Technology Needs for LYNX: Mirrors, Coatings and Metrology

J. Gaskin, NASA MSFC
**The People Behind Lynx**

Over 300 total members!

- 22 STDT Members
- 8 Science Working Groups
- Ex-officio International Members
- Instrument Working Group
- Communications Working Group
- Lynx Calibration Working Group
- Optics Working Group

<table>
<thead>
<tr>
<th>Orgs.</th>
<th>Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSFC</td>
<td>HDXI IDL runs</td>
</tr>
<tr>
<td></td>
<td>LXM IDL &amp; costing contributed effort</td>
</tr>
<tr>
<td></td>
<td>MDL (spacecraft)</td>
</tr>
<tr>
<td>JPL (ExEP) + X-ray Optics Community</td>
<td>Optics Trade Study facilitation &amp; Evaluation</td>
</tr>
<tr>
<td></td>
<td>Contributed effort (&gt;35 Volunteers)</td>
</tr>
<tr>
<td>X-Ray Grating Spectrometer Team</td>
<td>XGS Trade Study Team (&gt;10 Volunteers)</td>
</tr>
<tr>
<td>CAN Study Partners</td>
<td>Creare: LXM cryocooler study</td>
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<tr>
<td>&gt;50% overall contributed</td>
<td>Hypres: superconducting ADC study</td>
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<tr>
<td></td>
<td>Luxel: blocking filter fab. &amp; test</td>
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<tr>
<td></td>
<td>Lockheed Martin: LXM cryo-system</td>
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<tr>
<td></td>
<td>Northrop Grumman (w/Ball &amp; Harris): Observatory design &amp; analysis</td>
</tr>
<tr>
<td>UAH</td>
<td>MBSE modeling of interfaces, requirements &amp; Observatory error budget</td>
</tr>
<tr>
<td>Interim Report Red Team</td>
<td>Chair: C. Kouveliotou (GWU)</td>
</tr>
<tr>
<td></td>
<td>Contributed effort</td>
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</tbody>
</table>
Of the 4 large missions under study for the 2020 Astrophysics Decadal, Lynx is the only observatory that will be capable of directly observing the high-energy events that drive the formation and evolution of our Universe.

Lynx will provide unprecedented X-ray vision into the “Invisible” Universe with leaps in capability over Chandra and ATHENA:

- **Orders of magnitude gain in sensitivity** over Chandra and over Athena, via high throughput with high angular resolution
- **Increased field of view** for arcsecond or better imaging
- **Significantly higher spectral resolution** for point-like and extended sources
SCIENCE OF LYNX

Through a GO Program, Lynx will contribute to nearly every area of astrophysics and provide synergistic observations with future-generation ground-based and space-based observatories, including gravitational wave detectors.

The Dawn of Black Holes

The Invisible Drivers of Galaxy and Structure Formation

The Energetic Side of Stellar Evolution and Stellar Ecosystems

Endpoints of stellar evolution
Stellar birth, coronal physics, feedback
Impact of stellar activity on habitability of planets
2 m² of effective area at E = 1 keV is required to execute the three science pillars in under 50% of the 5-yr mission timeline. This is achieved with an outer diameter of 3-m with a focal length of 10-m.
Enabling Technologies TRL Assessment Summary

At Decadal Studies Management Team request, the ExEP, PCOS, and COR Program Offices and the Aerospace Corp assessed the TRL of tech gaps submitted by the teams as of Dec. 2016. Assessment was presented June 2017.

<table>
<thead>
<tr>
<th>ID</th>
<th>Technology Gap</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High-Resolution ‘Lightweight’ Optics</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Non-deforming X-ray Reflecting Coatings</td>
<td>3</td>
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<tr>
<td>3</td>
<td>Megapixel X-ray Imaging Detectors (HDXI)</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>X-ray Grating Arrays (XGS)</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Large-Format, High Spectral Resolution X-ray Detectors (LXM)</td>
<td>3</td>
</tr>
</tbody>
</table>

Multiple Technologies & Approaches being explored. Expect TRL 3-4 by mid-2020

Multiple Technologies
Multiple Technologies
Subsystem Heritage

THE TIME FOR LYNX IS NOW!
MIRROR CHALLENGES

**Science Driven Requirements**

<table>
<thead>
<tr>
<th>Lynx Optical Assembly</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Angular resolution (on-axis)</td>
<td>0.5 arcsec HPD (or better)</td>
</tr>
<tr>
<td>Effective area @ 1 keV</td>
<td>2 m² (met with 3-m OD)</td>
</tr>
<tr>
<td>Off-axis PSF (grasp), A*(FOV for HPD &lt; 1 arcsec)</td>
<td>600 m² arcmin²</td>
</tr>
</tbody>
</table>

**Chandra did it! And so can Lynx!**

- **Large effective area** is achieved by nesting a few hundred to many thousands of co-aligned, co-axial mirror pairs.
- Must fabricate **thinner mirrors** to allow for greater nesting of mirror pairs and larger effective area while reducing mass.
- These thin mirrors must be better than **0.5” HPD** requirement.
- Must **mount and coat** these thin optics **without deforming the optic**, or must be able to correct deformations.

LYNX MIRROR ASSEMBLY

FABRICATION

Thermal Forming (GSFC, SAO)

Full Shell (Brera, MSFC, SAO)

Si Optics (GSFC)

Air Bearing Slumping (MIT)

Testing/Simulation/Modeling

Piezo stress (SAO/PSU)

Deposition (MSFC, XRO)

Magnetic & deposition stress (NU)

Ion implant stress (MIT)

Ion beam figuring (OAB)

CORRECTION

Full shells Assembly

Segmented Wedge Assembly

Meta-Shell Assembly

INTEGRATION

Schattenburg talk to NASA PCOS SIG, 04/2016 - Modified
• The quantities listed are key to achieving mission science goals and are considered key technical performance metrics (TPMs).
  • Image quality (system)
  • Effective area
  • Spectral resolution
  • Observing efficiency (related to effective area)

• All key TPMs will have a budget to manage the flow down of requirements and make an assessment of expected performance (prediction) and the path to achieving the expected performance.
  • Gives confidence in the requirements vs. capabilities assessment
  • Gives confidence in the development path for the key payload elements
• Shows how Lynx collects data and makes an image on the celestial sphere
• Lynx looks like Chandra (structurally)
• Lynx Mirror Assembly is 1/3 the f/# so alignment/stability is tighter

IMAGE QUALITY— ERROR BUDGET

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Allocation or Requirement (arcsec HPD)</th>
<th>State of the Art (arcsec HPD)</th>
<th>Determination &amp; Verification</th>
<th>Bridging the Gap between State-of-Art and Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical Prescription</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffraction</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometric PSF (on-axis)</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mirror Segment Fabrication</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mirror Substrate</td>
<td>0.20</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coating</td>
<td>0.10</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Meta-Shell Construction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alignment</td>
<td>0.10</td>
<td>1.60</td>
<td></td>
<td></td>
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<tr>
<td>Bonding</td>
<td>0.20</td>
<td>0.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Integration of Meta-shells to XMA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alignment</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attachment</td>
<td>0.10</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ground to Orbit Effects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Launch shift</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
<td></td>
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<tr>
<td>Gravity Release</td>
<td>0.10</td>
<td>0.14</td>
<td></td>
<td></td>
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<tr>
<td>On-orbit thermal</td>
<td>0.10</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>On-Orbit Performance (RSS)</strong></td>
<td>0.40</td>
<td>1.77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Image Quality
- LMA 0.4 arcsec
- Alignment/Stability 0.07 arcsec
- Aspect Reconstruction 0.2 arcsec

Look! Values
NB: reserve is an rss

Credit: J. Arenberg (NGAS)
LYNX MIRROR ASSEMBLY – SILICON METASHELL OPTICS

- W. Zhang and Team (NASA GSFC)

<table>
<thead>
<tr>
<th>XMA Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>0.3–10 keV</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>0.5 arcsec HPD on-axis; &lt; 1 arcsec HPD across the FOV</td>
</tr>
<tr>
<td>Grasp (Effective Area * FOV for &lt;1 arcsecond PSF)</td>
<td>~600 m² arcminutes²</td>
</tr>
<tr>
<td>Field of View</td>
<td>10 arcmins radius</td>
</tr>
<tr>
<td>Effective Area @ 1 keV</td>
<td>2 m²</td>
</tr>
</tbody>
</table>

Direct polished mono-crystalline silicon

Silicon Composite

0.24 m

0.5 m

3.0 m

Centroid = (485, 487)

50%PD: 2.2" 90%PD: 8.0"

Fraction of Encircled Energy

Relative Intensity

Radius (arcsec)

Diameter (arcsec)
Direct Polished Fused Silica or Similar

- Distance between the primary and secondary surface is around 280 mm
- Obscuration 9%
- Spherical distribution of intersection planes to correct plate scale
- Shell fixation side: \( \Omega_{\text{MIN}} \) for the primary surface and \( \Omega_{\text{MAX}} \) for the secondary surface by means of flexures

FEASIBLE ALTERNATES - FULL SHELL & ADJUSTABLE OPTICS

- G. Pareschi, M. Civitani, S. Basso & INAF Team (INAF-OAB)
- K. Kiranmayee, J. Davis, R. Elsner D. Swartz & MSFC Team (MSFC/USRA)
- P. Reid
- SAO Adjustable Optics Team
- PSU Adjustable Optics Team

- Slumped glass with sputter deposited piezoelectric material

- Deposited piezo actuator layer
- Outer electrode segment
- Inner actuator electrode
- Glass mirror substrate
- X-ray reflective coating (e.g., Ir)
X-RAY MIRROR ASSEMBLY (XMA) METROLOGY

State-of-the-art metrology is required to determine the mirror quality over the entire range of spatial frequencies.

- **Highest spatial frequency** (microroughness) \((\text{sub-nm accuracy required})\)
  - Assessed with a phase-shifting interferometer with a millimeter-class FOV
  - Or, Atomic Force Microscope

- **Lowest spatial frequency** (figure error) \((\text{several-nm accuracy required})\)
  - Assessed with a phase-shifting interferometer with a much larger FOV
  - For full-shell cylindrical optics, the optic must be extremely precisely rotated about its axis to allow stitching of multiple FOV’s
  - For segmented optics, the interferometer may cover the entire segment, but there are then additional, difficult alignment metrology requirements
    - For segmented optics with active figure correction, the correctors’ influence functions must also be precisely measured

- **Mid-spatial frequency** \((\text{few-nm accuracy required})\)
  - Usually assessed interferometrically, either by
    - Swapping the objective in the microroughness interferometer to expand the FOV
    - Taking great care to get very high resolution and excellent sensitivity and calibration accuracy in the low spatial frequency interferometer
    - (or both, for greatest spatial frequency overlap!)

XMA has a 3-m outer diameter, and contains hundreds or thousands of mirror elements!
The traditional dividing line between metrology and alignment is blurred for Lynx, because of:
- The large number of mirrors
- The possibility of a segmented architecture
- The flexibility of the thin mirrors

For full-shell cylindrical optics:
- The flexibility puts strenuous requirements on the transition from holding the optics for metrology, and ultimately attaching them to the structure while monitoring the alignment and aggregate image quality over the full aperture

For segmented optics:
- Precision metrology is required as the mirror elements are assembled into modules
- This metrology may combine direct measurements of the surface figure with indirect measurements of a module’s image quality
- Multiple modules must ultimately be coaligned, either by
  - Monitoring the alignment and aggregate image quality over the full aperture, or
  - Introducing transfer optics to each module that can generate an alignment reference to be compared against those of other modules

In all these cases, sub-arc-second accuracy is required, which at a focal length of 10 meters implies detection of image shifts or distortions of only a few microns.
• Low stress thin film coatings (~ 10 MPa) needed to preserve underlying sub-arcsecond figure of thin (~400 µm) substrates.

• High X-ray reflectance for a range of grazing incidence angles (~0.4° (innermost shell)-2.0° (outermost shell)).
  - Although the 2 m² effective area requirement is specified @ 1keV, a spectral response up to 10-15keV is desired.
  - Single layer coatings such as Pt, Au, and Ir provide good spectral response up to 10 keV for incidence angles less than the critical angle (i.e. the inner shells).
  - In this regime, (100-150 Å) single layer of Iridium offers best X-ray reflectivity, but coating stress is significant (i.e. ~4GPa (compressive))
  - Interference based coatings (such as multilayers) might be utilized on the outer shells to extend the spectral response at incidence angles beyond the critical angle.

• Low surface roughness to minimize X-ray light scattering (< 5-6Å).
  - Most stress mitigation techniques result in a film microstructure that causes some degree of increase in high frequency surface roughness
Stress balancing coatings on same side of substrate:
The technique utilizes a compensating layer(s) whose stress is
opposite in sign to the sign of the stress in the layer stack.

\[(\sigma h)_f^{Net} = \sigma_A h_A + \sigma_B h_B + \ldots + \sigma_N h_N + \Delta (\sigma h)_{CTE} \approx 0\]

The thickness of the compensating layer is tuned to balance the net
stress in the layer stack.

Example: Cr (tensile (+))/Ir (compressive (-))

Argon pressure optimization in magnetron sputtered Ir:
Zero stress @ 16.5 mTorr

\[\sum_{i}^{N} (\sigma h)_f^{front} = \sum_{j}^{M} (\sigma h)_j^{back}\]

Slide Provided by
David Broadway (MSFC)
THANK YOU!

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