Mirror Technology Development for The International X-ray Observatory Mission

Will Zhang
IXO Mirror Technology Lead Scientist
X-ray Astrophysics Laboratory
NASA Goddard Space Flight Center
International X-ray Observatory (IXO)

ESA
JAXA
NASA

Solar Panels
Mirror Assembly
Focal plane assembly

Extensible Optical Bench
Lightweight and High Resolution X-ray Optics is Needed

<table>
<thead>
<tr>
<th>State of the Art</th>
<th>IXO Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra</td>
<td>0.1 m²</td>
</tr>
<tr>
<td></td>
<td>0.5 arcsecs</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>0.4 m²</td>
</tr>
<tr>
<td></td>
<td>15 arcsecs</td>
</tr>
<tr>
<td>Suzaku</td>
<td>0.2 m²</td>
</tr>
<tr>
<td></td>
<td>120 arcsecs</td>
</tr>
<tr>
<td></td>
<td>3 m²</td>
</tr>
<tr>
<td></td>
<td>5 arcsecs</td>
</tr>
</tbody>
</table>
Modular Design of Mirror Assembly

<table>
<thead>
<tr>
<th>1 FMA</th>
<th>1 FMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 Inner Modules Radius: 370-690mm</td>
<td>24 Middle Modules Radius: 740-1110mm</td>
</tr>
<tr>
<td>143 P/H Pairs</td>
<td>155 P/H Pairs</td>
</tr>
<tr>
<td>12 Outer Modules Radius: 1160-1610mm</td>
<td></td>
</tr>
<tr>
<td>103 P/H Pairs</td>
<td></td>
</tr>
<tr>
<td>60 Modules</td>
<td></td>
</tr>
<tr>
<td>15,816 Mirror Segments</td>
<td></td>
</tr>
</tbody>
</table>
IXO Mirror Technology Development Objectives

- Identify problems unique to IXO mirrors that have not been encountered by, or solved for, previous missions
- Devise solutions to these problems; Demonstrate their validity through analysis and experimentation
- Establish design principles and build prototypes to prove that they meet requirements: angular resolution, effective area, mass, schedule and budget
- Subject the prototypes to X-ray and appropriate environment tests to demonstrate TRL-4, 5, and 6

Demonstrate the feasibility; Find out what’s and who’s out there to engineer and build the telescope!
# Focus of Technology Development

<table>
<thead>
<tr>
<th>Major Category</th>
<th>Minor Category</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Segment Fabrication</td>
<td>Forming Mandrel Fabrication</td>
<td>(1) Make mandrels for tech dev.; (2) Develop and optimize production techniques</td>
</tr>
<tr>
<td></td>
<td>Slumping</td>
<td>(1) Replicate forming mandrel figure</td>
</tr>
<tr>
<td></td>
<td>Post-Slumping Cutting</td>
<td>(1) Cut replica to dimension; (2) Create smooth edges; (3) Not change figure</td>
</tr>
<tr>
<td></td>
<td>Coating</td>
<td>(1) Maximize reflectivity without changing figure</td>
</tr>
<tr>
<td>Alignment and Integration Techniques</td>
<td>Suspending</td>
<td>(1) Set mirror segment to its natural figure</td>
</tr>
<tr>
<td></td>
<td>Temporary Bonding</td>
<td>Temporarily attach mirror segment to strongback such that mirror segment is free of stress and distortion</td>
</tr>
<tr>
<td></td>
<td>Alignment</td>
<td>Properly locate and orient mirror segment</td>
</tr>
<tr>
<td></td>
<td>Permanent Bonding</td>
<td>Permanently attach mirror segment to module housing</td>
</tr>
<tr>
<td>Module Design, Construction, and Test</td>
<td>Housing Material Selection</td>
<td>Achieve best possible compromise among CTE, thermal, mechanical, machinability, availability, etc.</td>
</tr>
<tr>
<td></td>
<td>Design &amp; Analysis</td>
<td>Achieve best possible compromise among optical, mechanical, thermal, and other aspects</td>
</tr>
<tr>
<td></td>
<td>Construction</td>
<td>Effectively combine and integrate the “alignment and integration techniques” to install mirror segments into housing</td>
</tr>
<tr>
<td></td>
<td>Tests</td>
<td>X-ray tests for angular resolution and effective area; Environment tests</td>
</tr>
</tbody>
</table>
Slumping - Status

Axial Figure Repeatability

Substrate 489S2070
Substrate 489S2073
RMS Difference: 10 nm

Mirror Substrate Pair HPD

HPD Two Reflection (arcsec)

Measured
Projected
Required
## Mirror Fabrication Progress

<table>
<thead>
<tr>
<th>Date</th>
<th>HPD (two reflections)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 2008</td>
<td>~16”</td>
<td>Normal incidence metrology, Full illumination X-ray tests; 60-deg segments</td>
</tr>
<tr>
<td>August 2009</td>
<td>~12”</td>
<td>Normal incidence metrology; 60-deg segments</td>
</tr>
<tr>
<td>October 2009</td>
<td>~10”</td>
<td>Normal incidence metrology; 30-deg segments</td>
</tr>
<tr>
<td>December 2009</td>
<td>~8.5”</td>
<td>Normal incidence metrology; 30-deg segments</td>
</tr>
<tr>
<td>January, 2010</td>
<td>~7.5”</td>
<td>Normal incidence metrology; 30-deg segments</td>
</tr>
<tr>
<td>April, 2010</td>
<td>~6.5”</td>
<td>Normal incidence metrology; 30-deg segments, Using IXO mandrels</td>
</tr>
<tr>
<td>December 2011</td>
<td>~3”</td>
<td>Using mandrels meeting IXO requirements; Meeting IXO requirements</td>
</tr>
</tbody>
</table>
Temporary Bonding - Status

Face-On View

Edge-On View
Temporary Bonding - Status

- The temporary bonding process probably has met requirements, at least for smaller mirrors
- More detailed and quantitative analysis is underway
- Need to conduct experimentation with big mirror segments
Alignment - Status

- Achieved excellent focus
- Improvement needed
  - Equipment stability
  - Lab temperature stability
Permanent Bonding - Status

- Active compensation to counter the effects of epoxy injection hydraulic and shrinkage forces
- Achieved single point bonding accuracy of 0.1 μm, meeting requirements
Mirror Housing Simulator (MHS) – TRL-4

- Designed and fabricated to hold one pair of mirror segments
- Fully open and accessible to facilitate alignment, bonding, and metrology verification
Mini-Module (TRL-5)

- Capable of handling multiple shells, fully testing the entire process of installing mirror segments into a module
- Capable of undergoing a full battery of tests, performance as well as environment
Flight-Like Module (TRL-6)

- Fully flight-like in every aspect
- Populated with both real mirror segments and mass dummies
- Will undergo a full battery of tests: X-ray, vibration, acoustic, thermal-vacuum, etc.

Angular resolution: 3.8” (half-power diameter or HPD)
Mirror Technology Development Team

M. Biskach\textsuperscript{3}, P.A. Blake, G. Byron\textsuperscript{3}, K.W. Chan\textsuperscript{1}, T. Evans\textsuperscript{3}, C. Fleetwood\textsuperscript{2}, C. He\textsuperscript{2}, M. Hill, M. Hong\textsuperscript{3}, Lalit Jalota\textsuperscript{1}, L. Kolos, J.M. Mazzarella\textsuperscript{3}, R. McClelland\textsuperscript{3}, L. Olsen\textsuperscript{3}, R. Petre, D. Robinson, T.T. Saha, M. Sharpe\textsuperscript{3}, W.W. Zhang

\textit{NASA Goddard Space Flight Center}

\textsuperscript{1} \textit{University of Maryland, Baltimore County}

\textsuperscript{2} \textit{Ball Aerospace and Technologies Corp.}

\textsuperscript{3} \textit{Stinger Ghaffarian Technologies, Inc.}

M.V. Gubarev, W.D. Jones, T. Kester, S.L. O’Dell

\textit{NASA Marshall Space Flight Center}

D. Caldwell, W. Davis, M. Freeman, W. Podgorski, P.B. Reid, S. Romaine

\textit{Smithsonian Astrophysical Observatory}
Outlook

• Mirror fabrication milestones
  – Consistent at ~5” HPD (two reflections) by December 2010
  – Consistently meeting requirements (~3” HPD two reflections) by December 2011

• Improvement of metrology to identify and isolate sources of error
  – Metrology mount
  – Upgrade null lens
  – Check for systematic effects
  – Cross-check figure quality using both normal and grazing incidence measurements

• Suspension Mount, Alignment, and Transfer (SMAAT)
  – Perfect and understand edge-bonding (December 2010)
  – Streamline and upgrade the alignment setup to improve thermal and structural stability (December 2010)
  – Transfer and bond single pairs of mirrors in mirror housing simulator (MHS) to achieve TRL-4 (July 2010)
  – Co-align and transfer and bond multiple mirror pairs to achieve TRL-5 (May 2011)

• Module
  – Housing material selection by December 2010
  – Design, analysis, and partial tests in 2011
  – Full TRL-6 by November 2012
Small Technology Firms that Have Made Direct Contributions to IXO Mirror Technology Development

4D Technology, Tucson, AZ
Optimax Systems, Inc., Ontario, NY
QED Technologies, Rochester, NY
Rodriguez Precision Optics, Gonzales, LA
Dallas Optical Systems, Inc., Rockwall, TX
RAPT Industries, Inc., Freemont, CA
Reflective X-ray Optics LLC, New York, NY
Acknowledgements

The work is supported in part by

NASA IXO Project Office

Goddard Space Flight Center Internal Research and Development Fund

A NASA Astronomy and Physics Research and Analysis (APRA) Grant