X-ray Surveyor — Science Perspective and Mission Approach

Jessica Gaskin[1], Harvey Tananbaum[2], Alexey Vikhlinin[2], Martin Weisskopf[1]

---

[1] MSFC
[2] SAO

White Paper submitted to PhysPAG on behalf of X-ray Surveyor community, 07-05-2015

It is a great challenge to understand the complexities of the universe in which we live. NASA Astrophysics is driven by three defining questions: How did we get here? How does the universe work? Are we alone? A multi-wavelength approach is required to address these questions, and astronomers have demonstrated that X-ray observations provide an essential element to this quest. The *X-ray Surveyor* mission will provide unique insights into the evolution of the universe from early epochs to the present while probing and elucidating 1.2 underlying physical processes on scales from cosmological to atmospheres of nearby stars and planetary systems. To achieve great gains, particularly in sensitivity, over currently operating and proposed X-ray observatories, the *X-ray Surveyor* utilizes revolutionary X-ray optics and cutting-edge instrumentation. In addition to the science, we briefly summarize the current mission concept, key technology approaches, and an initial mission study carried out by the MSFC Advanced Concepts Office.

Science Frontiers and Mission Drivers

Comprehensive community reports such as the 2010 Decadal Survey — "New Worlds, New Horizons" — and the 2013 NASA Astrophysics Roadmap — "Enduring Quests, Daring Visions" — provide detailed summaries of current knowledge and understanding while laying out many of the key questions for the decades ahead. The *X-ray Surveyor* is conceptualized to provide the X-ray channel(s) required along with major space and ground-based facilities such as JWST, ALMA, and 30m-class optical telescopes to address many of the most challenging and difficult of these questions, while greatly expanding the discovery space.

X-ray Surveyor is extremely well poised to uniquely contribute to fundamental studies of the roles which central black holes play in the evolution of galaxies, and shed light onto their origin. While JWST will see the earliest galaxies at redshifts 10 and beyond, it is not geared to detect the early black holes in these "first" galaxies. We already know that by redshifts 6–7 some supermassive black holes in quasars have grown to ~ $10^9\,M_{\rm Sun}$ or more, but we are in the dark about the nature of initial black hole seeds and their growth at early times. Black holes with $M < 10^6\,M_{\rm Sun}$ are best observed in the X-ray band due to shifting of the spectral peak to wavelengths shortward of UV, due to dust obscuration of optical and UV radiation, and due to shifting of the IR signatures of AGNs out of the JWST band for $z \sim 10$ objects. *X-ray Surveyor* is designed to have sufficient sensitivity to detect $10^4\,M_{\rm Sun}$ black holes out to $z \sim 10$ (for Eddington limited accretion, assuming 10% of the bolometric luminosity is emitted in the hard X-ray band [Hopkins et al.]). If more massive seeds form or grow at still earlier epochs, *X-ray Surveyor* will detect them out to redshifts 15 or greater. While JWST will detect the first galaxies, *X-ray Surveyor* will detect the first accretion light from central black holes in these galaxies.

Substantial gains in the detection sensitivity limit for *X-ray Surveyor* (see Table 1) require X-ray mirrors which combine large throughput with high angular resolution to avoid X-ray source confusion and background contamination. High angular resolution is also critical for providing unique identifications of faint X-ray sources with the high-redshift JWST galaxies. Figure 1 illustrates this situation with a simulated $2'\times2'$ deep field observed with JWST (left) along with 4 Ms exposures with *X-ray Surveyor* (center), and ESA's Athena mission (right). With its $0.5''$ angular resolution, *X-ray Surveyor* sees substantially deeper than *Chandra* and Athena and is well-matched for unique identifications of faint X-ray sources with JWST galaxies (0.03 JWST galaxies per $0.5''$ *X-ray Surveyor* beam). Due to its $5''$ angular resolution, Athena becomes confusion limited at a relatively high flux level, corresponding to a black hole of $3\times10^6\,M_{\rm Sun}$ at $z = 10$, well above the most interesting range for seed masses. Furthermore, the expected number density of JWST galaxies (~ 2×10^6 galaxies per square degree [Windhorst et al.]) corresponds to 3 objects per $5''$ beam, making unique identifications with Athena sources problematic except for yet brighter and rarer objects.

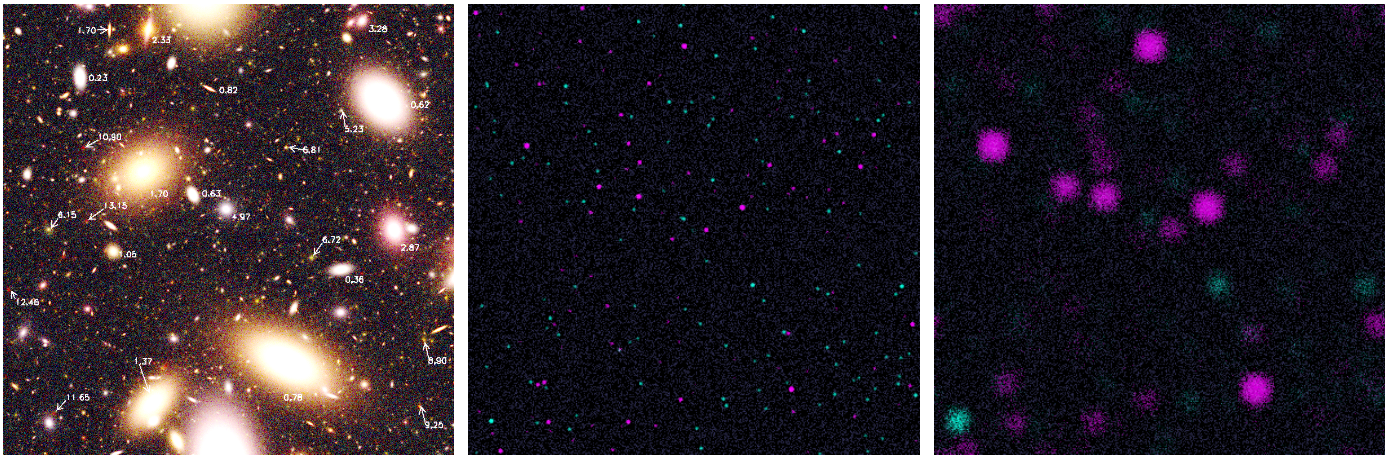

Fig. 1 — Simulated $2'\times2'$ region of a JWST deep survey (*left*, reproduced from Windhorst et al. 2002), and 4Ms exposures with *X-ray Surveyor* (*center*), and Athena (*right*). The X-ray log N – log S model is from Lehmer et al. (2012). AGNs and normal galaxies are shown in magenta and green, respectively.

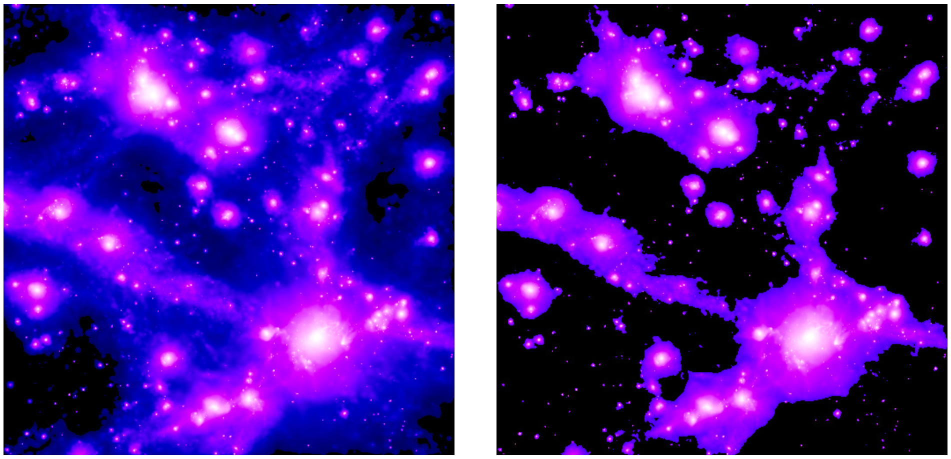

Fig. 2 — *Left:* Simulated X-ray surface brightness (0.5–2 keV band) in a 25 h^{-1} Mpc box around a massive (~10^{15} $M_{\rm Sun}$) galaxy cluster (numerical simulations are by Rasia, Dolag et al.). *Right:* Simulated brightness from the left panel clipped at the projected *X-ray Surveyor* surface brightness limit (~ 1/30 of that achieved in *Chandra* studies of the cluster outskirts). Most of the X-ray emissivity in this simulation is due to thermal bremsstrahlung of the H+He plasma. Any significant enrichment by heavy elements will further boost the X-ray flux.

In many astrophysical settings, gas with temperatures of a million degrees or higher is an essential and at times is the dominant form of the baryonic matter, tracing previous and ongoing physical processes. This hot gas is best observed in the X-rays. High angular resolution is essential for study of the relevant physical scales. For some of the most demanding applications, the very detection of hot diffuse gas depends on our ability to isolate the emission from discrete point-like sources. *X-ray Surveyor* will provide the capability to expose hot gas with phase space parameters and at distances substantially beyond the reach of any existing or planned facilities.

Theoretical modeling predicts that, in Milky Way-sized galaxies, baryons are divided into 3 roughly comparable components — stars; warm gas; and very large, pressure-supported, halos of hot (T ~ 10^6 K and higher) gas produced by energy feedback processes regulating galaxy formation. *X-ray Surveyor* will be able to detect and characterize these hot halos to z ~ 1, providing the most direct observational constraint on the energy feedback. This will be a key ingredient for the development of a consistent description of galaxy formation from initial conditions to early galaxies and to the beautiful spirals and ellipticals seen today. Woven through this entire fabric is the cosmic web of dark matter and baryons feeding gas into clusters, groups, and galaxies as they form and grow and also potentially collecting matter lost from these systems. *X-ray Surveyor* will be able to map hot baryons beyond the halos of individual galaxies, reaching into the cosmic web filaments. In today's Universe, most of the baryons appear to be outside the virial radii of any gravitationally bound structures. Some of these baryons are warm and can be detected in the O and Mg absorption lines in the UV, but a large fraction are hot ($T > 10^6$ K) and can be detected via absorption features they imprint on X-ray spectra of background AGN or through their X-ray emission. *X-ray Surveyor* will have the angular resolution to eliminate contamination from background and foreground sources and the sensitivity to enable detection in emission of at least half of the hot, diffuse baryons confined in the filamentary structures with density contrast $\rho/\rho_{\rm mean}$>30.

For hot gas expected to collect in deep gravitational potential wells associated with super-massive black holes at redshifts ~ 6–7 already discovered in the SDSS surveys and detected by *Chandra*, *X-ray Surveyor* will have the angular resolution and sensitivity to separate the bright, point-like quasar X-ray emission from extended X-ray emission produced by hot gas while actually measuring the spectral properties of the hot gas as it begins to form into the earliest groups and eventually clusters. At the opposite extreme of the cosmic distance scale, *X-ray Surveyor* will be able to penetrate into young star forming regions in the Milky Way and Local Group to characterize the origins of the hot ISM and its interactions with dense molecular clouds, while providing complete samples of young stars for detailed studies with 30m-class ground based telescopes.

In this short white paper, we simply identify a broad (and very incomplete) range of additional topics where *X-ray Surveyor* will provide unique information through its sensitivity, angular resolution, and spectroscopic capabilities. Examples include detailed studies of AGN feedback in clusters, groups, and galaxies with the ability to distinguish between sound wave and turbulent heating mechanisms; tracing winds and jets while deciphering the overall gas flow picture around supermassive black holes; unraveling the processes by which AGN jets are powered, collimated, and re-accelerated; unfolding the interactions of supernova blasts, shocks, and ejecta with circumstellar and interstellar material as well as mapping particle acceleration in supernova remnants and pulsar wind nebulae; and probing coronal activity in stars of all ages along with extending our understanding of star-planet interactions.

Clearly, as exemplified above, the superior angular resolution, sensitivity and spectroscopic capabilities of *X-ray Surveyor* enable very different science from Athena.

Table 1. — Comparison of several key capabilities of *Chandra*, Athena, and *X-ray Surveyor*

	Chandra	*X-ray Surveyor*	Athena
Relative effective area (0.5–2 keV band)	1	50	50
Angular resolution (50% power diameter)	0.5″	0.5″	5″
4 Ms point source sensitivity (erg/s/cm^2)	5×10^{-18}	3×10^{-19} (*)	2.5×10^{-17} (**)
Field of view with <1″ HPD (arcmin^2)	20	315	N/A
Spectral resolving power, *R*, for point sources	1000 (1 keV) 160 (6 keV)	5000 (0.2–1.2 keV) 1200 (6 keV)	200 (0.5 keV) 2400 (6 keV)
Spatial scale for *R*>1000 spectroscopy of extended sources	N/A	1″	5″
Wide FOV imaging	16′×16′ (ACIS), 30′×30′ (HRC)	22′×22′	40′×40′

* — For deep surveys based on limiting spurious detections in a wide area. The flux limit is $\approx10^{-19}$ erg/s/cm^2 for targeted objects.

** — limited by X-ray source confusion

X-ray Surveyor Concept Definition

Recently, NASA Marshall Space Flight Center, together with the Smithsonian Astrophysical Observatory, carried out an initial concept study for the *X-ray Surveyor* Mission. The study was implemented by the Advanced Concept Office (ACO) at MSFC, with a strawman payload and related requirements provided by an informal Mission Concept Team, comprised of MSFC and SAO scientists plus a diverse cross-section of the X-ray community. The study included a detailed assessment of requirements, a mission analysis, a preliminary design, and a preliminary cost analysis. In many areas, the mission requirements are no more stringent than those of *Chandra*, and the study also takes advantage of relevant studies for other large area missions carried out over the past two decades.

Payload: This concept study starts with a baseline payload consisting of a high resolution X-ray telescope, Critical Angle Transmission (CAT) grating, and instruments located at a focal length of 10 m, which include an X-ray Microcalorimeter Spectrometer (XMIS), a High Definition X-ray Imager (HDXI) and an X-ray Grating Spectrometer readout (CAT-XGS). The gratings can be inserted and retracted from the X-ray beam, and the XMIS and HDXI are mounted on a translation table which allows them to be swapped with each other at the telescope focus. The CAT-XGS is mounted in a fixed location at the focal plane.

The telescope consists of highly nested thin shells. A number of technical approaches are currently under development, including adjustable X-ray optics, differential deposition, and modern polishing techniques applied to a variety of substrates. The strawman *X-ray Surveyor* instruments are currently under development by several research groups so can be classified as cutting edge; the key is that this X-ray instrumentation exploits the new telescope's properties. XMS has a 5′×5′ field-of-view filled with 1″ pixels covering the energy range from 0.2 to 10 keV and will provide better than 5 eV resolution. The HDXI is a CMOS active pixel sensor with 0.33″ pixels covering a 22′×22′ field of view and sensitive to X-rays in the energy range from 0.2–10 keV. HDXI chips approximately follow the optimal focal surface of the X-ray mirror in the soft band. The CAT gratings will provide high-efficiency spectroscopy with resolving power of 5000 in the 0.2–1.2 keV band. An alternative grating spectrometer utilizing off-plane reflection gratings is also an option which will be assessed in future mission studies. At present, this is a strawman design, where future iterations will trade competing technologies for the telescope and the science instruments.

Spacecraft: The spacecraft design was designated Class B. Per NASA Procedural Requirement 8705.4, Class B payloads are typically fully redundant. There are no single point failures in the current spacecraft design. The spacecraft includes structure and mechanisms, propulsion, thermal systems, avionics, guidance and navigation control, electrical and power systems, and science instrument translation table. Overall spacecraft management of mechanisms, thermal control, power switching, communication interfaces, and storage of scientific data has been accounted for. Many of these systems are based on or derived from those of the *Chandra* Observatory. As such, there were no significant technology hurdles identified for the spacecraft.

Mission Profile: The *X-ray Surveyor* has been baselined for a Sun-Earth L2 Halo Orbit. The nominal mission duration is 5 years, with 20 years of on-board consumables. Based on experience with missions such as *Chandra* and XMM-Newton in high earth orbits, it is reasonable to expect a mission extending for 20 years or longer without having to design for that level in terms of components and subsystems. The estimated volume and mass with 30% margins, which is based on a Master Equipment List (MEL), meet the requirements of launch on an Atlas V 551 (or similar class vehicle). End-of-Life drift-away disposal will round out the mission.

Cost Prediction: The analogy-based NASA/Air Force Cost Model (NAFCOM) was employed to cost the spacecraft subsystems in this estimate, using the *Chandra* spacecraft as the analogy. The cost for the X-ray telescope assembly is a bottoms-up input from the MSFC/SAO team and costs for the scientific instruments were derived using JPL's NASA Instrument Cost Model (NICM). All costs are presented in 2015 dollars based on NASA's "New Start Inflation Indices for 2015". Fee, program support and vehicle integration were included in the cost. A 35% reserve was applied to the spacecraft and the X-ray Telescope Assembly. The instrument estimates from NICM were compiled at the 70% confidence level, which is deemed to be an appropriate and sufficient level of confidence consistent with NASA Procedural Requirement 7120.5E. Facilities cost to support pre-flight calibration are still under investigation and have not been included.

Table 2. — Cost Summary

Spacecraft	$1,650M
X-ray Telescope Assembly & Instruments	$866M
Pre-Launch Operations, Planning & Support	$196M
Launch with Atlas V 551	$240M
Total	**$2,952M**