PoET: Polarimeters for Energetic Transients

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Scott Barthelmy (GSFC)
Joe Hill (USRA)
POET Science Team

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Overview

- GRB Polarimetry Science
- POET mission
  - GRAPE
  - LEP
- POET Performance
- What Now?
Quest for the holy grail

- 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% ± 1.0%
  - @ 156°
Other Measurements

- Intercosmos (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
  - $98 \pm 33\%$

Willis et al. 2005
Current Status

- 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 have lowered the technical barriers
**Observed Prompt GRB Properties**

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

\[ dN/dE = E^\alpha \exp \left(-E/E_0\right) \]
\[ E_0 = E_{\text{peak}} / (2 + \alpha) \]
\[ E_{\text{break}} = (\alpha - \beta) E_0 \]
Standard Fireball Model

- Explains the late 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

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**Synchrotron Emission**

Dar et al., 2006
Cannon-ball model

Cannon balls ejected from central engine
Inverse Compton scattering of ambient photons
Unclear how the cannon balls would survive acc
over large dynamic range and Lorentz factors

Dar et al, 2006
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
  - Comptonization
  - Etc
Motivation for POET

- What is the magnetic structure of the jets?
- What is the geometric structure of GRB jets?
- What is the prompt radiation mechanism of GRBs?

Physical Model

Geometric model

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

- **P~80%** Generally difficult to achieve within synchrotron emission models. Could be Compton scattering jet viewed from outside the edge of the jet

- **20%<P<60%** is predicted if synchrotron emission in an ordered B-field or as a result of viewing the burst from near the edge of the jet

- **Low degrees of polarization** can be expected from hydrodynamical models in which the random magnetic fields are generated in the shocks with an on-beam viewing geometry
POET - Proposed SMEX Mission

POET - POlarimeters for Energetic Transients

Institutional Responsibilities

University of New Hampshire
- PI: Mark McConnell
- GRAPE Instrument

Universities Space Research Association
- Deputy PI: Joanne Hill
- LEP Instrument

Goddard Space Flight Center
- Mission Scientist: Scott Barthelmy
- Mission Operations Center (MOC)
- POET Data Center (PDC)
- Data Archive (HEASARC)

Charles S. Draper Laboratory
- Project Management
- Mission and Systems Engineering
- Safety and Mission Assurance

ATK Space, Inc
- Spacecraft Bus
- Observatory Integration and Test
POET GRB Science

POET will answer questions about GRBs that can only be answered by X-ray and Gamma-ray polarisation measurements

- What is the composition of GRBs?
- What is the prompt radiation mechanism?
- What is the small-scale geometry of the prompt emission region?
POET Characteristics
POET Characteristics

Sakamoto, et al.
# POET Instrument Suite

## LEP Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarimetry</td>
<td>2-15 keV</td>
</tr>
<tr>
<td>Detectors</td>
<td>Ne:CO₂:CH₃NO₂ Gas (8)</td>
</tr>
<tr>
<td>Spectroscopy</td>
<td>2-15 keV</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>±44° (non-imaging)</td>
</tr>
</tbody>
</table>

## GRAPE Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarimetry</td>
<td>60-500 keV</td>
</tr>
<tr>
<td>Detectors</td>
<td>BGO/plastic scintillator (62)</td>
</tr>
<tr>
<td>Spectroscopy</td>
<td>15 keV - 1 MeV</td>
</tr>
<tr>
<td>Detectors</td>
<td>NaI(Tl) scintillator (2)</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>±60° (non-imaging)</td>
</tr>
</tbody>
</table>
X-ray and Gamma-ray Polarimeters

- **Capitalize on**: correlation between the incident photon electric field vector and the photoelectron emission direction or scattered photon direction

- Fit function to the angular distribution

- **Modulation Factor, \( \mu \):**

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

Based on use of flat panel PMT.
Grape Performance

- $\mu = 33\% @ 69$ keV
- $\mu = 44\% @ 129$ keV
- Wide FoV and off-axis uniformity
GRAPE Engineering Balloon Flight

Balloon flight of an engineering prototype on June 21, 2007.

Measured background with (preliminary) simulated background.

27th June 2008
2008 Nanjing GRB Conference
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

**good modulation and high QE**

Black et al, NIM A, 2007
Prototype TPC Polarimeter Results

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

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

Wide FoV Prototype

- Active Element: Ne:CO$_2$:CH$_3$NO$_2$
- Active Volume: 24 x 24 x 24 cm$^3$
- Pressure: 780 Torr
- Energy Range: 2-15 keV
- Energy Resolution: 38% at 6keV
- $\mu$ @ 6 keV: 45%
- Field of View: ±44°
- Mass: 28.5 kg
- Power (peak/ave): 33/31 W
- Data Volume: 248 MB/day
- Temperature Range: 25 ± 1°C / -10 to 50 °C
- Peak Sensitivity: ~3.5 keV
Wide FoV Prototype

Spectra: Ne:CO$_2$

Spectra: Ne:CO$_2$:CH$_3$NO$_2$
Mission Concept

Mission Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date</td>
<td>May, 2012</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Standard SMEX</td>
</tr>
<tr>
<td>Orbit</td>
<td>600 km, 28.5° incl.</td>
</tr>
<tr>
<td>Mission Lifetime</td>
<td>2+ years</td>
</tr>
<tr>
<td>Pointing Mode</td>
<td>Zenith-pointed</td>
</tr>
<tr>
<td>Spin Rate</td>
<td>15 rpm</td>
</tr>
</tbody>
</table>

27th June 2008
POET Spacecraft
### POET Performance

#### # GRBs S/N>5

<table>
<thead>
<tr>
<th></th>
<th># GRBs Ep</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>99% &lt;10keV 20%</td>
</tr>
<tr>
<td>GRAPE</td>
<td>80% &lt;20 keV 50%</td>
</tr>
<tr>
<td>LEP+GRAPE</td>
<td>78% 0.2-1 MeV ~100%</td>
</tr>
</tbody>
</table>
Distinguish GRB Models

- Physical Models:
  - Ordered B-field
  - Synchrotron Emission

- Geometric Models:
  - Optimum viewing factor
  - Synchrotron Emission
  - Random B-field
  - Compton Drag

Graphs show the distribution of $\Pi$ (percentage) at different energy levels ($E_{\text{obs}}$ in keV) for SO, SR, and CD models.
What is the GRB radiation mechanism?

GRAPE and LEP will independently measure $\Pi$ above and below $E_{\text{peak}}$

<table>
<thead>
<tr>
<th>LEP</th>
<th>GRAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRBs</td>
<td>MDP</td>
</tr>
<tr>
<td>8</td>
<td>10%</td>
</tr>
<tr>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>*72</td>
<td>50%</td>
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POET was not selected for Phase A so now what?.....

- Improve readiness of GRAPE
  - Balloon flight
- Improve readiness of LEP
  - MidSTAR-2 GRBP (~2011)
  - GEMS in Phase-A (Gravity and Extreme Magnetism SMEX)
- Look for new opportunities
  - e.g. Space Station
The GRBP: A payload for MidStar 2

Area: 144 cm²
Depth: 5 cm
FoV: 1 steradian
Gas: Ne:CO₂:CS₂
Pressure: 1 atm

MDP averaged from 2 - 10 keV
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
Prototype Detector Design

Prototype chamber

HV Power Supplies
(mBAT - Mini BAT 1/8 scale)

**mBAT Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>15-150 keV</td>
</tr>
<tr>
<td>FoV</td>
<td>~2 str partial coding</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>~3 arcmin</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>~7 keV</td>
</tr>
<tr>
<td>Position Notice</td>
<td>~4 arcmin in 20 sec</td>
</tr>
</tbody>
</table>
Solar Flare Science

- How does the Sun release such large quantities of energy in a Solar Flare?
- How does the Sun accelerate electrons and ions with such high efficiency?
- POET will determine the angular beaming of electrons.
- Polarimetry measures the electron beaming.
- Models predict 20-30% polarization.

<table>
<thead>
<tr>
<th>Energy Band (keV)</th>
<th>23 July 2002 (X4.8) $\Delta t = 60$ s</th>
<th>M5 flare $\Delta t = 300$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-500</td>
<td>2.3%</td>
<td>27%</td>
</tr>
<tr>
<td>50-100</td>
<td>3.6%</td>
<td>43%</td>
</tr>
<tr>
<td>100-200</td>
<td>3.4%</td>
<td>40%</td>
</tr>
<tr>
<td>200-500</td>
<td>4.9%</td>
<td>62%</td>
</tr>
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GRAPE will measure polarization direction and magnitude of Solar Flares to answer these questions.
Pulsar Science

X-ray polarimetry is the only way to distinguish between the two leading models of accretion flow onto highly magnetized neutron stars.

Intensity (top), polarization position angle (middle) and degree of polarization (bottom) vs. phase predicted by different models for the Crab pulsar. All reproduce the intensity profile. Only polarization measurements can uniquely differentiate between models.

<table>
<thead>
<tr>
<th></th>
<th>LEP (2-10 keV)</th>
<th>MDP in 10 ksec</th>
<th>MDP in 1ksec</th>
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</thead>
<tbody>
<tr>
<td>CRAB</td>
<td>4%</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>1/10 CRAB</td>
<td>8%</td>
<td>15%</td>
<td></td>
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