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

Ana Virginia Penacchioni
In collaboration with João Braga, Manuel Castro and Flavio D'Amico

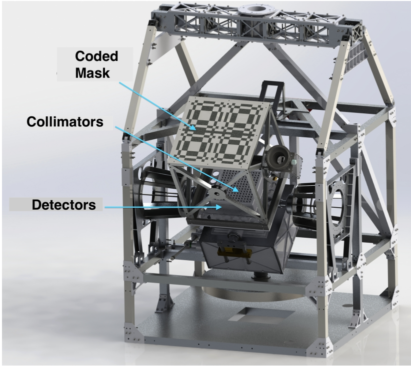
Instituto Nacional de Pesquisas Espaciais (INPE)
São José dos Campos, Brazil

VIII Workshop da PG-AST/DAS, 8 Abril 2015

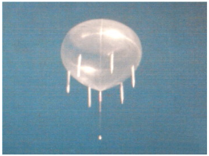
The ProtoMIRAX Experiment

- **What is it?**
  - Balloon-borne experiment
  - Hard X-ray imager telescope
  - X-ray coded-mask
- **Goal:** study the spectral and temporal variability of bright X-ray binaries. Prototype for the MIRAX mission.
- **Why?:** The development and testing, with subsequent flight verification/validation will pave the way for equivalent modeling of MIRAX, a space mission.

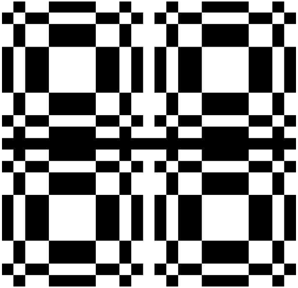
The ProtoMIRAX Experiment



CdZnTe detectors
Energy range: 30-200 keV
Effective area: $\sim$ 84 cm^2
Coded mask technique

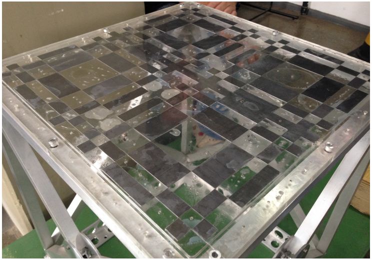


The coded-mask



Extended 4×4 pattern of a 13×13 Modified Uniformly Redundant Array (MURA).
$\sim 1^{\circ}45'$ angular resolution
$20^{\circ} \times 20^{\circ}$ fully-coded FoV

Gottesman and Fenimore 1989



Material: lead
Mask elements: 20mm×20mm in area and 1mm thick.

The sources

We modeled the emissions from the **Crab Nebula** and three sources in the Galactic center region:
1E 1740.7-2942, GRS 1758-258 and **GX 1+4**.

Diffuse background $\longrightarrow$ Noise source.
Altitude: ~ 42 km $\longrightarrow$ Atmospheric depth $x \approx 2.7$ g/cm^2.
Photons interact with the atmosphere, generating secondary particles. Flux is attenuated:

$$F = F_0 e^{-\frac{\mu}{\rho} x \, sec(z)}$$

$\frac{\mu}{\rho}=$ absorption coefficient of the air [cm^2/g] (depends on E),
$cos\, z = sin\,\phi\, sin\,\delta + cos\,\phi\, cos\,\delta\, cos\, H =$ zenith angle,
H=hour angle, ϕ=geographic latitude, δ=declination of the source.

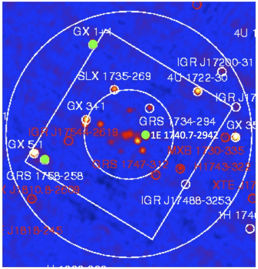
Incident Spectra [ph cm^{-2} s^{-1} keV^{-1}]

- Crab Nebula[a]: $F_0 = 14.44\, E^{-2.169}$
- 1E 1740.7-2942[b]: $F_0 = 10^{-4} \left(\frac{E}{100 keV}\right)^{-1.35}$
- GRS 1758-258[c]: $F_0 = 4.6 \times 10^{-5} \left(\frac{E}{100 keV}\right)^{-1.8}$
- GX 1+4[d]: $F_0 = 5.1 \times 10^{-4} \left(\frac{E}{30 keV}\right)^{-1.9}$

The number of particles arriving at the detector is given by:

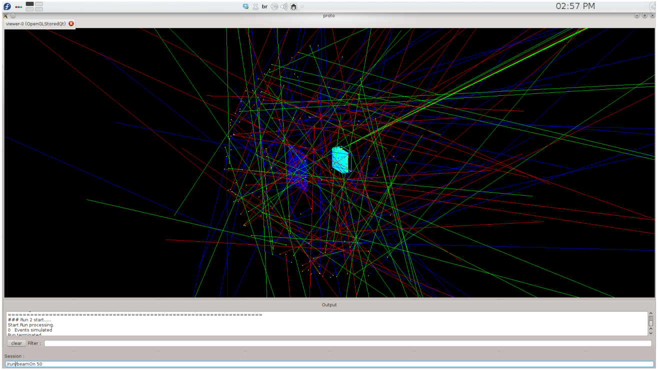
$$N = \int_0^T \int_{E_{min}}^{E_{max}} \int_S A_0 E^{-\gamma} e^{-\frac{\mu}{\rho}(E) x sec(z)} dE\, dt\, dS.$$

[a]Sizun et al. 2004, [b]Grebenev et al. 1995, [c]Sunyaev et al. 1991, [d]Deters et al. 1991



http://integral.esac.esa.int/BULGE/

GEANT4: Mass model

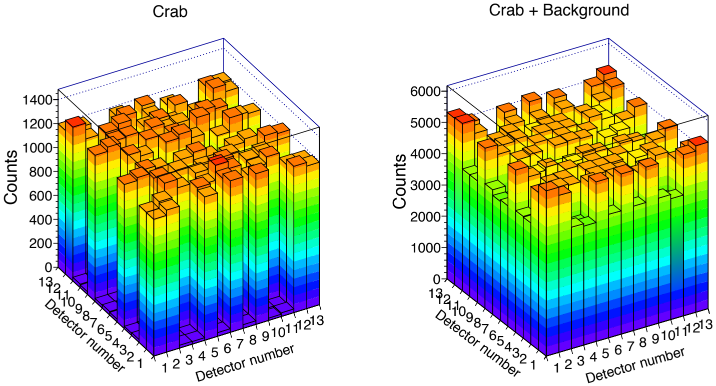


The GEANT4 (GEometry ANd Tracking) package was developed by CERN. It allows to perform simulations of the instrumental behaviour when a particle field interacts with the detector material.

Allison et al. 2006; Agostinelli et al. 2003

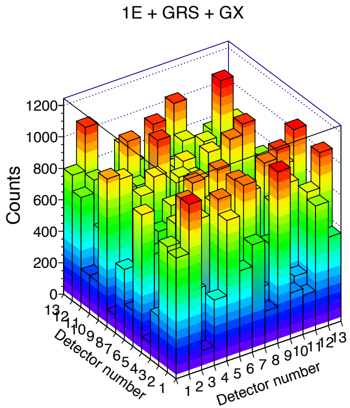
Simulation of the Crab + background

We simulated all the particles that reach the detector plane in 4h to get their distribution in energy and detector number (shadowgram). Each pixel corresponds to one CZT detector (1 cm^2).



Simulation of the GC region + noise

For the GC region, the simulation time was 8 hours.



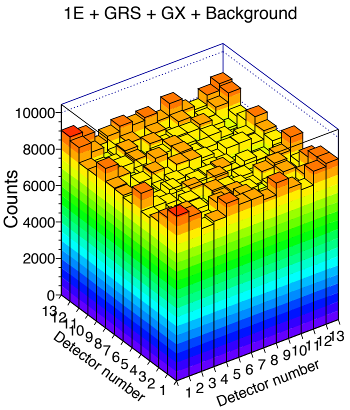


Image reconstruction

The recorded data can be represented as a matrix

$$D = S * A + B$$

where S is the reconstructed source distribution, A is a decoding function that mimics the mask pattern, and B is the background contribution.

The reconstructed source is given by: $S = D * G$, where G is a decoding function. Then,

$$S = D * G = S * A * G + B * G = S + B * G$$

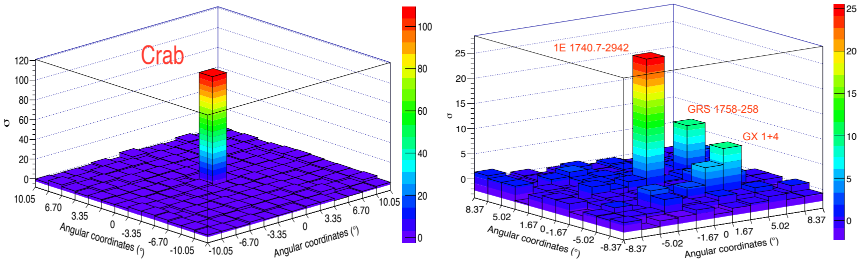
Fenimore & Canon 1978

The statistical signal to noise ratio (SNR) is given by

$$SNR = \frac{N_S}{\sqrt{N_S + N_T}}$$

Gottesman & Fenimore 1989

Image reconstruction



Simulated image of the Crab (left) and Galactic Centre (right) regions as seen by protoMIRAX for 4h and 8h, respectively. The SNRs for the Crab is 109, while for 1E 1740.72942, GRS 1758258 and GX 1+4 are, respectively, 26, 10 and 9. GX 1+4 counts are distributed in two sky bins.

Published Results

ARTICLE IN PRESS JHEAP:10

Journal of High Energy Astrophysics ••• (••••) •••–•••

ELSEVIER

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

A.V. Penacchioni *, J. Braga, M.A. Castro, F. D'Amico

Instituto Nacional de Pesquisas Espaciais (INPE), Av. dos Astronautas, 1758, CEP 12227-010, São José dos Campos, SP, Brazil

ARTICLE INFO

Article history:
Received 13 November 2014
Accepted 28 January 2015
Available online xxxx

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.

Conclusions

- In this work we presented results of simulated images of regions with bright X-ray sources with the protoMIRAX experiment at balloon altitudes.
- We reconstructed images of 2 regions of the sky: Crab Nebula and 3 sources in the GC: 1E 1740.7-2942, GRS 1758-258 and GX 1+4.
- Measured SNR of 109, 26, 9 and 10 for Crab, 1E, GX and GRS, respectively. 60% of the purely statistical values. Due to non-uniformity of the background across the detector plane, collimator response and gaps between the detectors.

Conclusions

- It is possible to make observations of crowded fields and provide flux and spectral information without source confusion.
- protoMIRAX plays an important role in testing new detector technology and imaging systems in a near-space environment. It is a pathfinder for the MIRAX mission.

THANK YOU!