Polarisation Measurements Of Soft Gamma Rays From The Crab And Cygnus X-1 Using A Small Compton Polarimeter To Fly On A Cubesat

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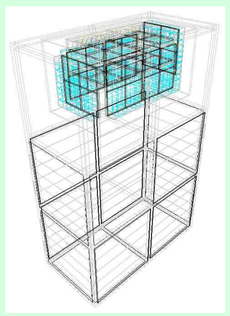
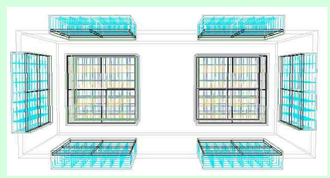
Abstract

Measurement of polarization is important in understanding radiation mechanisms of pulsars and coronal geometry of X-ray binaries. In this study, we propose to implement a small Compton Polarimeter on-board a 6U Cubesat to study the gamma ray polarization of the Crab and Cygnus X-1. The instrument is based on Gadolinium Aluminum Gallium Garnet (GAGG, chemical formula: $Gd_3Al_2Ga_3O_{12}$) scintillator arrays and silicon photomultipliers (SiPM) to convert the scintillation light to electric signals. In this paper, we estimate the Minimum Detectable Polarization (MDP) using the MEGAlib package for certain variations of the instrument models, including different configurations, energy threshold and read-out size of detectors. We will discuss the results for four energy ranges: 80-160 keV, 160-250 keV, 250-400 keV, and 400-2000 keV and try to obtain the optimised criteria for the lowest MDP, thus estimating the most sensitive instrument configuration to detect useful polarization information in the soft gamma-ray regime.

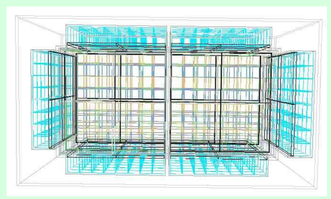
Instrumental Models



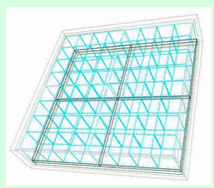
TSAC Model
(6U Cubesat)



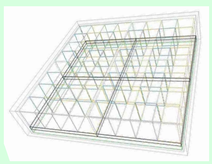
Version-1 of Detector Module
(with gaps)



Version-2 of Detector Module
(with no gaps)



12mm by 12mm inch
readout channel



6mm by 6mm inch
readout channel

(Designed by Tzu-Hsuan Lin [2])

Model 0:

- 6U bus: 30 x 20 x 10 cm^3
- 10 GAGG scintillator detectors : 2 x 2 array, 12mm by 12mm readout channel.
- GAGG scintillator: Encased with Al-$BaSO_4$ film and base is SiPM-PCB.
- Zenith Angle: 0 degree

Model 1:

- 6U bus, 10 detectors with GAGG scintillator (same as Model 0)
- The top 4 detectors are 2 x 2 array, 6mm by 6mm readout channel.
- Zenith Angle: 0 degree

Source Simulations

Simulations are done using *Cosmic Simulator for MEGAlib*(Cosima) simulation package. It is based on Geant4 software and part of the *Medium Energy Gamma-ray Astronomy Library*(MEGAlib).

The simulations are done for 10 Megaseconds using the source spectrum of Crab and Cygnus X-1 Sources

Crab Source:

$$A(E) = 11.6 \times E^{-2.11} \qquad E \le 81 \text{ keV}$$
$$A(E) = 11.6 \times E_b^{0.99} \times (1/1\text{ keV})^{-2.2} \qquad E > 81 \text{ keV}$$

Cygnus X-1 Source:

$$A(E) = 0.53 \times E^{-1.31} \times e^{-E/95.5\text{ keV}} + 2.47 \times E^{-2.05}$$

Background:

We have considered a 10 kiloseconds background model which is from a low earth orbit having altitude of 575 km.

Theory of MDP

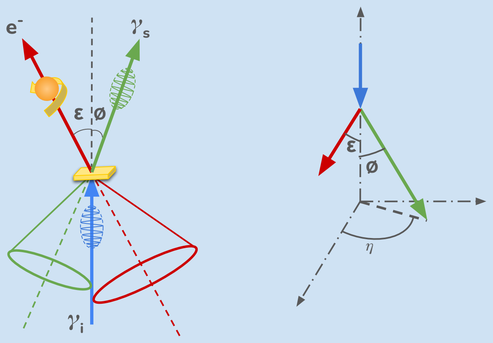


Fig: Compton Scattering with photon. Blue line: incident photon, Red line: recoiled electron, and Green line: Compton scattered photon. The green cone predicts the incident photon direction.

Klein-Nishima Model: If the photon is polarised, we can apply the azimuthual scatter angle η. Thus, the differential cross-section for the compton scattering of photons off an unbound electron is:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'_\gamma}{E_\gamma}\right)^2\left(\frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - 2\,\sin\phi^2\cos\eta^2\right)$$

Thus, we obtain after solving the differential, we obtain the pdf of scattering at a specific η as

$$P(\eta) = A\,\cos(2(\eta - \eta_0)) + P_0$$

where, P_0: offset, A : Amplitude,
η_0 : Polarization angle

Thus, the measured modulation is,

$$\mu = \frac{A}{P_0}$$

modulation factor for 100% polarization is,

$$\mu_{100} = \frac{P_{\max} - P_{min}}{P_{\max} + P_{min}}$$

Degree of polarization is,

$$\Pi = \frac{\mu}{\mu_{100}}$$

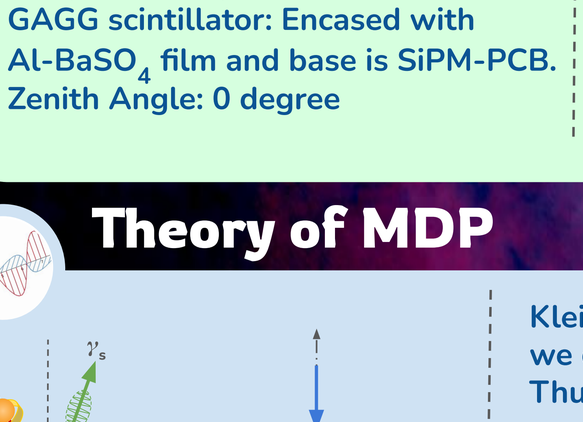
Thus, the MDP is,

$$MDP = \frac{4.29}{\mu_{100}\,R_S}\sqrt{\frac{R_S + R_B}{T}} = \frac{4.29}{\mu_{100}}\sqrt{\frac{C_S + C_B}{C_S}}$$

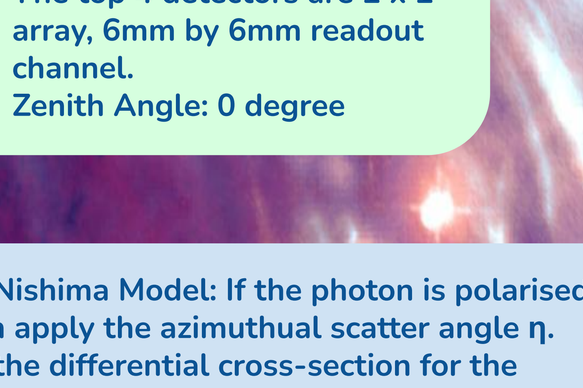
where,
4.29 corresponds to 3σ confidence level
C_S : Source Counts,
C_B : Background Counts,
R_S: Source Count Rate,
R_B: Background count rate, and
T : Simulation time

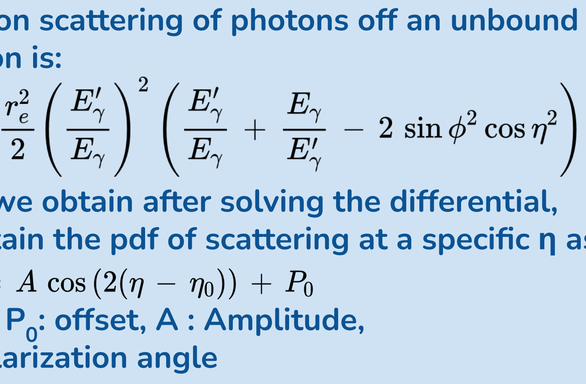
Results of MDP

Crab Source



Cygnus X-1 Source





Discussions

- Crab is a brighter source compared to Cygnus X-1. So, for the same energy range, the Minimum Detectable Polarization (MDP) is always less in Crab.
- Here, we have shown the MDP simulation in 4 energy ranges: 80-160 keV, 160-250 keV, 250-400 keV and 400-2000 keV.
- We have used 2 versions (one separated and one compact) of 2 models.
- For the Crab source, using both models, the MDP is lowest in the energy range of 250-400 keV. The lowest MDP is about 8% using the Model-1, Version 2.
- For the Cygnus X-1 source, the lowest MDP is about 16% in the energy range 160-250 keV using the Model-1, Version-2.
- Thus, we have so far decided to choose the Model-1, Version 2 for further analysis and instrumental design.
- The Model-1, Version-2 has better performance because of the 6x6 readout channel of the top 4 detectors which accounts for more event detections, as well as lower background counts due to the compact architecture.