Astroparticle Physics 82 (2016) 99–107

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Optimising a balloon-borne polarimeter in the hard X-ray domain: From the PoGOLite Pathfinder to PoGO+

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ARTICLE INFO

Article history:
Received 19 November 2015
Revised 7 April 2016
Accepted 7 June 2016
Available online 15 June 2016

Keywords:
X-ray
Polarimeter
Balloon
Crab
Simulation
Geant4

ABSTRACT

PoGOLite is a balloon-borne hard X-ray polarimeter dedicated to the study of point sources. Compton scattered events are registered using an array of plastic scintillator units to determine the polarisation of incident X-rays in the energy range 20–240 keV. In 2013, a near circumpolar balloon flight of 14 days duration was completed after launch from Esrange, Sweden, resulting in a measurement of the linear polarisation of the Crab emission. Building on the experience gained from this Pathfinder flight, the polarimeter is being modified to improve performance for a second flight in 2016. Such optimisations, based on Geant4 Monte Carlo simulations, take into account the source characteristics, the instrument response and the background environment which is dominated by atmospheric neutrons. This paper describes the optimisation of the polarimeter and details the associated increase in performance. The resulting design, PoGO+, is expected to improve the Minimum Detectable Polarisation (MDP) for the Crab from 19.8% to 11.1% for a 5 day flight. Assuming the same Crab polarisation fraction as measured during the 2013 flight, this improvement in MDP will allow a 5σ constrained result. It will also allow the study of the nebula emission only (Crab off-pulse) and Cygnus X-1 if in the hard state.

1. Introduction

Measuring the linear polarisation of X-ray emissions from astrophysical sources gives unique insight into the emission mechanisms at work and the geometry of the emitting region [1,2]. Due to the difficulties in making sensitive measurements in this energy domain, only a few instruments have been able to successfully detect polarisation [3–6]. The delicate control of systematic effects benefits from instruments specifically designed for polarimetric measurements.

PoGOLite is a purpose-built polarimeter working in the energy range 20–240 keV. It determines the linear polarisation of hard X-ray emission from point sources by measuring the distribution of Compton scattering angles in a plastic scintillator detector array. The PoGOLite Pathfinder mission was designed to validate the instrument concept. Launched from the Esrange Space Centre at 08:18 UT on July 12th 2013, the payload was airborne for 14 days, making an almost complete circumpolar flight around the North Pole (average latitude of 68°). The prominent Crab X-ray source was observed for 14 hours. Data from this first flight revealed limitations of the design and a challenging background environment dominated by atmospheric neutrons. Based on the accumulated experience, a new design that will significantly improve the polarimeter performance is proposed.

After describing the instrument and its numerical simulation, the different modifications are presented along with their associated increase in polarimetric performance in terms of Minimum Detectable Polarisation (MDP) [7].

In the final section the overall performance of the new design, PoGO+, is discussed for the Crab and Cygnus X-1 during the next balloon flight, planned for the summer of 2016.

2. The PoGOLite instrument

PoGOLite is a polarimeter making use of Compton scattering kinematics. When polarised photons undergo Compton scattering

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http://dx.doi.org/10.1016/j.astropartphys.2016.06.005
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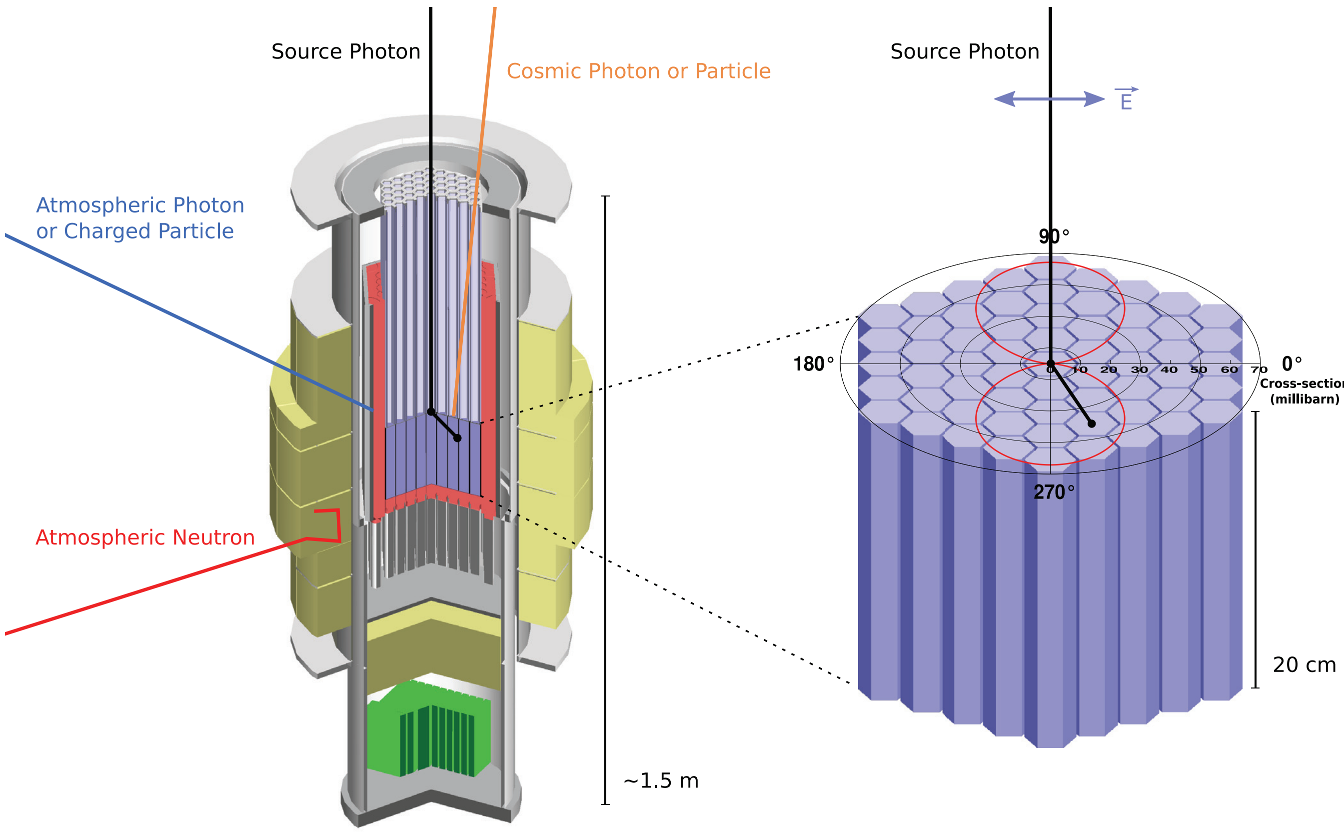

Fig. 1. PoGOLite Pathfinder schematic view and detection principle. Left: the detector made of plastic scintillators (blue), the BGO anti-coincidence (red), the active plastic scintillator collimators (light blue), the photomultiplier tubes (grey) and the electronic components (green) are enclosed in a cylindrical housing. This inner housing is rotated around the viewing axis in order to remove systematic effects in the measurements. The detectors are surrounded by a passive shield made of polyethylene (yellow) to reduce the neutron background. The background components and their interactions in the instrument are represented by different coloured lines. Right: close-up view of the detector assembly. The 61 plastic scintillator rods, about 3 cm wide and 20 cm long, are closely packed to provide the azimuthal angle between two consecutive interactions (black dots). The Compton cross-section is overlayed on top (not to scale) to show the preferential scattering direction of the incoming polarised photons. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

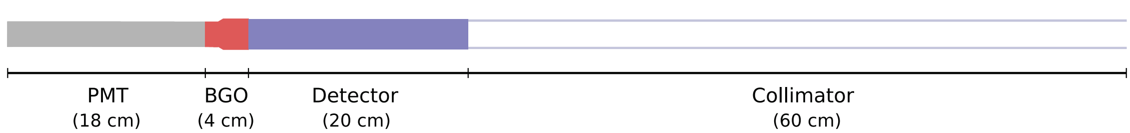

Fig. 2. Sketch of a PoGOLite Pathfinder detector unit. The main detector (blue) is sandwiched between a BGO crystal (red) and a hollow 2 mm thick active collimator made of plastic scintillator (light blue). The three scintillators are read-out by the same PMT (grey) and their signals are identified by their different waveform shape. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

they have higher probability to scatter perpendicular to their polarisation vector. This is described by the Klein–Nishina differential cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \epsilon^2 \left[\epsilon + \epsilon^{-1} - \sin^2\theta \cos^2\phi\right] \quad (1)$$

where r_0 is the classical electron radius, ϵ is the ratio between the scattered and incident photon energies, θ is the polar scattering angle and ϕ is the azimuthal scattering angle defined as the angle to the electric field vector. Within a polarimeter, this anisotropic process causes a modulation in the detected azimuthal angles and measuring the phase and amplitude of this modulation allows the polarisation angle and polarisation fraction of the source flux to be determined.

The PoGOLite Pathfinder uses an array of 61 plastic scintillator rods, giving an exposed detector area of 298 cm^2, and providing a high cross-section for scattering X-ray photons. The hexagonal rods are closely-packed to provide the azimuthal scattering angle of a photon interacting twice in the detector. Following the detection of an energy deposit above ~20 keV in one detector cell (assumed to be a photoelectric absorption event), the remaining cells are checked for a coincident lower energy deposit above ~0.5 keV (assumed to be a Compton scattering event). Each detector cell has a dynamic range of 20 - 120 keV. Since two-hit events are used for the polarisation analysis, the maximum (theoretical) energy range of the instrument becomes 20–240 keV. The polarimeter and detection concept are illustrated in Fig. 1.

A detector rod (20 cm long) is sandwiched between two anti-coincidence components: a BGO scintillator (4 cm long) and an active collimator (60 cm long) made of plastic scintillator (see Fig. 2). The three stacked scintillators are read out by the same photomultiplier tube (PMT) - based on the Hamamatsu R7899 design but modified to reduce the dark current. The sandwiched detector has a faster rise time to allow event discrimination based on the pulse shape. The anti-coincidence is complemented by 30 rods of BGO scintillators (60 cm tall) placed around the main detector