Journal of High Energy Astrophysics 5–6 (2015) 22–29

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap

Telescope performance and image simulations of the balloon-borne coded-mask protoMIRAX experiment

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ARTICLE INFO

Article history:
Received 13 November 2014
Accepted 28 January 2015

Keywords:
ProtoMIRAX
Astronomy
X-ray astrophysics
Astrophysics
Balloon experiment

ABSTRACT

In this work we present the results of imaging simulations performed with the help of the GEANT4 package for the protoMIRAX hard X-ray balloon experiment. The instrumental background was simulated taking into account the various radiation components and their angular dependence, as well as a detailed mass model of the experiment. We modeled the meridian transits of the Crab Nebula and the Galactic Centre region during balloon flights in Brazil (∼−23° of latitude and an altitude of ∼40 km) and introduced the correspondent spectra as inputs to the imaging simulations. We present images of the Crab and of three sources in the Galactic Centre region: 1E 1740.7–2942, GRS 1758–258 and GX 1+4. The results show that the protoMIRAX experiment is capable of making spectral and timing observations of bright hard X-ray sources as well as important imaging demonstrations that will contribute to the design of the MIRAX satellite mission.

1. Introduction

X and low-energy ($\lesssim$1 MeV) γ-ray photons coming from astrophysical sources interact in the Earth's atmosphere through photoelectric effect or Compton scattering, never reaching the surface. However, at usual stratospheric balloon altitudes (∼40 km), a major fraction of the X-ray photons with energy greater than ∼30 keV is able to pass through the remaining external atmosphere. This allows the detection and observation of cosmic sources above these energies with instruments carried by balloons.

In addition to photons coming directly from the astrophysical sources of interest, radiation from the atmosphere and from other cosmic sources (either point-like or diffuse) in the field of view of an X-ray telescope interacts with the instrument and the balloon platform, generating an intense background. Therefore, detailed predictions of the fluxes and spectra of cosmic sources are crucially dependent upon an accurate knowledge of this background. At balloon altitudes, this is a non-trivial task that has to take into account the several particle and photon fields incident upon the experiment and all the interactions that occur in the detectors and surrounding materials, as well as a detailed mass model of the instrument. By knowing the particle kinds, both primary and secondary, their energy spectra, and by following the secondary emission they produce when they interact, we can simulate the energy depositions on the detectors and identify the contribution of each background component. This is essential to estimate the instrument sensitivity as a function of energy.

In this work, we first show the results of background calculations necessary to make realistic simulations of the astrophysical observations to be carried out by the protoMIRAX experiment. protoMIRAX consists of a wide field coded-mask hard X-ray imager that will operate in a stabilized balloon gondola with fine pointing capability. Besides being a prototype designed to test several subsystems of the MIRAX satellite experiment (Braga et al., 2004; Braga, 2006) in a near-space environment, protoMIRAX is also capable to carry out spectral observations of bright X-ray sources.

We then present imaging simulations of known hard X-ray point sources in selected sky fields to be observed by the experiment in the 30–200 keV energy range. We use standard cross-correlation techniques to reconstruct the images with coded masks. Even though coded aperture imaging is inherently a low signal-to-noise-ratio (SNR) technique, since the whole detector area is used to measure both source and background, it remains the most used imaging technique at hard X-ray and low-energy γ-ray energies due to its relative simplicity of implementation and the capacity to image large fields of view with reasonable angular resolution. Although the **NuSTAR** mission has extended X-ray

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http://dx.doi.org/10.1016/j.jheap.2015.01.001

Table 1
Overview of the protoMIRAX balloon mission.

Mission	
Total mass	~600 kg
Altitude	~42 km at −23° latitude
Geometrical area	169 cm^2
Effective area @ 50 keV	50 cm^2 (through mask)
Detector system	
Single detector dimensions	10 mm × 10 mm × 2 mm
Material	Cadmium Zinc Telluride (CZT)
Number of detectors	169 (13 × 13)
Gap between detectors	10 mm
Energy range	30–200 keV
Time resolution	10 µs
Coded mask	
Material	Lead
Basic pattern	13 × 13 MURA
Extended pattern	2 × 2 basic (minus 1 line and 1 column)
Element size	20 mm × 20 mm × 1 mm
Open fraction	0.497
Total mask dimensions	500 × 500 mm^2
Position	650 mm from detector plane
Imaging parameters	
Angular resolution	1°45′
Total (fully-coded) FOV	21° × 21° (FWHM = 14.1° × 14.1°)

optics up to ~80 keV (Harrison et al., 2013; Hailey et al., 2010), coded masks are still important for hard X-ray and low-energy γ-ray wide field imaging instruments.

Even though protoMIRAX is chiefly a prototype designed to test several subsystems of the MIRAX satellite experiment in a near-space environment, we show in this work that the experiment is also capable of making spectral observations of selected bright hard X-ray sources and perform important imaging demonstrations that will contribute to the design of the MIRAX mission.

In Section 2 we describe the protoMIRAX experiment, which will be assembled in a gondola to fly on stratospheric balloons. In Section 3 we make a brief description of the nature of the hard X-ray point sources that we have used in our simulations. In Section 4 we describe the procedure we took to simulate the instrumental background using GEANT4. In Section 5 we show the calculations we made to simulate the detected fluxes of the sources during their meridian passages. In Section 6 we show the simulated images and discuss their properties. Finally, in Section 7 we present the conclusions.

2. The protoMIRAX experiment

The protoMIRAX balloon gondola houses the X-ray camera, which is the imaging unity of the experiment, and other subsystems. Table 1 presents an overview of the experiment and its baseline parameters.

The camera includes a coded mask based on an extended (4 × 4) pattern of 13 × 13 Modified Uniformly Redundant Arrays (MURA) (Gottesman and Fenimore, 1989), which is placed 650 mm away from a position-sensitive detector plane. The mask elements are made of lead with 20 mm × 20 mm in area and 1 mm thickness. Such a design will allow a ~1°45′ geometrical angular resolution and a ~20° × 20° fully-coded field of view (FOV).

The detector plane comprises 169 square (10 mm × 10 mm) Cadmium Zinc Telluride (CZT) detectors, 2-mm thick, providing a ~30–200 keV optimum energy coverage. The lower threshold is defined by atmospheric absorption at balloon altitudes, whereas the upper limit is due to the detector thickness. We have developed an electronics acquisition system for the CZTs and our current figure for energy resolution is ~8%@60 keV.

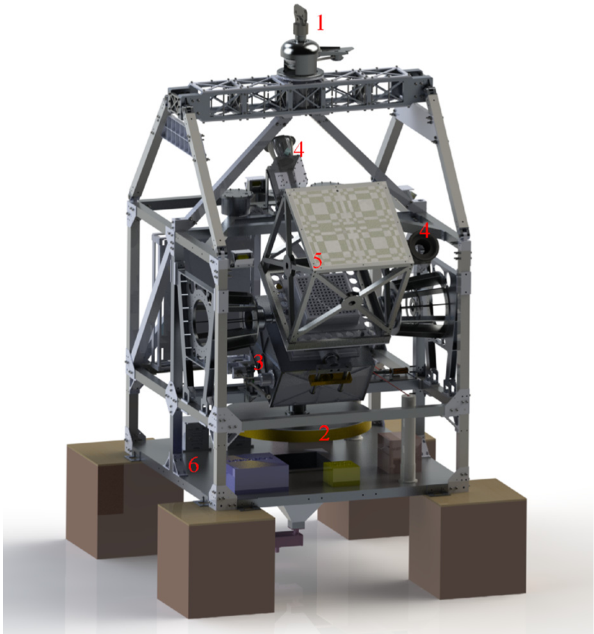

Fig. 1. Design of the protoMIRAX payload, consisting of: (1) the pivot with a decoupling mechanism for momentum dump; (2) the reaction wheel; (3) the elevation step-motor-controlled actuator; (4) star sensors; (5) the MURA-based coded-mask; and (6) the electronics bay. The gondola is ~2.4 m high, 1.4 m × 1.4 m in cross section, and its total mass is around 600 kg.

The capabilities of protoMIRAX in the time domain depend upon the strength of the source signals, which in turn depends on the detector area. The electronic time resolution is 10 µs. For strong sources, we will be able to detect time variability at a level of tens of seconds. According to the GEANT4 simulations, the expected count rate for the detector plane is approximately 50 counts/s. At those rates we will have a very low dead time and no pile-up problems.

The balloon gondola has an attitude control system that provides pointing capability both in azimuth and elevation with an accuracy of a few arc minutes. Fig. 1 shows a computer design of the protoMIRAX experiment.

3. The sample of simulated point sources

3.1. Crab Nebula

The well-known Crab Nebula (M1; $\alpha = 5$ h 34.5 m; $\delta = +22°01'$) is the remnant of a bright Galactic supernova recorded by Chinese astronomers in 1054. It is at a distance of 2.2 kpc from Earth and today has an apparent magnitude $m_v = 8.6$. The system encompasses a plethora of regions with different structures and emission mechanisms. At the centre of the nebula lies the Crab Pulsar, the only neutron star that emits coherent pulses in phase all the way from radio to γ-rays, with a period of $P = 33$ ms and $\dot{P} = 4.21 \times 10^{-13}$. The correspondent spin-down luminosity is $L_{sd} = 4\pi^2 I P^{-3} \dot{P} \sim 5 \times 10^{38}$ erg s^{-1}, where I is the moment of inertia of the neutron star (Frank et al., 2002). Only a small fraction of L_{sd} goes into pulsed emission; the majority is carried away by some combination of magnetic dipole radiation and an ultrarelativistic wind. This is the source of the energy that powers the Crab. It is currently believed that a Pulsar Wind Nebula (PWN) efficiently converts the energy of the shocked pulsar wind into the observed synchrotron emission, which accounts for ~26% of the total L_{sd}. For a comprehensive review on the Crab, see Hester (2008).