Design of the STAR-X telescope

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Outline

• Telescope designs considered
  – Wolter-Schwarzschild telescopes
  – Modified-Wolter-Schwarzschild telescopes

• Design principles of nested x-ray telescopes
  – Principal surface
  – Packaging considerations

• Baffle design
  – Telescope internal baffles
  – Front tube-baffles

• Optical performance of single pair design and nested design
  – Half power diameters calculated at 1.0 KeV and 4.0 KeV
  – At Gaussian focal plane
  – At best focal surface
  – 4 detector array in pyramid configuration

• Telescope effective area at 1.0 KeV and 4.0 KeV

• Conclusions
Considered telescope designs

- **Wolter-Schwarzschild (WS) telescope**
  - Principal surface is spherical and satisfies Abbe’s sine condition
  - \( h = f \sin(\alpha) \)

- **Modified-Wolter-Schwarzschild (MWS) telescope**
  - Adjust axial sag to optimize the on-axis and off-axis image size
Design of nested telescopes

- Primary-secondary intersections of the telescopes have to be on a spherical surface to optimize the off-axis image size.
- Adjacent surfaces cannot obstruct the field-of-view.
- Physical lengths of the telescopes are the same.
- Axial lengths and gaps between the mirrors are the same.
- Finite mirror shell thickness assumed.
Wide field of view nested telescope design

- Wolter-Schwarzschild, and Modified-Wolter-Schwarzschild telescopes have the same basic dimensions
- Minimum radial height is determined by field of view requirement
- 148 mirror pairs fit between minimum and maximum radii

Mirror thickness $= 0.4\text{mm}$

- Primary mirrors: $L_p=100\text{mm}$
- Secondary mirrors: $L_s=100\text{mm}$

- Primary gaps $= 3\text{mm}$
- Secondary gaps $= 3\text{mm}$

- $h_{\text{int}}$ range $= 175\text{mm}$ to $647\text{mm}$

- Focal length $f=5000\text{mm}$
- Half-field angle $= 0.5\text{deg}$
- Optical axis
- L range $= 5107\text{mm}$ to $5068\text{mm}$
Baffle design principles

- Baffles are placed to restrict the FOV of the detector to secondary mirrors only and FOV of the secondary mirror to primary mirrors only.
STAR-X baffle design

- Front tube-baffles
- Internal baffles of the primary mirrors and secondary mirrors
- Primary-secondary baffles at the intersections of the mirrors
Stray light of tightly packed design

- 148 nested telescopes
- Inner 29 primary mirrors and 77 secondary mirrors cannot be completely baffled

Exposed axial areas on the mirror surfaces
STAR-X front tube-baffle

- Limit axial length of the tube-baffles to 111.0 mm
  - 47 innermost telescope out of 148 telescopes need to be removed
  - Radial heights of the mirrors are limited to 284.0 mm – 650.0 mm
  - Inner 29 telescopes out of residual 101 telescopes have single reflection stray light problems

- Increased radial heights of the cavity of inner 29 telescopes to eliminate single-reflection stray light paths
Baffles in front of primary and secondary mirrors

- Increased cavity size of 29 innermost telescope allows taller baffles and eliminate single-reflection stray light
- Front baffles of the primary mirrors are mounted on front tube-baffles
- Primary-secondary baffles are placed on the principal surface of the telescopes
Internal baffles of primary and secondary mirrors

- Increased cavity size between inner 29 telescopes increases radial height of the baffles
- Baffles are mounted on the backside of the mirrors
Best focal surface of WS and MWS telescopes

- Best focal surface of WS telescope is parabolic
  - Field curvature is dominating aberration
- Best focal surface of MWS telescope is slightly worse
  - Added axial sag terms on the primary mirrors changes the shape of the best focal surface inside 0.15 degree field of view
- At higher energies best focal surfaces are steeper
HPDs at Gaussian focal plane

- Increase of HPD is parabolic. Field curvature is dominating aberration.
- Added axial sag of MWS telescope improves the optical performance very little at 1.0 KeV and 4.0 KeV.
HPDs at best focal surface

- Added axial sag (0.21 µm PV) of the primary mirrors of Modified-Wolter-Schwarzschild telescope distribute HPDs more uniformly across the field of view at 1.0 KeV and 4.0 KeV
- Minimum HPD is below 2.0 arc-sec

Optical performance at 1.0 KeV

Optical performance at 4.0 KeV
Optical performance of 4 focal plane detectors

• Inverted pyramid configuration of 4 detectors
  – Tip of the pyramid at the common focus of the telescopes
  – Edge of the field-of-view in the corners of the detectors

• HPD depends strongly along radial locations in 0.2-deg to 0.5-deg range

• 8 detectors needed to keep HPD below 5.0 arc-sec
Effective area

- Assumed Iridium coating on the optical surfaces
- No structural obscurations are assumed
  - Structural components reduce effective area typically ~25-30%
- At 1.0 KeV
  - On-axis effective area is ~4400 cm$^2$
  - Vignetting nearly halves the effective area at the edge of the field of view
- At 4.0 KeV
  - On-axis effective area is ~350 cm$^2$
  - Vignetting reduces the effective area to ~120 cm$^2$
  - Inner shells contribute more to the effective area leading to larger reduction in the effective area
Conclusions

• Utilization of spherical principal surface optimizes the off-axis optical performance on nested telescopes

• Nested mirrors of the design cannot be completely baffled for stray light without sacrificing a small fraction of on-axis effective area and a larger fraction of off-axis effective area

• Modified-Wolter-Schwarzschild designs provide uniform optical performance across the field of view

• At the best focal surface image aberrations can be controlled to ~3.4 arc-sec level at 1.0 KeV. At 4.0 KeV, the inner shells of the design significantly degrade the optical performance

• Effective area of well-baffled nested telescope is over 4000 cm$^2$ at 1.0 KeV for short focal length telescope designs