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.
IXPE ADDRESSES KEY SCIENTIFIC OBJECTIVES

- 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
**IXPE TEAM AND 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

**Institutional Roles and Responsibilities**

| NASA Marshall Space Flight Center | INFN INAF  
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<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>
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<td>Detector system funding, ground station</td>
<td>LASP Mission operations</td>
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<tr>
<td>Spacecraft, payload structure, payload, observatory I&amp;T</td>
<td>Stanford Scientific theory</td>
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<tr>
<td>McGill Science Working Group Co-Chair</td>
<td>MIT Massachusetts Institute of Technology</td>
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Science Advisory Team
Set of three mirror module assemblies (MMA) focus x rays onto three corresponding focal plane detector units.
**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
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>
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<tbody>
<tr>
<td>Number of modules</td>
<td>3</td>
</tr>
<tr>
<td>Mirror shells per module</td>
<td>24</td>
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<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>
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<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>
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<tr>
<td>Focal length</td>
<td>4 m</td>
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<tr>
<td>Mass (3 assemblies)</td>
<td>95 kg with contingency</td>
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</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.
Ray trace analysis was performed

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 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
X-RAY CALIBRATION

- **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

*Custom polarized sources for DU calibrations at IAPS*

*Stray-light test facility at MSFC*
**IXPE Schedule (Under Review)**

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**Mission Phases**
- Phase A
- Phase B
- Phase C/D
- Phase E
- Q Phase

**Mission Milestones**
- Phase A Select
- Bridge
- Phase B
- Phase C/D
- Phase E
- Q Phase

**Instrument (Italian Contribution)**
- Detector Units Fab / Test
- Design
- EU Mfg. & Test
- Flight Mirror Module Assembly & Test
- I-PDR
- I-CDR
- Calibration Readiness Review
- Deliver CSR
- KDP-B
- PDR
- CDR
- IRR
- DSU-PFM Sch. Margin (85d)
- Optics Assembly Sch. Margin (68d)
- Observatory I&T Sch. Margin (51d)
- Launch Site Operations Sch. Margin (15d)
- Launch (11/20/20)

**Optics Assembly**
- 0976348-05
- 0976348-05
- Calibration Prep
- Optics Calibration Sch. Margin (21d)
- IB
- ICalibrate/Mirror Module w/ Instrument
- Payload Development
- Payload I&T
- Payload I&T Sch. Margin (21d)
- Observatory I&T Sch. Margin (21d)
- Observatory & Sch. Margin (15d)
- Observatory I&T Sch. Margin (15d)
- Launch Site Operations
- Launch Site Operations (Ball) 0976348.10.95
- Launch Site Operations
- Launch Site Operations (Ball) 0976348.10.95
- Launch (11/20/20)
- Launch (11/20/20)
- SMSR
- DR
- DR