An Ultra High Throughput X-ray Astronomy Observatory with a New Mission Architecture

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X-Ray Astronomy

EM Band: 80 - 1 Angstroms or 0.15 to 12 keV

X-ray Emission Comes From Regions With One or More of the Following:

High Temperature, 1E06 to 100E06 K
High Energy Particles
High Magnetic Fields
Very Strong Gravity
X-ray Emitters
Compact and Diffuse

• Nuclei of Quasars and other Active Galaxies, believed to be million to billion solar mass black holes
• Clusters of Galaxies, the Intracluster Medium
• Compact Binary Systems Containing Black Holes and Neutron Stars
• Supernova Remnants and Active Supernova
• Nearby Stars with Active Coronas
• Interstellar Medium

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Chandra
X-Ray Observatory Center
Ultra High Throughput X-ray Supernovae

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Chandra X-ray Observatory

Centaurus A
Probing the intergalactic medium with background quasars
History of the Universe

Galaxy Surveys

Neutral Hydrogen

Intergalactic Stars

Absorption Clouds

Recombination

Reionization

Horizon of Current Optical Observations

First Star Clusters (NGST, SKA)

Quasars (DSS)

Free Electrons (MAP, Planck)

Galaxies (SIRTF, Keck)

H I

H II

H III

Comoving Distance

Last Scattering Surface of CMB

roughput X-ray

Z=0

Z=8

Z=10^3

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Performance Requirements Upon the “Generation-X” Ultra High Throughput X-ray Observatory

- Effective Area of 2 million sq. cm. at 1 keV
- Angular Resolution of the order of 1 arcsec
- Accommodating unlimited number and large variety of detectors
- Replacing detectors that are exhausted, failed, or obsolete
- No long period of construction required prior to use
- Not dependent upon single launch for success
- Long life, at least 15 years
- Moderate cost, not exceed current large space programs
A Large Telescope Needs Good Angular Resolution

ESA simulation of 5 arcmin square region for XEUS

Phase 1

Phase 2

2 arcsec  5  15
Optical Telescope Builders Are Thinking Big

**NOAO’s ELT**  \( D = 30 \text{ m} \)

**ESO’s OWL**  \( D = 100 \text{ m} \)

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# X-ray Observatories

<table>
<thead>
<tr>
<th>Name</th>
<th>Agency</th>
<th>Diameter</th>
<th>Launch Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra X-ray Obs.</td>
<td>NASA</td>
<td>1.2 m</td>
<td>June 1999</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>ESA</td>
<td>1.3 m (1)</td>
<td>Dec. 1999</td>
</tr>
<tr>
<td>Constellation X-ray Mission</td>
<td>NASA</td>
<td>3.2 m (2)</td>
<td>2005 ?</td>
</tr>
<tr>
<td>XEUS Phase 1</td>
<td>ESA</td>
<td>5 m</td>
<td>2008 ?</td>
</tr>
<tr>
<td>XEUS Phase 2</td>
<td>ESA</td>
<td>8 m</td>
<td>2012 ?</td>
</tr>
<tr>
<td>“Generation-X” Ultra-high Throughput</td>
<td>International</td>
<td>30 m</td>
<td>2015 (Begin)</td>
</tr>
</tbody>
</table>

(1) Three 0.7 m Telescopes  (2) Four 1.6 m Telescopes
The Chandra X-ray Observatory
High Angular Resolution

XMM-Newton
High Throughput

Their conventional spacecraft and mission architecture are inadequate for the future.

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The next generation Constellation X-ray Mission will introduce a modest change in the mission architecture by using multiple identical spacecraft. However it is not a model for future generations with much larger throughput.
Radically Different Mission Architectures Are Needed to Achieve the Ultimate in:

• Higher Throughput

and

• Higher Angular Resolution

Each Is a Subject of a NIAC Concept Study
The Approach

- A new mission architecture where the telescope and each detector are aboard their own spacecraft and can be launched independently
- “Formation Flying” between the telescope and active detector
- Telescope of 30 m diam. with focal length of 200 to 300 m
- Telescope is segmented into about 100 modules equipped with angle and position controllers
- Telescope is constructed in situ with phased delivery of modules
- Telescope is functional while under construction
Formation Flying,
LEO
Target in orbit plane

Orbit of Telescope
Trajectory of Detector
Advantages of the New Mission Architecture

- One launch of a very large mass is replaced by many launches of smaller mass payloads
- Simplification in construction and integration of telescope and detector spacecraft
- Allows in situ construction of telescope and use by observers while under construction
- Facilitates collaborations and participation by smaller institutions and cost sharing with other agencies
- Allows unlimited number of detectors and their replacement
- Not dependent upon success of single launch
Disadvantages of the New Mission Architecture

- Need for formation flying with accuracy of 1 mm in 3 dimensions
- Detector spacecraft need propulsion system for station keeping and target changes which require high power levels
- Every launch requires a rendezvous with the observatory
- Mission operations are more complex with need for traffic control of detector spacecraft
<table>
<thead>
<tr>
<th>Major New Technology Challenges for the Ultra High Throughput X-ray Observatory</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Optical Design of the Segmented Telescope: Filled or Unfilled Aperture, Double Conical or Kirkpatrick-Baez Orthogonal Plate Geometry**</td>
</tr>
<tr>
<td>• Remote Assembly and Alignment to a Common Focus of Telescope Segments Delivered Incrementally</td>
</tr>
<tr>
<td>• Achieve a Much Higher Ratio of Effective Area to Mass than Current Higher Resolution X-ray Telescopes</td>
</tr>
<tr>
<td>• Formation Flying Between the Telescope Spacecraft and the Detector Spacecraft at the focus to an Accuracy of One Millimeter</td>
</tr>
<tr>
<td>• Novel Means of Propulsion for Several Functions, Solar Powered Electric Propulsion, Tethers, etc ?*</td>
</tr>
</tbody>
</table>

**Largest subject of this study  
*Second largest subject
**Fundamental Technology Requirement Unique to UHT**

Design and construction of a 30 m diameter X-ray telescope with one arcsecond resolution that is segmented into modules.

**Enabling Technology Needs Shared with Other Programs**

- Lower cost launches and transfers? Tethers?
- Robotic Assembly of Telescope
- Propulsion Systems, Hall Thruster
- Formation Flying of Spacecraft

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Grazing Incidence X-Ray Telescopes

Wolter Type 1, Parabola + Hyperbola

Kirkpatrick-Baez

XMM Mirror (1 of 3)
Grazing Incidence Optics

Graze Angle is ~ 90 arc minutes. There are two reflections. Physical area of x-ray telescope is ~ 75x aperture. Substrate area of 30 m diameter telescope is 50,000 sq. m. or 115 acres!!!
Ultra High Throughput X-ray

X-ray Optics

Telescope is segmented into modules, equipped with positional controllers for in situ alignment to a common focus.

- Larger aperture efficiency
- Better ang. resol. in theory
- Better off-axis resolution
- Requires curved substrates
- Alignment of front section to rear section is critical

Wolter Type 1 (double conical) or K-B (orthogonal plates)

- Can be segmented into modules of equal size and shape, which is likely to simplify integration in situ
- Substrates within a module can be segmented down to even lower levels
- Can use flats but will benefit from substrate curvature
- Front to rear section alignment much less critical
Kirkpatrick-Baez Mirror, Orthogonal Parabolas
Segmenting a KB Mirror Into Equal Size Modules
Segmenting a Parabolic Reflector

Single Parabola

A Few Parabolic Segments

More Linear Segments
Segmenting KB and Wolter Mirrors
Extreme Sparse Aperture KB Telescope

Focal Length is Too Long
Not Modular or Compatible with Incremental Construction
## Materials for a High Throughput X-ray Telescope

<table>
<thead>
<tr>
<th>Material</th>
<th>Areal Den., g/sq.cm</th>
<th>Where</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al foil with epoxy replicated surface</td>
<td>0.034</td>
<td>GSFC ASTRO-E (launch failure)</td>
<td>Inexpensive but too floppy</td>
</tr>
<tr>
<td>Electroformed Ni Foil, 300 microns</td>
<td>2.67</td>
<td>Media Lario, Italy MSFC</td>
<td>Promising but heavy</td>
</tr>
<tr>
<td>Thermally slumped thin glass, 200 to 400 microns</td>
<td>0.05 to 0.10</td>
<td>Columbia U., Cal Tech, GSFC, SAO</td>
<td>Inexpensive, needs development</td>
</tr>
<tr>
<td>Thin glass with piezoelectric coat</td>
<td>0.05 to 0.10</td>
<td>SAO, ?</td>
<td>Relatively expensive, needs much development</td>
</tr>
<tr>
<td>Tensioned Membrane</td>
<td>0.06 (in frame)</td>
<td>SAO, LLNL</td>
<td>Suitable for flats, needs development, moderate cost</td>
</tr>
<tr>
<td>Free standing orthogonal membranes with piezoelectric control</td>
<td>0.024</td>
<td>Bekey Designs, Inc.</td>
<td>Sparse aperture only, needs much development, could be inexpensive</td>
</tr>
<tr>
<td>Mass of Ultra High Throughput X-ray Telescope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td></td>
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</tr>
<tr>
<td>Total Substrate Area = 50,000 sq. m.</td>
<td></td>
<td></td>
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<tr>
<td>Areal Density = 0.10 g/sq. cm. or 1 kg/sq. m.</td>
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<tr>
<td>(300 micron glass + piezoelectric layers)</td>
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<td></td>
</tr>
<tr>
<td>Substrate Mass = 50 tons</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Multiply by factor of 1.5 to allow telescope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>structure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mirror Mass = 75 tons, to be transported to L2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>incrementally over several years</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
300 Micron Gold Coated Nickel Foils, Media Lario, Italy
Thermally Formed Beryllium Reflector

Segment of Parabola/Hyperbola with Epoxy Replicated Surface + Gold
Tensioned Membrane Reflector

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Piezoelectric substrate
PIEZOELECTRIC FIGURE CONTROL
### Propulsion Requirements of the Ultra High Throughput X-ray Observatory

- Launching the telescope segments and multiple detector spacecraft into low Earth orbit (LEO)
- Transport from LEO to Sun-Earth L2
- Navigation to and rendezvous with the observatory site
- Station keeping and traffic control at L2 of telescope spacecraft and multiple detector spacecraft
- Formation flying between the telescope spacecraft and the selected detector spacecraft which is at the focus
- Changing targets: the telescope axis rotates to the new pointing position while simultaneously a detector spacecraft is displaced to its new position
- Attitude Control of the telescope pointing direction to better than one arcminute and the detector orientation to within 10 arcminutes
Innovation

- **Develop a Pulsed Hall Electric Propulsion System which is directly powerable from flywheels, capacitors, and solar array power sources**
  - Eliminates power processing

SOA Continuous Hall Electric Propulsion System

Innovative Pulsed Hall Electric Propulsion System
Objective

• **Design and Build** a *pulsed* Hall effect thruster laboratory model

• **Test** the model *directly powered* from Advanced — Flywheels — Capacitors — Solar Arrays

• Follow-on systems can be scaled to
  • Very high powers
    • For more economical primary propulsion
  • Very low powers
    • For secondary functions or microspacecraft

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* Pulses on the order of seconds to <10 minutes planned
### Advanced Propulsion Studies listed by Name, Phase, and Title

<table>
<thead>
<tr>
<th>Name</th>
<th>Phase</th>
<th>Proposal Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogart, Thomas J</td>
<td>I</td>
<td>Hypersonic Airplane Space Tether Orbital Launch System</td>
</tr>
<tr>
<td>Christensen, Cindy</td>
<td>I</td>
<td>Ultralight Solar Sails for Interstellar Travel</td>
</tr>
<tr>
<td>Edwards, Bradley C</td>
<td>I</td>
<td>The Space Elevator</td>
</tr>
<tr>
<td>Grant, John</td>
<td>II</td>
<td>Hypersonic Airplane Space Tether Orbital Launch (HASTOL) Study, Phase II</td>
</tr>
<tr>
<td>Hawk, Clark W</td>
<td>I</td>
<td>Plasma Pulsed Paver Generator</td>
</tr>
<tr>
<td>Howe, Steven D</td>
<td>I</td>
<td>Enabling-Exploration of Deep Space: High Density Storage of Antimatter</td>
</tr>
<tr>
<td>Hoyt, Robert P</td>
<td>I</td>
<td>Tether Transport System for LEO-MEO-CEO-Lunar Traffic</td>
</tr>
<tr>
<td>Hoyt, Robert P</td>
<td>II</td>
<td>Moon &amp; Mars Orbiting Spinning Tether Transport (MMOSTT)</td>
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<tr>
<td>Kammash, Terry</td>
<td>I</td>
<td>Antiproton-Driven, Magnetically Insulated Inertial Fusion (MICF)</td>
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<tr>
<td>LaPointe, Michael R</td>
<td>I</td>
<td>Primary Propulsion for Piloted Deep Space Exploration</td>
</tr>
<tr>
<td>Landis, Geoffrey A</td>
<td>I</td>
<td>Advanced Solar and Laser-Pushed Lightsail Concepts</td>
</tr>
<tr>
<td>Maise, George</td>
<td>I</td>
<td>Exploration of Jovian Atmosphere Using Nuclear Ramjet Flyer</td>
</tr>
<tr>
<td>McNutt, Ralph L</td>
<td>I</td>
<td>A Realistic Interstellar Explorer</td>
</tr>
<tr>
<td>McNutt, Ralph L</td>
<td>II</td>
<td>A Realistic Interstellar Explorer</td>
</tr>
<tr>
<td>Mack, Terry H</td>
<td>I</td>
<td>Cyclical Visits to Mars via Astronaut Hotels</td>
</tr>
<tr>
<td>Seward, Clint C</td>
<td>I</td>
<td>Low Cost Space Transportation Using Electron Spiral Toroid (EST) Propulsion</td>
</tr>
<tr>
<td>Slough, John</td>
<td>I</td>
<td>Rapid Manned Mars Mission With a Propagating Magnetic Wave Plasma Accelerator</td>
</tr>
<tr>
<td>Wingel, Robert M</td>
<td>I</td>
<td>Mini-Magnetospheric Plasma Propulsion</td>
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<tr>
<td>Wingel, Robert M</td>
<td>II</td>
<td>Mini-Magnetospheric Plasma Propulsion: M2P2</td>
</tr>
<tr>
<td>Zubrin, Robert</td>
<td>I</td>
<td>The Magnetic Sail</td>
</tr>
</tbody>
</table>
## Summary and Status

- Confirmed that the design and construction of the 30 m diam. telescope is the most challenging problem and that the mass of the full telescope will be 75 tons.
- Both the Wolter 1 and K-B geometry are still candidates. The Wolter geometry is superior but more difficult to construct.
- Results from the Chandra X-ray Observatory indicate that the requirement of 1 or a few arc seconds angular resolution should not be weakened.
- Flat segments approximating a parabola should be no smaller than 10 cm to avoid diffraction at 80 Ang.
- The most promising substrate is one utilizing piezoelectric forces to control the figure.
- Formation flying requirements are quite moderate compared to those of other investigations.
- The pulsed hall thruster operating on solar energy, perhaps with flywheel storage is a versatile engine that can perform several functions for the X-ray observatory such as transport to L2 and attitude control.
- We depend on major advances in space robotics to assemble the telescope in situ.