Next Generation X-ray Optics: High Resolution, Light Weight, and Low Cost

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Process of Building a Telescope

- \( \sim 10^4 \) Mirror Segments
- \( \sim 10^2 \) Modules
  Each containing \( \sim 10^2 \) mirror segments
- One or several mirror assemblies
Three Metrics

- Angular resolution
- Effective area (per unit mass)
- Production cost (per unit effective area)
  - Field of view (shorter shell length)
  - Energy bandwidth (multilayer coating)
Objectives

- **Point of departure (2002)**
  - Suzaku’s resolution (~120 arcsecs)
  - Suzaku’s eff. area per unit mass
  - Suzaku’s cost per unit area

- **Near term (2014)**
  - XMM-Newton’s resolution (~10 arcsecs)
  - Suzaku’s eff. area per unit mass
  - Suzaku’s cost per unit area

- **Long term (~2020)**
  - Chandra’s resolution (~0.5 arcsecs)
  - Suzaku’s eff. area per unit mass
  - Suzaku’s cost per unit area
## Development History & Future

<table>
<thead>
<tr>
<th>Year</th>
<th>Mirror Segment</th>
<th>Alignment &amp; Bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Technique</td>
<td>Contribution to HPD (&quot;)</td>
</tr>
<tr>
<td>2002</td>
<td>Slumped glass with epoxy replication</td>
<td>60</td>
</tr>
<tr>
<td>2007</td>
<td>Slumped glass</td>
<td>10</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>2013</td>
<td>Single Crystal Silicon (Machine &amp; Polish)</td>
<td>~1</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td>~0.1</td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td>~0.1</td>
</tr>
</tbody>
</table>
Glass Slumping (Zhang et al.)

- Simple, Reliable, Mature
- Producing good and consistent results
- Need to reduce mandrel cost & schedule

No. of Pairs per 0.5 Bin

All substrates
No selection

With Selection:
~6” HPD

Mirror Pair Performance (ArcSecond HPD)
Three Developments Since Chandra

- Fast and accurate measurement of segmented mirrors
  - Fizeau interferometers
  - Easily designed and built cylindrical null lens
- Commercially available deterministic polishing machines
  - QED: Magneto-Rheological Finishing (MRF)
  - ZEEKO: Intelligent Robotic Polishing (IRP)
  - Others….
- Abundantly and cheaply available large blocks of mono-crystalline silicon
  - “Perfect” single crystals: “Free” of internal stress
  - High thermal conductivity and relatively low CTE
  - Can be machined using precision wire-EDM
New Method for Fabricating Mirror Segment (Zhang et al.)

1. Procure mono-crystalline silicon: easy and cheaply available.
2. Apply heat and chemical treatments to remove all surface/subsurface damage (fast & cheap)

1. W-EDM machine conical shape (fast & cheap)
2. Apply heat and chemical treatments to remove damage (fast & cheap).
3. Polish using modern deterministic technique to achieve excellent figure and micro-roughness (fast & cheap? Need demonstration)

1. Slice off (using W-EDM) the thin mirror segment (fast & cheap)
2. Apply heat and chemical treatment to remove all damage from back and edges (fast & cheap)
Proof of Principle: Fabricate and then Light-weight

Before Light-weighting
55 mm thick (~0.1”)

After Light-weighting:
~2 mm thick (~0.5”)

1. What’s causing the degradation from ~0.1 to ~0.5”?
2. Would light-weighting to 0.5mm work as well?
Progression of Work

• **FY2102:** Demonstrate principle using flat mirrors – 2012 *(almost done)*
  – Polish a thick 55mm flat mirror
  – Slice off a wafer ~1mm thick
• **FY2013:** Make separate parabolic/hyperbolic segments or combined P-H segment *(lining up companies)*
• **FY2014:** Minimize cost maximize production efficiency
Coating: Sputter vs. ALD (Chan et al.)

1) Precursor pulse
2) Purge
3) Oxidant pulse
4) Purge
Alignment and Bonding
(Biskach et al.)

Drawing not to scale
Technology Development Module
(X-ray Performance Test)

3 Pairs
Co-aligned
Bonded
Module Engineering and Environmental Testing (McClelland et al.)

- Vibration test fixture designed and built
- Static and dynamic analyses completed
- Test being conducted today
Important Issues Being Worked On

- **Forming mandrels**
  - Increase rate of production
  - Decrease cost of production

- **Coating (Sputtering & Atomic layer deposition)**
  - Minimize figure distortion due to stress

- **Thermal environments**
  - CTE mismatch between mirror and housing
  - Potential lack of thermal equilibrium between mirror and housing

- **Epoxy instability**
  - Cure over long periods of time
  - Sensitivity to moisture
  - Visco-elasticity
Prospects

• Near term (1 to 2 yrs)
  – XMM’s angular resolution: ~10 arcseconds
  – Suzaku’s weight and cost
  – To enable AXSIO, N-CAL, N-XGS, N-WFI, and Explorer missions

• Long term (3 to 10 yrs)
  – Chandra’s angular resolution or better
  – Suzaku’s weight and cost per
  – To enable Generation-X, SMART-X…
Necessary and Sufficient Conditions for Making Good X-ray Optics

• Reasonable and adequate funding
• Competent people
• Good ideas
• Clear and well-formulated objectives
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