Optics for the Imaging X-ray Polarimetry Explorer

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For the IXPE Team
IXPE is a NASA Small Explorer Mission dedicated to X-ray polarimetry – the first of its kind – opening up the field of imaging polarimetry.

It was selected in January 2017 for a flight in 2020/2021.
Addresses key questions, providing new scientific results and constraints that trace back to the Astrophysics Roadmap and the Decadal Survey

- 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 integration time by a factor of 100 over our OSO-8 experiment
- Simultaneously provides imaging, energy, timing, and polarization data
- Devoid of instrument systematic effects at less than a fraction of a percent
- Meaningful polarization measurements for a large number of sources of different classes, as evidenced by our Design Reference Mission
Mission Design and Operations

- Pegasus XL launch from Kwajalein
- 540-km circular orbit at 0° inclination
- 2 year baseline mission, 1 year SEO
- Point-and-stare at known targets
- Science Operations Center at MSFC
- Mission Operations Center at CU/LASP
- Malindi ground station (Singapore Backup)
- Launch ready by end of 2020
Set of three mirror module assemblies (MMA) focus x-rays onto three corresponding focal plane detector units.

- Mirror modules provide imaging and background reduction.
- Detector Units (3x)
- Tip Tilt Rotate (TTR) Mechanism (used once to correct boom deployment offset)
- Deployable Payload Boom (covered by Thermal Sock)
- Shields (3x, to minimize X-ray background)
- Mirror Module Assembly (MMA) (3x)
- Detectors provide position, energy and polarization information, photon by photon, plus time stamp.
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
**MIRROR SHELL FABRICATION – ELECTROFORMED REPLICATION**

### 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
MSFC Infrastructure for X-ray Optics Fabrication

- Mandrel diamond turning
- Mandrel polishing
- Mandrel and shell metrology
- Nickel/Cobalt shell electroforming
- X-ray testing and calibration
MIRROR SHELL INTEGRATION AND ALIGNMENT

- Shell assembly proceeds from the inner shell outwards
- The assembly system holds each successive shell on a system of wires that can be moved radially and adjusted in tension.
- Keyence proximity sensors rotate around the hanging shell and measure radial displacements of the mirror external surface
- Software takes the displacement data as a function of rotation angle and fits various curves (and calculate various performance parameters) to aid in the alignment process.
- When shell performance is satisfactory, it is glued into the spider comb and the next shell is mounted
## 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>
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<tr>
<td>Total shell length</td>
<td>600 mm</td>
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<tr>
<td>Inner, outer shell thickness</td>
<td>180, 260 µm</td>
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<tr>
<td>Shell material</td>
<td>Nickel cobalt alloy</td>
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<tr>
<td>Effective area per module</td>
<td>210 cm² (2.3 keV)</td>
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<tr>
<td></td>
<td>&gt; 230 cm² (3-6 keV)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>≤ 25 arcsec HPD</td>
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<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>

![Pre-Detector Effective area (3 modules)](image)
Radiation from outside the instrument field of view can reflect off the mirror shells, end up in the detector, and constitute a background.

- This typically arises from single reflections from either the hyperbolic or parabolic segment of the mirror (depends on exact module geometry).
- For IXPE, only single reflections from the hyperbola (H singles) contribute.
Results of IXPE MMA stray radiation analysis:

- Stray radiation reaching detector is from a small annulus of the sky from 25 arcminutes off axis to just under 60 arcmin.
- Peak magnitude (effective area) is $\sim 300 \times$ lower than the on-axis signal, integrated over the whole detector.
  - Imaging further reduces this by a large amount (see above figure).
• Are there any very bright sources within 25 to 60 arcminute of an intended target that could increase the background for that observation?

• Not a problem for point sources as stray radiation is reduced by more than factor of $10^5$

• What about extended sources?

  • Use the MAXI (Monitor of All-sky X-ray Image) catalog of sources, appropriate for the IXPE energy range, to search around IXPE design reference mission targets

    • The only source affected is SGR B2, due to the bright source SAXJ1747-285 nearby. However, the imaging properties of IXPE will isolate this stray radiation at the edge of the detector, away from the target.
**THERMAL REQUIREMENTS**

- Thermal requirements derived from FEA analysis and subsequent ray tracing.
  - Looked at temp variations across mirror diameter and along axis.
  - Most sensitive to temp gradients from one side of mirror to other
  - Set requirements of max 2 °C variation across mirror assembly
  - Achieved with ~ 10 W orbit average power per module

Example of mirror shell distortions for 2°C change across mirror diameter

Affect of this on mirror shell performance

Thermal model of mirror module assembly.

Entrance and exit aperture thermal shields: 1.4 micron polyimide coated with 300 A aluminum
X-RAY SHIELDS

Deployed shields

Off-axis background

On-axis Target

Deployable shields

Mirror module assembly

Deployed shields (3)

Detector unit
If after deployment the Mirror Module Assemblies (MMAs) are out in translation, we would use a lookup table to tell us which tip/tilts to actuate and the amount of adjustment to apply.
MMA Activities

• **Build and test an engineering unit (in progress, completion in March 2018)**
  • Will have a subset of flight mirror shells
    • Will be used to:
      • *Exercise the whole fabrication and assembly process*
      • *Test all handling fixtures*
      • *Confirm the mechanical design through environmental testing*
      • *Provide a test system to verify procedures and hardware for the MMA and end-to-end ground calibration (along with a detector engineering unit).*

• **Build and test 4 flight units**
  • 3 Flight and 1 spare unit
    • Will all go through acceptance-level vibration tests
    • Will all be fully calibrated
**Plan**

- Calibrate Detector Units (DU) in Italy at INAF/IAPS
- Calibrate Mirror Module Assemblies (MMA) at MSFC
- Perform end to end calibration at MSFC
  - Preparations with engineering units of MMA and DU
  - Allows test of SOC systems

**Calibration Heritage**

- MSFC: Chandra, ART-XC, FOXSI and HERO calibration
- Italy: SXRP, BeppoSAX, Super AGILE, Fermi/LAT

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*Custom polarized sources for DU calibrations at IAPS*

*Stray-light test facility at MSFC*