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Design and Tests of the Hard X-ray Polarimeter X-Calibur

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Abstract

X-ray polarimetry promises to give qualitatively new information about high-energy astrophysical sources, such as binary black hole systems, micro-quasars, active galactic nuclei, and gamma-ray bursts. We designed, built and tested a hard X-ray polarimeter, *X-Calibur*, to be used in the focal plane of the InFOCuS grazing incidence hard X-ray telescope. X-Calibur combines a low-Z Compton scatterer with a CZT detector assembly to measure the polarization of $20-60$ keV X-rays making use of the fact that polarized photons Compton scatter preferentially perpendicular to the electric field orientation; in principal, a similar space-borne experiment could be operated in the $5-100$ keV regime. X-Calibur achieves a high detection efficiency of order unity.

Keywords: X-rays - polarization - black hole - InFOCuS - X-Calibur.

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1 Introduction

Motivation. Spectral and morphological studies in the X-ray energy band have become established tools to study the non-thermal emission processes of various astrophysical sources. However, many of the regions of interest (black hole vicinities, jet formation zones, etc.) are too small to be spatially resolved with current and future instruments. Spectro-polarimetric X-ray observations are capable of providing additional information – namely the fraction and orientation of linear polarization – and would help to constrain different emission models [1, 2] of sources with compact emission regions and high X-ray fluxes such as mass-accreting black holes (BHs) and neutron stars. So far, only a few missions have successfully measured polarization in the soft (OSO-8 [3]) and hard (Integral [4]) X-ray energy regime. The Crab nebula is the only source for which the polarization of the X-ray emission has been established with a high level of confidence [3, 4]. The source exhibits a polarization fraction of 20% at energies of $2.6-5.2$ keV (direction angle of 30° with respect to the X-ray jet) [3] and 46% ± 10% above 100 keV (direction aligned with the X-ray jet observed in the nebula). Integral observations of the X-ray binary Cygnus X-1 indicate a high fraction of polarization in the hard X-ray/gamma-ray bands [5]. Model predictions of polarization fraction for various source types lie slightly below the sensitivity of the past OSO-8 mission, making future, more sensitive polarimeter missions particularly interesting.

Future missions. As polarimetry was not the main objective of the Integral mission, the results are plagued by systematic uncertainties, and there are currently no other missions in orbit that are capable of making sensitive X-ray polarimetric observations. The situation could be changed by a mission like the *Gravity and Extreme Magnetism SMEX* (GEMS) [6] – using two Wolter-type X-ray mirrors to focus $2-10$ keV photons onto photo-effect polarimeters. For higher energies $E > 5$ keV X-ray polarimeter designs can make use of the Compton effect. The *Soft Gamma-Ray Imager* on *ASTRO-H* [7] (launch scheduled for 2015) will have capabilities of measuring polarization, but the results may suffer from similar systematic uncertainties as the ones

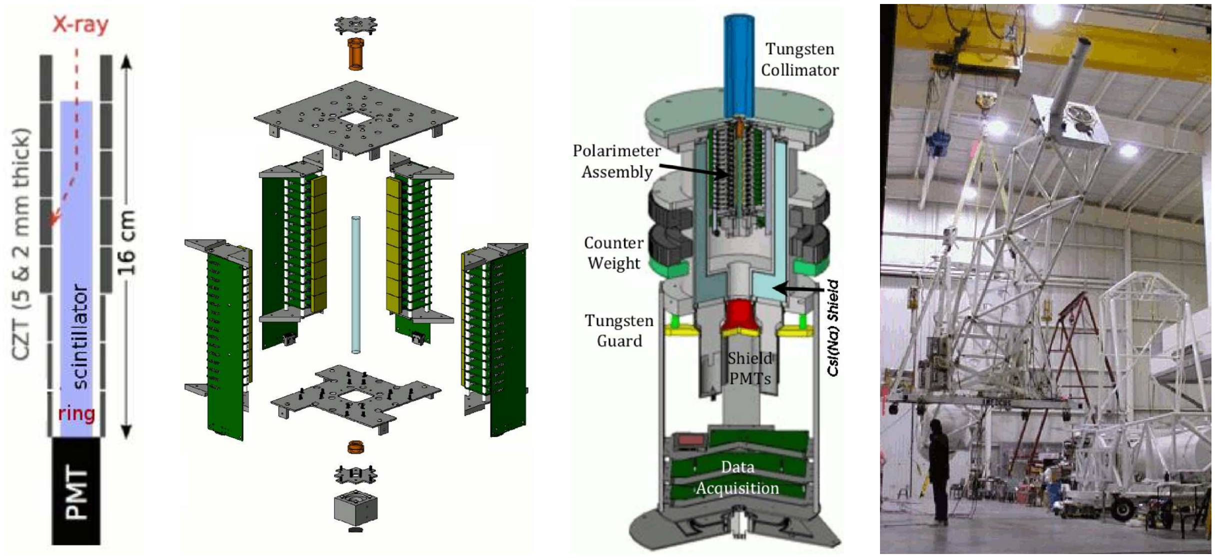

Figure 1: Left: Incoming X-rays are Compton-scattered (scintillator rod, optical axis) and subsequently photo-absorbed in one of the surrounding CZT detectors. **Middle left:** 'Exploded' view of the polarimeter: four sides of detector columns surround the central scintillator rod. **Middle right:** Polarimeter with CsI shield, electronic readout and azimuthal rotation bearing. **Right:** The InFOCuS balloon gondola.

measured by Integral. The CZT Imager on Astrosat (*http://astrosat.iucaa.in/*) is expected to be used for polarization measurements in the $150 - 250\,\mathrm{keV}$ band.

The hard X-ray polarimeter *X-Calibur* discussed in this paper has the potential to cover the energy range above 10 keV. Furthermore, X-Calibur combines a high detection efficiency with a low level of background and has well-controlled systematic errors. These features make it a particularly useful instrument for astronomical X-ray polarimetry.

Scientific potential. Polarization measurements are of general interest as tests of non-thermal emission processes in the Universe. Synchrotron emission, for example, will result in linearly polarized photons with their electric fields oriented perpendicular to the magnetic field lines (projected) and the observed polarization map in the X-rays can therefore be used to trace the magnetic field structure of the source. An observed polarization fraction close to theoretical limits can be interpreted as an indication of a highly ordered magnetic field since non-uniformities in the magnetic field will reduce the fraction of polarization. The polarized synchrotron photons can be inverse-Compton (IC) scattered by relativistic electrons – weakening the fraction of polarization (but not erasing it) and imprinting a scattering angle dependence [8] to the observed fraction of polarization. Such IC signals usually (but not always) appear in hard gamma-rays, where polarimetry is difficult, due to multiple scattering in pair production detectors. Another important mechanism for polarizing photons is Thomson scattering which creates a polarization perpendicular to the scattering plane. Curvature radiation is polarized, as well. For more details on the scientific prospects see for example [1] and references therein. Addressing these science goals requires spectro-polarimetric observations over the broadest possible energy range.

2 X-Calibur Design

The conceptual design of the X-Calibur polarimeter is illustrated in Figure 1. A low-Z scintillator ($\rho \approx 1\,\mathrm{g/cm}^3$) is used as Compton-scatterer: The cross section for photoelectric absorption and Compton scattering are equal around 15 keV ($0.26\,\mathrm{cm}^2/\mathrm{g}$). At 20 keV the cross section of the photoelectric absorption already drops to $0.1\,\mathrm{cm}^2/\mathrm{g}$ and can be neglected as compared to the Compton scattering for higher energies. The mean free path for the Compton scattering is $\approx 4\,\mathrm{cm}$ so that the length of the scintillator (14 cm) covers $\simeq 3.5$ path lengths leading to a $p \simeq 90\%$ probability for absorption in the energy regime of $20 - 60\,\mathrm{keV}$. For sufficiently energetic photons, the Compton interaction produces a measurable scintillator signal which is read by a PMT. The scattered X-rays are photo-absorbed in surrounding rings of high-Z Cadmium Zinc Telluride (CZT) detectors. This combination of scatterer/absorber leads to a high fraction of unambiguously detected Compton events. Linearly polarized X-rays will preferably Compton-scatter perpendicular to their E field vector – resulting in a modulation of the azimuthal event distribution.

The CZT detectors were ordered from different companies (Endicott Interconnect, Quikpak/Redlen, Creative Electron). Each detector ($2 \times 2\,\mathrm{cm}^2$) is contacted with a 64-pixel anode grid (2.5 mm pixel pitch) and a monolithic cathode facing the scintillator rod. Two detector thicknesses (2 mm and 5 mm) will be used. Each CZT detector is permanently bonded (anode side) to a ceramic chip carrier which is plugged into the electronic readout board. Each CZT detector is read out by two digitizer boards (32 channel ASIC developed by G. De Geronimo (BNL) and E. Wulf (NRL) [9] and a 12-bit ADC). The readout noise is as low as 2.5 keV FWHM. 16 digitizer boards (8 CZT detectors) are read out by one harvester board transmitting the data to a PC-104 computer with a rate of 6.25 Mbits/s. X-Calibur comprises 2048 data channels. Four detector units form a 'ring' surrounding the scintillator slab. The scintillator EJ-200 is read by a Hamamatsu R7600U-200 PMT. The (optional) PMT trigger information allows to effectively select scintillator/CZT events from the data, which represent likely Compton-scattering candidates. The polarimeter and the front-end readout electronics will be located inside an active CsI(Na) anti-coincidence shield with 5 cm thickness and a passive tungsten shield at the top (Fig. 1, middle right) to suppress charged and neutral particle backgrounds.

The X-Calibur polarimeter will be flown in a pressurized vessel located in the focal plane of the InFOCuS[1] X-ray telescope [10] (Fig. 1, right). The total mass of the gondola and the X-ray telescope will be 1,400 kg. A Wolter grazing incidence mirror focuses the X-rays on the polarimeter. The X-Calibur scintillator rod will be aligned parallel to the optical axis of the InFOCuS X-ray telescope. The focal length is ~ 8 m and the field of view (FWHM) is 10 arcmin. The design of InFOCuS allows for very stable pointing of the telescopes to <1 arcmin as the focus of the X-ray telescope moves across the sky. In order to reduce the systematic uncertainties of the polarization measurements (including biases generated by the active shield, a possible pitch of the polarimeter with respect to the X-ray telescope, etc.), the polarimeter and the active shield will be rotated around the optical axis (~ 3 rpm) using a ring bearing (see Fig. 1, middle right). A counter-rotating mass will be used to cancel the net-angular momentum of the polarimeter assembly during the flight. Power will be provided to the polarimeter by sliding contacts and communication will be done via a wireless network. The data will be stored to solid state drives and will be down-linked to the ground. The advantages of the X-Calibur/InFOCuS design are (i) a high detection efficiency by using more than 80% of photons impinging on the polarimeter, (ii) low background due to the usage of a focusing optics instead of large detector volumes, and (iii) minimization and control of systematic effects and achievement of a corresponding quantitative estimate thereof.

Detailed simulations were performed using the *Geant4* package [11]. An X-Calibur balloon flight in the focal plane of the InFOCuS mirror assembly was assumed. For a Crab-like source the simulations predict an event rate of 1.1(3.2) Hz with (without) requiring a triggered scintillator coincidence detected by the PMT. The X-Calibur modulation factor is $\mu = 0.52$ for a 100% polarized beam. The MDP in the $20-60$ keV energy range will be 4% assuming 5.6 hr of on-source observations of a Crab-like source combined with a 1.4 hr background observation of an adjacent empty field. More detailed simulations are discussed in Guo et al. (2010) [12].

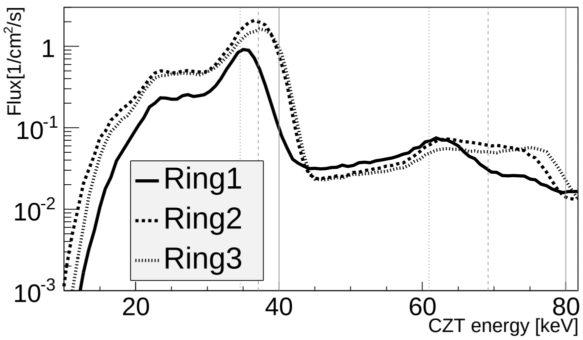

Figure 2: Energy spectra after Compton scattering of a 40/80 keV X-ray beam. Vertical lines: incoming beam energy (solid), energy after 90° scattering (dashed), and energy after 180° scattering (dotted).

3 Performance Measurements

Using funding from Washington University's McDonnell Center for the Space Sciences and NASA grant NNX12AD51G, a flight-ready version of the X-Calibur polarimeter was assembled and tested. For energy calibration of the CZT detectors a Eu^{152} source is placed inside the individual rings. The calibration data also allow to quantify the energy resolution and threshold on a pixel-by-pixel basis. We find an average resolution of 4.2 keV FWHM at 40 keV. In turn, we completed the full assembly and studied the X-Calibur respsonse to incoming X-ray beams.

In order to measure the response to a polarized X-ray beam we operated the X-Calibur polarimeter at the

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[1] `http://infocus.gsfc.nasa.gov/`

Cornell High Energy Synchrotron Source (CHESS) [13]. Using Bragg reflection from a 2-bounce silicon (220) monochrometer a 40 keV beam was generated (2^{nd} harmonic at 80 keV). The event rates were normalized by azimuthal acceptance on a pixel-by-pixel basis. The acceptance was determined from the response to an unpolarized beam (superposition of two perpendicular polarization planes).

The energy spectrum of the Compton scattered X-ray beam is shown in Fig. 2. Figure 3 shows the azimuthal scattering distribution of the polarized beam (analysis ongoing). The expected 180° modulation is clearly seen and the reconstructed orientation of the electric field agrees with the expected direction of the CHESS beam setup – confirming the functionality of the X-Calibur polarimeter.

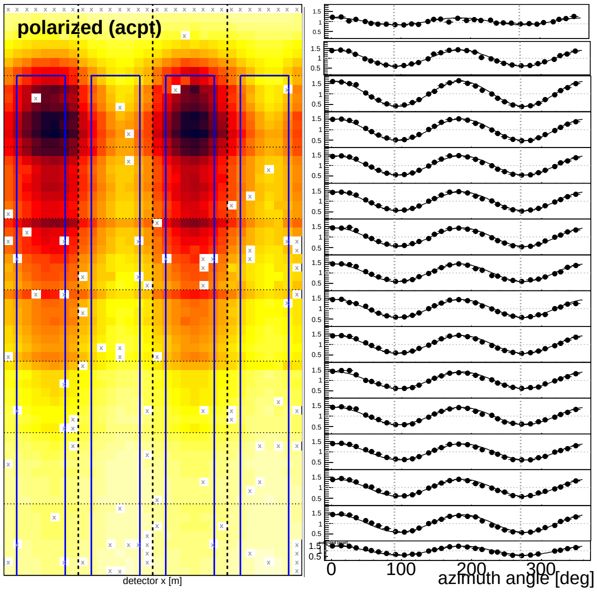

Figure 3: X-Calibur measurement of a polarized beam (energy cut: 36 – 40 keV). **Left:** 2D map (pixel-by-pixel) of counts. The (blue) boxes indicate the outline of the scintillator. **Right:** Azimuthal scattering distribution (corrected for azimuthal acceptance) for different rings. The data are fitted by a sine function. The vertical lines indicate the plane of the E field vector of the polarized beam.

4 Discussion and Conclusions

We designed a hard X-ray polarimeter, X-Calibur, and studied its performance and sensitivity. X-Calibur combines a detection efficiency of close to 100% with a high modulation factor of $\mu \approx 0.5$, as well as a good control over systematic effects. X-Calibur was successfully tested/calibrated in the laboratory and at the CHESS X-ray facility [13].

A 1-day X-Calibur/InFOCuS balloon flight is funded by NASA (NNX12AD51G) for fall 2013. Our tentative observation program includes galactic sources (Crab, Her X-1, Cyg X-1, GRS 1915, EXO 0331) and one extragalactic source (Mrk 421) for which sensitive polarization measurements will be carried through. We envision follow-up longer duration balloon flights (from the southern hemisphere). Successful balloon flights would motivate a satellite-borne hard X-ray polarimetry mission.

Acknowledgement

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References

[1] Krawczynski, H., et al.: 2011, APh. 34, 550.

[2] Schnittman, J.D., et al.: 2010, ApJ. 712, 908. doi:10.1088/0004-637X/712/2/908

[3] Weisskopf, M. C., et al.: 1978, ApJ. 220, L117. doi:10.1086/182648

[4] Dean, A. J., et al.: 2008, Science. 321, 1183. doi:10.1126/science.1149056

[5] Laurent, P., et al.: 2011, Science. 332, 438. doi:10.1126/science.1200848

[6] http://heasarc.gsfc.nasa.gov/docs/gems.

[7] Tajima, H., et al.: 2010, SPIE 7732, 34.

[8] Krawczynski, H.: 2012, ApJ 744, 30. doi:10.1088/0004-637X/744/1/30

[9] Wulf, E. A., et al.: 2007, NIMA 579, 371. doi:10.1016/j.nima.2007.04.085

[10] Ogasaka, Y, et. al.: 2005, SPIE 5900, 217.

[11] http://geant4.cern.ch/

[12] Guo, Q, et. al.: 2010, arXiv 1101.0595.

[13] http://www.chess.cornell.edu/

DISCUSSION

ROLAND WALTER's Comment: According to the current schedule the flight model of the hard X-ray polarimeter POLAR (http://www.isdc.unige.ch/polar/) should be delivered to China this year.

HERMAN MARSHALL: How is the unpolarized flux generated? Perhaps by rotating the polarization plane or by a radioactive source?

MATTHIAS BEILICKE: We super-imposed data with the orientation of the polarization plane of 90° and 0° and independently confirmed the findings with a radiactive source (unpolarized).