The X-ray Surveyor Mission: A Concept Study

Jessica A. Gaskin (MSFC)
On behalf of the X-ray Surveyor community
2020 Decadal Prioritization

- NASA Astrophysics Division white paper: Planning for the 2020 Decadal Survey

  Provided an Initial list of missions drawn from 2010 Decadal Survey and 2013 Astrophysics Roadmap that includes the X-ray Surveyor

  The three NASA Program Analysis Groups (PAGs) to coordinate community discussion to review and update list of missions

  - PAG reports will be sent to the Astrophysics Subcommittee and then to the Astrophysics Division for selection of mission concepts to study

  - Will result in a call for Science and Technology Definition Teams and assignment of lead NASA Center for each study

http://cor.gsfc.nasa.gov/copag/rfi/
X-ray Surveyor Goals

- **Leaps in Capability:** large area with high angular resolution for 1–2 orders of magnitude gains in sensitivity, large field of view with subarcsec imaging, high resolution spectroscopy for point-like and extended sources

- **Feasible:** *Chandra*-like mission with regards to cost and complexity with the new technology for optics and instruments already at TRL3 and proceeding to TRL6 before Phase B

- **Scientifically compelling:** frontier science from Solar system to first accretion light in Universe; revolution in understanding physics of astronomical systems

**Consistent with:**

*NASA Astrophysics Roadmap: Enduring Quests, Daring Visions*

*201 Astrophysics Decadal Survey: New Worlds, New Horizons*
X-ray Surveyor Mission Concept

- MSFC ACO Team Led by Randall Hopkins & Andrew Schnell

- Strawman definition:
  Spacecraft, instruments, optics, orbit, radiation environment, launch vehicle and costing

- Performed under the guidance of an informal mission concept team comprising the following:

  J. A. Gaskin (MSFC), A. Vikhlinin (SAO), M. C. Weisskopf (MSFC), H. Tananbaum (SAO), S. Bandler (GSFC), M. Bautz (MIT), D. Burrows (PSU), A. Falcone (PSU), F. Harrison (Cal Tech), R. Heilmann (MIT), S. Heinz (Wisconsin), C.A. Kilbourne (GSFC), C. Kouveliotou (GWU), R. Kraft (SAO), A. Kravtsov (Chicago), R. McEntaffer (Iowa), P. Natarajan (Yale), S.L. O'Dell (MSFC), A. Ptak (GSFC), R. Petre (GSFC), B.D. Ramsey (MSFC), P. Reid (SAO), D. Schwartz (SAO), L. Townsley (PSU)
X-ray Surveyor: A Successor to Chandra

- Angular resolution at least as good as Chandra
- Much higher photon throughput than Chandra (observations are photon-limited)

- Incorporates relevant prior (Con-X, IXO, AXSIO) development and Chandra heritage
- Limits most spacecraft requirements to Chandra-like
- Achieves Chandra-like cost
ACO Study Participants

**Study Lead**
Andrew Schnell (ED04)

**Study Lead Emeritus**
Randy Hopkins (ED04)

**Mission Analysis**
Dan Thomas (ED04)
Randy Hopkins (ED04)

**Configuration**
Mike Baysinger (ED04)

**Propulsion**
Dan Thomas (ED04)

**Power**
Leo Fabisinski (ED04)

**C&DH**
Ben Neighbors (ES12)

**Communications**
Ben Neighbors (ES12)

**GN&C**

**Thermal Analysis**
Andrew Schnell (ED04)

**Structural Analysis**
Jay Garcia (ED04)

**Mechanisms**
Alex Few (ES21)

**Environments**
Joe Minow (EV44)

**Cost**
Spencer Hill (CS50)

AtlasV 5m Long Shroud
Optics & Instruments

- High-resolution X-ray telescope
- Critical Angle Transmission XGS
- X-ray Microcalorimeter Imaging Spectrometer
- High Definition X-ray Imager

<table>
<thead>
<tr>
<th>Relative effective area (0.5 – 2 keV)</th>
<th>Chandra (HRMA + ACIS)</th>
<th>X-Ray Surveyor 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular resolution (50% power diam.)</td>
<td>0.5”</td>
<td>0.5”</td>
</tr>
<tr>
<td>4 Ms point source sensitivity (erg/s/cm²)</td>
<td>5x10⁻¹⁸</td>
<td>3x10⁻¹⁹</td>
</tr>
<tr>
<td>Field of View with &lt; 1” HPD (arcmin²)</td>
<td>20</td>
<td>315</td>
</tr>
<tr>
<td>Spectral resolving power, R, for point sources</td>
<td>1000 (1 keV) 160 (6 keV)</td>
<td>5000 (0.2-1.2 keV) 1200 (6 keV)</td>
</tr>
<tr>
<td>Spatial scale for R&gt;1000 of extended sources</td>
<td>N/A</td>
<td>1”</td>
</tr>
<tr>
<td>Wide FOV Imaging</td>
<td>16’ x 16’ (ACIS) 30’ x 30’ (HRC)</td>
<td>22’ x 22’</td>
</tr>
</tbody>
</table>

Concept Payload for:
- Feasibility (TRL 6)
- Mass
- Power
- Mechanical
- Costing

NOT THE FINAL CONFIGURATION
Light-Weight, Sub-Arcsecond Optics

- Build upon segmented optics approaches considered for Con-X, IXO, AXSIO
  - The segmented optics approach for IXO was progressing and a ~10” angular resolution was demonstrated

- Follow multiple technology developments for the reflecting surfaces

Fabrication  Alignment & Mounting  Integration
Wolter-Schwarzschild optical scheme
- 292 nested shells, segmented design
- 3m outer diameter
- 30x more effective area than Chandra HRMA
  -(2.3 m² @ 1 keV)
- 4Msec survey limit \( \sim 3 \times 10^{-19} \text{ erg/s/cm}^2 (0.5–2 \text{ keV}) \)
Obtaining Sub-Arcsecond Elements

APPROACHES

- Differential deposition
  - Fill in the valleys (MSFC/RXO)

- Adjustable optics
  - Piezoelectric film on the back surface (SAO/PSU)

ALSO WATCH

- Figuring, polishing, and slicing silicon into thin mirrors (GSFC)
- Magnetostrictive film on the back surface (Northwestern)
- Direct polishing of a variety of thin substrates (MSFC/Brera)
- Ion Implantation
Differential Deposition (MSFC, RXO)
• Micron-level corrections induced with <10V applied to 5–10 mm cells
• No reaction structure needed
• High yield — exceeds >90% in a university lab
• High uniformity — ~5% on curved segments demonstrated
• Uniform stress from deposition can be compensated by coating
• Row/column addressing — Implies on-orbit correction feasible
• 2D response of individual cells is a good match to that expected
• 10 cm diameter flat mirror, 86 $10 \times 5$ mm cells operated together to apply a deterministic figure in a $75 \times 50$ mm region

• Target correction (left) is approximated (middle) giving residuals shown on right

• Residuals converted to HPD for 2 reflections correspond to 3 arcseconds
**X-ray Microcalorimeter Imaging Spectrometer (XMIS)**

**Challenge:** Develop multiplexing approaches for achieving $\sim 10^5$ pixel arrays

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>0.2 – 10 keV</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1 arcsec</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>5 arcmin x 5 arcmin (min)</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>&lt; 5 eV</td>
</tr>
<tr>
<td>Count Rate Capability</td>
<td>&lt; 1 c/s per pixel</td>
</tr>
<tr>
<td>Pixel Size / array size (10-m focal length)</td>
<td>50 µm pixels / 300 x 300 pixel array</td>
</tr>
</tbody>
</table>

![Microcalorimeter Imaging Spectrometer](image-url)
Progress with respect to multiplexing:

- Transition Edge Sensors (TES) with SQUID readout.
- Multiple absorbers per one TES ("Hydra" design)

- Current lab results with $3 \times 3$ Hydra, 65μm pixels on 75 μm pitch shows 2.4 eV (FWHM) resolution at 6 keV

- $\Delta E \sim N$ for $N \times N$ Hydras, so current results imply $\sim 5 \times 5$ Hydras with 50 μm pixels and < 5eV energy resolution are achievable

High Definition X-ray Imager

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>0.2 – 10 keV</td>
</tr>
<tr>
<td>Field of View</td>
<td>22 arcmin x 22 arcmin</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>&gt; 90% (0.3-6 keV), &gt; 10% (0.2-9 keV)</td>
</tr>
<tr>
<td>Pixel Size / Array Size</td>
<td>&lt;16 µm (&lt; 0.33 arcsec/pixel) / 4096 x 4096 (or equivalent)</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>&gt; 100 frames/s (full frame)</td>
</tr>
<tr>
<td></td>
<td>&gt; 10000 frames/s (windowed region)</td>
</tr>
<tr>
<td>Read Noise</td>
<td>&lt; 4e⁻ rms</td>
</tr>
</tbody>
</table>

All have been demonstrated individually

Challenges: Develop sensor package that meets all requirements, and approximates the optimal focal surface
Advantages of Active Pixel Sensors

- Random-access pixel readouts
- Silicon-based devices:
  - Similarities to CCDs
    - Photoelectric absorption in silicon
    - Energy resolution comparable to CCDs
    - Large arrays like CCDs
  - High count rate capability with low pile-up
    - Arbitrary window readout vs entire device readout for CCD, and multiple output lines boosts full frame rate
  - Radiation hard (charge is not transferred across the device)
  - Low power (<100 mW for some devices)
  - On-chip integration of signal processing electronics (lower noise)
- Some devices have >200 μm depletion depths = Good QE over soft X-ray band
- Large formats (up to 4k × 4k abuttable devices)
- Pixel sizes from 8 μm to 100 μm

Hybrid
- Multiple bonded layers, with layers for photon detection and readout circuitry optimized independently
  - MIT/LL and PSU/Teledyne

Monolithic
- Single Si wafer used for both photon detection and read out electronics
  - SAO/Sarnoff and MPE

55Fe x-ray spectrum. T=300K

Spectrum with simple event Processing-grade selection. ΔE~160eV

Grating Spectrometer

- Resolving power = 5000 & effective area = 4000 cm$^2$
- Energy range 0.2 – 2.0 keV

Blazed Off-Plane Reflection gratings
(Univ. of Iowa)

Critical Angle Transmission (CAT) gratings (MIT)

Challenges: improving yield, developing efficient assembly processes, and improving efficiency
Critical Angle Transmission Gratings (MIT)

- CAT grating combines advantages of transmission gratings (relaxed alignment, low weight) with high efficiency of blazed reflection gratings.

- Blazing achieved via reflection from grating bar sidewalls at graze angles below the critical angle for total external reflection.

- High energy x rays undergo minimal absorption and contribute to effective area at focus.

Grating equation:

\[ m \lambda = p (\sin(\theta) + \sin(\beta_m)) \]

\( m \) = diffraction order

Blazing: \( \beta_m \approx \theta \)

High reflectivity:

\( \theta < \theta_c \) = critical angle of total external reflection

Strawman:
- Silicon grating, \( \theta = 1.5^\circ \)
- \( p = 200 \text{ nm} \)
- \( b = 40 \text{ nm} \)
- \( d = 6 \mu\text{m} \)
- aspect ratio \( d/b = 150 \)

200 nm pitch CAT grating bars
Critical Angle Transmission Gratings (MIT)

- Gratings, camera, and focus share same Rowland torus.

- Blazed gratings; only orders on one side are utilized.

- Only fraction (50%) of mirrors is covered: “sub-aperturing” boosts spectral resolution.

Advantages:
- low mass
- relaxed alignment & figure tolerances
- high diffraction efficiency
- up to 10X dispersion of Chandra HETGS
- no positive orders (i.e., smaller detector)

Schattenburg –XR-SIG meeting, Jan. 5, 2014
Costing: Surveyor’s *Chandra* Heritage

**Identical requirements**
- Angular resolution
- Focal length
- Pointing accuracy
- Pointing stability
- Dithering to average response over pixels and avoid gaps
- Aspect system & fiducial light system
- Contamination requirements and control
- Translation and focus adjust capability for the instruments
- Shielding for X-rays not passing through the optics
- Mission operations and data processing

**Somewhat different requirements**
- Magnetic broom (larger magnets)
- Pre and post telescope doors (larger)
- Telescope diameter (larger)
- Grating insertion mechanisms (similar)

No S/C technology challenges
All elements of the Mission are assumed to be at TRL 6 or better prior to phase B
Atlas V-551 launch vehicle (or equivalent)
L2 halo orbit & 5 year lifetime
Expendables sized for 20 years
Mass and power margins set to 30%
Cost margins set to 35% except for instruments
Instruments costed at 70%-confidence using NASA Instrument Cost Model (NICM)
Costs in FY 15$

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (FY 15$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft</td>
<td>$1,650M</td>
</tr>
<tr>
<td>X-ray Telescope Assembly</td>
<td>$ 489M</td>
</tr>
<tr>
<td>Scientific Instruments</td>
<td>$ 377M</td>
</tr>
<tr>
<td>Pre-Launch Operations, Planning &amp; Support</td>
<td>$ 196M</td>
</tr>
<tr>
<td>Launch Vehicle (Atlas 551)</td>
<td>$ 240M</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2,952M</strong></td>
</tr>
</tbody>
</table>

Mission Operations $45M/yr
Grants $25M/yr
THANK YOU!

Science Organizing Committee:
Jessica A. Gaskin (MSFC), Martin C. Weisskopf (MSFC), Harvey Tananbaum (SAO), Alexey Vikhlinin (SAO), Fabbiano Giuseppina (SAO), Christine Jones (SAO), Eric Feigelson (PSU), Neil Brandt (PSU), Leisa Townsley (PSU), Dave Burrows (PSU), Priya Natarajan (Yale), Maxim Markevitch (GSFC), Andrey Kravtsov (Chic.), Steve Allen (Stanford), Sebastian Heinz (Wisc.), Chryssa Kouveliotou (GWU), Roger Romani (Stanford), Feryal Ozel (Ariz.), Richard Mushotzky (UMD), Mike Nowak (MIT), Rachel Osten (STSCI)