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Preflight performance studies of the PoGOLite hard X-ray polarimeter

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ABSTRACT

Polarimetric studies of astrophysical sources can make important contributions to resolve the geometry of the emitting region and determine the photon emission mechanism. PoGOLite is a balloon-borne polarimeter operating in the hard X-ray band (25–240 keV), with a Pathfinder mission focussing on Crab observations. Within the polarimeter, the distribution of Compton scattering angles is used to determine the polarisation fraction and angle of incident photons. To assure an unbiased measurement of the polarisation during a balloon flight it is crucial to characterise the performance of the instrument before the launch. This paper presents the results of the PoGOLite calibration tests and simulations performed before the 2013 balloon flight. The tests performed confirm that the polarimeter does not have any intrinsic asymmetries and therefore does not induce bias into the measurements. Generally, good agreement is found between results from test data and simulations which allows the polarimeter performance to be estimated for Crab observations.

1. Introduction

The development of new observation techniques has enabled enormous progress in X-ray astrophysics as regards spectrometry, imaging and timing studies. Polarised X-ray emission is expected to arise from many sources as a result of non-thermal processes in highly asymmetric systems, e.g. columns and accretion disks. The addition of polarimetric observations results in two new parameters, the polarisation fraction and angle, and would allow geometrical and physical effects to be disentangled, leading to a model independent understanding of underlying emission processes [1–3]. In synchrotron processes, the electric field vector of the X-ray flux is perpendicular to the magnetic field lines in the emitting region and hence a polarisation measurement determines the direction and the degree of order of the magnetic field at the emission site. Relevant sources are rotation-powered neutron stars (e.g. Crab pulsar), pulsar wind nebulae (e.g. Crab nebula) and jets in active galactic nuclei (e.g. Markarian 501, 1E1959+65). In Compton scattering processes, the electric vector is perpendicular to the plane of scattering and a polarisation measurement determines the geometrical relation between the photon source and the scatterer. Accretion disks around black holes (e.g. Cygnus X-1) can be studied in this way. There is a paucity of data from instruments specifically designed to make polarimetric measurements (i.e. tested for this purpose prior to flight). The linear polarisation of X-ray emissions from the Crab were studied over 40 years ago using a dedicated polarimeter [4,5]. More recently, inventive use of instruments not originally designed for polarimetric observations have reinvigorated the field [6–8].

PoGOLite is a hard X-ray polarimeter which makes observations from a stabilised balloon-borne platform at an altitude of approximately 40 km [3]. A reduced effective area polarimeter, the PoGOLite Pathfinder [9], was first launched from the Esrange Space Centre in northern Sweden on 7 July 2011. The balloon was damaged during launch and the flight was terminated prematurely, precluding scientific measurements. A successful launch was achieved on 12 July 2013 and resulted in a near-circumpolar flight with multiple Crab observations.

The polarisation of incident X-rays is determined by reconstructing the azimuthal Compton scattering angle (η) in a close-packed array of plastic scintillators with hexagonal cross-section. Tests of the polarimetric concept using a prototype instrument exposed to a polarised synchrotron beam have been reported on previously [10–12]. In the current paper, the response and performance of the PoGOLite Pathfinder polarimeter was evaluated prior to flight during a series of tests using radioactive sources. Polarisation measurements rely on studying counting rate asymmetries in the detector volume and so constitute a positive definite quantity. One theme of this work is therefore a study of the polarimeter response to both polarised and

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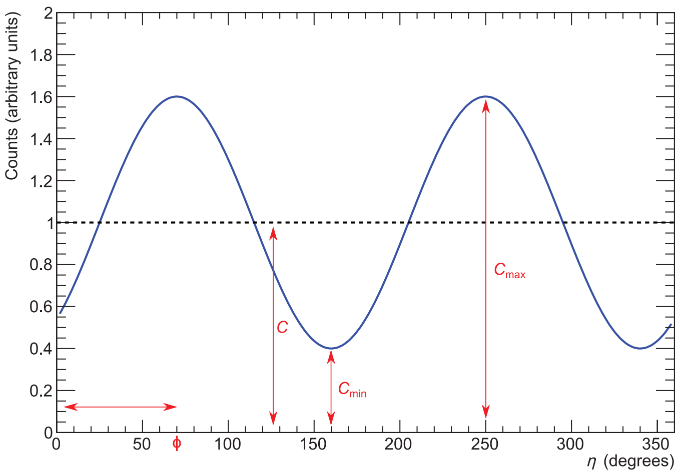

Fig. 1. A generalised modulation curve, as described by Eq. (2).

unpolarised X-ray beams. A second theme is to validate a Geant4 [13] simulation model of the polarimeter. An established figure-of-merit for X-ray polarimeters is the minimum detectable polarisation (*MDP*) [14],

$$MDP = \frac{4.29}{M_{100}R_s}\sqrt{\frac{R_s + R_b}{T}}, \tag{1}$$

where M_{100} is the modulation factor (%) for a 100% polarised source, R_s (R_b) is the signal (background) rate (Hz) for polarisation events and T (s) is the observation time. From a sinusoidal modulation curve fitted to the distribution of azimuthal scattering angles, the modulation factor, M, is defined as the ratio between the amplitude and the mean value of the modulation: $M = (C_{max} - C_{min})/(C_{max} + C_{min})$ (see Fig. 1). The factor of 4.29 signifies that this formulation describes the capability of rejecting the null hypothesis (no polarisation) at 99% confidence level. In order to define the MDP corresponding to the Gaussian 5σ detection level, a factor of 7.58 should be used, resulting in a correspondingly longer observation time. The value of M_{100} is determined from the Geant4 simulation model of the polarimeter. Moreover, the polarisation fraction, Π, of source emission can be expressed as M/M_{100}, and the polarisation angle is defined as the phase, ϕ, of the modulation curve.

For a generalised modulation curve shown in Fig. 1 the sinusoidal component with period 180° arises due to the azimuthal scattering angle dependence of the Compton scattering cross-section, as described by the Klein Nishina equation. The modulation curve can be parameterised as

$$f(\eta) = C\left[1 + M_S \cos\left(\frac{2\pi}{180}(\eta_S - \phi_S)\right)\right], \tag{2}$$

where, $C = (C_{max} + C_{min})/2$. If anisotropic background fluxes are incident on the sensitive volume of the polarimeter, two additional sinusoidal components with periods of 180° and 360° may arise. In this case, an appropriate parameterisation is given by

$$f(\eta) = C\left[1 + M_S \cos\left(\frac{2\pi}{180}(\eta_S - \phi_S)\right) + M_B \cos\left(\frac{2\pi}{180}(\eta_B - \phi_B)\right) + M_{360}\cos\left(\frac{2\pi}{360}(\eta - \phi_{360})\right)\right], \tag{3}$$

where the amplitude and phase of the background contribution are described by M_B and ϕ_B in the case of the 180° component and M_{360} and ϕ_{360} in the case of the 360° component.

In the next section the design of the Pathfinder polarimeter is described. In Section 3 the data acquisition system and trigger philosophy are detailed. This is followed in Section 4 by an overview of how candidate polarisation events are selected from data. In Section 5, the calibration procedure for the polarimeter is reviewed. A simulation model of the polarimeter is presented in Section 6 and model predictions are compared to experimental data. The polarimetric response to both unpolarised and polarised beams is described in Section 7. The impact of the test and simulation results on the scientific performance of the PoGOLite Pathfinder mission is discussed in Section 8. Conclusions are presented in Section 9.

2. Instrument description

The polarisation of incident photons is determined through the coincident detection of Compton scattering followed by another photon interaction like photo-absorption or Compton scattering in a close-packed hexagonal array of 61 plastic scintillator elements. The elements in the array, "phoswich detector cells" (PDCs), each comprise a stack of three scintillators: a 60 cm long plastic scintillator tube (Eljen Technology EJ240), a 20 cm long plastic scintillator rod (Eljen Technology EJ204) and a 4 cm long bismuth germanium oxide (BGO) piece. To increase the light yield the first two elements of the stack are wrapped by a 3M VM2000 film while the bottom BGO is coated with a layer of $BaSO_4$-loaded epoxy resin. Each PDC has a hexagonal cross-section of about 30 mm. The three elements provide active collimation, an active target for scattering or absorption and bottom anticoincidence, respectively. Each PDC is read out by a photomultiplier tube (PMT), Hamamatsu Photonics [15] R7899EGKNP. To provide additional collimation, each hollow plastic tube is first wrapped in a tin foil and then a lead one, each 50 μm thick. The lead foil absorbs off-axis photons and the tin foil absorbs fluorescence photons emitted by the lead. The hollow scintillator tube and BGO piece have decay times of about 300 ns ("slow"), while the solid scintillator rod has a decay time of 2 ns ("fast"). Since the component materials have different scintillation decay times, pulse shape discrimination allows vetoing events with interactions in the slow plastic scintillator or the BGO.

The detector array is surrounded by a segmented active side anticoincidence shield (SAS) made of BGO. This provides shielding against interactions from charged particles and photons originating from outside the instrument field-of-view, which is 2.4° × 2.6°, defined by the geometry of the plastic scintillator collimation tubes. SAS elements are read out by the same type of photomultiplier tubes as used for the PDCs, and the segmentation of the shield allows anisotropies in the background environment to be studied. A passive polyethylene shield with a thickness varying between 10 cm and 15 cm surrounds the detector array and reduces background from atmospheric neutrons, the dominant measurement background during balloon flights [16].

The detector array, photomultiplier tubes and associated electronics are housed inside a pressure vessel, which is rotated around the instrument viewing axis in order to cancel out systematic effects during measurements. These can arise due to intrinsic differences between PDC response or if a photomultiplier tube fails (as is the case for the measurements presented in this paper). One full revolution is completed during a standard 5 min long data acquisition run. The detector array is shown in Fig. 2.

An attitude control system [17] allows the instrument to acquire and track observational targets on the sky. It combines inputs from various sensors including differential GPS, magnetometers and optical star trackers and produces a pointing solution and corresponding control feedback for the actuator motors that govern the azimuth and elevation pointing of the instrument. The GPS is also used to provide an absolute time reference for photon time-tagging.

3. Data acquisition and trigger

The PoGOLite data acquisition system is built around analogue front-end electronics and waveform digitisers (implemented on 12