The Advanced X-ray Timing Array (AXTAR)

Paul Ray (NRL), Deepto Chakrabarty (MIT), Marc Christophersen (NRL), Bernard Phlips (NRL), Dimitrios Psaltis (Arizona), Ron Remillard (MIT), Colleen Wilson-Hodge (NASA/MSFC), Michael Wolff (NRL), Kent Wood (NRL), for the AXTAR Collaboration

http://xte.mit.edu/AXTAR

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AXTAR Basics

Collimated 1.8–80 keV X-ray timing and spectral mission with much larger area than RXTE

- Large Area Timing Array (LATA)
  - 3.2 m² effective area
  - <600 eV energy resolution
  - Low inclination LEO orbit

- Sky Monitor (SM)
  - Multiple coded-aperture cameras (40°x40° FOV each)
  - High duty cycle monitoring of sky
  - < 5 mCrab in 1 day

- Flexible scheduling and rapid response
  - Targets from GI program

Cost Category: Small (<$400M, excluding launch)

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**Cost Category:**
Small (≤$400M, excluding launch)
Fast timing probes short timescales such as the spin of a neutron star or the last stable orbit around a stellar-mass black hole.

A key metric is S/N per unit time (e.g. coherence time of an oscillation or rise time of a burst).

Example: In 1 ms, AXTAR gets S/N >10, while RXTE had S/N <3.

Two IXO science questions were key design drivers for AXTAR:

**How does matter behave at very high density?**
- Detailed studies of bursts in X-ray binaries

**What happens close to a black hole?**
- Multiple techniques, including high frequency QPO studies
Burst Oscillations Probe the Structure of Neutron Stars

- Pulse strength and shape depends on M/R or ‘compactness’ because of light bending (a General Relativistic effect).
  - More compact stars have weaker modulations.
  - Pulse shapes (harmonic content) also depend on relativistic effects (e.g. Doppler shifts due to rotation, which depends on $R$, since the spin frequency is known).

- For sources where phase-resolved spectroscopy is possible, rotational Doppler shift of hot spot emission also sensitive to radius (for known spin rate). This measurement is NOT possible with RXTE due to insufficient sensitivity.

- Model dependence is minimized by small size of spot at burst onset.

![Graph showing least-squares fit for burst oscillations](image1)

Nath, Strohmayer & Swank (2002)
Simulated AXTAR Lightcurve

- Use blackbody emission from neutron star surface.
- Circular hot region which grows linearly with time.
- Flux and spin rate for bursts from 4U 1636-53.
Neutron star mass-radius constraints with AXTAR: Simulation of an X-ray burst oscillation

AXTAR will routinely make 5–10% measurements of neutron star radii in X-ray bursters, thus conclusively discriminating between candidate equations of state for dense matter.
What Happens Close to a Black Hole?

- Multifaceted attack on BH spin
  - Continuum fitting
    - Large area and broad energy coverage are critical
  - Fe lines
    - Needs modest resolution and good coverage of continuum
  - HFQPOs
    - Unsolved problem that AXTAR can solve and integrate into 3-method solution
    - New QPO features distinguishes correct model

- Testing GR
  - Above assumes GR and using Kerr metric to measure BH spin
  - For any one observable (e.g. Fe line profile or single mode frequency) BH spin and deviation from Kerr are highly degenerate
  - Multiple modes or observables can break this and test GR


Two methods have different systematics, different model dependencies

Continuum fitting produces robust, repeatable measurements

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Why are HFQPOs Compelling?

- **HFQPOs and Strong Gravity**
  - QPO $\nu \sim$ dynamical frequencies of accretion disk for $R < 10R_g$
  - Stable $\nu$ (1st order) for each BH, despite large changes in $L_x$
  - 3:2 frequency ratio HFQPO pairs $\rightarrow$ common mechanism
  - Roughly $\nu \sim 1/M$ for cases of HFQPOs plus known BH mass
  - Study matter in strong gravity with immunity to $(D, A_v, i)$

- **Next slide describes how AXTAR can exploit this**
AXTAR Strategy for HFQPOs

- Large area yields high count rates to see weaker features in power spectrum
- Detect HFQPOs and weaker PDS features to rms ~ 0.3% at 5 σ in 10ks for ~20 BHBs
- Analyzing new modes will distinguish models
- Focus on spin (BHs with known mass) and combine HFQPO analyses with spin determinations from continuum fitting and Fe-line analyses.
- Observe BHs (most are transients) many times to cover all states (thermal, steep power law, hard/jet), to witness state transitions, and to sample different luminosities for further inputs for constructing HFQPO theory

D. Psaltis
Technical Requirements

- Effective Area: >3 m² (Recall RXTE was 0.6 m² initially, mostly <0.4 m²)
  - Largest area mission yet flown
- Energy Range: below 2 keV to at least 30 keV
- Achieve high count rates with minimal dead time
- Fast response to transients and state changes; flexible scheduling
- Sky monitor to provide triggers and context information, plus stand-alone science

### Table 1. Mission Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Drivers</th>
<th>Technology Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Large Area Timing Array (LATA)</strong></td>
<td></td>
</tr>
<tr>
<td>Effective Area</td>
<td>3.2 m²</td>
<td>NS radius, BH QPOs</td>
<td>Mass, cost, power</td>
</tr>
<tr>
<td>Minimum Energy</td>
<td>1.8 keV</td>
<td>Source states, absorption meas., soft srcs</td>
<td>Detector electronics noise</td>
</tr>
<tr>
<td>Maximum Energy</td>
<td>&gt;30 keV</td>
<td>BH QPOs, NS kHz QPOs, Cycl. lines</td>
<td>Silicon thickness</td>
</tr>
<tr>
<td>Deadtime</td>
<td>10%@10 Crab*</td>
<td>Bright sources, X-ray bursts</td>
<td>Digital elec. design, pixel size</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>1 μs</td>
<td>Resolve ms oscillations</td>
<td>Shaping time, GPS, Digital elec.</td>
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<td></td>
<td></td>
<td><strong>Sky Monitor (SM)</strong></td>
<td></td>
</tr>
<tr>
<td>Sensitivity (1 d)</td>
<td>&lt; 5 mCrab*</td>
<td>Faint transients, multi-source monitoring</td>
<td>Camera size/weight/power</td>
</tr>
<tr>
<td>Sky Coverage</td>
<td>&gt; 2 sr</td>
<td>TOO triggering, multi-source monitoring</td>
<td># cameras vs. gimbaled designs</td>
</tr>
<tr>
<td>Source Location</td>
<td>1 arcmin</td>
<td>Transient followup</td>
<td>Pixel size, camera dimensions</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>AXTAR Mission</strong></td>
<td></td>
</tr>
<tr>
<td>Solar Avoidance Ang.</td>
<td>30°</td>
<td>Access to transients</td>
<td>Thermal/Power design</td>
</tr>
<tr>
<td>Telemetry Rate</td>
<td>1 Mbps</td>
<td>Bright sources</td>
<td>Ground stations/TDRSS costs</td>
</tr>
<tr>
<td>Slew Rate</td>
<td>&gt; 6° min⁻¹</td>
<td>Flexible scheduling, fast TOO response</td>
<td>Reaction wheels</td>
</tr>
</tbody>
</table>

*1 Crab = 3.2 × 10⁻⁸ erg cm⁻² s⁻¹ (2–30 keV)
Large Area Timing Array (LATA) Supermodule

- Light shield
- Si pixel detector
- Interposer board
- Digital board
- Collimator (not to scale)

2025 cm² per supermodule
20 supermodules for AXTAR

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Sky Monitor (SM)

- Same Si pixel detectors provide 2-d imaging when paired with a coded mask
  - Arcminute source localizations
  - $\sim 300 \text{ cm}^2$ area per camera
  - $<5 \text{ mcrab}$ sensitivity (1 day), 20x better than RXTE/ASM

- 32 cameras could provide all-sky continuous coverage
  - Timescales from ms to years
  - Reduced configurations still provide high duty-cycle monitoring

Critical for BH science!
Capabilities

- 1.8–50 keV coverage with $\Delta E < 600$ eV
- Count rate of 120,000 cts/s on 1 Crab
  - S/N > 10 in 1 ms on 1 Crab source!
- Ms exposures on range of X-ray binaries over large luminosity range and transitions through all spectral states
- SM live-sky coverage ~50%
  - Transient source and spectral state monitoring
  - Eyes for GW detectors, tidal disruption events, GRB survey and much more science as well
Technology Development Options

- **Micromachined Tantalum Collimators**
  - Reduce instrument mass by a factor of five
  - Have demonstrated laser machining + chemical etching in NRL’s Nanoscience Institute
  - Need to develop large scale production techniques

- **Silicon Pixel Detectors and Readouts**
  - Optimize for LATA and SM designs

- **Silicon Drift Detectors (SDDs)**
  - Improve energy resolution by a factor of two to <300 eV
    - Improves Fe-line science
  - Reduce power requirements
  - Need to research techniques for making thick (>0.5 mm) SDDs and customize design for X-ray timing

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Benefit of an MDL Run

- Initial version of AXTAR concept studied by MSFC Advanced Concepts Office
  - Target was Taurus II launch
  - Collimator was clone of RXTE collimator (20 cm thick BeCu hexagonal cells)
    
    Study details presented in SPIE paper (arXiv:1007.0988), and NASA/TM-2011-216476

- New study needed for several reasons
  - Large mass reduction from Ta collimator drives redesign of S/V components and structure
    - Without S/V redesign, AXTAR is 2000 kg (RXTE was 3200 kg)

- Independent cost estimate

- MDL run will improve system fidelity and cost confidence in a mission with better performance

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Enormous improvement in effective area over RXTE:
7x @ 4keV, 14x @15 keV, 24x @20keV, 36x @30 keV

Recall that QPO S/N scales linearly with area $A$, not $A^{1/2}$
BACKUPS
BH High Frequency QPOs (100-450 Hz)

- Seen in 8 BH sources
- 4 have pairs of QPOs
  - All consistent with 3:2 ratio
- Frequencies are stable to ~5%
- Always seen in “Steep Power Law” state
- Immune to luminosity changes

QPO rms: 0.8–1.5%  2–5%  0.8–2.4%
Testing General Relativity

Nearly identical Fe-line profiles

For single mode frequency, spin and deviation from Kerr are degenerate

Solution: Measure two fundamental frequencies (e.g. c-mode and g-mode, or Fe line and one mode)

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Benefits of More Counts

Key equation for QPO sensitivity:

\[ \frac{S}{N} = \frac{1}{2} I r^2 \left( \frac{T}{\Delta \nu} \right)^{1/2} \]

van der Klis (1989)

Implications for 10x increase in area (with similar energy response):

- 1σ detection of a QPO becomes 10σ in same T ⇒ study of fainter QPOs, revealing harmonics, etc.
- 3σ detection in T becomes 3σ detection in 0.01T ⇒ weak detection 200 ks now can be detected and tracked every 2 ks, revealing evolution, true frequency width, correlation with spectral states, etc.