An Overview of High Energy Astronomical Polarimetry

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Outline

• Introduction
  o Low Energy Scattering Polarimeters
  o Photoelectric Polarimeters
  o Compton Polarimeters
  o Pair Polarimeters

• History of High Energy Astrophysical Polarimetry
  o Sounding Rocket
  o OSO-8
  o Integral/GAP etc

• Future of High Energy Astrophysical Polarimetry
  o IXPE/XIPE
  o GRAPE/LEAP
  o AdEPT
What Does Polarization Tell Us?

- Of all the observables for any photon, only the $E$-field orientation is asymmetric with respect to photon trajectory
  - Polarization measures geometry
  - Very few celestial sources are truly round, but few can be imaged directly: polarization provides a means to see geometry on length scales orders of magnitude smaller than imaging can probe

- Polarization is a probe of exotic physics: Strong fields
  - GR predicts bending of light – and thus alters the polarization vector
  - Bending dependent on energy, so energy dependent effects are expected

- Polarization magnitude depends on interactions with matter

- Cosmic Polarimetry from Micro to Macro Scales
Polarimetry Techniques

**Dedicated Polarimeters:**
- Ultra-low-Z scattering
- Photoelectric:
  - Gas Pixel Detectors (2001-)
  - Dichroic Materials (2006-)
  - TPCs (2006-)

**Dedicated Compton Polarimeters:**
- Low-Z converter, High-Z absorber (lower E)
- High-Z converter, absorber (higher E)
- Numerous development efforts

**Advanced Compton Telescopes:**
- Numerous technical approaches
- All have good polarization sensitivity

**Pair (and triplet) Telescopes:**
- Next generation soon to launch, but with no polarization sensitivity
- Only concept for polarimetry is with TPCs

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**Graph:**
- Plot of photon energy (MeV) vs. cross section in Arb.
- Light lines:
  - photoelectric
  - Compton
  - triplet production
  - pair production
- Dark line:
  - Soft X-ray
  - Hard X-ray
  - Soft γ
  - Hard γ

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*Cosmic Polarimetry from Micro to Macro Scales*
Low Energy Scattering Polarimeters

- Requires scattering material surrounded by X-ray detectors to detect the scattered photon
- Measure the variation of the counts in the detectors
- Bragg Crystal (2.6 keV & 5.2 keV)
  - 100% response
  - Limited energy range
  - Rotation required
- Thomson (2-15 keV)
  - Systematic effects need careful calibration
  - Rotation Required

Analyzing power: \[ \mu = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}} \]
Photoelectric Polarimeters

Broad Band Capability – High Efficiency, Modulation <100% due to detector limitations
Simultaneous Spectroscopy and Imaging (depending on implementation e.g. IXPE)

- As a result of an X-ray interaction, the photoelectron is ejected preferentially in the direction of the electric field
  - $sin^2 \theta cos^2 \phi$ distribution
  - intrinsic modulation factor $\mu = 1$

Analyzing power $\mu = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}}$

Cosmic Polarimetry from Micro to Macro Scales
Imaging Photoelectric Polarimeters

- Gas Detectors using low z gas as the detector medium
- Images the photoelectron track
- Gas Electron Multiplier to multiply the signal
- Detect on an charge sensitive ASIC with hexagonal pixels

Muleri 2014
Photoelectric Time Projection Chamber Polarimeters

- Design maximizes quantum efficiency with no polarization sensitivity loss
- A time-projection technique creates pixel images from a 1-d readout
- Drift distance (hence diffusion) largely independent of active depth
Compton Polarimeters

- 30-300 keV: Low z scattering elements (plastic scintillator) with high-z photon absorbers e.g. CsI
- 300-10 MeV: High z scattering elements are viable
- Photon scatters preferentially perpendicularly to the E-field vector
• The pair plane preferentially in the direction of the E-field
• $M \sim 10$-$30\%$
• Inhibited by multiple scatters of the electron-position pair
• Accurate measurements of the pair plane must be made within $<10^{-2}$ radiation lengths
• Required radiation length to resolution ratio can only be obtained in a gas
Development Challenges

• Stopping photons – Quantum Efficiency
  o Deep, dense detector mediums

• Maximizing polarization signal – Modulation Factor
  o Sometimes requires less dense material

• Systematic effects in the detector –
  o Well-calibrated detectors
  o Well-understood models
  o High statistics required for sensitive detector

• Background – Magnitude and systematic effects
  o Detailed models e.g. GEANT, Penelope etc.
  o Understanding of on-orbit effects

Minimum Detectable Polarization: \[ MDP = \frac{n_\alpha}{\mu_{100}} \sqrt{\frac{(F_s \varepsilon A_{eff} + B)T}{F_s \varepsilon A_{eff}T}} \]
History (2-10 keV)

- Observations of astrophysical X-ray polarization began with sounding rockets in 1971
  - Bragg Crystal Polarimeter
- Continued with OSO-8 (mid 1970s), obtaining measurements of the Crab Nebula and upper limits on other sources
  - Bragg Crystal Polarimeter
- SXRP built in 1990s but not flown
  - Bragg/Thomson Polarimeter
- GEMS selected (2010), not confirmed
  - Photoelectric Time Projection Polarimeter
- IXPE selected 2017 for launch in 2020
  - Photoelectric Imaging Polarimeter
History (2-10 keV)

- One definitive astrophysical measurement of the Crab (1978) at two energies (2.6 & 5.2 keV)
  - Weisskopf et al. e.g. P=19.2% ±1.0% @ 156°
- Progress since then inhibited by:
  - Systematic errors in non-optimised instruments
  - Low sensitivity (QE & Modulation Factor)
Hard X-ray History

- IKARUS/GAP (70-300 keV)
- The only purpose built hard X-ray polarimeter to fly in space
- Compton polarimeter 12 CsI scintillators surround a single plastic scintillator
Hard X-ray History

- **Intercosmos 11 (Tindo, 1970’s)**
  - Thomson scattering (15 keV) in Kr & CH$_4$, Solar Flares

- **Rhessi (Coburn & Boggs, Rutledge & Fox)**
  - Compton scattering in nine Germanium detectors, GRB

- **BATSE Albedo Polarimetry System (Willis)**
  - Used Earth albedo as a scatter for two GRBs

- **INTEGRAL-IBIS (Gotz)**
  - CdTe & CsI, Multiple Scatters
  - Crab Pulsar/Nebula & GRBs

- **INTEGRAL-SPI**
  - Multiple Events
  - Ge Detectors
  - Cyg-X-1, GRBs

- **Ikaros- GAP**
  - Yonetoku
  - Compton Polarimeter
  - 12 CsI Scintillators

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Kalemci et al., 2004

Willis et al. 2005
Transient Hard X-ray Measurements: Results to Date

Several results suggest very high polarization levels, but all are of limited statistical significance.

<table>
<thead>
<tr>
<th>Event</th>
<th>Mission</th>
<th>Energy (keV)</th>
<th>Result</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 930131</td>
<td>CGRO/BATSE</td>
<td>20 - 1000</td>
<td>(35-100%)</td>
<td>Willis et al. (2005)</td>
</tr>
<tr>
<td>GRB 960924</td>
<td>CGRO/BATSE</td>
<td>20 - 1000</td>
<td>(50-100%)</td>
<td>Willis et al. (2005)</td>
</tr>
<tr>
<td>GRB 021206</td>
<td>RHESSI</td>
<td>150 - 2000</td>
<td>80% ± 20%</td>
<td>Coburn &amp; Boggs (2003)*</td>
</tr>
<tr>
<td>GRB 041219a</td>
<td>INTEGRAL/SPI</td>
<td>100 - 350</td>
<td>98% ± 33%</td>
<td>Kalemci et al. (2007)</td>
</tr>
<tr>
<td>GRB 041219a</td>
<td>INTEGRAL/SPI</td>
<td>100 - 350</td>
<td>96% ± 40%</td>
<td>McGlynn et al. (2007)</td>
</tr>
<tr>
<td>GRB 041219a</td>
<td>INTEGRAL/IBIS</td>
<td>200 - 800</td>
<td>43% ± 25%</td>
<td>Götz et al. (2009)</td>
</tr>
<tr>
<td>GRB 061122</td>
<td>INTEGRAL/IBIS</td>
<td>250 - 800</td>
<td>&gt; 60%</td>
<td>Götz et al. (2013)</td>
</tr>
<tr>
<td>GRB 100826a</td>
<td>IKAROS/GAP</td>
<td>70 - 300</td>
<td>27% ± 11% (variable PA)</td>
<td>Yonetoku et al. (2011)</td>
</tr>
<tr>
<td>GRB 110301a</td>
<td>IKAROS/GAP</td>
<td>70 - 300</td>
<td>70% ± 22%</td>
<td>Yonetoku et al. (2012)</td>
</tr>
<tr>
<td>GRB 110721a</td>
<td>IKAROS/GAP</td>
<td>70 - 300</td>
<td>80% ± 22%</td>
<td>Yonetoku et al. (2012)</td>
</tr>
<tr>
<td>GRB 140206a</td>
<td>INTEGRAL/IBIS</td>
<td>200 - 800</td>
<td>&gt; 48%</td>
<td>Götz et al. (2014)</td>
</tr>
</tbody>
</table>

*Note the result was challenged (Rutledge & Fox, Wigger)
IXPE is 100 times more efficient than the original polarimeter that measured the Crab
See Gunji-san’s talk tomorrow afternoon

- He/DME (20/80) @ 1 atm
- Energy range 2-8 keV
- <30” half-power diameter
- 11’ Field of View

Weisskopf, 2016
Compton Polarimetry with GRAPE/LEAP

Large Area Burst Polarimeter for the ISS proposed in 2016 as a MOO
Designed to measure transient events (Gunji-san)

The LEAP instrument design is based on GRAPE balloon payload developed at UNH
- Wide FoV Compton Polarimeter
- 50-500 keV Polarimetry
- 20-5000 keV spectroscopy
LEAP Performance

LEAP instrument consists of 9 independent polarimeter modules

Number of GRBs Detected in 2 Years

<table>
<thead>
<tr>
<th></th>
<th>N &lt; 5% MDP</th>
<th>N &lt; 10% MDP</th>
<th>N &lt; 15% MDP</th>
<th>N &lt; 20% MDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Bckgd (4.0 cts/s/ cm²)</td>
<td>9</td>
<td>25</td>
<td>41</td>
<td>56</td>
</tr>
<tr>
<td>Low Bckgd (2.6 cts/s/ cm²)</td>
<td>10</td>
<td>31</td>
<td>51</td>
<td>68</td>
</tr>
</tbody>
</table>

Polarizations expected from different Gamma-ray Burst Models

- SO Model Synchrotron w/ Ordered B-Field
- SR Model Synchrotron w/ Random B-Field
- CD Model Compton Drag w/ Random B-Field
AdEPT Pair Polarimeter

Advanced Energetic Pair Telescope – In development, Hunter et al.

- Large Volume Gas Time Projection Chamber
- 3D Track Imager – Image the ionization trail from the positron-electron pair
  - TPC with 2D microwell readout
  - Negative ion drift
- Optimized for 2-500 MeV polarization
  - ~8 m³, Argon at 1.5 atm
  - Isotropic performance, 2π sr FOV
  - MDP< 10% for 10 mCrab sources
  - $\theta_{68} = 0.7^\circ$ at 67.5 MeV
  - Sensitivity < 3 x 10^{-6} MeV cm^{-2} s^{-1}
- Expect peak power output in the MeV range
• Optimizing for polarization also optimizes for angular resolution
• AdEPT will achieve angular resolution approaching the best allowed by the physics, i.e. equivalent of “diffraction limited” seeing!
• AdEPT \( \theta_{68} \) is \(~10\) times better than Fermi at 67.5 MeV, \( \approx \) to Fermi at \(~0.8\) GeV

Hunter et al., Astroparticle Physics 59, 18-28 (2014)
Summary

• This brief overview captures only a few of the many areas of development
• Upcoming talks with details of other polarimeter developments
• The future is bright for polarimetry
  o Developments at multiple wavelengths
  o Developments for both faint persistent sources
  o And Bright transient Sources
  o One mission selected in the 2-10 keV bandpass will launch in 2020