTI. At energies beyond 100 keV, the incident X-ray photons primarily interact by means of Compton scattering. The Compton scattering is intrinsically sensitive to the polarization of the incident photon in the sense that the incident photon is preferentially scattered in the direction perpendicular to that of the electric field vector of the incident photon. Thus any pixelated detector plane in principle can measure polarization of the incident X-rays. However, in practice, it is necessary to have a good combination of various important characteristics such as good efficiency for Compton scattering, appropriate scattering geometry to achieve good modulation factor, capability of processing electronics to preserve the polarimetric information, etc. The design of CZTI achieves an optimal combination of these characteristics to realize scientifically meaningful polarimetric sensitivity for bright X-ray sources.

The hard X-ray polarimetric capability of CZTI was extensively investigated by Chattopadhyay *et al.*[7], using Monte Carlo simulations. It was also experimentally verified before launch using polarized X-rays and more importantly, using unpolarized X-rays[8]. Thus CZTI is the first hard X-ray polarimeter in recent times having ground calibration with unpolarized X-rays. The polarimetric capabilities of CZTI have been well established with observations of the Crab nebula during the first year of AstroSat operation. CZTI has provided the first accurate polarization measurement of the Crab nebula in the energy range 100–380 keV with high detection significance. The black hole binary Cygnus X-1 is another bright X-ray source which has shown interesting indications of polarization signature. However, the most interesting result of the two enhanced capabilities of CZTI, i.e. hard X-ray monitoring and hard X-ray polarimetry is the polarization measurement of GRBs. The number of GRBs detected by CZTI during the initial period is suitable for polarization analysis and a few of them have shown promising results, including detection of very high degree of polarization (~90%).

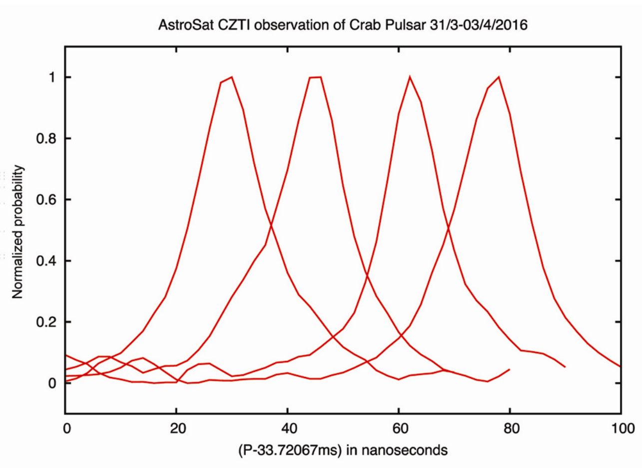

Figure 3. Pulse period of the Crab pulsar estimated from four consecutive sections of a CZTI observation, the length of each section being about half a day. The leftmost curve corresponds to the first section of the data and subsequent sections move progressively to the right. The vertical axis displays normalized fit probability. The best fit period for each section is at the peak of the corresponding curve. The spin-down of the pulsar is clearly demonstrated.

Timing the X-ray pulsar in Crab

The time-tagged event information recorded by CZTI for every photon detected by it makes it ideal for investigating fast time variability of intensity in hard X-ray sources. One of the best studied sources with fast hard X-ray intensity variation is the pulsar in the Crab nebula (see Buhler and Blandford[9] for a review). This is a strongly magnetized neutron star spinning on its axis 30 times/s, so the radiation observed from it has a periodicity of 33 ms. Accurate information about any small change in its spin period is available from continuous monitoring carried out by several radio observatories across the world. As a result, this pulsar has been chosen as the primary timing calibrator of the CZTI instrument and several observations of the Crab have been carried out since the launch of AstroSat.

The event time stamps provided by the local CZTI clock are converted to UTC via correlation with GPS time recorded by a spacecraft positioning system onboard AstroSat. For the timing analysis of the pulsar, the UTC time stamp of each event was used to compute the time of arrival of the corresponding photon at the solar system barycentre (SSB), by correcting for the time of flight of photons from SSB to the moving spacecraft.

An illustration of the timing stability and accuracy of the CZTI is provided by determining the pulse period of Crab pulsar from different sections of the data, and thereby tracking the evolution of spin of the pulsar. Figure 3 shows the determination of the best-fit pulse period from data sections spaced approximately by half a day. The steady spin-down of the pulsar is immediately apparent. A linear fit to the measured period versus time over a period of about three days (Figure 4) yields an estimated spin-down rate of 36.3 ± 0.2 ns/day, which matches the

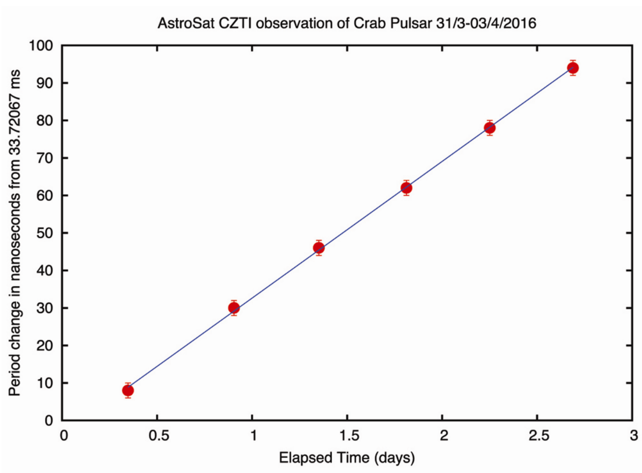

Figure 4. The spin-down rate of the Crab pulsar as measured by AstroSat CZTI. The period is determined in six contiguous sections of about half a day each (points). The linear fit plotted as the blue line has a slope of 36.3 ns/day.

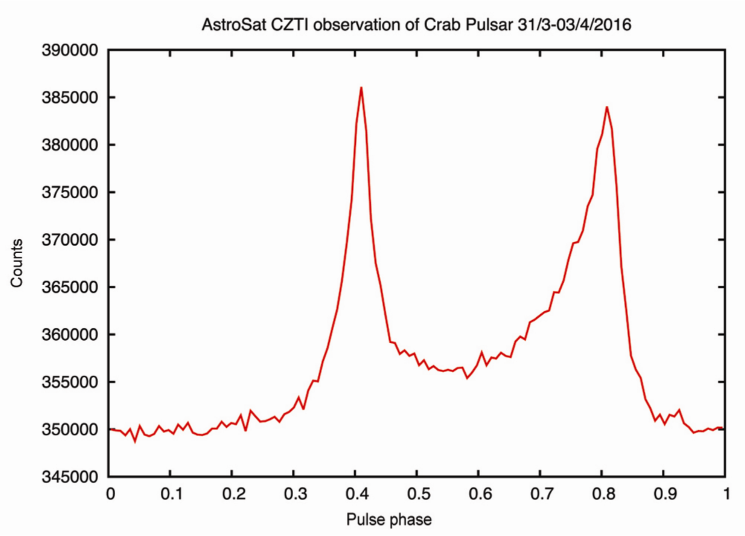

Figure 5. Folded pulse profile of the Crab pulsar in the CZTI energy band 30–250 keV for an observation carried out during 31 March–3 April 2016. The time of arrival of the left peak has been used to calibrate the absolute timing of the CZTI instrument.

spin-down rate measured independently by radio observations.

An exercise to calibrate the absolute time reference of CZTI was then taken up. Data were folded by taking into account the spin period and its derivatives to create a pulse profile from each observation. Figure 5 shows one such pulse profile. The absolute time of arrival of the main pulse (first peak) according to the CZTI clock was compared with that of the radio pulse, as estimated by the Ooty Radio Telescope, the Giant Metrewave Radio Telescope and the Jodrell Bank Observatory. Ten such determinations using observations spread over the first four months after launch have demonstrated that the CZTI clock has a fixed offset of 2.0 ± 0.5 ms with respect to the Jodrell Bank reference[10] (see also http://www.jb.man.ac.uk/~pulsar/crab.html).

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