POLAR: an Instrument to measure Gamma Ray Bursts Polarisation

EPFL 11 June 2012

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Outline

- What are Gamma Ray Bursts?
- Theoretical motivation
- Importance of polarisation measurement
- Current experimental situation
- POLAR detector and its working principle
- Data processing scheme
- Preliminary results from recent beam tests.
- Summary
What are Gamma Ray Bursts?

- Gamma ray bursts (GRB) are flashes of gamma rays randomly distributed in the sky and time.
- Brightest events in the universe since Big Bang: some releasing more energy in 10 seconds than what the Sun will emit in its entire 10 billion year lifetime!
- About 1 GRB/day observed
Gamma Ray Bursts

- Spectrum usually described by a class of functions similar to a broken power law:

\[ N(E) = N_0 \begin{cases} 
  (E)^\alpha \exp\left(-\frac{E}{E_0}\right), & \text{for } E < (\alpha - \beta)E_0 \\
  ((\alpha - \beta)E_0)^{(\alpha-\beta)}(E)^\beta \exp(\beta - \alpha), & \text{for } E \geq (\alpha - \beta)E_0,
\end{cases} \]

- Light-curves, although very different from GRB to GRB, show three parts:
  - Pre-burst
  - Prompt emission ($\gamma$, $X$, $\nu$ ?)
  - Broadband long-lasting afterglow ($X$, optical, radio)

- Two main models of GRB origin:
  - Merging of binary neutron stars into black hole: short GRB < 2-5 s
  - Hypernova: high-mass star collapsing into black hole: long GRB > 5 s
The GRB is produced by internal dissipation within the relativistic jet launched from the centre of the explosion.

The afterglow is the synchrotron emission of electrons accelerated in a collision-less shock driven by the interaction of the jet with the surrounding medium (Zhang 2007).
Importance of Polarisation

- The emission mechanism of prompt signal (and the origin and structure of magnetic fields in GRBs) is an open questions concerning the nature of the central engine of GRBs.

- In spite of extensive observational efforts, these questions are difficult or even impossible to infer with the spectral and lightcurve information currently collected.

Polarimetric observations of GRBs can address the following:

- **Magnetic composition of GRB jets**
  
  It is highly speculated that strong magnetic fields are generated at the GRB central engine, and may play an essential role in the launch of the relativistic jets. However, it is unclear whether the burst emission region is penetrated by a globally structured, dynamically important magnetic field, and whether the burst is due to shock dissipation or magnetic reconnection (Lyutikov et al. 2003).

- **Geometric structure of GRB jets**
  
  Although it is generally believed that GRB outflows are collimated, the distribution of the jet opening angles, the observer's viewing direction, and whether there are small-scale structures within the global jet are not well understood.

- **Emission mechanisms of the bursts**
  
  They can be constrained by using the statistical properties of GRB polarisations
Emission mechanisms of GRBs

...Emission mechanisms of the bursts can be constrained by using the statistical properties of GRB polarisations.

The leading models are:

- **Synchrotron** emission from relativistic electrons in a globally ordered magnetic field carried from the central engine (Lyutikov et al. 2003), or
- **random** magnetic fields generated in-situ in the shock dissipation region (Rees & Mészáros 1994).

Other suggestions:

- **Compton drag** of ambient soft photons (Lazzati et al. 2004),
- synchrotron self-Compton emission (Panaitescu & Meszaros 2000),
- the combination of a thermal component from the photosphere and a non-thermal component (e.g., synchrotron) (Ioka et al. 2007).
Actual Experimental Situation

So far, polarisation measurement has been neglected.

Only one conclusive measurement:

- GAP on board IKAROS. GRB 100826A 27±11 % (2.9 σ CL).

Other find mostly important polarisation, but systematic effects poses difficult problems:

- Coburn Boggs 2003 GRB 021206 80±20%
  Proven wrong. Final correct (Wigger) 30±30%
- BATSE using Earth reflection GRB 930131 > 30%
- GRB 960924 > 50%. Difficult to trust because of systematics due to Earth atmosph. sim.
- INTEGRAL GRB 041219A 96±40%. Cannot exclude Systematic effects.
- SPI GRB061122 <60%
- An other group (Goetz at al) find time varying polarisation

Solid INTEGRAL measurement of Crab nebula polarisation 46±10%
Polarimetry in Space

**GAP** on board IKAROS; D. Yonetoku *et al.*

**PENGUIN-M** solar flare on board Coronas-Photon; V.A. Dergachev *et al.*

**GRAPE** Gamma Ray Polarisation Experiment: Low Z - high Z hybrid, 50-300 keV; M. McConnell *et al.*

**PoGO** Polarized Gamma-ray Observer: phoswich of slow-fast units with AC, 30-100 keV; T. Mizuno *et al.*

**SGD** Soft Gamma-ray Detector: Compton telescope of Si-strips and CdTe pixels and AC, E<300 keV; H. Tajima

**CIPHER** Coded Imager and Polarimeter for High Energy Radiation: CdTe array, E<1 MeV; R. Curado da Silva

**RHESSI** High Energy Solar Spectrometric Imager: 9 large Ge, active/passive modes, E>10 keV; M. McConnell, C. Wigger

**Athena (...), GRIPS...** future payloads and 2020 ESA cosmic vision...
Detector Requirements and Design Consideration

- Compton polarimeter made as a simple, compact instrument
  - Deliberately abandon precise energy measurement
  - Plastic to maximize Compton scattering
- Dedicated to GRB observations only
- Large area, large modulation factor and large field of view
- Relies on given burst position and spectrum
- Optimised for high signal to background ratio and large control of systematic effects
POLAR is a Compton polarimeter devoted to study the prompt emission of GRBs in the energy range 50–500 keV (N. Produit, et al., NIM (2005))

- Compact (~30kg, ~30x30x30 cm³)
- Field of view: ~1/3 full sky
- Min. detectable polarisation (MDP): < ~10%

~10 GRB / year

- Assembly of qualification model (QM) ongoing (due summer 2012).
- Space qualification campaign in 2012-2013.
  - Vibration, acceleration and thermovacuum tests
- Mounted on Chinese spacelab TG-2 (atmosphere opaque for X-rays)
- Launch expected in 2014.
- Lifespan: 3 years
POLAR Detector

- Consists of 25 modular units
- Each modular unit composed of 8x8 plastic scintillator bars (6x6x176mm³) read-out by one Multi Anode PMT and ASIC readout electronics.
- Total: 1600 plastic scintillator bars + 25 MAPMT
Compton Polarimetry

Photons tend to Compton scatter at right angles to the incident polarisation direction: (Klein-Nishina equation)

$$d\sigma = \frac{r_0^2}{2} d\Omega \left( \frac{E'}{E_o} \right)^2 \left( \frac{E_o}{E'} + \frac{E'}{E_o} - 2\sin^2\theta \cos^2\eta \right)$$

Where:

- $\eta$ - Azimuthal Scatter Angle
- $\theta$ - Compton Scatter Angle

![Graph showing arbitrary counts vs. $\xi$ (deg)]

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Modulation Curve

![Graph showing modulation curve with peak amplitude and mean value labeled.]

Modulation factor: \( \mu = \frac{\text{Peak amplitude}}{\text{Mean value}} \)

Polarization: \( \Pi = \frac{\mu}{\mu_{100}} \)

where \( \mu_{100} \) is the modulation factor for 100% polarized photons.
ESRF 2011 Beam Tests
Europeam Synchrotron Radiation Facility

- Available energies at beamline:
  30 keV - ~ 500 keV
- Used energies:
  122, 200, 288, 356, 511 keV
- Minimum useful energy in 2009:
  200keV (CE 88 keV)
- Minimum energy in 2011:
  122keV (CE 39 keV)
- Beam off-axis:
  $\theta = 0^\circ, 15^\circ, 30^\circ, 45^\circ \text{ and } 60^\circ$

6 modular units, FE electronics:
- 4: PSI, built early 2011
- 1: PSI, built Nov 2011 (prototype of QM)
- 1: IHEP

Goal: assess new module capabilities, also with off-axis beam.
Data Processing Scheme

- Raw data → Backup data
- Optimized data
- Processed data
- X-talk corrected
- Energy calib.
- Cluster identif.

Corrections for:
- missing parameters,
- module interchange, etc.
- Pedestal subtraction

Comparison to MC simulations

Before merging: 1TTree / module
After merging: 1TTree for full polar

Cluster identif.
Pedestal Subtraction

- Before DAQ is started, pedestals are measured.
- For each channel, the mean of its pedestal spectrum is computed.
- The values obtained are then subtracted from the physical ADC values.
Crosstalk Correction

When the beam illuminates one bar, the signal registered in the other 63 bars can be produced either by x-talk, by the background, or by a secondary interaction of the photon when it scatters on the initial bar.

Methods:
- For each bar, consider all pairs constituted by the bar fired and each one of the other 63 bars of the target.
- This provides the probability for a bar-couple to be simultaneously active and allows to build a $64 \times 64$ matrix ($M$), called cross-talk matrix.
- The true values ($Y$) are related to the observed values ($X$) by:
  $$X = M \cdot Y$$
- The inverse of $M$, called the deconvolution matrix, allows us to retrieve the true values:
  $$Y = M^{-1} \cdot X$$
Crosstalk Correction

More in details... \( E_\gamma = 511 \text{ keV} \)

Method for crosstalk matrix:
- Draw \( pm[y]:pm[x] \) 2D histo and cut it into x-slices.
- Find max of distribution. Smooth histo with gaussian fit (below and around the max).
- Fit max of all slices with straight line.

Hypothesis:
- Crosstalk effect is dominant.
- Thick blob coming from the poor scintillator plastic resolution.
- What is below the max is essentially due to first order crosstalk.
Crosstalk Correction

Distribution of all crosstalk values

One crosstalk fit after correction

- Amount of optical crosstalk inferred from calibrated data is \(~10\text{-}15\%\).
- Residual crosstalk is of order of a few percent.
Energy Calibration

Goal: Calibrate each MAPM channel by fitting the Compton edge (CE) and get a conversion from ADC channel to keV.

Steps:
1) For each module, fit the spectra of each channel with a step-like function:

\[ f(x) = a_0 + a_1 \cdot \text{Erfc}[(x - a_2) \cdot a_3] \]

where

\[ \text{Erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t} dt \]

\(a_2\) gives the position of the CE, whose value in keV can be analytically computed.

2) Do step 1 for different energies.

3) Plot the position of the CE in ADC channel with respect to the theoretical value, for the different energies.
   Fit a line crossing 0.

4) Correct the data collected in each channel with the conversion factor given by the fit.
Energy Calibration CE Fit

Fit of the CE position of channel 63 for $E_\gamma = 511$ keV and FE 129.
Fit of the CE position of FE 129 for $E_\gamma = 511$ keV.
Energy Calibration CE Fit

Linear fit of the CE position in ADC channel wrsto CE theoretical value, for FE 129.
Computation of some Variables

We select the two largest energy hits to compute the azimuthal angle of scattering $\xi$, used in modulation curves.

Method:
- Select bar with highest E deposition.
- Look for second highest energy deposition and accept it if:
  - $E >$ threshold.
  - Minimum distance between bars $> 2$ pitches, when the 2 clusters are in the same module.
  - All 8 neighbours bars have lower E.

All variables saved in the data to ease and speed the analysis.
ESRF Data
Preliminary Results

First modulation curves...

Energy threshold 5 keV

Distribution of scattering angle ($\xi$), incoming photons energy $E_{\gamma}=356$ keV

Cuts: $2 \leq nb\, clusters \leq 3, E_{\text{dep}} < 400\, keV$
ESRF Data
Preliminary Results

Ratio of modulation curves (polarized data / unpolarized data)
Systematics effects greatly reduced

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Distribution of scattering angle ($\xi$), incoming photons energy $E_\gamma=356$ keV

Cuts: $2 \leq \text{nb clusters} \leq 3$, $E_{\text{dep}} < 400$ keV
Summary

- POLAR is a novel and compact Compton polarimeter devoted to study the prompt emission of GRBs in the energy range 50 – 500 keV.
- Successful beam test with 100% polarized synchrotron radiation in Nov 2011
- Construction and assembly of qualification model (QM) ongoing.
- **Launch** on the Chinese Spacelab TG-2 in 2014
- Lifetime: 3 years
Backup Slides
Science Goal

Answer the question:

Are most of the Gamma Ray Bursts strongly polarized?
Project Approach

- Answer a very important scientific question
- Do it simple and trustworthy
- Use proven and reliable technologies
- Do it fast keeping all quality assurance
- Describe the smallest model that is still able to do science (design modular so can be increased)
Experimental Goal

Perform first ever successful polarisation measurement of hard photons in space with high statistical significance and controlled systematic effects.
Other Physics

- If speed of light depends on polarisation (some models of quantum gravity) then polarisation get destroyed
- Polarisation of source (Crab) can be used to calibrate
ESRF 2011 Experimental Setup

- POLAR modules
- Aluminum grid
- Tilt (heavy load)
- Vertical translating stage
- X-ray beam
- (Counterweight)
- Xyz translating table (heavy load)
ESRF Data
Preliminary Results

First modulation curves...

**horizontal polarization (run 2335)**

Distribution of scattering angle ($\xi$)
Incoming photons energy $E_\gamma=356$ keV

- **Modulation factor**: $0.444 \pm 0.005$
- **Angle**: $91.000 \pm 0.022$

**vertical polarization (run 2411)**

- **Modulation factor**: $0.623 \pm 0.005$
- **Angle**: $0.000 \pm 0.012$
ESRF Data
Preliminary Results

Ratio of modulation curves (polarized data / unpolarized data)
Systematics effects greatly reduced

Distribution of scattering angle ($\xi$)
Incoming photons energy $E \gamma = 356$ keV
Distance between Hits

\[ E_\gamma = 356 \text{ keV} \]

\[ \text{dist \{isped==0 && isbad==0 && imod[0]==24 && second>0 && edepmod[0]>0 && n<10\}} \]

\begin{itemize}
  \item **htemp**
  \begin{itemize}
    \item Entries: 74379
    \item Constant: 9.361 ± 0.013
    \item Slope: -0.0874 ± 0.0005
  \end{itemize}
\end{itemize}

Mean free path 11.4 mm
Distance between Hits

$E_{\gamma} = 511$ keV

Mean free path 9.4 mm

$h_{\text{temp}}$

- Entries: 89789
- Constant: $9.768 \pm 0.012$
- Slope: $-0.106 \pm 0.031$

```
c dist (isped==0 && isbad==0 && imod[0]==24 && second==0 && edepmod[0]>0 && n<10)
```
### Background

<table>
<thead>
<tr>
<th>Source</th>
<th>Counts in modulation curve [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB</td>
<td>6453</td>
</tr>
<tr>
<td>Diffuse cosmic X-ray</td>
<td>746</td>
</tr>
<tr>
<td>Neutrons</td>
<td>47</td>
</tr>
<tr>
<td>Electrons</td>
<td>61</td>
</tr>
<tr>
<td>Protons</td>
<td>420</td>
</tr>
<tr>
<td>Positrons</td>
<td>24</td>
</tr>
<tr>
<td>Crab</td>
<td>24</td>
</tr>
<tr>
<td>S/B</td>
<td>4.97</td>
</tr>
<tr>
<td>S/√(S+B)</td>
<td>73.3</td>
</tr>
</tbody>
</table>

- X-ray albedo: cut off by space station behind (90-95%). Depending on GRB incoming angle, $\mu_{100}$ reduction of ~12%.
- Backscattering from Station: $\mu_{100}$ reduction of ~12%.