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

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Current X-ray Telescopes

Chandra
Zerodur Shells

XMM-Newton
Electro-formed Nickel Shells

Suzaku
Epoxy-replicated aluminum foils

NuSTAR
Slumped glass segments
Technology Context

[Graph showing technology context with axes for Angular Resolution (ArcSec, HPD) and Effective Area (@1keV) Per Mass (cm²/kg). Points labeled Past, Future, and State of the Art. Key points include XMM-Newton, Suzaku, Chandra, Tech Status, IXO Rqrmnt, and Gen-X. Accomplished, Short Term Goal, and Long Term Goal are indicated.]
Process of Building a Telescope

1. Fabrication of mirror segments
2. Integration of mirror segments into mirror module
3. Integration of mirror modules into mirror assembly
Two Core Techniques

- Mirror segment fabrication
  - Substrate fabrication
    - Figure
    - Micro-roughness
  - Coating
    - Stress
    - Micro-roughness
- Mirror segment bonding
Nature and Challenge of X-ray Optics

- Grazing Incidence
- Nested Concentric Shells
- Typical Requirements of a Future X-ray Mission
  - Thin: <0.5 mm
  - Lightweight: < 1 kg/m²
  - Large mirror area: ~1,000 m²
    - HST: 4.5 m²
    - Chandra: 20 m²
    - JWST: 33 m²
Problem and Solutions

**Problem**: How to make ~1,000 m\(^2\) of lightweight mirror area for ~$100M?

**Two Solutions**

– **Near term solution**: Slumped glass mirrors
  - A replication process
  - Fully developed and mature
  - Need to reduce forming mandrel cost

– **Long term solution**: Thin and lightweight mono-crystalline silicon mirrors
Best mirror substrates are ~4” HPD (2 reflections)

Reliably and consistently making 6.5” HPD (2 reflections) substrates

Mass production capability demonstrated with NuSTAR

Expect to consistently make 5” substrates by end of 2013
Comparison between Mirror Segment and Mandrel
Fabrication of Forming Mandrels

• Full shell mandrels
  – fused quartz ones being made at GSFC
  – High temperature alloy ones being made by Dallas Optical Systems

• Segmented fused quartz mandrels
  – Fused quartz ones being made at Chubu University, Japan using ZEEKO’s Intelligent Robotic Polishers
Two Developments Since Chandra

- Deterministic polishing machines have become commercially available
  - QED: Magneto-Rheological Finishing (MRF)
  - ZEEKO: Intelligent Robotic Polishing (IRP)
  - Others....

- Large blocks of mono-crystalline silicon have become easily and cheaply available
  - “Perfect” single crystals – “Free” of internal stress
  - High thermal conductivity and relatively low CTE
  - Can be machined using precision wire-EDM
Lightweight Single Crystal Silicon Mirrors

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

1. W-EDM machine conical shape.
2. Apply heat and chemical treatments to remove damage.
3. Polish using a state of the art technique (e.g., MRF, IRP) to achieve excellent figure and micro-roughness

1. Slice off the thin mirror segment
2. Apply heat and chemical treatment to remove all damage from back and edges
Progression of Work

- Demonstrate principle using flat mirrors – 2012
  - Polish a thick 55mm flat mirror
  - Slice off a wafer ~1mm thick

- Make separate parabolic/hyperbolic segments or combined P-H segment
  - Topic for a future presentation
Initial Result from a Flat Mirror

Figure before slicing

After slicing

After acid etch of back

After re-annealing
Future Work

• Near term – Slumped glass mirrors
  – Perfect the glass slumping process
  – Reduce forming mandrel cost and schedule

• Long term – Figured and lightweighted single crystal silicon mirrors
  – Proof of concept by making flat mirrors
  – Make lightweight Wolter-I mirrors
  – Industrialize the process to make silicon mirrors quickly and cheaply