IXPE Deployed

5.2 m total length
4.0 m focal length
IXPE Exists!

Janice Houston, IXPE Lead Systems Engineer in residence at Ball, with stowed observatory
### The IXPE Team

<table>
<thead>
<tr>
<th>NASA Marshall Space Flight Center</th>
<th>POL Aps</th>
<th>INAF</th>
<th>INFN</th>
<th>OHB Italia</th>
</tr>
</thead>
<tbody>
<tr>
<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>
<td>Polarization-sensitive imaging detector systems</td>
<td>Mission operations</td>
<td>Scientific theory</td>
<td>Co-Investigator</td>
</tr>
<tr>
<td>Detector system funding, ground station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nagoya University Thermal Shields</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Science Advisory Team</td>
<td>SAT currently comprises &gt; 90 scientists from 12 countries</td>
<td></td>
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</tr>
</tbody>
</table>
The Science Team

- Investigators

- Collaborators (75 from 12 countries)
The Working Groups

- **Science Working Group (SWG)**
  - G. Matt (IT) & S. O’Dell (US), Co-Chairs

- **Science Advisory Team (SAT)**
  - G. Matt (IT) & R. Romani (US), Co-Chairs

- **SAT Topical Working Groups (TWG), Leads**
  - Pulsar Wind Nebula & Radio Pulsars, N. Bucciantini (IT)
  - Supernova remnants, P. Slane (US)
  - Accreting stellar-mass black holes, M. Dovčiak (CZ)
  - Accreting neutron stars, J. Poutanen (FI)
  - Magnetars, R. Turolla (IT)
  - Radio-quiet AGN and Sgr A*, F. Marin (FR)
  - Blazars & radio galaxies, A. Marscher (US)

- **Calibration Working Group**
  - W. Baumgartner (US), F. Muleri (IT), & J. Kolodziejczak (US)

- **Science Analysis & Simulation Working Group**
  - L. Baldini (IT) & H. Marshall (US)
Shield and Collimator Suppress Background

- Detector Unit
- Collimator
- X-ray Shield
- Mirror Module Assembly
- Off-axis Background
- On-axis Target
- X-ray Shield

Chart 7
Mirror-Shell 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
The Optics

<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>4 m</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>0.16–0.25 mm</td>
</tr>
<tr>
<td>Shell material</td>
<td>Electroformed nickel–cobalt alloy</td>
</tr>
<tr>
<td>Effective area per mirror module</td>
<td>166 cm² (@ 2.3 keV); &gt; 175 cm² (3–6 keV)</td>
</tr>
<tr>
<td>Angular resolution (HPD)</td>
<td>≤ 27 arcsec</td>
</tr>
<tr>
<td>Field of view (detector limited)</td>
<td>12.9 arcmin square</td>
</tr>
</tbody>
</table>

MMA, showing 24 shells

Three IXPE Mirror Module Assemblies

MMA with Thermal Shield on end

Chart 9
• X-ray calibration of the optics occurred at MSFC’s 100-m X-ray test facility
Angular Resolution

<table>
<thead>
<tr>
<th>MMA</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4 keV</td>
<td>18.9″</td>
<td>24.8″</td>
<td>24.2″</td>
</tr>
<tr>
<td>4.5 keV</td>
<td>18.9″</td>
<td>25.0″</td>
<td>26.9″</td>
</tr>
<tr>
<td>2.3 keV</td>
<td>18.7″</td>
<td>24.5″</td>
<td>26.7″</td>
</tr>
</tbody>
</table>

Values in the table are half-power diameters (HPDs) for the individual MMAs alone. After adjustment for alignment errors, detector resolution, focus, etc., the on-orbit system-level resolution is 28″.

At-focus images for MMA1, MMA2 and MMA3 (left to right) taken at 2.3 keV, 4.5 keV and 6.4 keV (top to bottom).
Imaging polarimetry

- IXPE 30” half-power diameter on Chandra image of the Crab Nebula
Detection Principle

- The detection principle is based upon the photoelectric effect.

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

- The initial direction of the K-shell photoelectron is determined by the orientation of the incident photon’s electric vector.

- The distribution of the photoelectron initial directions measures the degree of polarization and the position angle.
# 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 asymptotic pressure</td>
<td>DME @ 0.656 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>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>0.57 keV @ 2 keV (∝ √E)</td>
</tr>
<tr>
<td>Useful energy range</td>
<td>2 - 8 keV</td>
</tr>
</tbody>
</table>
The Detectors

• The Detectors mounted to the spacecraft top deck at Ball Aerospace
Filter and Calibration Wheel (FCW), providing open, attenuated, and closed positions, plus four $^{55}$Fe-powered calibration sources:
- Cal A – Bragg-reflected polarized 2.98-keV (Ag-Lα fluorescence) and 5.89-keV (Mn-Kα)
- Cal B – unpolarized 5.89-keV spot
- Cal C – unpolarized 5.89-keV flood
- Cal D – unpolarized 1.74-keV (Si-Kα fluorescence) flood
Minimum Detectable Polarization (MDP)

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

- $R_S$ 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
Baseline moments analysis is a simple, effective, long-studied and well-understood method of extracting information from ionization tracks made by the photo-electron in the detector gas.

- Machine Learning (neural-network) techniques can extract more information from each track:
  - Improves position-angle (PA) measurements, especially at higher energies
  - Allows one to compute statistical and reconstruction errors for each event
  - Mildly improves estimates of the energy and conversion point of each event
First Year’s Mission — Release 1

- Next version will be released 6 months prior to launch
- Observing plan is from input from the IXPE Science Advisory Team
  - Seven Topical Working Groups (TWG), based upon category of source
- Needed exposure times assume moments-method event reconstruction
  - Will increase somewhat, based upon results from recent calibration
- However, neural-network event reconstruction will enhance the sensitivity
  - Improves MDP$_{99}$ by $\sim$15% (relative) for fixed exposure time
  - Reduces exposure time by $\sim$30% for fixed MDP$_{99}$

<table>
<thead>
<tr>
<th>Source Category</th>
<th># Sources</th>
<th>Time (Ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar Wind Nebulae</td>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>Supernova Remnants</td>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>Accreting Neutron Stars</td>
<td>8</td>
<td>1.8</td>
</tr>
<tr>
<td>Accreting Black Holes</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>Magnetars</td>
<td>2</td>
<td>2.0</td>
</tr>
<tr>
<td>Radio Quiet AGN and Sgr A*</td>
<td>4</td>
<td>2.8</td>
</tr>
<tr>
<td>Blazars and Radio Galaxies</td>
<td>11</td>
<td>3.2</td>
</tr>
<tr>
<td>ToOs</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>39</strong></td>
<td><strong>19</strong></td>
</tr>
</tbody>
</table>
Radio Pulsars

- Perform X-ray phase-resolved polarimetry to test models for a radio pulsar’s X-ray emission
  - Crab Pulsar — 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 a 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 of the Crab pulsar gives ample statistics to track polarization degree and position angle.
Microquasars

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

For a microquasar 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 may be 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)
Active Galaxies: Cen A

- Active galaxies powered by supermassive black holes with jets
  - Radio polarization implies the magnetic field is aligned with jet
  - Different electron-acceleration models predict different dependences in X-rays

<table>
<thead>
<tr>
<th>Region</th>
<th>MDP&lt;sub&gt;99&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>1.4%</td>
</tr>
<tr>
<td>Knots</td>
<td>21%</td>
</tr>
<tr>
<td>C+F+G</td>
<td></td>
</tr>
<tr>
<td>ULXs</td>
<td>25%, 15%</td>
</tr>
</tbody>
</table>
• 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
Conclusion

We are keenly looking forward to opening this new window on the sky by adding image resolved polarimetry to the arsenal of tools to study the X-ray emission from astrophysical sources.

Scheduled launch date is 2021 November 17!