X-ray Optics at NASA/MSFC

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Birth of X-Ray Astronomy

- In 1962, Riccardo Giacconi and colleagues at AS& E flew sounding rocket to look at x-ray fluorescence from the moon

- Lunar signal was overshadowed by very strong emission from the Scorpius region

- Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background

- This was the effective birth of x-ray astronomy
First X-Ray Satellite

The UHURU spacecraft was launched in 1970

It weighed just 140 pounds, not much more than the rocket experiment

It operated for 3 years and discovered 339 sources in the whole sky
Today .. The Chandra Observatory

• School-bus-size x-ray observatory

• 100,000 times more powerful than UHURU

• Uses special mirrors to form highly detailed images

• In deep fields, more than 1000 new sources per square degree
X-Ray Optics

Why focus x rays?
1) Imaging - obvious
2) Background reduction
   - Signal from cosmic sources very faint, observed against a large background
   - Background depends on size of detector and amount of sky viewed
     > Concentrate flux from small area of sky on to small detector
       ⇒ enormous increase in sensitivity

First dedicated x-ray astronomy satellite - UHURU
mapped 340 sources with large area detector (no optics)

Chandra observatory - ~ same collecting area as UHURU
⇒ 5 orders of mag more sensitivity --- 1,000 sources / sq degree in deep fields
⇒ 1 background count / keV year!

X-Ray Optics has revolutionized x-ray astronomy
X-ray Optics

Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter.
Approaches (flown so far [Soft X Ray])

**Classical Optical Grinding and Polishing**
Chandra, Rosat, Einstein
Advantage: Superb angular resolution
Disadvantage: High cost, large mass, difficult to nest

**Electroformed Nickel Replication** *
XMM, JETX/Swift, SAX
Advantage: High nesting factor, good resolution
Disadvantage: Significant mass (high density of nickel)

**Segmented foil**
ASTRO-E, ASCA, BBXRT
Advantage: Light weight, low cost
Disadvantage: Relatively poor angular resolution (few-arc-minute-level)
Electroformed Nickel Replication

**Mandrel Preparation**

1. CNC machine mandrel from aluminum bar
2. Chemical clean and activation & electroless nickel (EN) plate
3. Diamond-turn to ~600Å, sub-micron figure accuracy
4. Superpolish to 3 - 4Å rms finish
5. Metrology on mandrel

**Shell Fabrication**

6. Ultrasonic clean and passivation
7. Electroform NiCo shell onto mandrel
8. Separate optic from mandrel in cold water bath
MSFC Infrastructure
MSFC Developments: Electroformed Nickel Replication

Mandrel - machining Al bar, electroless Nickel coating, diamond turning and polishing

Metrology on mandrel

Electroform Ni/Co shell onto mandrel

Separate optic from mandrel in cold water bath

Replicated X-ray shells

Sandia Apr 2015
Nickel is a heavy material (9 g / cm$^3$). For light-weight optics, shells must be very thin (~ 0.1 mm [0.004”] at ~0.25-m diameter to meet Con X HXT weight budget) yet strong enough to withstand the stresses of fabrication and subsequent handling without being permanently deformed at the micron level.

Adhesion / Release

- Reduce adhesion of plated shell to mandrel so that shell can release easily

Material Properties

- Develop nickel alloy with much higher strength than pure nickel

Stress Control

- Small amount of stress distorts thin-shell optics
  - Fine tune plating bath chemistry and keep electric fields uniform
• Release Coatings

- Electroplating must adhere to mandrel so that shell will grow, but must be loose enough to separate easily.

- Have developed mandrel-surface treatments that give very low adhesion and do not significantly degrade surface with multiple replications.

- All involve generating an oxide on the surface of the mandrel

  > Typically give $\sim 7 \times 10^5$ Pa (100 psi) adhesion

  – This is a minimum to support the electroforming
Thin shells can experience large strain stresses under separation from a mandrel

\[ \text{Stress} = (\text{CTE}_{\text{ar}} - \text{CTE}_{\text{ni}}) \Delta T \text{Youngs mod} \]

Example at right, show 0.25-mm-thick shell released from treated mandrel. Stress ~ 35 MPa (5 ksi)

A shell 0.12-mm thick would experience twice this stress

Small stresses, well below the yield stress of a material can cause microyielding, of importance to high-resolution optics

We have developed alloys with higher yield strengths than pure nickel

Have made shells from this alloy, just 0.075-mm-thick (0.003”)

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**Permanent Strain Versus Applied Stress**

- Nickel Cobalt Alloy
- Regular Nickel

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**Stress (ksi)**

**Strain (ppm)**
ENR Development

Plating stress control

Need to control the stress to ~ 10’s psi to maintain 10-arcsec-level figure ... adjust chemistry of bath to give flat uniform stress

Stress still varies with plating current density, so in turn need to control field ... use models of plating bath to fine-tune layout of shields which modify field

Resulting deposit is very uniform, so stress variations are very low
Replicated X-ray optic projects at MSFC

**Astronomical applications**
- ART-XC
- FOXS
- ART-XC
- eROSITA

**Non-astronomical applications**
- Medical imaging
- Neutron imaging

*Navigator*

*HEROES*

*Sandia Apr 2015*
**Description:**
ART-XC is a medium energy x-ray telescope that will fly aboard the Russian Spectrum-Rontgen-Gamma Mission.
ART-XC will fly in 2016 and during its 7-year mission will conduct a 4-year survey of the sky, with an additional 3 years for follow-on studies. MSFC will provide x-ray optics modules for the ART-XC instrument. Delivery of the optics is scheduled for late Summer 2014.

**Customer:**
Space Research Institute of the Russian Academy of Sciences (IKI)
Funded under an International Reimbursable Agreement between NASA and IKI.
**ART-XC Optics Configuration**

*MSFC has designed and is fabricating*

- **four ART x-ray optics modules** under an International Reimbursable Agreement between NASA and with IKI (delivery – August 2014)
- **three + one spare ART modules** under Agreement regarding Cooperation on the ART-XC Instrument onboard the SRG Mission between NASA and IKI (delivery – October 2014)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of Mirror Modules</td>
<td>7=4+3 (plus 1 spare)</td>
</tr>
<tr>
<td>Number of Shells per Module</td>
<td>28</td>
</tr>
<tr>
<td>Shell Coating</td>
<td>&gt; 10 nm of iridium (&gt; 90% bulk density)</td>
</tr>
<tr>
<td>Shell Total Length, inner and outer diameters</td>
<td>580 mm, 50 mm, 150 mm</td>
</tr>
<tr>
<td>Encircled Half Energy Width</td>
<td>25 arcsec HPD on axis (measured)</td>
</tr>
<tr>
<td>Mirror Module Effective Area</td>
<td>≥ 65 cm² at 8 keV (on axis)</td>
</tr>
<tr>
<td>Module Focal Length</td>
<td>2700±1 mm</td>
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Description:
FOXSI is a sounding rocket based payload consisting of x-ray optics (provided by MSFC) and focal plane detectors provided by ISAS/Japan.
FOXSI has 7 mirror modules each with 7 (10 Foxsi-2) nested shells. Measured FWHM = 6-7 arcsec (with 5 arcsec detector).
FOXSI designed to make hard-x-ray observations (5-15 keV) of solar nanoflares, thought to play an important role in heating the corona to millions of degrees.
FOXSI was launched from White Sands missile range on 2 Nov, 2012, for a ~ 6 min flight.
FOXSI-2 version had successful flight from White Sands on 11 Dec, 2014

Customer:
University of California, Berkeley
P.I. Sam Krucker
Funded by the Science Mission Directorate, through the low-cost access to space program.
Mirror shell alignment and installation station

Module net angular resolution after detector resolution removed

fwhm = 4.3 +/- 0.6
Description:
Micro-X is a sounding rocket based payload consisting of x-ray optics (provided by MSFC) and a calorimeter detector led by MIT. Micro-X will fly in early 2017 and make high-spectral-resolution images of supernova remnants Puppis A and Cas A. The 0.5m diameter optics are under construction at MSFC. Completion schedule for 2016.

Customer:
Massachusetts Institute of Technology / Tali Figueroa

Funded by the Science Mission Directorate, through the low-cost access to space program.
**High Energy Replicated Optics to Explore The Sun**

HEROES mission, a collaboration with GSFC, was part of the Hands On Project Experience (HOPE), with the primary goal of training NASA scientists and engineers to fly a hard x-ray (20-75 keV) telescope on a balloon platform.

**Heliophysics**
- Investigate electron acceleration in the non-flaring solar corona by searching for the hard X-ray signature of energetic electrons.
- Investigate the acceleration and transport of energetic electrons in solar flares.

**Astrophysics**
- Investigate the scale of high energy processes in a pulsar wind nebula.
- Investigate the hard X-ray properties of astrophysical targets such as X-ray binaries and active galactic nuclei.

**Launch (9/21/2013)**

**Flight**

*Sandia Apr 2015*
### HEROES Optics

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
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<tbody>
<tr>
<td>Mirror shells per module</td>
<td>14 (6 mod), 13 (2 mod)</td>
</tr>
<tr>
<td>Inner, outer shell diameters</td>
<td>50, 94 mm</td>
</tr>
<tr>
<td>Total shell length</td>
<td>610 mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>6 m</td>
</tr>
<tr>
<td>Coating</td>
<td>Sputtered iridium, ~20 nm thick</td>
</tr>
<tr>
<td>Number of mirror modules</td>
<td>8</td>
</tr>
<tr>
<td>Effective area</td>
<td>~ 85 cm(^2) at 40 keV, ~ 40 cm(^2) at 60 keV</td>
</tr>
<tr>
<td>Angular resolution (module)</td>
<td>~25 arcsec FWHM</td>
</tr>
<tr>
<td>Field of View</td>
<td>9 arcmin at 40 keV, 5 arcmin at 60 keV</td>
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Spinoff Application: Neutron Microscopy

Demonstration with small prototype microscope

- Built for small mammal x-ray imaging
- Lens composed of ellipsoid and hyperboloid sections
- 3 nested Ni mirrors (nesting increases flux collection)
- Observed Performance:
  - 75 μm spatial resolution
  - 1 cm FOV & 4x magnification
  - 5 mm depth of focus
  - 5x gain in intensity to pinhole

- 2cm x 2cm Pinhole mask, with 0.1 mm diameters on 0.2 mm centers
- Left: Contact Image; Right: Lens Image

Sandia Apr 2015
Optics for new cold neutron imaging instrument at NIST

Applications:
- Fuel cell development (resolving concentration gradients in electrodes requires the highest possible spatial resolution)
- Lithium-air batteries development (lithium-air batteries have 10x storage capacity of commercial lithium-ion batteries)
- Non-destructive evaluation of nuclear fuel rods life cycle

Also:
- Understand targeted drug delivery
- Advance oil and gas recovery
- Improve the safety of nuclear fuel cladding by imaging the grain structure of ZrH
- Develop additive manufacturing of metal alloys
- Reveal solar cell morphologies to reduce the cost of large area solar arrays
- Enhance efficiency of room temp. magnetic refrigeration by imaging 3D magnetic structures
- Solve protein structures in solution, 2/3 of all proteins can’t be crystallized
- Understand polymer and block copolymer self-assembly and hydrogels
- Distinguish internal structure and morphology of graded nanoparticles
- Understand magnetic nanoparticles for hyperthermic cancer treatment, MRI contrast agents
- And more ...

Source for funding – NIST director’s fund
- Task 1 (Demonstration of high resolution neutron optics)
- Task 2 (Neutron optics with magnification 1)
- Task 3 (Neutron optics with large magnification)

Status – Negotiations on an Interagency Agreement for Task 1

Sandia Apr 2015
Development a grazing incidence optics for medical applications – radionuclide imaging in small animals to perform functional analysis

**Optics**

Novel use of reflective optics

Can provide 100 µm spatial resolution which is 10 fold better resolution compared to existing techniques in the field

~60 mm in length and ~30 mm in diameter; much smaller in size compared to the astronomical optics regularly fabricated at MSFC

**Collaborators**

Lawrence Livermore National Laboratories
Harvard-Smithsonian Center for Astrophysics
University of California @ San Francisco

Funded by – National Institute of Health

**Radionuclide imaging X-ray optics**

Geometry details
Total length = 3 m
Object distance (u) = 0.6 m
Image distance (v) = 2.4 m
Magnification = 4
Reflection angle = 0.5 deg

**Nested shells - Confocal hyperbola and ellipse geometry**
New Developments: Differential Deposition

• **What**
  • Differential deposition is a technique for correcting figure errors in optics

• **How**
  • Use physical vapor deposition to selectively deposit material on the mirror surface to smooth out figure imperfections

• **Why**
  • Can be used on any type of optic, full-shell or segmented, mounted or unmounted
  • Can be used to correct a wide range of spatial errors. Could be used in conjunction with other techniques... e.g. active optics.
  • Technique has been used by various groups working on synchrotron optics to achieve sub-μradian-level slope errors
Process Sequence - Differential Deposition

1. Surface profile metrology
2. Develop correction profile "Hitmap"
3. Simulations - translation velocity of shell
4. Differential deposition
5. Surface profile metrology
6. X-ray testing
Process Sequence – Differential Deposition

Simulated correction sequence showing parabolic axial figure profile before (top left) and after 3 stages of correction using a beam of FWHM = 14mm, 5.2 mm and 1.7 mm respectively. The dotted line gives the desired figure and the solid line gives the figure obtained at each stage. Overall, resolution improved from 7.8 arcsec to 0.9 arcsec HEW (2 bounce equivalent).
Possible Practical Limitations We Are Addressing

- Variation of sputtered beam profile along the length of mirror – particularly for short focal length mirrors – **Model and correct**

- Deviation in the simulated sputtered beam profile from actual profile, beam non-uniformities, etc. – **Quantify and correct**

- Positional inaccuracy of the slit with respect to mirror – **Model effects to derive requirements**

- Metrology uncertainty – **Upgrade metrology system**

- Stress effects – **Quantify and control stress**
Coating Systems (DC magnetron)

Vertical chamber for segmented optics

Horizontal chamber for 0.25-m-scale full shell optics
Coating Systems

*Horizontal differential-deposition chamber*

- X-ray mirror held in a rotating and translating collet
- Sputtering target
- Mask

*Sputtering head with copper mask positioned inside shell*
Test #1: 150 mm diameter shell P-end, 2 stages of correction

Profile pre- & post-correction

Higher-frequencies of profile

Calculated HPD

RMS value of higher-order frequencies
Test # 2: 150 mm diameter shell - 2 stages of correction

Profile pre- & post- correction

Higher-frequencies of profile

Calculated HPD

RMS value of higher-order frequencies

2 bounce equivalent

λ < 4 cm

λ < 4 cm

λ < 4 cm
Differential Deposition – Top Challenges

• Metrology on the inside of the thin shells is very challenging. For 2 stages of correction need to get reliable and repeatable metrology to 10’s Angstrom. Removing and mounting the thin shells for metrology is a tricky business. In-situ metrology, planned in current APRA proposal, would significantly improve matters.

• Stress control is also a challenge. We believe we can demonstrate very-low-stress coatings, but have to investigate the relationship between the properties of coatings in the differential deposition chambers and those in the stress characterization chamber. As an interesting aside it may be possible to use a thin layer of a stressed coating to change the figure instead of filling it in. We are also investigating this.