An Overview of X-ray Polarimetry of Astronomical Sources

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Outline

- A look to the past
  - Experimental techniques
- Electron tracking
- IXPE the mission
- IXPE the science
Why is polarization useful?

- The degree of polarization and the “position angle” depend on the conditions under which the X-rays are produced.
- Thus modeling of what we see must also predict the degree of polarization and the position angle.
In the beginning

- July 1968 – Lithium-block, “Thomson”-scattering polarimeter flown on an Aerobee -150 rocket
  - Target was the brightest X-ray source Sco X-1

Fig. 1. (a) Schematic representation of the polarimeter concept. (b) Mounting of the polarimeter and ancillary equipment in the rocket.
Scattering polarimeter

- Thomson cross-section approximates the angular dependence

\[
d\sigma / d\Omega = (e^2 / mc^2)^2 (\cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi)
\]

- From bound electrons one must account for both coherent and incoherent scattering and photoelectric absorption

\[
\frac{d\sigma_{\text{coh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi \rangle |F|^2
\]

\[
\frac{d\sigma_{\text{incoh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi \rangle I
\]
Thompson approximation

Cos (polar scattering angle)

Azimuthal scattering angle
Considerations

- Minimize the background
- Achieve as large a sensitivity to polarization as possible
  - Optimize the “MDP” at the 99% confidence level

\[
MDP_{99}(\%) = \left(\frac{4.29 \times 10^4}{M(\%)}\right) \sqrt{(R_S + R_B) / \sqrt{R_S^2 t}}
\]

- \( MDP \) is the degree of polarization detected at the 99% confidence independent of the position angle
- \( M \) is the modulation from a 100% polarized beam with \( R_B = 0 \)
Rocket 17.09 (1971)

- Two instruments in one payload!
  - Lithium scattering polarimeter
  - 4 Bragg crystal polarimeters
• 1971 Aerobee 350
  • Crab detection!
    • $P = 15\% \pm 5\%$
    • $\varphi = 156 \pm 10^\circ$
Crystal polarimeters on OSO-8

- 1975 OSO-8 crystal polarimeter
- Precision measurement of integrated emission from the Crab Nebula polarization at 2.6 keV
  - $P = 19\% \pm 1\%$
  - $\phi = 156 \pm 2^\circ$ (NNE)
Compare to detailed optical results

Next came the Stellar X-ray Polarimeter (SXRP)

• Planned to fly on the Russian Spectrum-X Gamma Mission in the early 1990s

• Soviet Union Collapsed --- never launched
The direction of the *initial* K-shell photoelectron is determined by the electric vector and the direction of the incoming photon.

\[
\frac{d\sigma}{d\Omega} = f(\xi) r_0^2 Z^5 \alpha_0^4 \left( \frac{mc^2}{h\nu} \right)^{7/2} 4\sqrt{2} \sin^2 \theta \cos^2 \phi
\]

- **Optical Imaging Chamber**
  - Austin & Ramsey 1992

- **Pixelated Gas Multiplication**
  - Costa et al. 2001

- **Time Projection Chamber**
  - Black et al. 2007
Site of initial ionization and Auger electron cloud produced by a 54 keV photon in a mixture of argon (90%), methane (5%), and trimethylamine (5%) at two atmospheres.
Imaging X-ray Polarimetry Explorer (IXPE)

• Three sets of identical X-ray mirror modules and imaging, polarization-sensitive detectors
IXPE new science with new capabilities

• Opens a new window on the universe — imaging (30") X-ray polarimetry
• Addresses key questions, providing new scientific results and constraints
  – What is the spin of a black hole?
  – What are the geometry and magnetic-field strength in magnetars?
  – Was our Galactic Center an Active Galactic Nucleus in the recent past?
  – What is the magnetic field structure in synchrotron X-ray sources?
  – What are the geometries and origins of X-rays from pulsars (isolated and accreting)?
• Provides powerful and unique capabilities
  – Reduces observing time by a factor of 100 compared to OSO-8
  – Simultaneously provides imaging, spectral, timing, and polarization data
  – Is free of false-polarization systematic effects at less than 0.3%
  – Enables meaningful polarization measurements for many sources of different classes
Institutions and countries involved

<table>
<thead>
<tr>
<th>Institution/Location</th>
<th>Role/Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Marshall Space Flight Center</td>
<td>PI team, project management, SE and S&amp;MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving</td>
</tr>
<tr>
<td>IAPS INAF INFN</td>
<td>Polarization-sensitive imaging detector systems</td>
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<tr>
<td>Caltech LASP</td>
<td>Mission operations</td>
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<tr>
<td>University of Rome TRE Stanford University</td>
<td>Scientific theory</td>
</tr>
<tr>
<td>McGill University</td>
<td>Science Working Group Co-Chair</td>
</tr>
<tr>
<td>MIT Massachusetts Institute of Technology</td>
<td>Co-Investigator</td>
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</table>

Flag of participating countries:
The Science Team

Co-Investigators

Collaborators
- Pegasus XL launch from Kwajalein
- Launch ready by early 2021
- 540-km circular orbit at 0° inclination
- 2-year baseline mission, 1 year extension
- Point-and-stare at known targets
- Malindi ground station (Singapore Backup)
- Mission Operations Center at CU/LASP
- Science Operations Center at MSFC
IXPE deployed

- Solar Array
- Boom w/ Thermal Sock deployed
- X-ray Shields (×3) deployed
- Forward Star Tracker
- Metrology Camera
- Aft Star Tracker
- Spacecraft w/ Avionics
- Detector Unit (×3)
- Tip/Tilt/Rotate Mechanism
- Mirror Module Assembly (×3)

5.2-m total length deployed
4.0-m focal length
- **Polarization degree**
  - $\Pi = \text{Modulation} / \mu(E)$
Electroformed X-ray optics @ MSFC

**ART-XC (satellite)**
8 Modules, 28 shells, qualified and delivered for flight in 2018

**FOXSI (rocket)**
7 Modules, 7/10 shells, flown in 2012 & 2014

**HERO/HEROES (balloon)**
8 Modules, 13/14 shells, latest flight in 2013
Replication Process

**Mandrel Fabrication**
1. Machine mandrel from aluminum bar
2. Coat mandrel with electroless nickel (NiP)
3. Diamond turn mandrel for sub-micron figure
4. Polish mandrel to 0.3-0.4 nm rms
5. Metrology on mandrel

**Mirror Shell Fabrication**
6. Passivate mandrel surface to reduce shell adhesion
7. Electroform Nickel/Cobalt shell on to mandrel
8. Separate shell from mandrel in cold water bath

NiCo electroformed mirror shells
Mirror Module Assembly

Design approach

• Uses a single rigid spider to support the 24 nested shells and attach module to structure
• Light-weight housing mainly for thermal control
• Limit (rear) spider does not support mirror shells but limits their vibrations during launch
• Mounting combs provide shell attachment points
The X-ray mirror modules

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mirror modules</td>
<td>3</td>
</tr>
<tr>
<td>Number of shells per mirror module</td>
<td>24</td>
</tr>
<tr>
<td>Focal length</td>
<td>4000 mm</td>
</tr>
<tr>
<td>Total shell length</td>
<td>600 mm</td>
</tr>
<tr>
<td>Range of shell diameters</td>
<td>162–272 mm</td>
</tr>
<tr>
<td>Range of shell thicknesses</td>
<td>0.16–0.26 mm</td>
</tr>
<tr>
<td>Shell material</td>
<td>Electroformed nickel–cobalt alloy</td>
</tr>
<tr>
<td>Effective area per mirror module</td>
<td>230 cm$^2$ (at 2.3 keV); &gt;240 cm$^2$ (3–6 keV)</td>
</tr>
<tr>
<td>Angular resolution (HPD)</td>
<td>$\leq 25$ arcsec</td>
</tr>
<tr>
<td>Field of view (detector limited)</td>
<td>12.9 arcmin square</td>
</tr>
</tbody>
</table>
The IXPE detectors

The polarization sensitive detectors

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Sensitive area</td>
<td>15 mm × 15 mm</td>
</tr>
<tr>
<td>Fill gas and composition</td>
<td>He/DME (20/80) @ 1 atm</td>
</tr>
<tr>
<td>Detector window</td>
<td>50-μm thick beryllium</td>
</tr>
<tr>
<td>Absorption and drift region depth</td>
<td>10 mm</td>
</tr>
<tr>
<td>GEM (gas electron multiplier)</td>
<td>copper-plated 50-μm liquid-crystal polymer</td>
</tr>
<tr>
<td>GEM hole pitch</td>
<td>50 μm triangular lattice</td>
</tr>
<tr>
<td>Number ASIC readout pixels</td>
<td>300 × 352</td>
</tr>
<tr>
<td>ASIC pixelated anode</td>
<td>Hexagonal @ 50-μm pitch</td>
</tr>
<tr>
<td>Spatial resolution (FWHM)</td>
<td>≤ 123 μm (6.4 arcsec) @ 2 keV</td>
</tr>
<tr>
<td>Energy resolution (FWHM)</td>
<td>0.54 keV @ 2 keV (∝ √E)</td>
</tr>
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</table>
Measure black-hole spin in twisted space-time

- For a micro-quasar GRX1915+105 in an accretion dominated state
  - Scattering polarizes the thermal disk emission
  - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays
  - Priors on disk orientation also constrain model
    \[ a = 0.50 \pm 0.04; 0.900 \pm 0.008; 0.99800 \pm 0.00003 \]
    
    (200-ks observation)
Map magnetic field of synchrotron sources

- Probe sites of cosmic-ray acceleration: Cas A
  - Lines and thermal continuum dominate 1-4 keV
  - Non-thermal emission dominates 4-6 keV

Cas A image at IXPE resolution (1.5-Ms)
Test quantum electrodynamics

- Magnetar is a neutron star with magnetic field up to $10^{15}$ Gauss
  - Non-linear QED predicts magnetized-vacuum birefringence
    - Refractive indices of the two polarization modes differ from 1 and each other
    - Impacts polarization and position angle as functions of pulse phase
  - Example is the magnetar 1RXS J170849.0-400910, with an 11-s pulse period
    - Can easily exclude QED-off at better in 250-ks observation
Was Sgr A* recently $10^6 \times$ more active?

- Galactic Center molecular clouds (MC) are known X-ray sources
  - If MCs reflect X-rays from Sgr A* (supermassive black hole in the Galactic center)
    - X-radiation would be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A*
    - Sgr A* X-ray luminosity was $10^6$ larger $\approx 300$ years ago
• Emission geometry and processes are unsettled
  – Competing models predict differing polarization behavior with pulse phase
• X-rays provide clean probe of geometry
  – process entirely different in radio band
  – We recently discovered no pulse phase-dependent variation in polarization degree and position angle @ 1.4 GHz
  – Absorption likely more prevalent in visible band
• 140-ks observation gives ample statistics to track polarization degree and position angle
Active galaxies are powered by supermassive BHs with jets
- Radio polarization implies the magnetic field is aligned with jet
- Different models for electron acceleration predict different dependence in X-rays

Two Ultra Luminous X-ray sources (one to SW on detector but not visible in 6-arcmin-square displayed region)

<table>
<thead>
<tr>
<th>Region</th>
<th>$\text{MDP}_{99}$</th>
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<tbody>
<tr>
<td>Core</td>
<td>&lt;7.0%</td>
</tr>
<tr>
<td>Jet</td>
<td>10.9%</td>
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<tr>
<td>Knot A +B</td>
<td>17.6%</td>
</tr>
<tr>
<td>Knot C</td>
<td>16.5%</td>
</tr>
<tr>
<td>Knot F</td>
<td>23.5%</td>
</tr>
<tr>
<td>Knot G</td>
<td>30.9%</td>
</tr>
<tr>
<td>ULX</td>
<td>14.8%</td>
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Includes effects of dilution by unpolarized diffuse emission
Capturing the imagination
Accreting magnetized compact objects

- Determine the accretion geometry in X-ray pulsars (e.g. fan vs pencil beam)

- Check models of X-ray emission of Accreting Millisecond Pulsars to help constrain M/R
Scattering polarimeter

- Thomson cross-section approximates the angular dependence

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