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.
The Atmosphere Protects Us

Altitude (km)

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First X-Ray Satellite

The UHURU spacecraft was launched in 1970

It weighed just 140 pounds, not much more than the rocket experiment
X-Ray Astronomy

UHURU

Used a simple collimator system, to locate x-ray sources in sky

It operated for 3 years and discovered 339 sources in the whole sky

5. Scan geometry of the UHURU X-ray detectors shown as the projection on a. As the satellite rotates the X-ray detectors view in a $5^\circ$ band, $90^\circ$ from the spin axis.
X-Ray Astronomy

Early observations

From these early observations a picture emerged of a typical x-ray source:

A compact object (neutron star, black hole, white dwarf) orbiting around a normal star

Matter streams down on to the compact object forming an accretion disk

As the matter spirals down and is compressed it gets very hot and emits x rays
Today .. The Chandra Observatory

X-Ray Astronomy Group
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
Chandra Images: Cas-A Supernova Remnant
Chandra Images: Center of our Galaxy
The Crab Nebula and its Pulsar
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 Astronomy Group
X-Ray Optics

- **X Rays undergo total external reflection at shallow graze angles**
  - Critical angle (away from absorption edges)
    \[ \theta_c (\text{deg}) = 0.93 \frac{\lambda (\text{nm})}{\sqrt{\rho (\text{g/cm}^3)}} \]

- **Can use this phenomenon in focusing x-ray telescopes**
  - Reflect x rays to a common focus
  - Single parabola gives severe off-axis distortions, ...
  - Wolter-1 geometry adopted

![Graph showing X-ray reflectivity, nickel at 0.5 deg](image)

![Diagram illustrating paraboloid and hyperboloid surfaces focusing X-rays](image)
Approaches to Fabrication

• X-ray optics are very challenging to fabricate. Because of very short wavelength of x-rays the mirror surface must be smooth to ~ 0.5 nm rms.

• Also, for good angular resolution, the figure must be accurate to < 1 micron.
Approaches to Fabrication

**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: Medium cost, mass (high density of nickel)

**Segmented foil**
ASTRO-E, ASTRO-F, ASCA, BBXRT
Advantage: Light weight, low cost
Disadvantage: Relatively poor angular resolution (arc-minute-level)
Approaches: Chandra
Approaches: Chandra

- Fabricated using thick ceramic, which is meticulously polished and figured, one shell at a time.

- Obtain superb angular resolution \( \text{0.5 arcsec HPD} \)

- But very costly to fabricate ($500M) and very heavy (1000 kg)

- So, other approaches to x-ray optics have been used that trade the superb angular resolution for ease of fabrication and lighter weight (and cost)
Approaches: Foil Optics

- Fabricated using very thin aluminum foils as reflectors. Foils held in slots in housing.

- Obtain poor angular resolution – 1-2 arcminute HPD

- But extremely light weight allowing for many individual reflectors, and thus large collecting area
Approaches: Electroformed Nickel Replication (ENR)

- Electroform thin nickel shells from superpolished and figured masters (mandrels)
- Obtain intermediate level angular resolution (~ 15 arcsec HPD)
- But considerably less expensive to fabricate and considerably lighter
- Electroformed nickel optics are being fabricated at MSFC for various programs.
Challenges for Future Missions

Einstein Observatory (HEAO-2)
1978-1981 (f = 3.3 m, A = 0.04 m²) 10"

Röntgen Satellit (ROSAT)
1990-1999 (f = 2.4 m, A = 0.10 m²) 5"

Chandra X-ray Observatory (AXAF)
1999-? (f = 10 m, A = 0.11 m²) 0.6"

XMM-Newton
1999-? (f = 7.5 m, A = 3 × 0.18 m²) 14"

International X-ray Observatory (IXO)
2022+ (f ≈ 20 m, A ≈ 3 m²) 5"

Generation X
2035+ (f ≈ 60 m, A ≈ 50 m²) 0.1"

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Mirror Fabrication for (near) Future Missions

Slumping 0.4-mm glass

Cutting

Coating

Measuring

<table>
<thead>
<tr>
<th>Mandrel</th>
<th>Mirror</th>
<th>Transfer Mount</th>
<th>Module</th>
<th>Assembly</th>
<th>Observatory</th>
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Schedule/Cost → Core of Technology Development → Design, Analysis, & Test
How can we achieve sub-arcsec resolution with thin optics?

One option is to utilize active control of mirror figure, as is done in optical astronomy.

Figure 3: By appropriate adjustment of an array of surface-tangential actuators, a controlled deformation corrects the figure of a distorted mirror at the longer spatial wavelengths. The left panel schematically represents such an array on the back of a thin mirror segment. The right panel illustrates the application of a correction map to an error map, resulting in a mirror with low-spatial-frequency distortions removed.
Mirrors for (far) Future Missions – Active Optics

Technique has been used for synchrotron x-ray optics, but in its infancy in x-ray astronomy.

• Difficulty is the football-field-size areas that must be controlled.

• Algorithms needed that converge

• Power requirements and stability, etc
Mirrors for Future Missions – Differential Deposition

Vacuum deposit a filler material to compensate for figure imperfections

Proof of concept work underway at MSFC

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Process sequence - differential deposition

- X-ray testing
- Surface profile metrology
- Develop correction profile "Hitmap"
- Simulations - translation velocity of shell
- Differential deposition
- Surface profile metrology
- X-ray testing
Theoretical performance improvement

Simulations performed on X-ray shell profile of 8 arc sec simulated HPD

<table>
<thead>
<tr>
<th>Correction stage</th>
<th>Average deposition amplitude (nm)</th>
<th>Slit-size (mm)</th>
<th>Angular resolution (arc secs)</th>
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<tr>
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Possible practical limitations

• Variation of sputtered beam profile along the length of mirror - particularly for short focal length mirrors

• Deviation in the simulated sputtered beam profile from actual profile, beam non-uniformities, etc

• Positional inaccuracy of the slit with respect to mirror

• Stress effects

• Metrology uncertainty

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# Metrology limitation

Simulations performed on X-ray shell of 8 arc sec

Simulated HPD

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<tr>
<th>Correction stage</th>
<th>Average deposition amplitude (nm)</th>
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<td>0.5</td>
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<td></td>
<td>± 2</td>
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- Potential for ~arc-second-level resolution - with MSFC's metrology equipment
- Sub-arc sec resolution could be possible with the state-of-art metrology equipment
Mirrors for Future Missions – Differential Deposition

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### Material and process selection

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<th>Deposition Rate</th>
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<td>1.868</td>
<td>0.370</td>
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Units: power-Watts, pressure-mTorr, roughness- Å rms, deposition rate – Å/sec
Proof of concept on few-cm-scale medical imaging optics

Slope error improvement from 12 arc sec to 7 arc sec rms

Figure error improvement from 0.11 µm to 0.058 µm rms

X-Ray Astronomy Group
Current Status

- Since submitting this RFI response we have been notified of APRA /ARA funding
- This will allow us to build a custom system and demonstrate the technique on larger full shell (MSFC) and segmented (GSFC) optics
- We hope to be able to demonstrate < 5 arcsec performance in 3 years
- To go beyond this, (arcsecond level) is very difficult to judge as we have not yet discovered the problems.
  - May necessitate in-situ metrology, stress reduction investigations, correcting for gravity effects, correcting for temperature effects
  - Some of this will become obvious in early parts of the investigation
  - Top-of-head estimate - ~ 5 years total and additional $2-3M
Long Trace Profiler

• Pencil beam interferometry

• Measure spatial wavelengths starting from 1 mm up to several 100’s of mm

• Laser beam scans point-by-point - slope data

• Position of the beam at the detector - direct measure of the slope

• Accuracies possible <1 urad

• Multiple measurements - 2D topography

 cười Time taken to measure is about 5 mins for 300 mm sample length

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Increase the speed?

- Make use of advanced technology
- Higher resolution 2D detectors
- Stable optical sources
- Increase the speed & accuracies of measurements
- Higher density data - complete information of mandrel or shell
- Multiple beams - simultaneous measurements?
Multi-beam LTP

- Proof-of-concept
- To study the limitations of the approach

X-Ray Astronomy Group

- Number of beams - 5 to 10
- Spatial separation of beams - 1 to 2 mm
Multi-beam LTP Requirements

- Target – decrease the time of measurement – reasonable accuracy

- Existing systems
  - linear array detector – 25 µm X 2.5 mm pixel size
  - 1 m focal length FT lens
  - Lens and detector → 0.25 µrad

- 2D detector requirements
  - multiple beams in one plane and
    beam translation on other plane
  - angular range +/- 15 mrad
  - Detector at least 20 mm X 20 mm area
  - < 8 µm pixel size

<table>
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<tr>
<th>fl (mm)</th>
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<th>550</th>
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<th>700</th>
<th>800</th>
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Resolution (µrad)

X-Ray Astronomy Group
2D CCD detector & FT lens

- Detector Procured (1st Vision's JAI AM-1600GE)
  - 36 mm x 24 mm area
  - 7.4 x 7.4 µm pixel size
  - 3.04 fps

- Custom designed FT lens
  - 500 mm focal length
  - 50 mm diameter
  - Low distortion - minimize the effects of lens on systematic errors
FT lens design

- Less number of elements - two element system
- Air-spaced doublet lens

### Table: FT lens design

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<td>It has no distortion for config</td>
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### Diagram:

- Beam splitter
- FT lens

- Anti-reflection coating

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Multiple beam generation

- Multiple beams of almost equal intensity
- Spatial separation (2.4 mm)
- Angular separation (250 µrad)
- Wedged etalon approach
- Customized coating on one side
- 100% reflection coating on the other

- Dimension - 50 x 50 x 3 mm
- Wedge - 60 µrad
Coating - wedged etalon

Possible approaches

- Continuous ideal gradient coating
- Linear approximation to ideal
- Multilayers
- Discrete coatings - each with constant reflectivity

X-Ray Astronomy Group
Multiple beam generation - wedged etalon

- Silver coating with step reflectivity approach

<table>
<thead>
<tr>
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<th>2</th>
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<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_z %$</td>
<td>93.33</td>
<td>92.86</td>
<td>92.31</td>
<td>91.67</td>
<td>90.91</td>
<td>90.00</td>
<td>88.89</td>
<td>87.50</td>
<td>85.71</td>
<td>83.33</td>
</tr>
<tr>
<td>$T_z %$</td>
<td>6.67</td>
<td>7.14</td>
<td>7.69</td>
<td>8.33</td>
<td>9.09</td>
<td>10.00</td>
<td>11.11</td>
<td>12.50</td>
<td>14.29</td>
<td>16.67</td>
</tr>
</tbody>
</table>
Cube beamsplitter

- Purchased 50mm X 50 mm beam splitter - tested with zygo for wavefront error
- Analysis of test result in progress
Software

- Berkeley National Labs - provided software code
- 3 beams - being adapted to new detector for multiple beams - Maxima of single peak
- Tests are underway to check the speed of readout & processing - 0.5 fps for full frame of 4872x3248 - 1.3 fps for partial frame of 4872x800
Future work

- Immediate work
  - Replace detector
  - Etalon test & analysis
  - Detector software

- Assemble components
- Test measurements
- Modular approach