A Burst Chasing X-ray Polarimeter

Joe Hill

Astrophysics Science Division
NASA/Goddard Space Flight Center
Overview

- Science Drivers for GRB Polarimetry
- Small pixel CCD Polarimeters
- Micropattern Gas Polarimeters
- Time-Projection Photoelectric Polarimeter
- Prototype Results
- Plans for the Future
Context

- X-ray polarimetry will be a valuable diagnostic of high magnetic field geometry and strong gravity

- Only one definitive astrophysical measurement (1978)
What are GRBs?

- Discovered in 1967 by the Vela Satellites
- Data classified until 1973
- 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
**Observed Prompt Properties**

- High variability: \( \sim \) ms
- Prompt Spectrum:
  - Band Function \( \alpha \approx -1 \pm 1 \quad \beta \approx 2^{+1}_{-2} \)
  - Huge release of energy: \( 10^{51} \) erg
  - Relativistic process to avoid pair-production opacity paradigm
  - Achromatic steepening implies GRB jet

![Graph showing energy distribution](image)

\[
\begin{align*}
E_0 &= E_{\text{peak}} / (2 + \alpha) \\
E^\alpha \exp(-E/E_0) \\
E_{\text{break}} &= (\alpha - \beta) E_0
\end{align*}
\]
Standard Fireball Model

- 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

---

Diagram of a fireball model with labels for core collapse SNe, GRB central engine, NS-NS Merger, internal shock, external shock, ISM, prompt emission, and afterglow. Graph showing observed polarization vs. spectral index.
Cannon-ball model

- Cannon balls ejected from central engine
- Inverse Compton scattering of ambient light
- Unclear how the cannon balls would survive acc\textsuperscript{n} over large dynamic range and Lorentz factors
Motivation

- Discriminating between emission models
- Discriminating between central engine models
- Proof of Jet structure
- Proof of technology concept for larger missions
The theories on the GRB production mechanism can be constrained by different degrees of linear polarization (P):

- $P > 80\%$: IC with optimum view
- $P < 80\%$: 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 outside 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....?
The Experimental Landscape
An Overview of Development Efforts

**Dedicated Polarimeters:**
- Thompson Scattering
- Bragg Scattering (SXR)
- Small Pixel CCDs
- Gas Pixel Detectors
- Dichroic Materials
- TPCs

**Advanced Compton Telescopes:**
- Numerous technical approaches
- All have good polarization sensitivity
- TPCs a component in some

**X-ray**
- Soft $\gamma$
- Medium $\gamma$
- Hard $\gamma$

**Cross section in Ar (arb)**

**Pair (and triplet) Telescopes:**
- Next generation soon to launch
- No polarization sensitivity
- Only notion for polarimetry w/TPCs

**Photon Energy (MeV)**

J.K. Black, Journal of Physics: Conference series, to be published
GRB X-ray emission

- X-ray is where the photons are
- Photoelectric effect is dominant process
The Photoelectric Effect

- 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 loses its energy with elastic and inelastic collisions creating small charge clouds.
Photoelectric Polarimetry

- Capitalizes on: correlation between the X-ray electric field vector and the photoelectron emission direction:

\[
\frac{\partial \sigma}{\partial \Omega} = r_0^2 \frac{Z^5}{137^4} \left( \frac{mc^2}{h\nu} \right)^{7/2} \frac{4\sqrt{2} \sin^2(\theta)\cos^2(\phi)}{(1 - \beta \cos(\theta))^4}
\]

- Fit function to the angular distribution:

\[
N(\phi) = A + B \cos^2(\phi + \phi_{pol})
\]

- Modulation Factor, \( \mu \):

\[
\mu = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}} = \frac{B}{2A + B}
\]

Kaaret et al
Rotation Angle (degrees)
Polarimeter Figure of Merit

- Polarimeter Minimum Detectable Polarization (apparent polarization arising from statistical fluctuations in unpolarized data):

\[ MDP = \frac{1}{\mu \varepsilon} \frac{n_\sigma}{S} \left( \frac{2(\varepsilon S + B)}{t} \right)^{\frac{1}{2}} \]

- 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
Small Pixel CCD Polarimeters

- Quantum Efficiency (fraction)
- Maximum Photoelectron Range (μm)
- Incident X-ray Energy (keV)
- Observing Time (Seconds)
- X-ray Intensity (2 keV / (keV cm^2 sec))
Polarimeter Requirements

- 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
Micropattern Gas Polarimeter

- 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
Gas Micropattern Polarimeter Results

1 atm 50:50 Ne:DME

Polarized 5.41 keV
μ = 51.1 +/- 0.9%

Unpolarized 5.9 keV
μ = 0.05 +/- 1.47%

Bellazzini, SPIE, 2006
Gas Micropattern Polarimeter Results

- High Modulation
- Limited QE:
  - requires XEUS Optics

Bellazzini, SPIE, 2006
Polarimeter Requirements

- 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 quantum efficiency, modulation
- Ideal polarimeter is an electron track imager with:
  - resolution elements $<$ mean free path
  - 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
Time-Projection Chamber Polarimeter

Charge pulses arriving at the strips

Strip anode
Drift Direction (y)

Drift Electrode

\( \sin^2(\theta) \cos^2(\varphi) \) probability distribution

End point
Interaction point

Strip Number (130 microns)

Time Bin (40 ns)

NASA
Joint Physics/Space Physics Seminar
University of Iowa: 6th March 2007
The TPC Polarimeter

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

Black et al, submitted to NIM A
Trade-offs in a TPC polarimeter

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

The TPC polarimeter measures the orthogonal coordinates in fundamentally different ways, making it rotationally asymmetric. Care is required to prevent the high statistical sensitivity from being lost to systematic errors.
Prototype TPC polarimeter

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

Reconstructed 6.4 keV track images
Prototype TPC Polarimeter Results

<table>
<thead>
<tr>
<th>Polarization Phase</th>
<th>Measured Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modulation (%)</td>
<td>Phase (degrees)</td>
</tr>
<tr>
<td>unpolarized</td>
<td>0.49 ± 0.54</td>
<td>44.6 ± 28.7</td>
</tr>
<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
- No false modulation
- Modulation consistent with gas pixel detectors
- Unit QE possible
**TPC Spectral Response**

- Spectral response from the cathode (or strip electrode)
- Typical proportional counter resolution

Cathode $^{55}$Fe Spectrum

$\Delta E/E = \sim 22\%$
Wide field-of-view GRB polarimeter

Enables large volume detectors with wide of view
GRB X-ray Polarimeter

- Make a scientific measurement
- Multiple band pass possible
- Low cost proof-of-concept:
  - Measure the expected high levels (10-80%) of polarization of very bright GRBs
GRB Polarimeter:
MoO
Midex/Smex

Area: 35 x 35 cm²
Depth: 30 cm
FoV: 1 steradian
Low E: Ne CS₂
High E: Ar CS₂

Polarization averaged over energy band

Number of bursts in a year

<table>
<thead>
<tr>
<th>MDP(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>35</td>
</tr>
<tr>
<td>40</td>
</tr>
</tbody>
</table>

20% < P < 60%: Synchrotron emission

P ~ 10%: Partial depolarization from randomly oriented B-fields

P ~ 80%: Shock Accelerated Synchrotron or tuned Compton Drag model

2-10 keV
15-50 keV
The GRBP: A payload for MidStar 2

Area: See plot
Depth: 5 cm
FoV: 1 steradian
Gas 50:50 Ne:DME
Pressure: 1 atm

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

- MidStar offers dual opportunities:
  - Space qualify an exciting 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
Further Work

- In-situ drift velocity calibration and monitoring
  - In the lab (rapid turn-a-round)
  - On-orbit
- GEM configuration
  - Alignment
  - Mounting
- Large area GEMs
- Background simulations
  - X-rays
  - Charged-particles
"The Day in the Life of a Scientist": An interactive experience

- Build a gas chamber based on TPC design
  - 12"x12"x12" transparent chamber
- Provide hands on experience for visitors
  - Show how tracks differ for Cosmic-rays, Alpha-particles and Beta-particles and X-rays
  - Will show different properties of radiation
  - Demonstrate different stopping materials for the different radiation
Other Applications
Polarimetry Prospects in X-ray Astronomy (1 keV-100 keV)

- Remains the only largely unexploited tool
  - Instruments have not been sensitive enough warrant investment
  - Two unambiguous measurements of one source (Crab nebula) at 2.6 and 5.2 keV
  - Best chance for pathfinder (SXRP on Spectrum-X I mission ~1993) never flew

- Interest and development efforts have exploded in the last 10 years
  - As other observational techniques have matured, need for polarimetry has become more apparent
  - Controversial polarization measurements for GRBs and solar flares
  - New techniques are lowering the technical barriers
Polarization addresses fundamental physics and astrophysics

- How important is particle acceleration in supernova remnants?
- How is energy extracted from gas flowing into black holes?
- Does General Relativity predict gravity’s effect on polarization?

- What is the history of the black hole at the center of the galaxy?
- What happens to gas near accreting neutron stars?
- Do magnetars show polarization of the vacuum?
High Efficiency TPC polarimeters for X-ray Telescopes

- High efficiency enables sensitive observations of extragalactic sources, even in a small mission.
- Adjustable optical depth allows TPC to be used in conjunction with focal plane instrument in a large multi-purpose mission.

Jahoda et al, 2007
High Efficiency TPC polarimeters for X-ray Telescopes

TPC polarimetry enables measurements of low levels of polarization (<10%) of faint objects, e.g. AGN, with a small mission.
Modulation Collimator Imaging Polarimeter for Solar Flares

- Rotation Modulation Collimator provides few arcsecond imaging of extended sources with a non-imaging detector.

Dennis et al.

Figure 5.6. A simplified diagram of the magnetic structure and radiation emission sites of a solar flare (Phillips 1992).
Future looks bright for X-ray Polarimetry!!!