A Burst Chasing X-ray Polarimeter


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Overview

- Gamma-ray Bursts
- Time-Projection Chamber
  Photoelectric Polarimeter
- MidSTAR-2 Mission
- POET: POlarimeters for Energetic Transients
Vela Satellites launched in mid-1960s to monitor the Atmospheric Test Ban Treaty
Strange pulses discovered in 1969 by Ray Klebesadel of LANL
Data classified until 1973
Compton Gamma-Ray Observatory launched in April 1991

BATSE: 2609 bursts in 8.5 years

- Bursts are isotropic
- Frequency $\sim 1$ burst per day
- Not clear whether they are nearby or distant

SPTF: 26th-30th August 2007, San Diego
GRB Characteristics (BATSE)

- Characteristics:
  - About 1 per day
  - Powerful
    - brightest γ-ray object in sky
    - Typically $10^{51}$ ergs
  - Isotropic distribution
  - Bi-model distribution of durations
  - Unique lightcurves
  - Finite extent
Gravitational collapse of a massive star to form a Black-hole - Long bursts

Merger of two compact objects (BH-NS or NS-NS) - Short bursts

SPIE 26th -30th August 2007, San Diego
- High variability: ~ms
- Prompt Spectrum:
  - Band Function
- Huge release of energy: $10^{51}$ erg
- Relativistic process to avoid pair-production opacity paradigm
- Achromatic steepening implies GRB jet
- Explains the afterglow observations well
- Debates for prompt emission on-going
  - Internal shock model solves the rapid variability problem
  - Energy has to be extracted from KE of shells
    - Low efficiency
    - Requires additional mechanisms
Cannon balls ejected from central engine
Inverse Compton scattering of ambient light
Unclear how the cannon balls would survive acc^n over large dynamic range and Lorentz factors
GRB Unknowns

- Unknown Fire Ball content
  - Kinetic Energy or magnetically dominated
- Unknown location of where the prompt emission is produced
  - Internal Shocks - favored
  - External Shocks
- Unknown dissipation mechanism
  - Shocks
  - Magnetic reconnection
- Unknown radiation mechanism
  - Synchrotron
  - Inverse Compton
GRB Science - from Polarimetry

- Discriminating between interaction models
- Discriminating between magnetic and non-magnetic models
- Understanding XRFs, XPPs, and GRBs
- Understanding the nature of the jet
- Relationships between GRBs and other phenomena

The theories on the GRB production mechanism can be constrained by different degrees of linear polarization (P):

- \( P > 80\% \) IC with optimum view
- \( P \sim 80\% \) shock accelerated synchrotron emission or a tuned Compton-drag model
- \( 20\% < P < 60\% \) implies synchrotron emission as the dominant source of radiation or as a result of viewing the burst from just out-side the edge of the jet
- Low degrees of polarization can be expected flux with a high degree of polarization experiencing partial depolarization, e.g. electrons in a randomly orientated magnetic field
How do we measure it....?
• X-ray polarimetry will be a valuable diagnostic of high magnetic field geometry and strong gravity.....

• One definitive astrophysical measurement (1978) at two energies
  • Weisskopf et al.
  • $P=19.2\% \pm 1.0\%$
  • @ 156°
- Intericosmos (Tindo)
  - Solar Flares
- Rhessi (Coburn & Boggs)
  - GRB 021206
- BATSE Albedo Polarimetry System (Willis)
  - GRB 930131 \( P > 35\% \)
  - GRB 960924 \( P > 50\% \)
- INTEGRAL (2 groups)
  - 2\(\sigma\) result
  - 98 ± 33\%
Recent instruments have not been optimised for polarimetry…
  …or never launched
Gazillion papers describing the importance
Need a way to break the cycle
  new techniques are lowering the technical barriers
X-ray is where the photons are!

- Photoelectric effect is dominant process

Sakamoto, et al.

GRB X-ray Emission

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M.S. Longair
The photoelectron is ejected with a $\sin^2 \theta \cos^2 \phi$ distribution aligned with the E-field of the incident X-ray.

The photoelectron looses its energy with elastic and inelastic collisions creating small charge clouds.
- Polarimeter Minimum Detectable Polarization (apparent polarization arising from statistical fluctuations in unpolarized data):
  \[ MDP = \frac{1}{n_\sigma} \left( \frac{2(\varepsilon S + B)}{\mu \varepsilon S t} \right)^{1/2} \]

- Polarimeter Figure of Merit (in the signal dominated case):
  \[ FoM = \mu \sqrt{\varepsilon} \quad \text{but, systematics are important!} \]

**Challenge:** High modulation AND high QE

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• **Challenge: both good modulation and high QE**

• Ideal polarimeter is an electron track imager:
  • resolution elements < mean free path

  • **Can only begin to approach this in a gas detector**
- X-ray interacts in the gas
- K-shell photoelectron ejected
- Photoelectron creates electron cloud
- Electron cloud drifts to cathode
- Electron multiplication occurs between cathode and anode
- Charge collected at the pixel readout
Challenge: both good modulation and high QE

- Scattering mean free path $\sim 0.1\%$ X-ray absorption depth

- Electron diffusion in the drift region creates a tradeoff between QE, modulation

Ideal polarimeter is an electron track imager with:
- Resolution elements $<$ mean free path
  - $\Rightarrow$ Gas Detector
- active depth $\geq$ absorption depth
  - $\Rightarrow$ resolution elements $<$ depth$/10^3$

One Solution is TPC Polarimeter
A Time-Projection Chamber (TPC) X-ray polarimeter

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Time-Projection Chamber
Polarimeter

Charge pulses arriving at the strips

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Max depth determined only by degree of X-ray beam
Resolution is (largely) independent of the active depth
Track images formed by time-projection by binning arrival times
GEM with strip readout

The TPC Polarimeter
TPC Trade-offs

Pros

1. Potential for 100% quantum efficiency
2. Simplicity of construction
3. Geometry enables multiple instrument concepts

Cons

1. Rotationally asymmetric: requires careful control of systematic errors
2. Not focal plane imaging
Prototype TPC polarimeter

- Made from off-the-shelf components:
  - 130 μm pitch
  - 13mm(w) x 30mm(d) active area
  - 24-channel ADC
  - Drift velocity: 40 nsec bin = 130 μm
  - 460 Torr Ne:DME (50:50)

Reconstructed 6.4 keV track images

SPE 26th-30th August 2007, San Diego
Prototype TPC Polarimeter Results

<table>
<thead>
<tr>
<th>Polarization Phase</th>
<th>Measured Parameters</th>
<th>$\chi^2$</th>
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<tbody>
<tr>
<td></td>
<td>Modulation (%)</td>
<td>Phase (degrees)</td>
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<tr>
<td>unpolarized</td>
<td>0.49 ± 0.54</td>
<td>44.6 ± 28.7</td>
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<tr>
<td>0°</td>
<td>45.0 ± 1.1</td>
<td>0.3 ± 0.6</td>
</tr>
<tr>
<td>45°</td>
<td>45.3 ± 1.1</td>
<td>45.2 ± 0.6</td>
</tr>
<tr>
<td>90°</td>
<td>44.7 ± 1.1</td>
<td>-89.9 ± 0.6</td>
</tr>
</tbody>
</table>

- Uniform response
- Modulation consistent with gas pixel detectors
- Unit QE possible

$^{56}$Fe unpolarized

6.5 keV polarized

Polarized 6.4 keV at 0°

Polarized 6.4 keV at 45°

Polarized 6.4 keV at 90°

Black et al, submitted to NIM A
Wide field-of-view GRB polarimeter

Enables large volume detectors with wide field of view
MidSTAR-2

- USNA Project
- High risk Low-cost
- Make a scientific measurement
  - Several GRBs in 2 yr lifetime
- Low cost proof-of-concept
- Launch ~2011
Area: 144 cm²
Depth: 5 cm
FoV: 1 steradian
Gas: Ne:CO₂:CS₂
Pressure: 1 atm

MDP averaged from 2 - 10 keV
The GRBP:
A payload for MidStar 2

- MidStar offers dual opportunities:
  - Space qualify a new technology
  - Measure the polarization of several Gamma-Ray bursts

- Proposed experiment is sized:
  - To provide an excellent chance of qualifying technology
  - To provide reasonable chance of exciting scientific result
POET: POLarimeters for ENergetic TRANSients

- UNH - PI Mark McConnell
- UNH - GRAPE:
  - 50-300 keV
  - Compton Scatter
- USRA/GSFC - LEP:
  - 2-10 keV
  - Photoelectric
- USRA/GSFC - MEP:
  - 15-30 keV
  - Photoelectric

SPIE 26th -30th August 2007, San Diego
Mission Statement: only

First definitive high E polarization measurements of transient sources.
> 50 transient sources/year
  Broadband Polarimetry
  Broadband Spectra: 2-300 keV
  Rapid Timing: msec
  Position: 3 deg

Sources: GRBs, Solar Flares, Magnetar Super Flares, SGRs.
Dual band polarization measurements of bright persistent sources.

What is the composition of GRBs?
What is the prompt emission radiation mechanism?
What is the small-scale geometry of the prompt emission region?
Theories on the GRB production mechanism can be constrained by different degrees of linear polarization (P):

- $P > 80\%$ IC with optimum view.
- $P \approx 80\%$ shock accelerated synchrotron emission or a tuned Compton-drag model.
- $20\% < P < 60\%$ synchrotron emission is the dominant source of radiation or viewing the burst from just out-side the edge of the jet.
- Low degrees of polarization: flux with a high degree of polarization experiencing partial depolarization, e.g. electrons in a randomly orientated magnetic field.

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<tr>
<th></th>
<th>LEP</th>
<th>GRAPE</th>
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<tbody>
<tr>
<td>GRBs</td>
<td>MDP</td>
<td>GRBs</td>
</tr>
<tr>
<td>21</td>
<td>10%</td>
<td>12</td>
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<tr>
<td>60</td>
<td>30%</td>
<td>86</td>
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<td>72</td>
<td>50%</td>
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Further Work

- In-situ drift velocity calibration and monitoring
  - Feedback into algorithm
  - On-orbit
- Large area GEMs
- Background simulations
  - X-rays
  - Charged-particles
Future looks bright for X-ray Polarimetry!!!