High energy transients: The millisecond domain

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Abstract. The search for high energy transients in the millisecond domain has come to the focus in recent times due to the detection of gravitational wave events and the identification of fast radio bursts as cosmological sources. Here we highlight the sensitivity limitations in the currently operating hard X-ray telescopes and give some details of the search for millisecond events in the AstroSat CZT Imager data.

Keywords. Black hole sources—gamma-ray bursts.

1. Introduction

Gamma-Ray Bursts (GRBs) are the archetypical transients in the hard X-ray domain. When they occur, they are the brightest objects in the sky. They are so bright that even a simple small area detector can detect them. They are intrinsically so luminous that we can see GRBs in the far corners of the Universe (for a review of GRBs, see Kumar & Zhang 2015). Observationally, GRBs span about four orders of magnitude in flux ($10^{-7}$–$10^{-3}$ erg cm$^{-2}$) and similar orders of magnitude in time ($\sim$10 ms to $>100$ s). At the fainter flux level, the GRB flux distribution is very flat (Fishman & Meegan 1995)—there are not many faint GRBs. GRBs are traditionally separated into short and long GRBs and the short GRBs peak at around 1 s (Berger 2014) and the number of GRBs with duration much less than a second is quite low. Further, GRBs have a low occurrence rate: the estimated all-sky rate is about one per day (Kumar & Zhang 2015).

The question, therefore, is whether there are populations of transients in the high energy domain with properties drastically different from those of GRBs: like say, in the domain spanned by lower flux level, shorter time scales and higher occurrence rates. This is particularly relevant due to some new inputs in recent times: the detection of Gravitational Wave (GW) events and the discovery of Fast Radio Bursts (FRBs).

The first GW event discovered on 2015 September 14 (Abbott et al. 2016) opened up the new and fascinating field of merging black holes. Finding electromagnetic counterparts of GW events is one of the major research goals: it is quite challenging due to the large positional inaccuracies of GW events. Hence, the report by Connaughton et al. (2016) that GW 150914 was accompanied, although 0.4 s later than the event, by a hard X-ray burst detected by the Gamma-ray Burst Monitor (GBM) onboard the Fermi satellite was seen as a breakthrough result. The authors claimed a 5.1 sigma detection with a false alarm probability of less than 1%. The same data, however, was re-analysed by Greiner et al. (2016) and they concluded that this burst was most likely a background fluctuation rather than an astrophysical event. This result highlights the difficulty of finding faint bursts by GRB monitors: by design they are open all-sky monitors and hence prone to background fluctuations and false events induced by the omnipresent cosmic rays.

The discovery of FRBs (for a review, see Katz 2016) demonstrates that real surprises are round the corner when unexplored parameter regions are observationally explored. Unlike GRBs, FRBs are much more common (estimated rates are several thousand per day), and they last for very short durations (milliseconds) and, so far, are confined only to the radio band of the electromagnetic radiation. These new discoveries of recent times (GW events and FRBs) compel one to explore high energy region in new unexplored regimes: shorter duration and fainter fluxes. It is argued here that CZT Imager (CZTI) of the AstroSat satellite has several new and fascinating features which will make it an ideal instrument to look for fainter hard X-ray events in the millisecond
domain. In the section 2, an overview of the difficulties of hard X-ray observations are highlighted and in section 3, the design characteristics of CZT Imager which makes it a sensitive hard X-ray monitor is described. We also give the recent results of the CZTI as a GRB monitor and highlight its efficacy as a sensitive instrument to search for hard X-ray bursts associated with GW events and FRBs.

2. The hard X-ray domain

The hard X-ray band, the region where the emission is dominated by non-thermal processes like synchrotron radiation and inverse Compton scattering, is the band which probes astrophysical sites exhibiting exotic phenomena like accretion onto black holes, jet launching and the mysterious GRBs possibly signalling the birth of black holes. Observationally, X-ray focussing techniques have achieved very high sensitivity for narrow field-of-view observatories like the NuSTAR satellite (Harrison et al. 2013) up to about 80 keV. But, for all-sky monitoring in this region, particularly above 80 keV, the available sensitivity of detectors is quite modest. For example, in this energy range the first all-sky survey was conducted by the HEAO-A satellite, and launched in 1977. In two years of operation, only 22 sources were recorded (Levine et al. 1984). Two of the most successful hard X-ray detectors of recent times fared better: the Swift/BAT detector (launched in 2004) recorded 86 sources above 80 keV in the first six years of its operation (Cusumano et al. 2010) and the Integral/IBIS instrument, launched in 2002, recorded 132 sources in its first eleven years of operation (Kravinos et al. 2010).

It can be noticed that in spite of all the advances of recent times in sophistication in detector technology and improvements in space hardware fabrication, the increased number of sources detected above 80 keV is rather a reflection of the increased duration of observation than any improvements in sensitivity. The major reason behind this is the large and fluctuating background in space environment (see Dean et al. 1991, for a discussion on space background in hard X-ray and gamma-ray regions).

The CZT-Imager (CZTI) of AstroSat has several innovative and new design features specifically implemented to improve the sensitivity above 80 keV. In the next section, we discuss these special design features and describe the utility of CZTI as a sensitive hard X-ray monitor.

3. CZT-Imager onboard AstroSat

The AstroSat satellite is a multi-wavelength astronomical observatory and it was launched in 2015 September 28. It includes three co-aligned X-ray instruments: the Soft X-ray Telescope (SXT), Large Area X-ray Proportional Counters (LAXPCs), and the Cadmium–Zinc–Telluride Imager (CZTI). Additionally, the Ultra-Violet Imaging Telescope (UVIT) provides a deep and wide field image of the sky and the Scanning Sky Monitor (SSM) observes about half the celestial sphere for X-ray transients Singh et al. 2014). The orbit of AstroSat is selected specifically for very low background for X-ray detectors: it has an altitude of 650 km in a nearly equatorial circular orbit (inclination of 6°).

The primary design considerations of CZT Imager was to have an area and sensitivity comparable to the recent/ current best hard X-ray telescopes like HEXTE onboard RXTE, BAT onboard Swift or IBIS onboard INTEGRAL. The hard X-ray observations were designed to complement the SXT and LAXPC data to provide continuum X-ray spectroscopy in an extremely wide bandwidth of 0.3–150 keV. Additionally, CZT Imager was built with a weight of about 50 kg and typical size of about 60 cm. This needs to be compared with the weight and size of the INTEGRAL (2000 kg and 500 cm) and Swift (1500 kg and 560 cm), respectively.

The hard X-ray detectors are generally very heavy because of the need to use heavy elements to block the off-axis X-ray and gamma-rays. This shield, sometimes generate its own characteristic X-rays and to suppress these, additional material of different atomic number is used which is called the graded-shield configuration Dean and Nikiforidis 1976). In the space environment, however, the omnipresent cosmic rays induce backgrounds in these very shields to increase the background Dean et al. 1991). To alleviate these problems, some special design features are introduced in CZTI. To start with, the shield is designed only for low energies (less than 100 keV) such that the weight is drastically reduced. The trade-off is the slightly inferior sensitivity above 100 keV for sources being targeted. This, however, is more than compensated by the fact that CZTI acts as a true all-sky monitor above these energies.

The low inclination (6°) of the AstroSat orbit offer stable and low background. In addition to this, CZTI uses pixelated semi-conductor devices arranged in a modular fashion and the facility to transfer individual photon data (correct to 20 µs) is extremely useful for using sophisticated off-line software for noise
Figure 1. CZT Imager is built from a mosaic of 64 Orbotech detector modules (shown as an inset at the top), arranged in four identical quadrants (top left). An elaborate cooling arrangement with heat pipes is used to keep the detectors at a controlled temperature of 5–10 °C (left middle and bottom). The assembled CZT Imager (right middle and bottom) with an external radiator plate is built with a total weight of about 50 kg.

reduction. Further, a coded aperture mask enables the simultaneous measurement of background. In Fig. 1, the configuration of CZTI is shown and more technical details can be found in Bhalerao et al. (2017b).

3.1 CZT-Imager as a GRB monitor

AstroSat CZT Imager detected GRB 151006A on the first day of operation. This GRB was incident at 60°.7 from vertical (θx = 34°; θy = 58°) (Rao et al. 2016). GRB 151006A was extensively studied by combining data from Fermi-GBM and Swift-BAT (see also Basak et al. 2017). This is a peculiar GRB with peak energy of 2 MeV. Joint spectral fitting with GBM, BAT, CZTI and CZTI-Veto demonstrated that CZTI with Swift-BAT can provide spectral results comparable to that obtained from Fermi. It was also demonstrated that CZTI can also provide coarse localization. CZTI along with Fermi and Swift, currently provide complementary information on GRBs. In the first year of operation, there were a total of 214 GRBs detected by various satellite missions (about 150 from Fermi and about 60 from Swift). From a targeted search, about 40–50 GRBs were found in CZTI data during this period. A rigorous software to look for GRBs in the CZTI data is being developed and it is envisaged that CZTI should detect about 100–150 GRBs per year. A full AstroSat mass model is generated to enable a formal and proper localization of CZTI detected GRBs (Fig. 2).

CZTI has best sensitivity to GRBs in the 150–400 keV energy range and one of the most important and exciting capability of CZTI is its ability to measure the hard X-ray polarization (150–400 keV) of bright GRBs (Chattopadhyay et al. 2017). A systematic analysis of the eleven brightest GRBs detected by CZTI during its first year of operation yielded significant polarization measurements. Significant hard X-ray polarization was measured in seven of the eleven GRBs and meaningful upper limits could be placed for the remaining four GRBs. This number effectively doubles the number of GRBs with measured hard X-ray polarization (Toma et al. 2009).

4. CZT-Imager and GW events

The detection of GW events on 2015 September 14 (Abbott et al. 2016) opened up new and exciting fields of GW astrophysics. One of the crucial and path-breaking research in present day high-energy astrophysics is the measuring of electromagnetic counterparts of GW events. This first GW event was thought to be associated with a gamma-ray counterpart (Connaughton et al. 2009).
2016), which, however, could not be corroborated by further rigorous statistical tests for association (Greiner et al. 2016). This emphasizes the need for localization (even at the level of a few degrees) for faint transients. With its wide field-of-view, higher sensitivity and some limited localization capabilities, CZT Imager can provide very exciting inputs in this field.

The association of the GW event, GW170104 and GRB170105A is a case in point (Bhalerao et al. 2017a). The GW event was reported by the LIGO-Virgo collaboration (triggered on 2017 Jan 4 at 10:11:58.599 UTC) and the localization accuracy spanned about a thousand square degrees (Bhalerao et al. 2017a). Looking for associated transients in such large error regions in the sky, however, was a challenge. The ATLAS collaboration reported a object called ATLAS17aeu: a fading optical object from the same general direction as GW170104. This object was thoroughly studied and the GROWTH collaboration made a fit to the exponentially falling light curve and it derived a reasonably robust start time of this optical event. It was found that the start time is delayed as compared to the GW event by as much as $21.5 \pm 1.0$ h (Bhalerao et al. 2017a). The AstroSat CZTI data was analysed thoroughly and it was found that at the time of this extrapolated start time, there was indeed a gamma-ray burst, named GRB 170105A. Bhalerao et al. (2017a) gave a detailed analysis of these results and concluded that GRB 170105A is unrelated but fortuitously having a spatial coincidence with GW170104. The CZTI data could provide a rough localization which helped in the association of the afterglow with the GRB. CZTI could also provide flux upper limits during the GW event, which is the most stringent in the 0.1 s time scale.

For short events, CZTI has excellent sensitivity (about $10^{-7}$ erg cm$^{-2}$ s$^{-1}$) and it can be improved upon by more careful data screening. In the unexplored region of the millisecond regime, CZTI can provide good data which will be useful for GW searches, short GRBs and exploring new regions of parameter space.

5. Conclusions

The CZT Imager of the AstroSat satellite is proving to be a good monitor for GRBs above 100 keV. It has the best sensitivity in the 100–300 keV region (most of the GRBs have peak energy here). By using the satellite structure as a coder, it has some localization capability for bright GRBs. The availability of individual photon counting and position information is very crucial for understanding the systematics in the data and it will be
very useful to identify very faint short events. A systematic analysis for all events is going on and it is expected to provide very critical information on GRBs like polarization, search for faint short events, etc.

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