An overview of the history of X-ray polarimetry and IXPE - the mission and its science

Martin C. Weisskopf
On behalf of the IXPE team

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One does not expect all astrophysical systems to be strongly polarized.

Instruments typically not fully sensitive to polarization

Measured parameter is positive definite – i.e. one always measures something, even in the absence of a polarized source
Rocket history

• 1968 Aerobee 150
  • Sco X-1 upper limit
• 1969 Aerobee 150
  • Crab upper limit
• 1971 Aerobee 350
  • Crab detection!
    • $P = 15\% \pm 5\%$
    • $\varphi = 156^\circ \pm 10^\circ$
• Two instruments
  • Lithium scattering polarimeter
  • 4 Bragg crystal polarimeters
On to the satellite experiment

- 1975 OSO-8 crystal polarimeter
- Precision measurement of integrated Crab Nebula polarization at 2.6 keV
  - $\Pi = 19\% \pm 1\%$
  - $\varphi = 156^\circ \pm 2^\circ$ (NNE) agrees with optical
• Three redundant telescope-detector systems
• Gas pixel electron-tracking detectors developed in Italy
• Replicated X-ray telescopes with <30 arcsecond angular resolution (half-power diameter) developed at MSFC
Participating Institutions & Roles

- NASA/MSFC- PI Team, project management, systems engineering, technical oversight, telescope fabrication, X-ray calibration, science operations, data analysis
- Istituto di Astrofisica e Planetologia Spaziale/Istituto Nazionale di Astrofisica (IAPS/INAF, Rome) & Istituto Nazionale di Fisica Nucleare (INFN, Pisa & Torino) – Polarization-sensitive detectors & electronics, detector calibration & data analysis
- Agenzia Spaziale Italiana (ASI) – Malindi Ground Station
- Ball Aerospace – Spacecraft, Payload Structure, Payload and Observatory I&T
- Laboratory for Astronomy & Space Physics (Boulder) – Mission Operations
- Stanford University & University Roma Tre – Theory
- McGill University & MIT – Co-Chair SWG & Co-Is
Science Team

Martin C. Weisskopf (MSFC) – PI
Luca Baldini (INFN) – Co-I
Ronaldo Bellazzini (INFN,) – Co-I and Italian Co-PI
Enrico Costa (IAPS/INAF) – Senior Co-I
Ronald Elsner (MSFC) –Co-I & Science Systems Eng.
Victoria Kaspi (McGill) – Co-I & SWG Co-Chair
Jeffery Kolodziejczak (MSFC) – Co-I & Calibration Scientist
Luca Latronico (INFN) – Co-I
Herman Marshall (MIT) – Co-I
Giorgio Matt (Univ Roma Tre) – Co-I & Theory
Fabio Muleri (IAPS/INAF) – Co-I
Stephen O’Dell (MSFC) – Co-I & Project Scientist
Brian Ramsey (MSFC) – Co-I, Deputy PI, Payload Scientist
Roger Romani (Stanford) – Co-I & Theory
Paolo Soffita (IAPS/INAF) – Co-I and PI for Italian effort
Allyn Tennant (MSFC) – Co-I & Science Data Ops Lead
The direction of the K-shell photoelectron is determined by the electric vector and the direction of the incoming photon.

\[
\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left( \frac{1}{\beta} \right)^{7/2} 4\sqrt{2} \sin^2 \theta \cos^2 \varphi
\]

where \(\beta \equiv \frac{E}{mc^2} = \frac{hv}{mc^2}\)
Electron tracking - 2

- Optical Imaging Chamber
- Austin & Ramsey 1992
Site of initial ionization produced by 54 keV X-ray and the Auger electron cloud

- 2 atm:
  - argon (90%)
  - methane (5%)
  - trimethyamine (5%)
- Track is 14 mm long
The distribution of the photoelectron directions determines the degree of polarization and the position angle.
# The polarization sensitive detectors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<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 (∝ \sqrt{E})</td>
</tr>
</tbody>
</table>
Measurements of the detector modulation with a 100%-polarized beam at 3.7 keV
Measurements of the detector modulation with an un-polarized beam at 3.7 keV
Modulation factor as a function of energy
Comparison to simulations
The X-ray telescopes

An ART-XC flight module in its support frame (rear view)
The IXPE 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 cm² (@ 2.3 keV); &gt;240 cm² (3–6 keV)</td>
</tr>
<tr>
<td>Angular resolution (HPD)</td>
<td>≤ 25 arcsec</td>
</tr>
<tr>
<td>Field of view (detector limited)</td>
<td>12.9 arcmin square</td>
</tr>
</tbody>
</table>
The Energy Response

Modulation factor × square root of the effective area versus energy
End-to-end flow from detected photon to scientific data products

IXPE
Photons to Data Products
Obtain X-ray polarimetric images of an AGN core and jet
Exploit imaging polarimetry to infer past activity of Sgr A*
Map magnetic field of X-ray-emitting regions in Pulsar Wind Nebulae and in shell-type Supernova Remnants
Perform phase-resolved polarimetry of rotation-powered pulsars using imaging to reduce nebular background
Explore Magnetar physics and vacuum birefringence
Obtain energy-resolved polarimetry of AGN and microquasars to test models and assess black-hole spin
Perform phase- and energy-resolved polarimetry of accreting X-ray pulsars to test emission models
Sensitivity

Time to reach a minimum detectable polarization as a function of source flux

![Graph showing time to reach minimum detectable polarization as a function of source flux for different types of sources, including PWNes, SNRs, Magnetars, Classical Accreting Binary Pulsars, LMXBs/AMSPs, Micro-Quasars, Black-hole binaries, Galactic center, Sgr B2, and AGNs. The graph includes data points for different flux levels and shows the minimum detectable polarization (MDP) values for 99% of all sources.]
For a micro-quasar 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 constrain GRX1915+105
model $a = 0.50 \pm 0.04; 0.900 \pm 0.008; 0.99800 \pm 0.00003$ (200-ks)
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

Imaging Cen A allows isolating other sources in the field
• Two Ultra Luminous X-ray sources (one to SW on detector but not visible in 6-arcmin-square displayed region)

Includes effects of dilution by unpolarized diffuse emission
Exploit imaging polarimetry to infer past activity of Sgr A*
Fundamental New Measurements - PWNe

- Map the magnetic field of X-ray-emitting regions in Pulsar Wind Nebulae
Emission geometry and processes are unsettled
  - Competing models predict differing polarization behavior with pulse phase

X-rays provide cleaner 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
Magnetar is a neutron star with magnetic field up to $10^{15}$ G
Non-linear QED predicts magnetized-vacuum birefringence
  - Refractive indices of the two polarization modes differ from 1 & 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 where we can exclude QED-off at better than 99.9% confidence in 250-ks
- Lines and thermal continuum dominate @ 1-4 keV
- Non-thermal emission dominates @ 4-6 keV

Cas A image at IXPE resolution (1.5-Ms)