Optics requirements for the Generation-X x-ray telescope

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Generation-X Astrophysics Strategic Mission Concept Study is underway.

- **Generation-X** would launch in 2030+.
  - Largest-area, highest-resolution x-ray telescope
- **Purpose of ASCMS**
  - Make science case for mission.
  - Identify plausible mission architecture.
    - Aries-V launch to sun-earth L2
  - Lay out technology development plan.
    - Science instruments
    - **X-ray optics**
      - Identify key technology & manufacturability issues.
      - Formulate a roadmap to bring to technology readiness level TRL6 ... and to manufacturing readiness.
Outline

- **Fundamental needs for future x-ray telescopes**
  - Sharp images $\Rightarrow$ excellent angular resolution.
  - High throughput $\Rightarrow$ large aperture areas.

- **Generation-X optics technical challenges**
  - High resolution $\Rightarrow$ precision mirrors & alignment.
  - Large apertures $\Rightarrow$ lots of lightweight mirrors.

- **Innovation needed for technical readiness**
  - 4 top-level error terms contribute to image size.
  - There are approaches to controlling those errors.

- **Innovation needed for manufacturing readiness**
  - Programmatic issues are at least as severe.
Higher resolution improves both imaging quality and sensitivity (noise reduction).

Aperture area improves sensitivity (signal increase), down to the confusion limit.
Astronomical x-ray telescopes need large area and high-resolution imaging.

- **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**
  - 1999-2020 (f = 10 m, A = 0.11 m²) 0.6″

- **XMM-Newton**
  - 1999-2030+ (f = 7.5 m, A = 0.5 m²) 14″

- **International X-ray Observatory (IXO)**
  - ≈2020 (f ≈ 20 m, A ≈ 4 m²) 5″

- **Generation X**
  - 2030+ (f ≈ 50 m, A ≈ 60 m²) 0.1″
NASA, ESA, & JAXA are developing two candidate optics technologies for IXO.

**SLUMPED GLASS**

- Mandrel: 6" 2.0"
- Mirror: 10" 3.5"
- Transfer Mount: 10" 3.6"
- Module: 12" 4.0"
- Assembly: 13" 4.5"
- Observatory: 15" 5.0"

**SILICON PORE STACKS**

- Cutting
- Coating
- Measuring

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The aperture areal-mass constraint for Generation X is similar to that of IXO.

≈100× better angular resolution
The aperture-area requirement for Generation X more than $10 \times$ that of IXO.

≈10× larger aperture area

- Generation X goal
- IXO rqmt:demo (slumped glass)
- IXO rqmt:demo (silicon pore)
- XMM-Newton (nickel replicas)
- Chandra (Zerodur)
- ROSAT (Zerodur)
- Einstein (quartz)

Half-power diameter [arcsec]

Aperature area [m²]
In principle, segmented optics may be scalable to arbitrarily large areas.
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There are 4 top-level terms in the error budget for 0.1” HPD (0.074” RMS blur)

- Mirror surface quality
  - Microroughness scatters far outside 0.1” ⊗.
  - Slope deviations < 0.026” = 0.125 μrad RMS.
- Mirror mounting
  - Mount must not distort mirror, or
  - Must be able to correct any distortions.
- Mirror-pair (P–S) alignment
  - Accuracy of P–S slope difference < 0.037” RMS.
- Positioning of aligned mirror pairs
  - Accuracy of co-location < 0.36μ×F RMS.
    - P–S pairs are not sensitive to overall tilt errors.
There are alternative approaches for addressing each error contribution.

- **Mirror surface quality**
  - Replicate to requirements at >mid-f.
  - Correct >mid-f figure of replica (in situ).

- **Mirror mounting**
  - Align very stiff mirrors with correct low-f figure.
  - Actively correct low-f figure of flexible mirrors.

- **Mirror-pair (P–S) alignment**
  - Align separate P and S replicated mirrors.
  - Replicate integral P+S mirror from mandrel.

- **Positioning**
  - May need rigid-body adjustment on-orbit.
Requirement on axial-slope deviation is near state-of-art, even for thick mirrors.

- Chandra optics
- Con-X TD full mandrels
- Con-X TD slab mandrels
- 5" IXO optics rqmt
- 2" IXO mandrel rqmt
- Generation-X optics rqmt
- Synchrotron spheres
- Synchrotron flats

BESSY flat, figured to 0.12-μrad RMS residual slope, by Zeiss

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For a typical x-ray band, surface area is about 200 times the aperture area.

- Grazing-incidence imaging requires at least 2 reflections.
  - Area of each secondary mirror is nearly equal to that of its corresponding primary mirror.
- The typical grazing angle \( \approx 0.01 \) radian.
  - \( \alpha < \alpha_c = 0.029 \sqrt{f_1 \rho/A} \div E_{keV} \approx 0.018 (\sqrt{\rho}) \div E_{keV} \rightarrow 0.08 \div E_{keV} \) for typical x-ray coating (Ir, Pt, Au).
  - Energy range \( \Rightarrow \alpha = R/(4F) = D/(8F) \): f-number.
- Large apertures \( \Rightarrow \) very large mirror areas.
  - IXO mirror surface area \( \approx 1000 \) m\(^2\).
  - Generation-X mirror surface area \( \approx 10000 \) m\(^2\).
Generation X needs 10000 m² of precision mirrors. RMS errors are approximately 0.1 μm.
While the Generation-X observatory is huge, the Aries V can place it in L2. Total is well within the 60-tonne throw of Aries V to L2.
Programmatic constraints require innovation for manufacturing readiness.

- Optimize mandrel fabrication and replication.
  - Minimize post-replication corrections.
- Automate all processes as fully as possible.
  - Implement closed-loop fabrication & metrology.

- Mass constraint
  - Total mirror mass \( \leq 10 \text{ tonne} \)
  - Mirror areal density \( \leq 1 \text{ kg/m}^2 \)

- Monetary constraint
  - Total mirror cost \( \leq 0.5 \text{ G$} \)
  - Mirror areal cost \( \leq 50 \text{ k$/m}^2 \)

- Schedule constraint
  - Mirror fabrication time \( \leq 4 \text{ years} \)
  - Production rate \( \geq 8 \text{ m}^2/\text{day} \)

\[ \text{10000 m}^2 \quad 0.1-\mu\text{rad (RMS)} \]
\[ \text{mirror surfaces} \]
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Optical factors favor multiple telescopes over a single one of the same total area.

- N telescopes with individual area $A_N = A_1/N$
  - Other x-ray observatories use this approach.
    - XMM/3; ASCA/4; Suzaku/4; eROSITA/7; HERO/8
  - Leverages the replication approach.
    - Reduces mandrel area and cost by $\sqrt{N}$ to $N$. $\$\$
  - Each telescope is more compact by $\sqrt{N}$.
    - Radius $R_N = R_1/\sqrt{N}$; focal length $F_N = F_1/\sqrt{N}$.
    - Eases handling, alignment, assembly, and testing. $\$\$
      - May simplify and reduce risks of deployment. $\$\$
  - Sensitivity, detector & mirror area are invariant.
- Trade against multiple focal-plane detectors.