The Imaging X-ray Polarimetry Explorer

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**OUTLINE**

- A brief history of polarimetry in the classical X-ray band
  - Sounding rocket experiments
  - OSO-8 crystal polarimeter
  - The Stellar X-ray Polarimeter on Spektrum-X

- IXPE
  - Introduction
  - How it works
  - The science
July 1968 – Lithium-block, “Thomson”- scattering polarimeter flown on an Aerobee 150 sounding 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.
Rocket 17.09 (Aerobee 350) 1971
Rocket 17.09

- Crab detection!
  - \( P = 15\% \pm 5\% \)
  - \( \phi = 156^\circ \pm 10^\circ \)

Yes, I am the handsome one
CRYSTAL POLARIMETERS ON OSO-8

• 1975 OSO-8 crystal polarimeter
• Precision measurement of the integrated emission from the Crab Nebula polarization at 2.6 keV (with minimal contamination from the pulsar)
  • $P = 19\% \pm 1\%$
  • $\phi = 156^\circ \pm 2^\circ$ (NNE)
**Did OSO-8 result make sense?**

- Yes --- Compare to HST mapping (Moran, P., Shearer, A., Mignani, R.P., et al. 2013)
- IXPE detailed mapping is the next important step
• Chandra image with IXPE 30” half-power diameter
THE STELLAR X-RAY POLARIMETER (SXRP)

- Planned to fly on the Russian Spectrum-X Gamma Mission in the early 1990s --- but was never launched.
• IXPE will accomplish, *for the first time*, high-sensitivity measurements of the polarization of X-rays coming to us from some of the most exciting types of astronomical objects — neutron stars and black holes

• IXPE will accomplish, *for the first time*, imaging X-ray polarization measurements from extended objects such as supernova remnants and at least one jet attached to super-massive black holes

• IXPE measurements are made possible by *new technology* advanced by our Italian partners

• IXPE measurements are astrophysically *unique*, adding two new dimensions to information space:
  • Polarization degree
  • Polarization angle
The IXPE Team

SAT currently comprises ~ 80 scientists from 12 countries
THE SCIENCE OBJECTIVES

- IXPE will study targets over a broad range of types of astronomical X-ray sources with emphasis on black holes and neutron stars

- IXPE will (some detailed examples on future slides):
  - Constrain the radiation processes and detailed properties of different types of cosmic X-ray sources
  - Investigate general relativistic and quantum effects in extreme environments
  - Constrain the geometry of AGN and microquasars
  - Establish the geometry and strength of the magnetic field in magnetars
  - Constrain the geometry and origin of the X-radiation from radio pulsars
  - Learn how particles are accelerated in Pulsar Wind Nebulae and in (shell-type) Supernova Remnants
MISSION DESCRIPTION

• Launch April 2021
• 540-km circular orbit at 0° inclination
• 2-year baseline mission, 1 year extension (at least!)
• Point and stare at pre-selected targets
• Malindi ground station (Singapore backup)
• Mission Operations Center at the University of Colorado, Laboratory for Atmospheric and Space Physics
• Sciences Operations Center at MSFC
• Data archiving at NASA’s HEASARC
  • No proprietary data
IXPE DEPLOYED

- Detector Unit (x3)
- Tip-Tilt Rotate Mechanism
- Boom w/ Thermal Sock deployed
- Aft Star Tracker
- Solar Array
- Forward Star Tracker
- X-ray Shields (x3) deployed
- Mirror Module Assembly (x3)

5.2 m total length deployed
4.0 m focal length
The initial direction of the K-shell photoelectron is determined by the electric vector.

The distribution of the photoelectron initial directions determines the degree of polarization and the position angle.

\[
\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left( \frac{1}{\beta} \right)^{7/2} 4\sqrt{2} \sin^2 \theta \cos^2 \varphi, \quad \text{where} \quad \beta \equiv \frac{E}{mc^2} = \frac{\hbar \nu}{mc^2}
\]
# Detector Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive area</td>
<td>15 mm × 15 mm (13 x 13 arcmin)</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>
<tr>
<td>Useful energy range</td>
<td>2 - 8 keV</td>
</tr>
</tbody>
</table>
• The modulation factor is the variation in the position angle for a 100%-polarized beam
**MIRROR PRODUCTION PROCESS**

**Mandrel fabrication**

1. Machine mandrel from aluminum bar
2. Coat mandrel with electroless nickel (Ni-P)
3. Diamond turn mandrel to sub-micron figure accuracy
4. Polish mandrel to 0.3-0.4 nm RMS
5. Conduct metrology on the mandrel

**Mirror-shell forming**

6. Passivate mandrel surface to reduce shell adhesion
7. Electroform Nickel/Cobalt shell onto mandrel
8. Separate shell from mandrel in chilled water

Ni/Co electroformed IXPE mirror shell
**MIRROR MODULE ASSEMBLY**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of modules</td>
<td>3</td>
</tr>
<tr>
<td>Mirror shells per module</td>
<td>24</td>
</tr>
<tr>
<td>Inner, outer shell diameter</td>
<td>162, 272 mm</td>
</tr>
<tr>
<td>Total shell length</td>
<td>600 mm</td>
</tr>
<tr>
<td>Inner, outer shell thickness</td>
<td>180, 260 µm</td>
</tr>
<tr>
<td>Shell material</td>
<td>Nickel cobalt alloy</td>
</tr>
<tr>
<td>Effective area per module</td>
<td>210 cm² (2.3 keV)</td>
</tr>
<tr>
<td></td>
<td>&gt; 230 cm² (3-6 keV)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>≤ 25 arcsec HPD</td>
</tr>
<tr>
<td>Detector limited FOV</td>
<td>12.9 arcmin</td>
</tr>
<tr>
<td>Focal length</td>
<td>4 m</td>
</tr>
<tr>
<td>Mass (3 assemblies)</td>
<td>95 kg with contingency</td>
</tr>
</tbody>
</table>
MMA – ENGINEERING UNIT

Measured angular resolution 20 arcsec @ 2.3 and 4.5 keV
**Microquasars**

- Perform X-ray spectral polarimetry on microquasars to help localize the emission site (accretion disk, corona, jet) position angle.

For a micro-quasar in an accretion-dominated state, scattering polarizes the disk emission. Polarization rotation versus energy is greatest for emission from inner disk.
  - Inner disk is hotter, producing higher energy X-rays.

Disk orientation from other experiments used to constrain GRX1915+105 model.

\[ a = 0.50 \pm 0.04; 0.900 \pm 0.008; 0.99800 \pm 0.00003 \] (200-ks observation)
Radio Pulsars

- Perform X-ray phase-resolved polarimetry to test models for a radio pulsar’s X-ray emission, which are distinct from those for its radio emission.
- Grey is optical, blue is IXPE.

**Emission geometry and processes are still unsettled.**
- Competing models predict differing polarization behavior with pulse phase.

**X-rays provide clean probe of geometry.**
- Absorption likely more prevalent in visible band.
- Radiation process entirely different in radio band.
  - Recently discovered no pulse phase-dependent variation in polarization degree and position angle @ 1.4 GHz.
- 140-ks observation gives ample statistics to track polarization degree and position angle.
**MILLISECOND PULSARS**

- Figure shows the phase dependence of flux, polarization degree, and position angle for an accreting millisecond with two hot spots and a 3.3-ms period.
- Assumes a NS radius, $R = 2.5 \ R_g$, and different combinations of angles, $I$, between the rotation axis and line of sight and $\theta$ between the rotation and magnetic axes.
- In favorable cases, IXPE phase-resolved polarimetry allows measurement of geometry-dependent position-angle variations, which flux measurements alone cannot accomplish.
Supernova Remnants (SNR – e.g. CAS-A)

- Use X-ray polarmimetric imaging to examine the magnetic-field topology in the X-ray emitting regions of (shell-type) SNR, which are candidate sites for cosmic-ray acceleration (Entire image measured simultaneously)

Lines and thermal continuum dominate 1-4 keV.
Non-thermal emission dominates 4-6 keV.
**Was SGR A* Recently $10^6 \times$ More Active?**

- Galactic Center molecular clouds (MC) are known X-ray sources
  - If the MCs reflect X-rays from Sgr A* the X-radiation would be highly polarized perpendicular to plane of reflection and indicates the direction back to Sgr A*
    - If true implied Sgr A* X-ray luminosity was $10^6$ larger $\approx 300$ years ago
    - If not, still a discovery
• Study Magnetars (pulsing neutron stars with magnetic fields up to $10^{15}$ Gauss)
  • Non-linear QED predicts magnetized-vacuum birefringence
    – Refractive indices of the two polarization modes differ from 1 and from each other
    – Impacts polarization and position angle as functions of pulse phase, but not the flux
    – Example is 1RXS J170849.0-400910, with an 11-s pulse period
    – Can exclude QED-off at better than 99.9% confidence in 250-ks observation