X-ray Surveyor Science Workshop

October 6-8 2015, Washington, DC, National Museum of the American Indian

Mission concept developed by the MSFC Advanced Concepts Office

Strawman payload definition: Structures, Thermal control, Mechanisms, Propulsion, Guidance, navigation & control, Avionics, Power, Orbit trade & launch vehicle, Radiation environments, Initial cost estimates.

under the guidance of informal mission concept team:

M. Weisskopf will present results at the special AAS/HEAD meeting in Chicago on June 29 – July 1.
**X-ray Surveyor capabilities: Sensitivity & field of view**

- ×50 more effective area than *Chandra* (due to mirror & QE improvements)
- Neither background nor confusion-limited for PSF better than ~1” HPD, so sensitivity is proportional to area. 4 Msec *Chandra* Deep Field done in 80 ksec. 4 Msec detection limit is ~ 1×10⁻¹⁹ erg/s/cm² (0.5–2 keV band)
- ×10 larger solid angle for sub-arcsec imaging with shorter mirrors and Wolter-Schwarzschild optical scheme
- ×500 higher survey speed
X-ray Surveyor Capabilities: 
Spatially resolved spectroscopy

Chandra image of M87: jet from the central supermassive black hole interacts with intracluster medium.

1 pixel = 1” = 90pc

X-ray Surveyor will add 3rd dimension to the data (chemistry, kinematics)
CRITICAL-ANGLE TRANSMISSION GRATINGS CONCEPT

Credit: R. Heilmann

<111> planes

CAT grating bars

Level 2 support

Off-plane reflection gratings concept
Credit: R. McEntaffer

X-ray Surveyor Capabilities: High-resolution spectroscopy

- Recent technological advances improve grating efficiency to \( \sim 0.5 \) in the soft X-ray band
- X-ray Surveyor can accommodate insertable gratings with \( R=5000 \) and effective area \( \sim 4,000 \text{ cm}^2 \)
- This is a factor of \( \sim 250 \) improvement in throughput and 5–10 in resolving power over the current state-of-the-art
First generations of supermassive black holes

- Age of the Universe at $z=6$ is barely enough for quasars with $M_{BH}>10^9 M_{Sun}$ to grow via accretion. Likely, quick violent formation of massive seeds, followed by fast accretion.

- Lower-mass black holes, $M_{BH}<10^6 M_{Sun}$, are best observed in X-rays:
  - Spectral peak ($\lambda_{\text{max}} \sim M_{BH}^{1/4}$) shifts towards X-ray band, reducing optical/UV output.
  - Dust obscuration impacts optical/UV. Common IR signatures of obscured AGNs are redshifted out of JWST band at $z=10$.
  - For small seeds, $L_{opt,AGN}<L_{gal}$
  - X-ray emission is direct probe of accretion, the primary black hole growth channel

- X-ray Surveyor will detect first accretion light in the Universe: unobscured hard X-rays, $E > 2$ keV in rest frame, from hot accretion disk corona ($\sim 10\%$ of $L_{bol}$) at $z=10$ from Eddington-accreting black holes with $M_{BH} \sim 10,000 M_{Sun}$
Angular resolution requirements for detecting first accretion light

Simulated 2x2 arcmin deep fields observed with JWST, X-ray Surveyor, and ATHENA

- JWST will detect $\sim 2 \times 10^6$ gal/deg$^2$ at its sensitivity limit (Windhorst et al.). This corresponds to 0.03 galaxies per 0.5” X-ray Surveyor beam (not confused), and 3 galaxies per ATHENA 5” beam (confused).

- X-ray confusion limit for ATHENA is $2.5 \times 10^{-17}$ erg/s/cm$^2$ (5× worse than the current depth of Chandra Deep Field). This corresponds to $M_{BH} \sim 3 \times 10^6 \, M_{Sun}$ at $z=10$ — above seed mass range. Confusion in OIR id’s further increases the limit ($M_{BH} \sim 10^7 \, M_{Sun}$ at $z=8$ is quoted by ATHENA team).

- X-ray Surveyor will reach $1 \times 10^{-19}$ erg/s/cm$^2$. This corresponds to $M_{BH} \sim 10,000 \, M_{Sun}$ at $z=10$ — well within the plausible seed mass range. Each X-ray Surveyor source will be associated with a unique JWST-detected galaxy.
Galaxy formation: solving the nature of feedback problem

~ 40% of baryons are converted to stars
~ 30% are observable in UV absorption
~ 30% are heated to X-ray temperatures — unique signature of energy feedback

Goals: detect and characterize hot halos around Milky Way-size galaxies to z~1, hot gas in group-sized objects at z=6, including those around SDSS quasars; map in detail galaxy winds at z~0.01.

Required capability: sensitivity & ability to separate diffuse emission from central sources
Diffuse ionized intergalactic gas contains most of baryons in the local Universe. A large fraction of these baryons is heated to X-ray temperatures, $T > 10^6$. Current absorption line observations in UV (OVI) and X-rays (OVII) only probe a small fraction of volume and phase space. For full understanding of the intergalactic gas, need ability to map Hydrogen + Helium. Regions with $\rho/\rho_{\text{mean}}$ above $\sim 30$ and $T > 1.5 \times 10^6$ K (containing $\sim 50\%$ of hot diffuse baryons by mass) will be observable with X-ray Surveyor in emission.

**Required capability:** resolve and remove cosmic X-ray background sources.
Plasma Physics in astronomical objects

Chandra image of Perseus cluster: energy output from supermassive black hole balances radiative cooling.

Credit: J. Sanders

Unsharp mask image. Ripple interfaces are < 1 arcsec wide.

Sound waves in viscous plasma (Fabian et al. 2003), or turbulence in a stratified atmosphere (Zhuravleva, …, Fabian, … et al. 2015)?
Plasma Physics in astronomical objects

Chandra image of Perseus cluster: energy output from supermassive black hole balances radiative cooling.

Bulk motions with $v=30\text{km/s}$ and $100\text{km/s}$ Doppler line widths can be measured with microcalorimeter (compare with $c_s \approx 1000\text{ km/s}$).

X-ray Surveyor: detailed 3D tomography.

ATHENA: overall Doppler line widths.

Required capability: spatially resolved spectroscopy on dissipation scales (close to $\sim 1''$ based on Chandra images)
Plasma physics, gas dynamics, relativistic flows in astronomical objects

Spatially resolved spectroscopy also critical for:

• Detailed structure of supernova remnants

• Particle acceleration in pulsar wind nebulae

• Jet-IGM interactions

• Studies of plasma flows in the Solar system, stellar winds & ISM via charge exchange emission
High throughput, high resolution spectroscopy

X-ray Surveyor will improve resolving power by x5-10, and throughput for grating spectroscopy by >2 orders of magnitude. Expect revolution in studies of

- Coronal activity in young stars
- Star-planet interactions (e.g. close-in Hot Jupiter systems)
- Gas flows in the vicinity of the AGN central engine
- X-ray absorption line detections (Cosmic Web, galactic halos)

Brickhouse et al. 2010
Beyond the core region, the energetic impact of radio jets and their role in building up entropy in group and cluster gas is poorly understood. The energy input from strong shocks expected to occur in typical environments is not taken into account in the scaling relations between radio luminosity and jet power (e.g. Bîrzan et al. 2008), and cannot be reliably determined from radio data. 

Athena+ will enable the dynamics and source age and thus jet power to be assessed robustly via direct bulk velocity measurements of expanding hot gas shells around radio lobes extending up to Mpc scales. At higher redshifts, the identification of characteristic features associated with strong shocks in high-resolution WFI temperature maps will measure age, power and energetic impact for large representative samples.

2.1.4. The missing baryons and the Warm-Hot Intergalactic Medium

The intergalactic medium contains 90% of the baryons at the current epoch, and is the visible tracer of the large scale dark matter structure of the local Universe. Theory predicts that the state of most of these baryons evolves from low temperatures, as manifested in the Lyα forest at z>2, to a warm-hot phase (10^5-10^7 K) at late times shaped by the filamentary structure of dark matter (Cen & Ostriker 2006). Most of the metals are predicted to reside in the warm-hot phase already at z~4. Thermal continuum emission from this gas is extremely hard to detect. The only characteristic radiation from this medium will be in the discrete transitions of highly ionized metals. Evidence for the warm tail of the WHIM, where 10-15% of the missing baryons reside, has been obtained via UV-absorption line studies with FUSE and HST-COS (Shull et al 2012). However, around 50% of the baryons at redshifts z<2 and 90% of the metals at redshifts z<3, locked in the hot phase, remain unobserved. In order to reveal the underlying mechanisms driving the distribution of this gas on various scales, as well as different metal circulation and feedback processes the chemical and physical states of about a hundred filaments must be characterized. This can only be done in X-rays. Present facilities can marginally detect a few filaments (Nicastro et al 2013), but not characterize their physical properties. Athena+ will probe these baryons in three dimensions, through a combination of absorption and emission studies using the X-IFU. Deep observations of bright AGN combined with Gamma-Ray Burst (GRB) afterglows will be used as back lights for absorption studies through the warm and hot gas. Lines from the high ionization states of O, Ne, Si and Fe, seen simultaneously, enable unique identification of the filamentary structures of the cosmic web (Figure 5), with the detection and characterization of about hundred filaments. At the same time the emission from these structures is mapped by X-ray lines. Combining the two measurements allows the projected size of the structures to be derived while the shapes of the lines and their position reveal the kinematics of the baryons, which, together with the clustering information from the emission lines, pinpoints their origin for the first time.

In Table 1, we summarize the key issues addressed in this section.

Figure 5: Simulated emission and absorption line spectra captured in a single Athena+ observation for two filaments at different redshifts.

Lower panel: absorption spectrum from a sight line where two different filamentary systems are illuminated by a bright background source. Upper Panel: corresponding emission from a 2’x2’ region from the same filaments for a 1 Ms exposure time. The high spectral resolution allows us to distinguish both components. Athena+ will be able to study ~100 of these sight lines in detail.

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<tr>
<th>Athena</th>
<th>X-ray Surveyor</th>
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<tr>
<td>Spectroscopy with $R\approx1000$</td>
<td>✓ 50x sensitivity</td>
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<td>At the expense of coarser angular resolution (10x) &amp; sensitivity (5x)</td>
<td>✓ $R\approx1000$ spectroscopy on 1” scales adds 3rd dimension to the data</td>
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<td>Wide field (40’x40’)</td>
<td>✓ $R\approx5000$ spectroscopy for point sources</td>
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<td>✓ While preserving Chandra angular resolution (0.5”)</td>
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<td>✓ 10x field of view with fine imaging</td>
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X-ray Surveyor strawman mission concept

- Technology incorporates Chandra heritage and IXO development
- Most spacecraft requirements similar to those achieved for Chandra, with some required extensions (power, data rate) being straightforward
- Chandra-like cost

Next-generation science instruments, e.g.:
- $5' \times 5'$ microcalorimeter with 1'' pixels and high spectral resolution, 0.2–10 keV
- $22' \times 22'$ CMOS imager with 0.33'' pixels, 0.2–8 keV
- insertable gratings, $R = 5000$, 0.2–1.2 keV

Next-generation mirrors. Lower mass, same angular resolution, same focal length as Chandra’s. A factor of 30 (50 with QE gains) more effective area. Sub-arcsec imaging over $15' \times 15'$ field.
X-ray Surveyor strawman mission concept


Looked at Structures, Thermal control, Mechanisms, Propulsion, Guidance, navigation & control, Avionics, Power, Orbit trade & launch vehicle, Radiation environments, Initial cost estimates.

Detailed report at the June 2015 HEAD meeting in Chicago. Preliminary highlights:

- Indeed, a Chandra-like mission
- No system-level show stoppers
- Can be launched to L2 with Atlas V-551
- Cost roughly $2.5B–$3B with lots of refinements still in progress
Technologies for next-generation X-ray mirror

New mirror can be built from densely packed thin segments, mounted into modules.
~1200 kg for 2.3m² of collecting area

Chandra mirror shells are 2.5cm thick.
1,500 kg for 0.08m² of collecting area

Make optics adjustable: piezo cells + integrated electronics + strain gauges for in-flight feedback and control

or / and

correction via differential deposition

several other techniques under study
**Microcalorimeter:** High spectral resolution for small pixels has been demonstrated in the lab. **Challenge:** Develop multiplexing approaches for building $10^5$ pixel arrays.

*Much of future development is similar to ATHENA needs.*

**Active pixel Si detectors:** Many required components (small pixels, high QE, low noise & dark current, radiation hardness, fast readout) have been demonstrated individually. **Challenges:** Develop sensor package meeting all requirements, extend to a large-format camera, possibly approximate optimal focal surface for the mirrors.

**Gratings:** Basic technology for both critical-angle transmission gratings and off-plane reflecting gratings is lab-proven. **Challenges:** continue improving production yield, develop techniques for robotic assembly.
• **Capable** — 1–2 orders of magnitude gains in capabilities across the board.

• **Scientifically compelling** — Frontier science in objects from Solar system to stars to first accretion light in the Universe, revolution in high-resolution spectroscopy, and in understanding of plasma physics in astronomical objects.

• **Feasible** — Chandra-like mission, promising pace of technology development.