CHANDRA BRINGS X-RAY ASTRONOMY to FOREFRONT

Chandra imaging 0.5-1" comparable to typical ground-based O/IR telescopes

More than 2000 Chandra investigators to date publishing nearly 500 refereed papers per year

Most X-ray SPECTRA still colors like U/B/V

Grating exposures show richness of data - but only for brightest sources with long exposures

CONSTELLATION-X OPENS WINDOW of X-RAY SPECTROSCOPY

Throughput: 50-100x Chandra and XMM gratings

Resolution: 300-1500 (3000 goal)

Good spectra ( >~ 1000 cts at f$_x$ $\sim$10^{-15}) for 1000's of sources

THE PHYSICS IS IN THE SPECTRA
X-ray Astronomy becomes X-ray Astrophysics
CONSTITUTION-X SCIENCE OBJECTIVES

*Black Holes*
- Observe matter spiraling into Black Holes & test the predictions of General Relativity
- Study distant/faint sources to trace the evolution of Black Holes with cosmic time

*Dark Matter and Dark Energy*
- Use clusters of galaxies to trace dark matter and as probes for amount and evolution of dark energy

*Cycles of Matter and Energy*
- Investigate the influence of Black Holes on galaxy formation
- Search for the hot missing matter in the Cosmic Web
- Study behavior of matter at extreme densities & magnetic fields using neutron stars
- Measure production of heavy elements in Supernovae
SCIENCE PRIORITY  (reviews by National Academy)


The NRC study Connecting Quarks with the Cosmos strongly endorsed the Constellation-X mission and provided a context for the overall Beyond Einstein program.

CONSTELLATION-X PAYLOAD

Baseline configuration of 4 SXT and 12 HXT divided across four spacecraft

All instruments operate simultaneously

Hard X-ray Telescope

Mirror

10 M Focal Length

Hard X-ray Imaging Camera

OD = 1.6m

X-rays

40 cm

Off-plane Gratings

Off-plane Gratings

Arc of Diffraction

Telescope Focus

Telescope

Mirrors

Spectroscopy X-ray Telescope

CONSTELLATION-X PAYLOAD

Baseline configuration of 4 SXT and 12 HXT divided across four spacecraft

All instruments operate simultaneously

Hard X-ray Telescope

Mirror

10 M Focal Length

Hard X-ray Imaging Camera

OD = 1.6m

X-rays

40 cm

Off-plane Gratings

Off-plane Gratings

Arc of Diffraction

Telescope Focus

Telescope

Mirrors

Spectroscopy X-ray Telescope
SHORT HISTORY of CONSTELLATION-X

- Merger of 2 proposals selected in 1995 for concept studies
- Ranked immediately after JWST in AANM Decadal Survey
- Approved as new start in FY04 NASA Budget (along with LISA)
- Funding reduced in FY05 with announcement of Exploration Initiative
- Funding reduced mid-2006 with release of FY07 budget request
- Future budget projections for NASA Astrophysics "tight"
- Slips for any mission add ~3-3.5% per year due to inflation
- Launch costs have escalated substantially

Can we simplify the mission and reduce its cost?
A STREAM-LINED CONFIGURATION

- Retain effective area over 0.6-10 keV band (Fe K lines)
- Reduce mass and envelope to fit within single Atlas V 551
- Requires dropping Reflection Grating Assembly and Hard X-ray Telescope and either fewer or smaller Spectroscopy X-ray Telescopes with Calorimeters
- Significant cost reductions - $720 Million RY$ less than 2 launch 4 satellite TRIP configuration
- Launch in 2017. Possibly 2016 with increase in early year $$
- Estimated cost of streamlined mission - $1946 Million RY$
  - $100 Million Science Enhancement Package included
  - $480 Million MO&DA for pre-launch and five year life time
X-RAY SPECTROSCOPIC TECHNIQUES: WHY CALORIMETERS

Grating spectrometers have very high resolution at low energies, which degrades with increasing energy. Lower efficiency (typically 20%) and not well-suited for extended sources.

X-ray CCDs are excellent for imaging over large fields of view, but have comparatively low spectral resolution with count rate limitations due to pile-up for brighter sources.

X-ray micro-calorimeters provide high throughput (close to 1) across a broad energy band, 2-4 eV energy resolution, and ability to handle count rates ranging to 1000 c/s per pixel. Most importantly they image extended sources such as supernova remnants, galaxies, and clusters.
### IMPACTS TO SCIENCE WITH SXT AND CALORIMETER ONLY

- BH/GR studies utilize HXT
  - Assess options for measuring underlying continuum needed for Fe line shapes
- WHIM/AGN outflow studies utilize RGS
  - Assess trades involving throughput below 1 keV, energy resolution, exposure time, and science achievable with Ne as well as O lines.

<table>
<thead>
<tr>
<th>Core Science Objectives</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 GR</td>
<td>1—0.9</td>
</tr>
<tr>
<td>1.2 BH properties</td>
<td>1—0.9</td>
</tr>
<tr>
<td>2.1 DE/DM</td>
<td>1.0</td>
</tr>
<tr>
<td>2.2 ICM Shocks</td>
<td>1.0</td>
</tr>
<tr>
<td>2.3 DM, abundances</td>
<td>1.0</td>
</tr>
<tr>
<td>2.4 WHIM</td>
<td>0.5</td>
</tr>
<tr>
<td>3.1 CXRB CDF</td>
<td>1.0</td>
</tr>
<tr>
<td>3.2 AGN evolution</td>
<td>1.0</td>
</tr>
<tr>
<td>3.3 outflows, AGN+</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observatory Science</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 SNR</td>
<td>1.0</td>
</tr>
<tr>
<td>4.2 X-ray Binary f(m)</td>
<td>1.0</td>
</tr>
<tr>
<td>4.3 Accretion dynamics</td>
<td>1.0</td>
</tr>
<tr>
<td>4.4 NS EOS</td>
<td>0.9</td>
</tr>
<tr>
<td>4.5 stars</td>
<td>0.8</td>
</tr>
<tr>
<td>4.6 comets</td>
<td>1.0</td>
</tr>
</tbody>
</table>
POSSIBLE SCIENCE ENHANCEMENT CONCEPTS

100 kg of mass and $100M budgeted for science instrument(s) to be added to basic SXT/Calorimeter to achieve Con-X science objectives

- High Energies (> 10keV):
  - Ir or Multi-layers on inner mirrors
  - Calorimeter to higher Energies
  - A limited number of HXT telescopes

- Lower Energies (< 1keV):
  - Hybrid Calorimeter with some pixels providing 1-2 eV resolution below 1 keV
  - Simplified grating/detector system
CON-X SINGLE ATLAS-V LAUNCH WITH 3 or 4 SXTs and 1 SPACECRAFT
3 vs 4 TELESCOPES

3 telescopes

- Characteristics
  - OD = 1.5m, ID = 0.3m, 204 shells each
  - 10116 mirror segments and 54 modules total
- Possibly less expensive
- Only 3 calorimeters
  - lower cost
  - reduced build schedule (although mirrors are critical path)
- Only 3 SEP units if they use SXT
- Optical bench simpler and lighter
- Potentially lower mass
- Less tightly constrained in fairing

4 telescopes

- Characteristics
  - OD = 1.3m, ID = 0.3m, 163 shells each
  - 13040 mirror segments and 40 modules total
- Higher throughput 3-10 keV
- Fewer mandrels needed
  - lower up front cost
  - less time to make mandrels
- FMA design may be simpler
- Needs full cost trade of fewer mandrels against additional instrument and optical bench complexity
Maximizing the science performance

- Top level issue:
  - 4 SXT: Maximize the science performance of the SXT+XMS at 6 keV
  - 3 SXT: Minimize cost and mission mass

- Decision to maximize the science performance at 6 keV
## PRELIMINARY MASS TABLE

<table>
<thead>
<tr>
<th>Major Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror End</td>
<td>2179</td>
</tr>
<tr>
<td>Optical Bench/Metering Structure</td>
<td>1011</td>
</tr>
<tr>
<td>Detector End</td>
<td>1366</td>
</tr>
<tr>
<td>Science Enhancement</td>
<td>100</td>
</tr>
<tr>
<td>Launch Vehicle Interface</td>
<td>198</td>
</tr>
<tr>
<td>Propellant</td>
<td>214</td>
</tr>
<tr>
<td>Total Wet Mass</td>
<td>5068</td>
</tr>
<tr>
<td>Atlas Capability to L2 (TRIP)</td>
<td>6498</td>
</tr>
<tr>
<td>Contingency</td>
<td>~30%</td>
</tr>
</tbody>
</table>
SXT Mirror Segment Progress

Substrate Fabrication

- Accurate mirror surfaces are the key to attaining the SXT 5 arc sec HPD goal
- Substrate
  - Thermally formed thin float glass: 0.4mm
  - Excellent figure at low spatial frequencies (<0.1 cycle/mm)
  - Conforming to forming mandrel to better than 40 nm RMS
- Forming mandrels for technology development
  - Fabricated by GSFC using fused quartz and by Zeiss using both fused quartz and Keatite
- Replication mandrels for technology development
  - Fabricated by Zeiss of electroless Ni and Zerodur
  - 7.5 arc second HPD
- Replicated segment performance
  - Current performance at better than 20” HPD level, within a factor of 2 of requirements.
  - Next generation segments will incorporate forming process improvements, precise forming mandrels, and should approach 10” HPD.
SPECTROSCOPY X-RAY TELESCOPE REFLECTOR PROGRESS

Dominant Error Term
Axial RMS Height Error (nanometer)

Calendar Year

Requirement
Goal

Typical Values
Best Values
X-RAY MICRO-CALORIMETER SPECTROMETERS

Thermal detection of individual X-rays gives 20-40x better spectral resolution than Chandra CCDs

Arrays have been successfully demonstrated on sounding rockets and Suzaku (Astro-E2)

XRS: 32 pixels, 640 µm pixels

Suzaku X-ray calorimeter array achieved 7 eV resolution on orbit

Con-X arrays under development and approaching goal of 2 eV at 6 keV.

High filling factor

8x8 development TES array for Con-X with 250 µm pixels

2.5 eV ± 0.2 eV FWHM
Extended FOV - Position-Sensitive TES (“PoST”)

Thermal diffusion gives rise to different pulse responses and hence position; summing signals gives x-ray energy. “PoST” provides path to larger fields of view without significantly increasing electronics.
BEST POST RESOLUTION SO FAR:

Mn Kα @ abs 4
7.6 +/- 0.7 eV FWHM

Linearity

Pulse height [A.U.]

Energy [eV]

Counts

Residual

6000 eV

6000 eV

Abs 4

Baseline

8.1 +/- 0.1 eV

Cl Kα

7.4 +/- 2.1 eV

K Kα

8.6 +/- 0.3 eV

Mn Kα 7.6 +/- 0.7 eV

K Kβ

8.8 +/- 0.3 eV

Mn Kβ
SUMMARY

Constellation-X opens the window of X-ray spectroscopy to address compelling and high priority science questions on Black Holes, Dark Matter and Dark Energy and the Cycles of Matter and Energy.

The technology development continues to make substantial progress.

Con-X launched on a single ATLAS V is now our focus, with further simplification and cost savings under study.

http://constellation.gsfc.nasa.gov
Effective Area vs Energy (Pt Coating)