Capabilities and Science Drivers for the X-ray Surveyor mission concept

A. Vikhlinin
on behalf of the X-ray Surveyor community
Martin Weisskopf will describe a possible mission configuration and its study at MSFC ACO (next talk)
Leap in sensitivity: High throughput with sub-arcsec resolution

- ×50 more effective area than Chandra. 4 Msec Chandra Deep Field done in 80 ksec. Threshold for blind detections in a 4Msec survey is ~ $3 \times 10^{-19}$ erg/s/cm$^2$ (0.5–2 keV band)
- ×16 larger solid angle for sub-arcsec imaging — out to 10 arcmin radius
- ×800 higher survey speed at the Chandra Deep Field limit
Black holes: from birth to today’s monsters

What is their origin?

How do they co-evolve with galaxies and affect environment?

Also:

- Electromagnetic signatures of black hole mergers
- Using X-ray binary population as tracers of star formation, their role in cosmic reionization
- Jets
Black holes: what is the nature of their seeds?

Light seeds: PopIII star remnants, $M_{\text{BH}} \sim 10^2 M_{\odot}$

Collapse of nuclear star cluster, $M_{\text{BH}} \sim 10^3 M_{\odot}$

Sustained super-Eddington growth to $M_{\text{BH}} \sim 10^4 M_{\odot}$ or more

Massive seeds: Direct collapse of supermassive star or a quasi-star object, $M_{\text{BH}} \sim 10^5 M_{\odot}$

What is their origin?

$z=6, M_{\text{BH}}=10^9 M_{\odot}$ quasar

$\Delta r_{\text{BH}} c R$

Chandra

SDSS
Nature of black hole seeds —
First accretion light in the Universe

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).

• Each X-ray Surveyor source will be associated with a unique JWST-detected galaxy. Limiting sensitivity, \( \sim 1 \times 10^{-19} \) erg/s/cm\(^2\), corresponds to \( L_X \sim 1 \times 10^{41} \) erg/s or \( M_{\text{BH}} \sim 10,000 \) \( M_{\odot} \) at \( z=10 \) — well within the plausible seed mass range.

• 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 \( M_{\text{BH}} \sim 3 \times 10^6 \) \( M_{\odot} \) at \( z=10 \) — above seed mass range. Confusion in O&IR id’s further increases the limit (\( M_{\text{BH}} \sim 10^7 \) \( M_{\odot} \) at \( z=8 \) is quoted by ATHENA team).
Cycles of baryons in and out of galaxies

How did the “universe of galaxies” emerge from initial conditions?

Structure of the Cosmic Web through observations of hot IGM in emission

Tarantula nebula

Generation of hot ISM in young star-forming regions. How does hot ISM push molecular gas away and quench star formation?

Molecular gas (IR)

Hot ISM (X-rays)

How did the “universe of galaxies” emerge from initial conditions?
Simulated 500 kpc box around a Milky Way type galaxy.
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~ 40% of baryons are converted to stars, ~ 60% ejected outside
  ~ 30% are observable in UV absorption
  ~ 30% are heated to X-ray temperatures — unique signature of energy feedback

**Required observations:** detect and characterize hot halos around Milky Way-size galaxies to z~1.

**Required capability:** ~ 100× sensitivity & angular resolution to separate diffuse emission from bright central sources
What physics is behind the structure of astronomical objects?

Plasma physics, gas dynamics, relativistic flows in astronomical objects:

• Supernova remnants
• Particle acceleration in pulsar wind nebulae
• Jet-IGM interactions
• Hot-cold gas interfaces in galaxy clusters and Galactic ISM
• Plasma flows in the Solar system, stellar winds & ISM via charge exchange emission
• Off-setting radiative cooling in clusters, groups & galaxies
• ...

Required capability: high-resolution spectroscopy and resolving relevant physical scales
New capability:
Add 3rd dimension to the data

X-ray microcalorimeter will provide high-resolution, high throughput spectroscopy with 1 arcsec pixels — detailed kinematics, chemistry & ionisation state of hot plasmas
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Plasma physics in astronomical objects

*Chandra* image of Perseus cluster: energy output from supermassive black hole balances radiative cooling.
Plasma physics in astronomical objects

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

Unsharp mask image

ripples with thin (< 1") interfaces

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

Sound waves in viscous plasma (Fabian et al. 2003)?
Turbulence in stratified atmosphere (Zhuravleva, ..., Fabian, ... et al. 2015)?
Plasma physics in astronomical objects
Plasma physics in astronomical objects

Sound waves: in-plane motions

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

**X-ray Surveyor**: detailed 3D tomography.

**ATHENA**: overall Doppler line widths.

Turbulence: line of sight motions
Capability leap: high throughput X-ray gratings spectroscopy

Chandra HETG spectrum of NGC 3783. Note the wealth of emission and absorption lines with $\lambda \sim 10\text{Å}$ ($E \sim 1\text{ keV}$)

X-ray Surveyor gratings will provide $R \approx 5000$ and $4000 \text{ cm}^2$ effective area, adding $250\times$ in throughput and $5\times$ in resolving power compared to Chandra (50\times throughput and 20\times resolving power compared to XMM Newton)

Physics of the “New Worlds”, e.g.:

- Star-planet interactions & atmospheres of “hot Jupiters”
- Stellar coronae, dynamos in sub-stellar regime
- Stellar winds

Inner workings of the black hole central engine, e.g.

- spectroscopy of outflows
- tidal disruption events
Key Goals:

- Microcalorimeter spectroscopy ($R \approx 1000$)
- Wide, medium-sensitivity surveys

Area is built up at the expense of coarser angular resolution ($10 \times$ worse) & sensitivity ($5 \times$ worse than \textit{Chandra})

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Key Goals:

- Sensitivity ($50 \times$ better than \textit{Chandra})
- $R \approx 1000$ spectroscopy on 1" scales, adding 3rd dimension to the data
- $R \approx 5000$ spectroscopy for point sources

✓ Area is built up while preserving \textit{Chandra} angular resolution (0.5"
✓ 16× field of view with sub-arcsec imaging
**X-ray Surveyor**

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

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

- **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

*Unique opportunity to explore new discovery space and expand our understanding of how the Universe works and how it came to look the way we see it*
BACKUP SLIDES
Angular resolution requirements for detecting first accretion light

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• 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.
Origin of black hole seeds

- Age of the Universe at $z=6$ is barely enough for quasars with $M_{BH}>10^9 M_{\text{Sun}}$ to grow via accretion. Likely, quick violent formation of massive seeds, followed by fast accretion.
- Lower-mass black holes, $M_{BH}<10^6 M_{\text{Sun}}$, 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, $L_{\text{opt,AGN}}<L_{\text{gal}}$
  - 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 coronae ($\sim 10\%$ of $L_{\text{bol}}$) at $z=10$ from Eddington-accreting black holes with $M_{BH} \sim 10,000 M_{\text{Sun}}$