Observational Aspects of Hard X-ray Polarimetry

Thesis Summary of **Tanmoy Chattopadhyay**

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The research work during the PhD focuses on the study of various aspects of X-ray polarimetry in hard X-rays. The dissertation can be broadly divided into two parts where the first part discusses the development of a dedicated Compton polarimeter at the focal plane of a hard X-ray telescope. The other part of the thesis discusses the prospects of the hard X-ray polarimetry with Cadmium Zinc Telluride Imager (CZTI) onboard Astrosat, India's first astronomical satellite launched on September 28, 2015.

Sensitive polarization measurements in X-ray may address a wealth of astrophysical phenomena, which so far remain beyond our understanding inspite of the extensive X-ray spectroscopic, imaging, and timing studies. Though scientific potential of X-ray polarimetry was realized long ago, there has not been any significant advancement in this field for last four decades since the birth of X-ray astronomy. Primary reason behind the lack in progress is its extreme photon hungry nature, which results in poor sensitivity of the polarimeters. Recently, in the last decade or so, with the advancement in detection technology, X-ray polarimetry may see a significant progress in near future, especially in soft X-rays with the invention of photoelectron tracking polarimeters. Though photoelectric polarimeters are expected to provide sensitive polarization measurements of celestial X-ray sources, they are sensitive only in soft X-rays, where the radiation from the sources is dominated by thermal radiation and therefore expected to be less polarized. Polarization measurements in hard X-rays, on the other hand, promises to address few interesting scientific issues regarding geometry of corona for black hole sources, emission mechanism responsible for the higher energy peak in the blazars, accretion geometry close to the magnetic poles in accreting neutron star systems and acceleration mechanism in solar flares. Compton polarimeters provide better sensitivity than photoelectric polarimeters in hard X-rays with a broad energy band of operation. Recently, with the development of hard X-ray focusing optics e.g. NuSTAR, Astro-H, it is now possible to conceive Compton polarimeters at the focal plane of such hard X-ray telescopes, which may provide sensitive polarization measurements due to flux concentration in hard X-rays with a very low background. On the other hand, such a configuration ensures implementation of an optimized geometry close to an ideal one for the Compton polarimeters. In this context, we initiated the development of a focal plane Compton polarimeter, consisting of a plastic scatterer surrounded by a cylindrical array of CsI(Tl) scintillators. Geant−4 simulations of the planned configuration estimates 1% MDP for a 100 mCrab source in 1 million seconds of exposure. Sensitivity of the instrument is found to be critically dependent on the lower energy detection limit of the plastic scatterer; lower the threshold, better is the sensitivity. In the actual experiment, the plastic is readout by a photomultiplier tube procured from Saint-Gobain. We carried out extensive experiments to characterize the plastic especially for lower energy depositions. We did extensive numerical modelling to predict the lowe energy detection probability of the plastic scatterer. The CsI(Tl) scintillators are readout by Si photomultipliers (SiPM). SiPMs are small in size and robust and therefore provide the compactness necessary for the designing of focal plane detectors. Each of the CsI(Tl)-SiPM systems was characterized precisely to estimate their energy threshold and detection probability along the length of the scintillators away from SiPM. Finally, we integrated the Compton polarimeter and tested its response to polarized and unpolarized radiation and compared the experimental results with Geant−4 simulation.

Despite the growing realization of the scientific values of X-ray polarimetry and the efforts in developing sensitive X-ray polarimeters, there has not been a single dedicated X-ray polarimetry mission planned in near future. In this scenario, it is equally important to attempt polarization measurements from the existing or planned instruments which are not meant for X-ray polarization measurements but could be sensitive to it. Cadmium Zinc Telluride Imager (CZTI) onboard Astrosat, India’s first astronomical mission, is one of such instruments which is expected to provide sensitive polarization measurements for bright X-ray sources. CZTI consists of 64 CZT detector modules, each of which is 5 mm thick and 4 cm × 4 cm in size. Each CZT module is subdivided into 256 pixels with pixel pitch of 2.5 mm. Due to its pixelation nature and significant

Compton scattering efficiency at energies beyond 100 keV, CZTI can work as a sensitive Compton polarimeter in hard X-rays. We attempted detailed Geant−4 simulations and polarization experiments with the flight configuration of CZTI for partially polarized and 100% unpolarized radiation with varying polarization angles. The results demonstrate that CZTI will have significant polarization measurement capability for bright sources in hard X-rays. In last 15 months of successful operation of AstroSat, CZTI has observed Crab, the Pulsar nebula for ~500 ks and we could detect ~34% polarization of Crab with ~6sigma detection significance. The high detection significance also allows to attempt for phase resolved polarimetry of Crab, results of which are extremely interesting and could be vital to constrain the theoretical models on pulsar emission geometry and mechanism. CZTI can also be explored as a wide angle GRB monitor at energies beyond 100 keV and in last 12 months after the launch, CZTI has detected 47 GRBs, among which 11 GRBs show clear and statistically significant polarization signature.

Polarization measurement is an additional capability of CZTI. CZTI is primarily a spectroscopic instrument with coded mask imaging. To properly utilize the spectroscopic capabilities of CZT detectors, it is important to generate accurate response matrix for CZTI, which in turn requires precise modelling of the CZT lines shapes for monoenergetic X-ray interaction. CZT detectors show an extended lower energy tail of an otherwise Gaussian line shape due to low mobility and lifetime of the charge carriers. On the other hand, interpixel charge sharing may also contribute to the lower energy tail making the line shape more complicated. In my PhD research, I have developed a model to predict the line shapes from CZTI detector taking into account the mobility and lifetime of the charge carriers and charge sharing fractions. The model predicts the line shape quite well and has been used to generate pixel-wise response matrix for CZTI for spectroscopic studies of the X-ray sources.

Please find the full thesis at https://zenodo.org/record/50640#.WMXLqN8QZac

PUBLICATIONS (resulted from the thesis)

1. Orthogonal components in the hard X-ray polarisation of the Crab
S. V. Vadawale, **T. Chattopadhyay**, N.P.S. Mithun, A.R.Rao, D. Bhattacharya, A. Vibhute, V.B. Bhalerao, G.C. Dewangan, R. Misra, B. Paul, S. Sreekumar, P. Vinod, E. Samuel, P. Priya, S. Seetha
(Under communication with Nature Astronomy)

2. Prompt emission polarimetry of Gamma Ray Bursts with AstroSat CZT-Imager
T. Chattopadhyay, S. V. Vadawale, A. R Rao, et al. (To be submitted)

3. Line profile modelling for multi-pixel CZT detectors.
T. Chattopadhyay, S. V. Vadawale, A. R. Rao, D. Bhattacharya, Mithun N. P. S., V. Bhalerao
Proc. SPIE, vol − 9905, 2016

4. Prospects of hard X-ray polarimetry with Astrosat-CZTI
T. Chattopadhyay, S.V. Vadawale, A. R. Rao, S. Sreekumar, D. Bhattachariya
Experimental Astronomy, vol − 37, page − 555, year − 2014

5. Hard X-ray Polarimetry with Astrosat-CZTI
S. V. Vadawale, **T. Chattopadhyay**, A. R. Rao, D. Bhattacharya, V. B. Bhalerao, N. Vagshette, P. Pawar, S. Sreekumar
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6. Development of a Hard X-ray focal plane Compton Polarimeter: A compact polarimetric configuration with Scintillators and Si photomultipliers
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T. Chattopadhyay, S. V. Vadawale, J. Pendharkar
Experimental Astronomy, vol − 35, page − 391, year − 2013

9. A conceptual design of hard X-ray focal plane detector for simultaneous x-ray polarimetric, spectroscopic, and timing measurements
S. V. Vadawale, **T. Chattopadhyay**, J. Pendharkar
Proc. SPIE, vol − 8443, 2012