The Imaging X-ray Polarimeter (IXPE) Part 1

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on behalf of the IXPE Science Team
NASA/MSFC (Emeritus)

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The IXPE Team

Science Advisory Team

SAT currently comprises > 175 scientists from 13 countries
IXPE Mission Description

- Launched 2021 December 9, on a Falcon 9 from KSC
- 600-km circular orbit at a nominal 0° inclination
- 2-year baseline mission, optional extension with GO program
- Point and stare (with dither) at pre-selected targets
- Malindi ground station - primary (Singapore - secondary)
- Mission Operations Center (MOC) at the University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)
- Sciences Operations Center (SOC) at MSFC
- Data archiving at NASA’s HEASARC
  - During the first 3 months of the mission, including orbital checkout, all IXPE data shall be made publicly available at the HEASARC within 30 days of the end of an observation.
  - After the first 3 months of the mission, data shall be made available to the HEASARC within 1 week of the end of an observation
Launch 1:00 AM December 9, 2021

Equatorial Orbit
600 km altitude
MMA = Mirror Module Assembly
DU = Detector Unit

5.2 m total length
4.0 m focal length
Release from the Falcon 9

Folded solar panel (1 of 5)

Instrument thermal radiator

Aft Star Tracker
Shield and Collimator Suppress Background

Detector unit

Collimator

X-ray Shield

Shield

Mirror Module Assembly

Off-axis background

On-axis

Target
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
The Optics
# Mirror Module Assembly Properties

<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, 250 µm</td>
</tr>
<tr>
<td>Shell material</td>
<td>Nickel cobalt alloy</td>
</tr>
<tr>
<td>Effective area per module</td>
<td>163 cm² (2.3 keV)</td>
</tr>
<tr>
<td></td>
<td>~ 192 cm² (3-6 keV)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>≤ 27 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>93.12 kg</td>
</tr>
</tbody>
</table>

![Pre-detector Effective Area (3 modules) Graph](image-url)
Imaging polarimetry

- IXPE 30” half-power diameter on Chandra image
The detection principle is based on the photoelectric effect.
The distribution of the photoelectron initial directions determines the degree of polarization and the position angle

\[ \frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left( \frac{1}{\beta} \right)^{7/2} 4\sqrt{2} \sin^2 \theta \cos^2 \varphi , \] where \( \beta \equiv \frac{E}{mc^2} = \frac{hv}{mc^2} \).
The Detectors

- The Detector Units (DUs) mounted to the spacecraft top deck at Ball
Filter and Calibration Wheel Assembly (FCW), providing open, attenuator, and closed positions, plus four $^{55}$Fe-powered calibration sources:

- Cal A – Bragg-reflected polarized 2.98-keV (Ag-L$_\alpha$ fluorescence) and 5.89-keV (Mn-K$_\alpha$) sources
- Cal B – unpolarized 5.89-keV spot
- Cal C – unpolarized 5.89-keV flood
- Cal D – unpolarized 1.74-keV (Si-K$_\alpha$ fluorescence) flood
### 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>DME @ 0.8 atmosphere</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>ASIC pixelated anode</td>
<td>Hexagonal @ 50-µm pitch</td>
</tr>
<tr>
<td>Number ASIC readout pixels</td>
<td>300 × 352</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>0.57 keV @ 2 keV (∝ √E)</td>
</tr>
<tr>
<td>Useful energy range</td>
<td>2 - 8 keV</td>
</tr>
</tbody>
</table>
On-Ground Calibration

- Detector Units calibrated in Italy using both polarized and unpolarized X-ray sources
- Mirror Module Assemblies calibrated at MSFC using both polarized and unpolarized sources
- One complete telescope (MMA+DU) also calibrated at MSFC
MSFC “Stray Light” X-ray Test Facility
Effective Area and Modulation Factor

- Mirror effective area (x3 MMA)
- IXPE total effective area
- Modulation response function

On axis response [cm²] vs Energy [keV]

- 80.0 cm² at 2.26 keV
- 19.4 cm² at 2.86 keV

Modulation factor vs Energy [keV]
The Minimum Detectable Polarization (MDP)

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

- \( R_S \) is the observed source counting rate
- \( R_B \) is the observed background counting rate
- \( t \) is the integration time
- \( M \) is the **modulation factor**, i.e. the amplitude of the variation of the ensemble of position angles for a 100% polarized source
Replay of a sample of events obtained by one of IXPE’s three detectors
(39 ks livetime, segment 1 of 2 of the Crab nebula observation)
The Early Results

- IXPE’s first observations have been *especially* rewarding with many leading to unexpected results
  - See the following talks for details
The Imaging X-ray Polarimetry Explorer (IXPE) Science Results One Year Post-Launch

Steven Ehlert, IXPE Project Scientist
(NASA Marshall Space Flight Center)
on behalf of the IXPE Science Team
IXPE’s first year of observations has resulted in many new discoveries about familiar X-ray sources.

GRB 221009A

2022 December 8
Sources observed: 39
Observations completed: 54
Observations processed: 52
Polarization detected (> 99.99% confidence): 19
IXPE Science is divided up into seven different topical working groups (TWG’s):

1. Pulsar Wind Nebulae and Radio Pulsars
2. Supernova Remnants
3. Accreting Stellar Mass Black Holes
4. Accreting White Dwarf and Neutron Stars
5. Magnetars
6. Radio Quiet Active Galactic Nuclei and the Galactic Center
7. Blazars and Radio Galaxies
Pulsar Wind Nebulae

IXPE has shown that pulsar wind nebulae are sources of highly ordered magnetic fields, with polarization degrees approaching the limits for synchrotron radiation.

Crab: Bucciantini et al, submitted to Nature Astronomy
Vela: Xie et al, Nature
IXPE has measured the presence of radial magnetic fields and the maximum scale length of turbulence in two supernova remnants.

**Cas A:** $\Pi = (1.8 \pm 0.3)\%$ azimuthal angle  
$\lambda \sim 10^{17} \text{ cm}$  
Vink et al, Astrophysical Journal

**Tycho:** $\Pi = (9.1 \pm 2.1)\%$ azimuthal angle  
$\lambda \sim 10^{18} \text{ cm}$  
Ferrazzoli et al, Astrophysical Journal
Polarization measurements from IXPE provide essential information about the geometry of the X-ray emitting region in low-mass X-ray binaries such as Cygnus X-1.

\[ \Pi = (4.0 \pm 0.2)\% \quad \psi = (-20.7 \pm 1.4)^\circ \]

Krawczynski et al, Science
Accreting neutron stars have shown much lower polarization degrees than models predicted, suggesting the need for major changes to our understanding of these objects.

\[
\text{\textit{Her X} – 1: } \Pi = (8.6 \pm 0.5)\% \quad \psi = (+62 \pm 2)^\circ
\]

Doroshenko et al, Nature Astronomy

\[
\text{\textit{Vela X} – 1: } \Pi = (3.9 \pm 0.9)\% \quad \psi = (-52 \pm 7)^\circ
\]

Magnetars

IXPE observations of magnetars show evidence of the exotic physics predicted from their extremely high magnetic fields.

\[ \Pi = (13.5 \pm 0.8)\% \quad \psi = (+48.5 \pm 1.6)\degree \]
Taverna et al, Science

\[ \Pi = (35.1 \pm 1.3)\% \quad \psi = (-62.1 \pm 1.3)\degree \]
Zane et al, accepted ApJ
Observations of blazars with synchrotron peaks in the IXPE bandpass show compelling evidence of energy-stratified shock acceleration that can vary with time.

Mrk 501: $\Pi = (10 \pm 2)\%$  \hspace{1cm} $\psi = (-45 \pm 5)\degree$

Liodakis et al, Nature

Mrk 421: $\Pi = (10 \pm 1)\%$  \hspace{1cm} $\psi' = (77 \pm 2.4)\degree$/day

Di Gesu et al, in prep
For AGN jets where only upper limits can be measured, IXPE can nevertheless place important constraints on how particle acceleration operates in these systems.

*Cen A:* $\Pi < 6.5\%$. Ehlert et al, Astrophysical Journal

*BL Lac:* $\Pi < 14\%$. Middei et al, accepted MNRAS
IXPE was able to observe GRB 221009A, the brightest gamma-ray burst to encounter Earth since we have had gamma-ray detectors

**Core (Afterglow):** $\Pi < 13.8\%$

**Rings (Prompt):** $\Pi < 55 - 82\%$