Technical Challenges for AXIS

R. Mushotzky for the AXIS team
### AXIS in a Nutshell

**Advanced X-ray Imaging Satellite**  
R. Mushotzky  UMD

- **New lightweight single-crystal silicon optics** with high angular resolution and collecting area and a modern CCD with higher sensitivity and spectral resolution than Chandra
- **LEO orbit** will minimize background, allow rapid response to TOOs and extend lifetime (>5 yrs, no consumables)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Resolution</td>
<td>~0.3 arc sec</td>
</tr>
<tr>
<td>Bandpass</td>
<td>~0.1-12 keV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>4400 cm$^2$ @1 keV; 1500 cm$^2$ @ 6 keV</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>150 eV @ 6 keV (CCD resolution)</td>
</tr>
<tr>
<td>Total count rate /source</td>
<td>10x Chandra’s at launch</td>
</tr>
<tr>
<td>Detector Background</td>
<td>5x lower than Chandra</td>
</tr>
</tbody>
</table>
Top Level Science Goals

- Image galaxies at the peak of star formation
- Probe regions within $10R_s$ of black holes via gravitational lensing
- Understand how accretion occurs in active galaxies via imaging the Bondi radius
- Constrain star formation and AGN feedback out to very high redshifts
- Measuring black hole mergers by obtaining the largest sample of 'dual' AGN
- Search for the first black holes
- Provide rapid response for transient/time variability science

Other science: a vast increase in sample size of objects with “exciting” structure, such as clusters of galaxies, SNR, PWN, spatially resolved SNR in local group galaxies, jets, and star forming regions and x-ray binaries to $D \sim 5$ Mpc.
Goals and Implementation

High Angular Resolution with large collecting area and large field of view.
Minimum 10x Chandra's collecting area at 1 keV and similar or better angular resolution with wider field of view.

Baseline Design
Programmatic Constraints

AXIS is a Probe class mission being considered for submission to the 2020 NAS Decadal Survey In Astronomy and Astrophysics

Probe class <$1B (strong limit)- mass is $$- keep it light and as simple as possible One telescope, one detector

Desire to be selected by Decadal for a launch in ~2028

Schedule
Will have an 'engineering run' at GSFC IDL and MDL in Jan/Feb 2018- need sufficient inputs by then to get a good handle on costs and issues

Report to be delivered to NASA Hdqtrs Dec 2018 (costs to be reviewed by NASA SOMA in spring 2019)

Decadal review mid-2019-late 2020
IF Decadal 'selects' AXIS could have start of phase-A in FY 2022

To support that date need
telescope and detector TRL 5 by 2020
need high TRL by 2022
Technical Challenges for X-ray Optics

How to achieve high angular resolution at low mass and low cost consistent with the other requirements

Chandra mirrors (1995 technology) are heavy and expensive

A 20 year program dating back to Con-X/IXO to develop lightweight optics with the right parameters

(GSFC team led by W. Zhang)

Optical design
  Fundamental geometry and physics
  AXIS mirror design

Technology
  Substrate fabrication
  Coating
  Alignment and bonding

Engineering
  Structural, thermal, and optical performance
X-ray Optics- Geometry and Physics

(1/2)

• X-rays reflect only at grazing angles
  – Grazing angles decrease with energy
  – Field of view decreases with energy

• An X-ray telescope is really different
  – Many concentric shells
  – X-rays from different shells add incoherently

Chandra web site
Practical Implications

• On-axis PSF conflicts with FOV
  – Good on-axis PSF demands long shells
  – Good off-axis PSF demands short shells

• Dichotomy of Soft and Hard X-rays for a nearly diffraction-limited Telescope
  – Soft X-rays: poor on-axis PSF because of diffraction, but large FOV because of geometry
  – Hard X-rays: good on-axis PSF because of diffraction, but small FOV because of geometry and basic physics
### An Example Design for AXIS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length (mm)</td>
<td>9,000</td>
</tr>
<tr>
<td>Outer Diameter (mm)</td>
<td>1,500</td>
</tr>
<tr>
<td>Inner Diameter (mm)</td>
<td>400</td>
</tr>
<tr>
<td>Mirror Segment Axial Length (mm)</td>
<td>200</td>
</tr>
<tr>
<td>Mirror Segment Thickness (mm)</td>
<td>0.5 (1.0)</td>
</tr>
<tr>
<td>Unobstructed FOV (arcmin)</td>
<td>15</td>
</tr>
<tr>
<td>Coating</td>
<td>iridium</td>
</tr>
<tr>
<td>No. of shells</td>
<td>163</td>
</tr>
<tr>
<td>Diffraction limits (arcsec 90%dia.)</td>
<td>0.2 @ 1 keV</td>
</tr>
<tr>
<td>Mass of Mirror Assembly (kg)</td>
<td>~500 (~1,000)</td>
</tr>
</tbody>
</table>
Base Line Design

Under reasonable assumptions:

Focal length: 9 meters
Outer diameter: 1.5 meter
Mirror thickness: 0.5 mm

• AXIS mirror can have effective areas
  – 5,000 cm$^2$ at 1 keV beats Chandra by 10x
  – 100 cm$^2$ at 10 keV beats Chandra by 20x

• AXIS’s PSF and FOV
  – More or less uniform 0.5” HPD in a 15-arcmin dia. FOV- beats Chandra by 8x
  – Similar or Better PSF on-axis
Chandra/AXIS Effective Area Ratio vs. Energy

![Graph showing Chandra/AXIS Effective Area Ratio vs. Energy]
The Meta-Shell Paradigm

- Each mirror segment is fabricated, qualified, and then aligned by and bonded to four spacers which kinematically constrain it.
- Several hundred mirror segments are aligned and bonded to form a meta-shell.
- A dozen or so meta-shells of different diameters form the final mirror assembly.
Fabrication Steps

- Monocrystalline silicon block
- Conical form generated
- Light-weighted substrate
- Etched substrate
- Polished mirror substrate
- Trimmed mirror substrate
Summary of Engineering

• Meta-shell approach
  – Advantages of full shell optics but with an order of magnitude more collecting area

• Preliminary structural, thermal, and optical analysis completed to mature the system design
  – Shows 0.5” mission is feasible

• Prototype load testing demonstrates the meta-shells are robust

• Development continues: design, analysis, testing
Technical Accomplishment/Challenges

Development of thin shells with the required figure and surface roughness ✔

Coating the shells in progress

Aligning and Bonding the shells to a mirror assembly current priority

Integration of mirror assemblies into telescope in progress

_all areas are being actively pursued_
Technical Challenge: Mirror Fabrication

• Mirror substrate fabrication
  – A combination of traditional polishing and ion-beam figuring can meet figure and roughness requirements.
  – Challenge: precision lapping tool manufacturing.

• Measurement of mirror segments
  – Use a combination of Fizeau interferometer and a cylindrical null lens that converts between plane wave and cylindrical wave.
  – Challenges:
    • Fabrication of flat reference standard
    • Fabrication of cylindrical lens

• Production process engineering
  – Use a combination of commercially procured machines and parts.
  – Challenges: process automation using robotics to minimize labor cost and shorten manufacturing time.
Technical Challenge: Coating

• Coating
  – Use either the magnetron sputter process or the atomic layer deposition process to coat a thick layer of iridium as the baseline reflecting material.
  – Adding an overcoat, such as $\text{B}_4\text{C}$, $\text{Al}_2\text{O}_3$ can significantly increase reflectivity.
  – Challenge: need a way to cancel or balance the coating stress to preserve mirror figure.
Technical Challenge: Mirror Bonding

• Mirror segments are bonded with epoxy to form meta-shells which are, in turn, bonded to a spider for structural interface to observatory.

• Challenges: Need an epoxy that meets the following requirements
  – Low out-gas.
  – At least as strong as Hysol 9309 which is more or less a standard epoxy uses for many spaceflight applications.
  – Much shorter cure time than Hysol 9309’s 24 hours. A 2 hour cure time would be ideal.
Need to convince the Decadal!

- **Performance**
  - Effective area
  - Angular resolution

- **Mass**
  - Mass is money!
  - AXIS mirror assembly ~ 500 kg

- **Cost/Schedule**
  - Mirror cost should be less than $160M + 30%=$200M in RY$. (Cf. Chandra’s FY99 $600M for 1,500kg $0.4M/kg). AXIS’s mirror is also $0.4M/kg, but with RY$.
  - Must be done in less than 5 years, preferably in 4 years.
Detector Drivers

Want to sample the mirror PSF (plate scale is $\sim 50\mu$ arc sec, 0.3" HWFM PSF, x-ray PSFs are $\sim$ Lorentzian in shape)

Cover large energy range (0.1-12kev) consistent with mirror capability

Good energy resolution (as close as possible to Fano factor limited)

Little or no pile-up for 'most' science targets

'Good' time resolution

Low detector background

Long detector life

Cover field of view
Detector technology and capabilities

Available technologies
   CCD (charge coupled device)
   APS (active pixel sensor)

CCD is Notional AXIS detector

trades involve
   • background
   • radiation damage to detectors
   • cost and schedule
   • pixel size
   • energy resolution
   • energy range covered
   • read-out rate
   • power consumption
   • operating temperature
CCD Detector

- doped, depleted Si substrate converts X-rays to charge
- transfer charge across device to readout
  - integration time ~ seconds; limited by readout from frame store region, amplifier speed, external analog-to-digital converter
- flown on ASCA, Chandra, XMM, Suzaku, Swift, Hitomi, ...
- development for Lynx, Explorers (MIT/LL)
CCD Advantages
Proven performance in many missions: proven spectral resolution, low readout noise, high uniformity, proven soft response, possibility of small pixels and deep depletion

Drawbacks: lower readout rates, radiation damage, power consumption

Active Pixel Sensor Advantages

higher read-out rate
less sensitive to radiation
on-chip integration of signal processing electronics
lower power consumption

drawback: lower TRL level
# CCDs vs. APS

<table>
<thead>
<tr>
<th>Feature</th>
<th>APS</th>
<th>CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>fast readout</strong></td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>why: reduce pile-up, improve dynamic range, timing resolution</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>problems: increased noise, power (Fano limit @ 0.2 keV is 2.5 e⁻)</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td><strong>small pixels</strong></td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>why: take advantage of angular resolution, better BG rejection</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>problems: manufacturing, requires faster readout, more digital processing, more split events so very accurate pixel gain calibration required (over high dynamic range for APS)</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td><strong>deep depletion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>why: increase hard X-ray sensitivity, better BG rejection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>problems: complicated by structure of 3-D integrated detector + amplifier (monolithic CMOS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>radiation tolerant</strong></td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>why: better spectral resolution, lower dark current, fewer bad pixels</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>problems: requires cooling, charge injection, optimal orbit</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td><strong>flight heritage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>why: detectors need to work in space</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>problems: only CCDs have flown for X-ray detectors</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Base Line Detector Design

- 4 back-illuminated (BI) CCDs in 2x2 array, 4.2 cm (15’) FOV
- 2600 x 2600 imaging array of 8 µm (0.2”) pixels
  - Optional onboard binning to 16 µm (0.4”)
- 50–100 µm depletion (0.2–10 keV sensitivity)
- 64–128 outputs @ 2–5 MHz readout rate
- 20–75 frame/sec (60–200x Chandra)
  - Minimize pile-up, allow fast timing
- Readout noise < 2e⁻ (but charge splitting with small pixels)
- Frame-transfer architecture
- Charge injection to mitigate radiation-induced CTI
- CBF QE with OBF: 25% (0.2 keV), 75% (0.5 keV), >90%
CCD Analog Electronics

• Convert analog voltage from CCD outputs to digital pixel values
• Must read 256–512 channels each at 2–5 MHz
  • ~1–2 Gpix/s total
• Additional noise < 1e- (charge splitting with small pixels)
• Use ASICs? e.g. Athena:
  • 64 channels each operating at 500 kHz using 0.5 W
  • Amplifiers limited to 0.5 MHz ?
• Some power, mass, thermal considerations
• Other possible technologies?
Technical Challenges: CCD Amplifiers

- Fast frame transfer (5 MHz) with low noise (1 e⁻)
- Previous X-ray CCDs use n-channel MOSFET with 2 e⁻ noise at < 1 MHz (e.g. Chandra/ACIS)
- Current designs use p-channel JFET with 5 e⁻ noise at < 5 Mhz
- AXIS amplifier design must be single-electron-sensitive with high responsivity to take advantage of spatial resolution
  - Charge from X-rays split into many pixels
  - Pixels are combined to reconstruct photon energy
  - Noise term adds per pixel!
- Development of fast, low-noise amplifiers is vital need
Technical Challenges: CCD Power

- CCDs transfer charge by varying voltage of gate electrodes ("bucket-brigade")
- Previous gate structure uses multiple layers of polysilicon, and requires high voltage and power to clock many pixels rapidly and reliably
- New single-layer gate structure in development
  - Fewer fabrication steps, fewer defects, more uniform
  - More reliable charge transfer
  - Low (<3 V) clock swings can be controlled by CMOS circuitry, allowing huge power savings
- Development of low power CCDs is vital need
Technical Challenges: On-board Processing

- Find and filter X-ray events; we can’t telemeter the entire image frame!
- Must process ~1–2 Gpix/s:
  - Find events from local maxima
  - Filter based on surrounding pixels (remove particle tracks)
  - Any science processing (e.g. source catalog, find transients)
  - Package and telemeter event list
- CPU on TESS processes pixels at 4% of this rate
- Major power, mass, thermal considerations
- Development of fast, low-power, high-TRL processing electronics is vital need
Low Inclination LEO Gives Very Low Cosmic ray Dose - Long Detector Life

Displacement Damage Dose (MeV g(Si)^{-1})

- high-Earth (Chandra)
- high-Earth (L2)
- low-Earth 32° inclination (Suzaku)
- low-Earth 0° inclination (equatorial)

Thickness (mm)

Catherine Grant (MIT)
Low Inclination LEO Gives Very Low Detector background at E > 1 keV

Gives ~10x lower background at E > 1 keV
The Spacecraft and Mission

- Need for rapid slewing to obtain high observing efficiency
  - Issues: long spacecraft (>9m), moderate mass ∼1600kg, moderate power ∼650W, keep costs low
- Desire for 'large' fraction of the sky to be available at any one time
  - Issues: movable solar panels and thermal design
- Need very accurate astrometry (goal is 0.1" relative astronomy, 0.3" absolute)
  - Issues: thermal environment in LEO: ability to 'rapidly' settle after slews; relative alignment of detector to sky and to telescope, jitter at < 0.1" on detector read-out times (∼50ms), metrology of spacecraft/fiducial light system.
- Need to keep contamination low (outgassing on detector filters)
Rapid Response Goal

Be similar to the Swift mission:

• Swift gets ~1 request/day for a 24 hour response. Only 2.7% of all Target-of-Opportunity (TOO) requests require a <= 4 hour response (~30/year).

• Total number of requests is ~1000/yr (400 of which request response within 1 week).
The Spacecraft and Mission

- Launch vehicle of choice (today) Falcon 9
  - issues: need to fit in Falcon 9 fairing (gain in science up to ~12m); ability to launch to low inclination LEO
- Mission ops: Science driver of ability to do TOOs requires 'rapid' replan activity (goal is ~4 hours response several times a week similar to Swift):
  - Issues flexible planning, ease of contact with the spacecraft, data rates
- Onboard processing of data
  - Event processing to only telemeter X-ray photon events
## Chandra Aspect System Requirements and Performance

<table>
<thead>
<tr>
<th>Description</th>
<th>Requirement</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Celestial location</td>
<td>1.0″ (RMS radius)</td>
<td>0.53″</td>
</tr>
<tr>
<td>Image reconstruction</td>
<td>0.5″ (RMS diameter)</td>
<td>0.3″</td>
</tr>
<tr>
<td>Absolute celestial pointing</td>
<td>30.0″ (99.0%, radial)</td>
<td>8″</td>
</tr>
<tr>
<td>PCAD 10 sec pointing stability</td>
<td>0.12″ (95% RMS)</td>
<td>0.06 ″ (pitch)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.05″ (yaw)</td>
</tr>
</tbody>
</table>

For AXIS we would like 0.1″ astrometry, 0.1″ image reconstruction, 30″ absolute pointing and 0.07″ 10sec pointing stability
Can we meet our pointing stability and slewing requirements in LEO?
• With combination of mechanical jitter mitigation, accurate metrology, spacecraft design, and operations we think YES. Costs and details, of this and deorbiting, TBD

What is the ideal balance of FoV, on-axis PSF and PSF uniformity?
• We think we can achieve 0.5” over 15’ diameter. Is this FoV wide enough?

APS or CCD?
• We are pursuing point designs of both to compare readiness, energy range, energy resolution, thermal and power requirements, radiation damage, readout rates, processing requirements.

APS and CCD.
• Electronics and processing details TBD.
• Depletion depth? Hard QE versus soft QE and energy reconstruction
• Pixel size? Need readout noise low enough so that we sample the PSF while maintaining good energy resolution and knowledge
• Contamination – blocking filter and impact on low-energy QE, heating
• Detector layout – can the chips be tiled to maximize PSF uniformity?
Extra Slides
Detector Drivers

Want to sample the mirror PSF (plate scale is ~50µ/arc sec, 0.3" HWFM PSF)

Cover large energy range (0.1-12kev) consistent with mirror capability

Good energy resolution (minimum is CCD Fano factor limited)

Little or no pile-up for 'most' science targets

Good time resolution

Low detector background

Long detector life
Detector Resolution

Baseline detector Digital CCDs with read out rate of $x$

8$\mu$m pixels- for 15' FOV Diameter $55 \times 10^3 \times 55 \times 10^3$ pixels ($3 \times 10^9$ pixels)

Low earth low inclination orbit for long life

Modern back illuminated CCDs or APS for low E response

Available technologies
- CCD (charge coupled device)
- APS (active pixel sensor)
**Digital CCD – MIT Lincoln Laboratory/MKI**

**Concept:** Hybrid CCD-CMOS Imager
- High Frame Rate
  - Very fast outputs (~5 MHz)
  - Integrated parallel signal chains
- Low Noise: High-responsivity, sub-electron read noise amplifier
- Low-power: CMOS-compatible CCD

**Current status:** CMOS-compatible CCD with conventional amplifier:
- Noise < 7 e^- RMS @ 2.5 MHz (25x faster than Chandra)
- Excellent charge transfer at CMOS levels (±1V; ~same clock power/area as Chandra @ 25x higher rate)
- 8 μm pixels (oversamples Lynx PSF)

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![Test Device Image]

**Response at 2.5 MHz**
- FWHM 142 eV at 5.9 keV

\[ FWHM_{Fano} = 116 \text{ eV} \]
# Optics Top Level Error Budget

<table>
<thead>
<tr>
<th>Parameter or Process</th>
<th>Contribution to HPD (&quot;)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mirror Segment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial figure (sag)</td>
<td>0.1</td>
<td>Shown as of June 2017</td>
</tr>
<tr>
<td>Axial figure (other than sag)</td>
<td>0.2</td>
<td>Shown as of June 2017</td>
</tr>
<tr>
<td>Focus (roundness, cone angle and its variation)</td>
<td>0.2</td>
<td>Probably can be shown by 2018</td>
</tr>
<tr>
<td>Coating (distortion to axial figure and focus)</td>
<td>0.1</td>
<td>Difficult to assess due to insufficient data.</td>
</tr>
<tr>
<td><strong>Integration of segments to meta-shells</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alignment</td>
<td>0.1</td>
<td>By 2019</td>
</tr>
<tr>
<td>Bonding</td>
<td>0.2</td>
<td>Difficult to assess. Emphasis of work in coming years. Tallest pole!!!</td>
</tr>
<tr>
<td><strong>Integration of meta-shells to assembly</strong></td>
<td>0.1</td>
<td>Can be done relatively easily.</td>
</tr>
<tr>
<td>Launch shift</td>
<td>0.1</td>
<td>Need to be looked at.</td>
</tr>
<tr>
<td>Thermal gradients</td>
<td>0.1</td>
<td>Shown by analysis as of June 2017.</td>
</tr>
<tr>
<td>Gravity release</td>
<td>0.1</td>
<td>Shown by analysis as of June 2017.</td>
</tr>
<tr>
<td><strong>Mirror Assembly Fabrication Total</strong></td>
<td>0.4</td>
<td>RSS of all above numbers.</td>
</tr>
<tr>
<td><strong>Mirror Assembly Optical Design Total</strong></td>
<td>0.3</td>
<td>Timo Saha’s design memo.</td>
</tr>
<tr>
<td><strong>Mirror Assembly On-Orbit Performance</strong></td>
<td>0.5</td>
<td>RSS of above two numbers.</td>
</tr>
</tbody>
</table>
Coating

- Coating is an essential part of a strategy to meet effective area requirements
  - A good coating is a necessity, not an option

- Noble metal coating
  - Au: Low stress ↔ Low reflectivity
  - Pt: Medium stress ↔ Medium reflectivity
  - Ir: High stress ↔ High reflectivity

- Other possibilities
  - An iridium layer plus an overcoat of B$_4$C or Al$_2$O$_3$
Approach to Alignment & Bonding

- Use **kinematic mount** to minimize/eliminate distortion to mirror segments
- Use **finite element analysis** to optimize locations of supports
- Use epoxy as **adhesive only**, not as a filler of any space that is not precisely controlled
- Use **gravity**, the most repeatable force, as the nesting force
Proof of Concept Module

Accomplished as of May 2017
Single pair of mirrors aligned, bonded, and X-ray tested.

Expected to be accomplished by December 2017
Multiple pairs of mirrors aligned, bonded, and X-ray tested.
Meta-Shell Approach

• Meta-shell integrates many four spacer mounted segments
  – Interlocking layers of mirror segments bonded onto a central structural shell (silicon)
  – Mirrors are cantilevered off structural shell similar to NuSTAR
  – Brick-like buildup spreads the load
• Once complete, meta-shell is similar to a full shell with an order of magnitude more collecting area
  – Structurally stiff (all silicon)
  – Rotationally symmetric
  – Insensitive to tilt
  – Leverage Chandra and XMM-Newton heritage
Mirror Assembly Production (2/2)

• One prime contractor with TBD subcontractors
  – Two to four parallel lines of production of mirror substrates
  – Two parallel lines of meta-shell construction
  – One mirror assembly integrator and tester (I&T)

• Detailed production facility and schedule
  – All needed information in hand for making step-by-step or blow-by-blow schedule

• Detailed grass-roots cost estimate
  – Production and engineering costs understood
  – Management cost to be estimated based on past experience
NASA TRL

TRL 9
• Actual system “flight proven” through successful mission operations

TRL 8
• Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 7
• System prototype demonstration in a space environment

TRL 6
• System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
• Component and/or breadboard validation in relevant environment

TRL 4
• Component and/or breadboard validation in laboratory environment

TRL 3
• Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
• Technology concept and/or application formulated

TRL 1
Total Backgrounds
Instrument+ Sky
Figure of Merit for Background Limited Observations

A - effective area
F = focal length
B = detector background
~100x Chandra
Comparison of Chandra and AXIS

Incomplete Charge Collection

AXIS and Chandra Spectrum of Highly Absorbed Source
Better charge collection—much smaller tail to events
High Energy Comparison

20x more area at E > 9 keV
Baseline Detector

Back illuminated digital CCDs with read out rate of ~0.2 sec in full imaging mode- (8x faster in window mode)

8µ pixels- for 15' FOV Diameter $45 \times 10^3 \times 45 \times 10^3$ pixels ($31 \times 10^6$ pixels)

Low earth low inclination orbit for long life

• 50–100 µm depletion (0.1–10 keV sensitivity)
• 16 outputs @ 5 MHz 6 frame/sec (20x Chandra)

Goal of 122 frames/sec (400x Chandra) with 128 outputs – timing science and minimize pile-up; 3.8Ghz rate
Technical Challenge: Mirror Fabrication

• **Figure quality is almost met**
  – A combination of traditional polishing and ion-beam figuring
  – Micro-roughness can be met as well

• **Measurement challenges**
  – Flat reference standard needed for measuring figure error
  – A high quality cylindrical lens needed to convert plane waves to cylindrical waves

• **Production process engineering challenges**
  – Automation design and implementation
  – Robotics to minimize labor need
Technical Challenge: Coating

• Coating stress
  – Thin film (~20nm of iridium) stress severely distorts mirror figure, leading to PSF degradation.
  – Many proposals exist to use an overcoat, such as B₄C, Al₂O₃ to significantly increase reflectivity, but these overcoats also have high stress.
    • Need a way to cancel or balance the coating stress to preserve mirror figure.
Technical Challenge: Mirror Bonding

• Epoxy shrinkage that tends to distort mirror
  – Need an un-doped epoxy that has the least amount of shrinkage during cure

• Epoxy strength
  – Need an epoxy that is stronger than Hysol 9309 which is commonly used for spaceflight.

• Epoxy cure time
  – Epoxy must cure fast so that many mirrors can be bonded in a given amount of time.
  – Need an epoxy that is as stronger than Hysol 9309, but can cure in less than 2 hours.

  – In sum Need an epoxy that is as stronger than Hysol 9309, but can cure in less than 2 hours that has little shrinkage
Engineering Challenge

• Integration of meta-shells into the mirror assembly issues
  – Large parallel optical beam: 2 m in diameter
  – Effect of gravity

• Need Overall Systems engineering
  – Structural and thermal design and analysis
  – Ray-trace all deformations to understand their effects on PSF