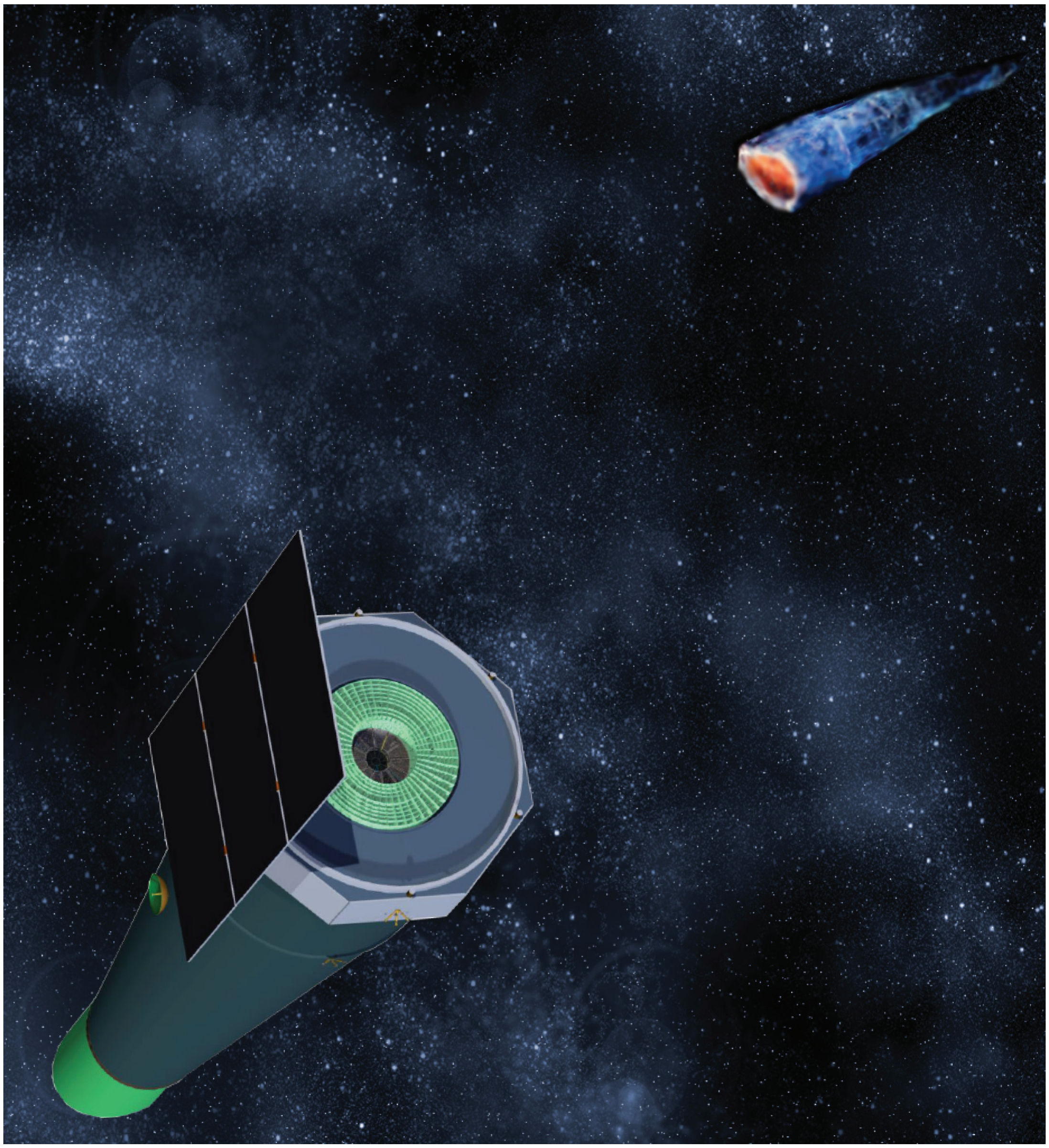
AXSIO

The Advanced X-ray Spectroscopic Imaging Observatory

Mission concept: *A broad bandpass high-sensitivity high-resolution X-ray imaging spectroscopy mission*

A submission available for workshop presentation in response to NASA 2011 RFI NNH11ZDA018L



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Submitted on behalf of the AXSIO team

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SUMMARY

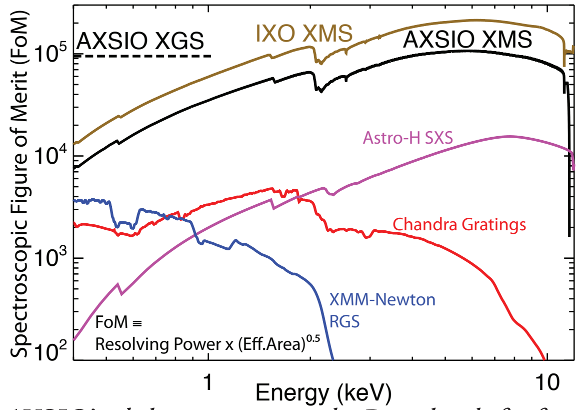
Following recommendations from the 2010 ``New Worlds, New Horizons" (NWNH) report, the Advanced X-ray Spectroscopy and Imaging Observatory (AXSIO) concept streamlines the International X-ray Observatory (IXO) mission[1] to concentrate on the IXO and NWNH science objectives that are enabled by high-resolution spectroscopic capabilities. AXSIO addresses fundamental and timely questions in astrophysics:

What happens close to a black hole?
How did supermassive black holes grow?
How does large scale structure form?
What is the connection between these processes?

The scientific grasp of AXSIO compares favorably with IXO and the NWNH recommendations (Table 1). AXSIO will address seven of IXO's eight key science objectives[2,3] (see §1). AXSIO will trace orbits close to the event horizon of black holes, measure black hole spin for sixty supermassive black holes (SMBH), use spectroscopy to characterize outflows and the environment of AGN during their peak activity, observe SMBH out to redshift z=6, map bulk motions and turbulence in galaxy clusters, find the missing baryons in the cosmic web using background quasars, and observe the process of cosmic feedback where black holes and supernovae inject energy on galactic and intergalactic scales. AXSIO's observing plan modestly reduces sample sizes (relative to IXO) and uses targeted observations instead of a high-redshift SMBH survey, but redirecting the survey time will avoid compromising the other underlying science goals.

These measurements are enabled by the 0.9 m^2 collecting area at 1.25 keV – six times more collecting area than any previous X-ray observatory. A microcalorimeter array provides high-resolution spectroscopic imaging; a modest re-configuration of IXO's calorimeter focal plane has allowed for recovery of essentially all of the science that would have been accomplished by IXO's High Time Resolution Spectrometer (HTRS) by using multiple pixel sizes. An inner array is optimized for high count rate sources and the highest possible energy resolution for point sources, while an outer array extends the field of view for diffuse sources. AXSIO has a substantially larger field-of-regard (now ±45º) compared to IXO (±20º), significantly improving its ability to execute Target of Opportunity investigations.

A retractable high efficiency grating spectrometer enables high-resolution spectroscopy of point sources, used either in tandem with the calorimeter or removed when observing diffuse sources. AXSIO delivers a 30-fold increase in effective area for high-resolution spectroscopy, microsecond spectroscopic timing, and high count rate capability compared to current missions, an improvement equivalent to a transition from the 200 inch Palomar telescope to a 12 m telescope while shifting from spectral band imaging to an integral field spectrograph.



AXSIO's ability to measure the Doppler shift of emission and absorption lines shows a modest reduction compared to IXO and large increase relative to other high-resolution spectroscopy missions.

The AXSIO implementation streamlines the IXO design, exploiting the many concept studies executed for both IXO and its predecessor, the Constellation-X mission. The key simplifications are guided by recommendations in the panel report from NWNH and include a reduction in focal length from 20m to 10m, eliminating the extendable optical bench, and a reduction in the instrument complement from six to two, avoiding a movable instrument platform. The smaller optic requires many fewer shells, while a focus on spectroscopic science allows the spatial resolution requirement to be relaxed to 10 arc sec (with a 5 arc sec goal), together lowering the difficulty and cost of fabrication.

These simplifications, combined with a fully Government/Commercial Off-The-Shelf (GOTS/COTS) mission operations model and advances in optics and detector technology since NWNH decrease the total mission cost to under \$2B (FY12), the cost to NASA recommended by NWNH. AXSIO will be available to the entire astronomical community with observing allocations based on peer-review. Previous experience assures us that unexpected discoveries will abound, and AXSIO will contribute to the understanding of new phenomena as they are uncovered. The mission could be started in this decade for launch in the early 2020s to an L2 orbit, with a five-year lifetime and consumables for 10 years.

Table 1: AXSIO Capabilities Regarding IXO and NWNH (Astro2010) Science

Science Questions	Status (§)
What happens close to a black hole?	
Orbit-resolved black hole disk studies	✓ (1.1.1)
When and how did SMBH grow?	
High-redshift SMBH survey	✗ (see 1.2)
SMBH spin survey	✓ (1.2)
How does large scale structure evolve?	
Absorption line studies of IGM	✓ (1.3.4)
Cluster studies to redshift z=2	✓ (1.3.3)
Cosmic Feedback	
Cluster survey	✓ (1.3.2)
Cluster cavity & AGN jet studies	✓ (1.3.1)
Matter at very high densities	✓ (1.1.2)
Other NWNH 2010 science	
How do stars form?	✓ (1.4)
Rotation, magnetic fields in stars	✓ (1.4)
Type Ia and massive star death	✓ (1.4)
Evolution of circumstellar disks	✓ (1.4)
Flares on planet-hosting stars	✓ (1.4)

1. SCIENCE

X-ray astronomy addresses several leading unsolved mysteries of the universe. It reveals how matter, energy, space, and time behave under such diverse conditions from black holes and neutron stars to the largest virialized systems of the universe, galaxy clusters. Not only do X-rays provide fundamental insights into their nature, but we discover how they grow and evolve. Furthermore, the small is related to the large in that the vast energy supplied by supermassive black holes likely has a profound effect on properties of galaxies and clusters through the process known as feedback.

The driving science goals of AXSIO are to determine the properties of the extreme environment and evolution of black holes and map the temperatures, abundances and dynamics in hot gas on scales ranging from the local ISM to galaxy clusters (over cosmological time): AXSIO will directly measure the feedback mechanisms regulating galaxy and supermassive black hole growth. AXSIO measurements will provide constraints on the structure of neutron stars and the dynamics of supernovae explosions.

IXO's science objectives (Table 1) were slightly broader and often achieved using multiple instru-

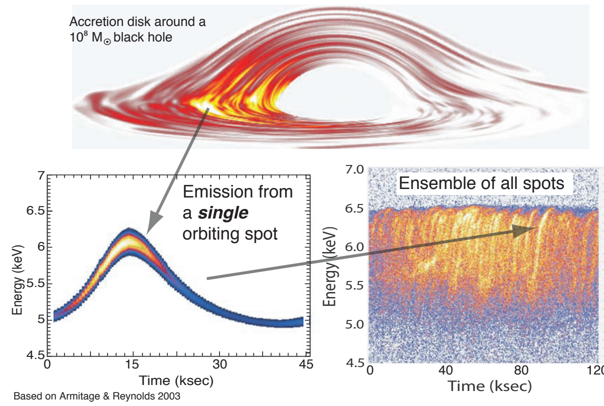


Figure 1. AXSIO will resolve multiple hot spots in energy and time as they orbit the SMBH, each of which traces the Kerr metric at a particular radius. In the time-energy plane, the emission from these hot spots appears as "arcs," each corresponding to an orbit of a given bright region.[5]

ments, *i.e.* strong gravity and high-density equation of state studies via spectroscopy, polarimetry and timing. In other cases, the removal of the WFI, HXI, and XPOL[1,2] instruments results in losses that are often recoverable using multiple pointings and longer observations. For example, most IXO observations did not require instantaneous effective area, so longer exposure times can recover the science. Likewise, the loss of the HXI bandpass impacts spin measurements, recoverable with longer observations to determine the continuum at 6 keV. The only unrecoverable losses result from (1) the joint requirements on area, field of view and spatial resolution needed to execute the high redshift SMBH survey and (2) the X-ray polarization measurements of magnetars.

AXSIO's large improvement in the available discovery space paves the way for exciting serendipitous discoveries characteristic of all major advances in astronomical capabilities.

1.1 Matter Under Extreme Conditions

Black holes and neutron stars provide the strongest gravitational field gradients and generally the most extreme environments in the Universe. AXSIO's capabilities will allow us to probe these regions in a manner not possible in other wavebands.

1.1.1 Strong Gravity

The observational consequences of strong gravity can be seen close to the event horizon, where the extreme effects of General Relativity (GR) are evident in the form of gravitational redshift, light bending, and frame dragging. The spectral signatures needed to determine the physics of the inner-

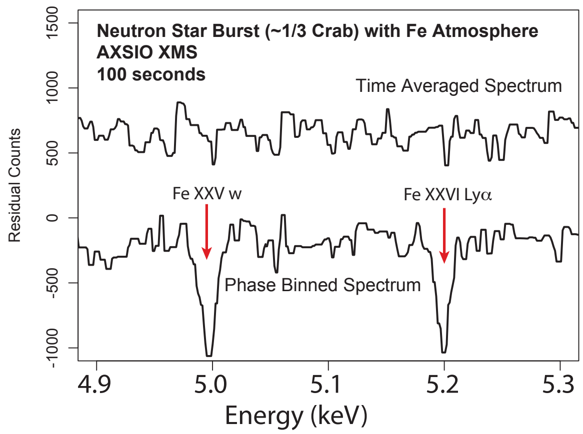


Figure 2. A burst spectrum from a rapidly-spinning NS reveals narrow atmospheric lines in a 100s integration after phase-binning the data (bottom cuve) that is invisible in the time-averaged spectrum (top curve). This requires a high-count-rate, high-spectral resolution detector such as the XMS, but recovers the gravitational redshift (z=0.3) of the lines and simultaneously yields the mass and radius.

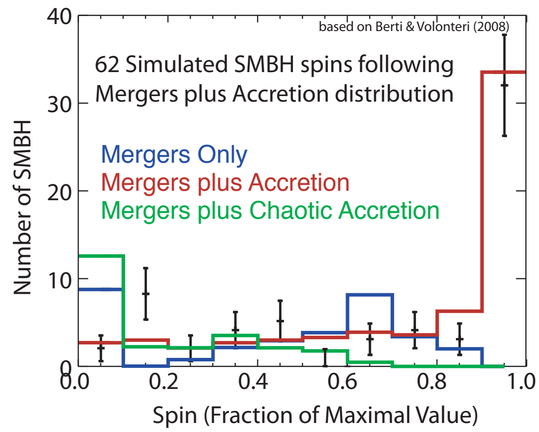


Figure 3. An AXSIO survey will distinguish between possible spin distributions of z<1 SMBHs resulting from different SMBH evolution models.[13]

most accretion flow into the black hole are only seen in X-rays. AXSIO will observe orbiting features in these disks where strong gravity effects dominate (Figure 1; NWNH 'Physics of the Universe', p.200).

Observations of SMBH with XMM-Newton have revealed evidence of "hot spots" on the disk that light up in the iron Kα line, allowing us to infer their motions.[4] Tracing these on sub-orbital timescales, however, requires the 0.2 m^2 effective area around 6 keV provided by AXSIO. Time-resolved spectroscopy reveals the mass and spin of the black hole and the inclination of the accretion disk. Deviations from the GR predictions will create apparent changes in these parameters as a function of time or hot spot radius. AXSIO will enable the first orbit-time-resolved studies of ~20 SMBH and provide a direct probe of the physics of strong gravity.

1.1.2 Neutron Star Equation of State

Neutron stars have the highest known matter densities in nature, utterly beyond the densities produced in terrestrial laboratories. The appearance of exotic excitations and phase transitions to strange matter have been predicted, but these predictions are uncertain due to the complexity of Quantum Chromodynamics (QCD) in this high-density regime. These uncertainties lead to widely differing equations of state, each of which imply a different neutron star radius for a given mass.[6] AXSIO will determine the mass-radius relationship for dozens of neutron stars of various masses with four distinct methods: (1) the gravitational redshift and (2) Doppler shift and broadening of atmospheric absorption lines, (3) pulse timing distortions due to gravitational lensing, and (4) pressure broadening of line profiles, all enabled by high resolution spectroscopy and energy-resolved fast timing (NWNH 'Frontiers of Knowledge', p.68).[7,8] Figure 2 shows how the gravitational redshift imprinted on narrow atmospheric lines originating in the burst ignition point can be recovered by binning the spectra at the rotational period of the NS, which removes the Doppler broadening. The inner point source array on the AXSIO calorimeter, with its high rate capacity, is uniquely suited to this task.

1.2 Black Hole Evolution

SMBHs are a critical component in the formation and evolution of galaxies. Future observatories including JWST, ALMA and 30m-class ground-based telescopes will observe the starlight from the earliest galaxies, while LSST and eROSITA surveys will discover large numbers of AGN at redshifts of z=1–6. IXO's area, spatial resolution, and field of view would have played a key role in detecting these early black holes. While not suited for wide field surveys, AXSIO will play a crucial role by detecting the accretion power from embedded SMBHs (10^7-10^9 $M_\odot$), even when obscured. AXSIO's high throughput for imaging and spectroscopy are critical for observing these sources, particularly the key "blowout" phase in the evolution of massive galaxies at z~1-3, when AGN winds terminated star formation. AXSIO will measure velocity, column density, metallicity, and ionization in the outflows responsible for cosmic feedback out to z~1, a critical ingredient in models of galaxy evolution.

Another approach to constraining SMBH evolution is via measurements of their spin.[9] AXSIO will measure the black hole spin in four independent ways: relativistic disk line spectroscopy, reverberation mapping, disk hot spot mapping, and power spectral analysis (NWNH 'Cosmic Order', p.57). A key observational signature is the iron Kα emission line, produced via the illumination of the disk by the primary X-ray continuum and distorted in energy and strength by the gravitational field and relativistic motions around the black hole. In SMBHs, either accretion or merger can change the spin. The current spin distribution is a record of the relative importance of mergers versus accretion in the growth history of black holes. Simulations show that longer observations compensate for the lack of 30 keV response (HXI) in the AXSIO configuration. Recent Swift BAT catalogs have identified significantly more than 60 bright Seyfert Type I SMBHs whose spins could be determined to <10%, sufficient to distinguish merger from accretion models and providing a new constraint on galaxy evolution (Figure 3).

In contrast, stellar-mass black hole spin is set at birth, so AXSIO measurements of ~100 such sources will uniquely reveal the angular momentum of the massive star progenitors before they exploded (NWNH 'Cosmic Order', p.57).

1.3 Large Scale Structure

The extraordinary capabilities of AXSIO will reveal the major baryonic component of the Universe, in clusters, groups and the intergalactic medium (IGM), and the interplay between these hot baryons and the energetic processes responsible for cosmic feedback. AXSIO will open a new era in the study of galaxy clusters by directly mapping the gas bulk velocity field and turbulence (Figure 4) and enabling far deeper observations than possible with current X-ray satellites.

1.3.1 Cosmic Feedback from SMBHs

Energetic processes around black holes result in huge radiative and mechanical outputs,[10] which can potentially have a profound effect on their larger scale environment in galaxies, clusters and the intergalactic medium (NWNH 'Cosmic Order', p.57). The black hole can heat surrounding gas via its radiative output, and drive outflows via radiation pressure. Mechanical power emerging in winds or jets can also provide heating and pressure. The high spectral resolution and imaging of AXSIO will provide the necessary spectral diagnostics to distinguish which process dominates.

For outflows that are radiatively accelerated in AGN, X-ray observations will determine the total column density and flow velocity, and hence

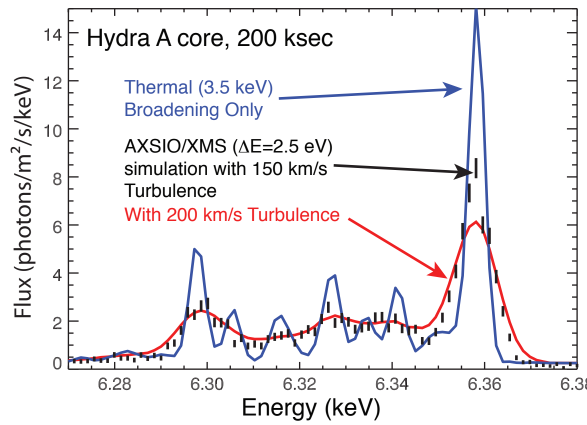


Figure 4. AXSIO spectrum of Fe XXV lines shows that turbulence of 150 km/s (simulated points) may be distinguished from 200 km/s or thermal broadening alone, an impossibility at CCD resolution.

the kinetic energy flux. AXSIO will be sensitive to ionization states from Fe I to Fe XXVI over a wide redshift range, allowing the first determination of how feedback affects all phases of interstellar and intergalactic gas. These measurements will uniquely probe over 10 decades in radial scale, from the inner accretion flow where the outflows are generated, to the halos of galaxies and clusters where the outflows deposit their energy.

Mechanical power from the central AGN acting through jets is thought to somehow compensate for the radiative cooling across scales of tens to hundreds of kpc. AXSIO can determine how this power is deposited into the gas through spectral observations that can identify both shock heating and turbulent mixing.

1.3.2 Galaxy Cluster Evolution

Entropy evolution from the formation epoch onwards is the key to disentangling the various non-gravitational processes: cooling and heating via SMBH feedback and supernova-driven galactic winds. AXSIO will measure the gas entropy and metallicity of clusters to z ~ 2 to reveal whether the excess energy observed in present-day clusters was introduced early in the formation of the first halos or gradually over time, crucial input to our understanding of galaxy and star formation.

Measuring the evolution of the metal content and abundance pattern of the IGM with AXSIO will show when and how the metals are produced, in particular the relative contribution of Type Ia and core-collapse supernovae, and the stellar sources of carbon and nitrogen. Precise abundance profiles from AXSIO measurements will constrain how the metals produced in the galaxies are ejected and redistributed into the intra-cluster medium.

1.3.3 Cosmology

The mystery of Dark Energy can be studied by observing the expansion history of the Universe and the growth of structure. X-ray observations of galaxy clusters with AXSIO will provide both tests, complementing other planned cosmological experiments (NWNH 'Physics of the Universe', p.200). Combining the distance-redshift relation [*d(z)*] and growth of structure data will dramatically improve constraints on the Dark Energy equation of state. These AXSIO data also test whether the cosmic acceleration is caused by modifications to Einstein's theory of gravity on large scales.

AXSIO will provide the precise temperature measurements essential to determine the cluster masses. AXSIO observations of hundreds of relaxed clusters selected from eROSITA, ground-based optical and SZ surveys will give an independent *d(z)* measurement.[11] eROSITA will not spatially resolve most clusters and will not have the spectral resolution and throughput to determine which clusters detected in its all-sky survey are relaxed. The spectral capabilities of AXSIO will provide direct checks on the relaxed state of a cluster through velocity measurements of the intra-cluster medium.

A recent advance in using galaxy clusters for cosmology was made by combining Chandra observations with advances in numerical modeling, leading to new dark energy constraints from both geometric and growth of structure methods.[12,13] Similarly, combining weak lensing and AXSIO observations of high-z clusters will reduce systematic errors for effective mass calibration and constrain the growth factor to 1% accuracy at $z>1$, leading to competitive uncertainties in cluster-based cosmological measurements.

1.3.4 The Missing Baryons

Less than 10% of the baryons in the local Universe lie in galaxies as stars or cold gas, with the remainder predicted to exist as a dilute gaseous filamentary network—the cosmic web. Some of this cosmic web is detected in Lyα and OVI absorption lines, but half remains undetected. Growth of structure simulations predict that these "missing" baryons are shock heated up to temperatures of 10^7 K in unvirialized cosmic filaments and chemically enriched by galactic superwinds.[14]

Despite local success in finding hot gas in the halo of the Milky Way, observations with the grating spectrometers on XMM-Newton and Chandra have not yielded conclusive proof for the existence

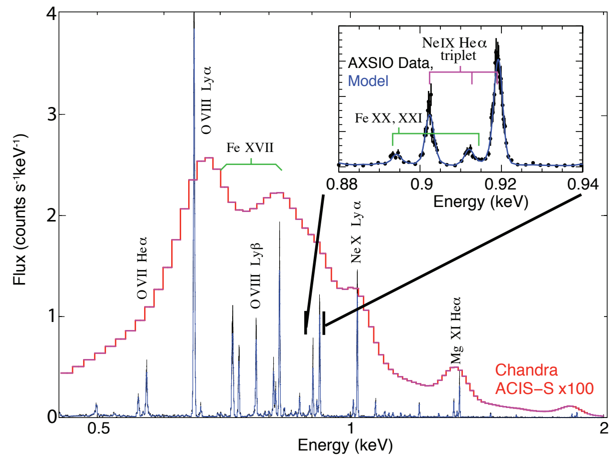


Figure 5. AXSIO high-resolution X-ray spectra (blue) show the metal-enriched hot gas outflowing from a starburst galaxy, a part of the feedback process unresolvable with current X-ray CCD data (red).

of the hot cosmic web at z > 0.[15] The order of magnitude increase in collecting area and R = 3000 spectral resolution of AXSIO is required to enable detection of the missing baryons and characterize their velocity distribution along at least 30 lines of sight (NWNH 'Cosmic Dawn', p.192). This distribution of mass as a function of temperature can be determined from X-ray absorption line grating spectroscopy of highly ionized C, N, and O detected against background AGNs. The extent and nature of galactic superwinds that enrich the web will also be measured both from the proximity of absorption sites to galaxies and the dynamics of the hot gas. We will combine these absorption measurements with imaging high-resolution emission measurements outside the virial radius of galaxy clusters that will reveal gas just now falling into the cluster.

Most galaxies, in fact, have lost more than 2/3 of their baryons, relative to the cosmological ratio of baryons to dark matter.[16] These missing baryons are probably hot, but we do not know if they were expelled as part of a starburst-phase galactic wind, or pre-heated so that they simply never coalesced. X-ray absorption line observations with AXSIO will, for the first time, identify the location and metallicity of these Local Group baryons from the line centroids and equivalent widths of hot C, N, and O ions, revealing a crucial aspect of galaxy formation (NWNH 'Cosmic Order',p.57).[17]

1.4 Life Cycles of Matter and Energy

The dispersal of metals from galaxies can occur as starbursts drive out hot gas that is both heated and enriched by supernovae. This metal-enriched gas is detected with current X-ray missions, but AX-

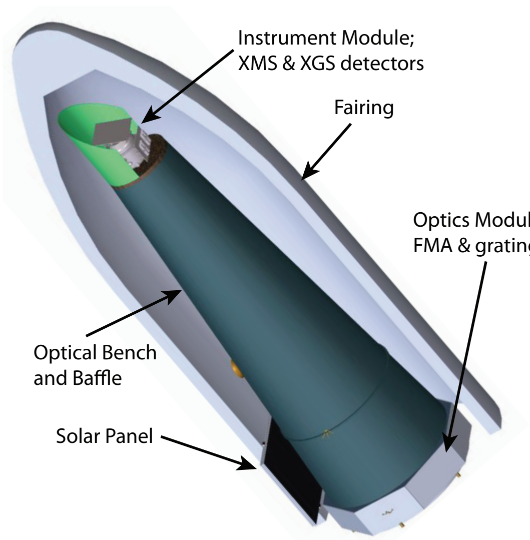


Figure 6. AXSIO payload within Atlas fairing

SIO is needed to measure the hot gas flow velocity using high-throughput spectroscopic imaging (Fig. 5), and in turn determine the galactic wind properties and their effects.

The distribution of metal abundances in the Milky Way, including both the gas and dust components, will be mapped using absorption line measurements along hundreds of lines of sight. On smaller scales, emission from gaseous remnants of Type Ia and Type II supernovae seen with AXSIO will offer a comprehensive three-dimensional view of the ejecta composition and velocity structure, allowing detailed studies of nucleosynthesis models for individual explosions (NWNH 'Cosmic Order', p.57).

AXSIO will reveal the influence of stars on their local environment via measurements of their coronal activity and stellar winds (NWNH 'Cosmic Order', p.57). This influence also includes their effect on habitable zones as well as on planet formation. Observations of star-forming regions have shown that X-rays from stellar flares irradiate protoplanetary disks, changing the ion-molecular chemistry as well as inducing disk turbulence.[18] While Chandra has detected a few immense flares,[19] the most significant impact on the protoplanetary disk is in the integrated output of the smaller flares, which can only be characterized using AXSIO (NWNH 'New Worlds', p.196).

2. MISSION OVERVIEW

AXSIO is a facility-class observatory that will be placed via direct insertion into an 800,000 km semi-major axis halo orbit around the Sun-Earth L2 libration point using an Evolved Expendable Launch Vehicle. An Atlas V-521 provides substantial throw margins. The mission design life is 5 years, with consumables sized for 10 years. Essential performance parameters derived from the science are shown in Table 2.

2.1 Observatory Overview

The observatory's modular design is well defined, building on studies performed over the last decade for Constellation-X and IXO, and has strong heritage from previous space flight missions. The observatory technical resources summary is shown in Table 3. The L2 orbit facilitates the high observational efficiency (>85%) and provides a stable thermal and radiation environment that simplified the overall mission architecture. The allowed attitude relative to the sun line is 45°–135° (pitch), ±180° (yaw), ±10° (roll).

2.2 Spacecraft Overview

A NASA/GSFC MDL study concluded that the AXSIO spacecraft could be built with fully mature technologies. All subsystems utilize established hardware with substantial flight heritage. Most components are "off-the-shelf." The AXSIO spacecraft concept is robust; all AXSIO resource margins

Table 2. Essential AXSIO Performance Parameters

Parameter	Value	Science Driver	Inst.
Mirror Effective Area	$0.93\ m^2$ @ 1.25 keV $0.20\ m^2$ @ 6 keV	Black Hole Evolution Strong Gravity	
Spectral Resolution	$\Delta E < 3$ eV (FWHM) $E/\Delta E = 3000$	Cluster Evolution Missing Baryons	XMS XGS
Angular Resolution	10 arcsec HPD	Cosmic Feedback, Cluster Evolution	XMS
Field of View	4x4 $arcmin^2$	Cluster Evolution	XMS Full
Bandpass	0.2-10 keV 0.2-1.5 keV	Growth of SMBH Cosmic Web	XMS XGS
Count Rate	15,000 cps with <10% deadtime	Neutron Star Equation of State	XMS PSA

Table 3. Technical Resources Summary (Mass, Power & Data)

	Estimated Value	Growth Contingency %	Maximum Expected Value	Margin %	Minimum Available Resource	Total Growth Reserve %
Launch Mass [kg]	2292*	18%	2696*	46%	3935 (LV Throw Mass)	72%
Power Consumption [W]	1935	30%	2516	13%	2840 (S/A Output)	47%
Stored Data (72 hr) [Gbits]	135	30%	176	14%	200 (On-board Memory)	48%

*Masses calculated assuming consumables needed for 10 years of operations.

meet or exceed requirements. Substantial redundancy for contingency mode operations assure that no credible single failure will degrade the mission. The spacecraft pointing control requirement is 6 arc sec (3σ, radial), with post-facto aspect reconstruction accuracy of 1.3 arc sec (3σ, radial); these accuracies are achievable with adequate margin.

2.3 AXSIO Mission Operations

A reference AXSIO Operations Concept has been developed that describes the envisioned AXSIO mission operations approach and architecture of the supporting ground data systems. Primary telemetry, tracking, and command services will be provided by NASA's Deep Space Network (DSN), with short (<30min) daily ground contacts. Flight and science operations will be conducted from a joint AXSIO Science and Operations Center (ASOC). The ASOC is staffed with an eight-hour shift seven days per week during normal operations, utilizing automation for off-shift routine operations. Observing sequences are uploaded weekly, while daily contacts allow for precision timing (100μsec) and monitoring of instrument health and safety. Up to 2 Target-of-Opportunity (ToO) observations per month can be accommodated.

3. INSTRUMENT OVERVIEW

3.1 Payload Overview

The AXSIO payload (Fig.6) consists of 1) the Flight Mirror Assembly (FMA), a large area grazing incidence mirror; 2) the X-ray Microcalorimeter Spectrometer (XMS); and 3) an X-ray Grating Spectrometer (XGS) that intercepts and disperses a fraction of the beam from the mirror onto a CCD camera, which can either operate simultaneously with the XMS or be removed from the beam if not needed.

The Flight Mirror Assembly provides effective area of 0.93 m^2 at 1.25 keV and 0.2 m^2 at 6 keV. The technology is based on a segmented design with precision-slumped glass mirror segments[20]. The process of building the mirror assembly is illustrated in Figure 7: forming mandrel fabrication, mirror segment fabrication, module construction, and alignment and integration of mirror modules into the flight mirror assembly.

Mirror technology development has recently matured a number of techniques that are at the core of building the mirror assembly. Three pairs of forming mandrels have been successfully fabricated with a standard polishing process, meeting both AXSIO performance and cost requirements. The process is being upgraded and automated to be amenable to mass production to manufacture the several hundred forming mandrels required for implementing AXSIO. A precision glass slumping process has been developed that replicates the optical figure of the forming mandrels onto thin (0.4mm) commercially available float glass sheets. With the three pairs of forming mandrels, the slumping process has consistently produced substrates that have been shown by precision optical measurement to meet the optical figure (better than 6.5 arc sec HPD, two reflections), yield (higher than 75%), cost, and production schedule required for implementing the AXSIO mission. A sputtering process used to coat these substrates with a thin (~15nm) film of iridium to maximize their X-ray reflectance has been demonstrated with small coupons. AXSIO substrates are being coated and measured to qualify them for flight use. A complete process of aligning and bonding mirror segments into a module housing has been developed and is being carefully evaluated and qualified. Single parabolic and hyperbolic pairs of mirror segments have been repeatedly aligned, bonded, and tested in an X-ray beam, consistently achieving better than 10 arc sec HPD images.

A number of experiments are being conducted to characterize and understand the behavior of the epoxy bonds that attach the mirror segments to the housing. Results from these experiments will enable the selection of the best possible epoxy and design

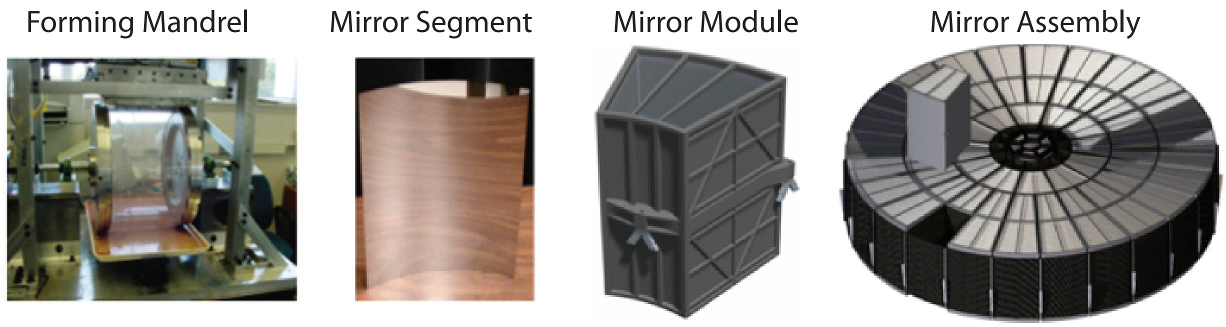


Figure 7. Building the mirror assembly starts with forming mandrels whose precision optical figures are replicated to mirror segments. A number of mirror segments are precisely aligned and bonded together to become mirror modules, which are aligned and integrated into a superstructure to become the flight mirror assembly.

for optimal bond geometry, achieving both short-term (~hours) alignment and bonding accuracy and long-term (~years) stability. Work is underway to co-align and bond multiple pairs of mirror segments into a single module housing to conduct X-ray performance and environmental tests. The completion of these tests is expected for the end of 2012, achieving Technology Readiness Level (TRL) 5. Alignment and integration of mirror modules into a superstructure to form the final flight mirror assembly requires no technology development; substantially similar tasks have been done for other missions.

The X-ray Microcalorimeter Spectrometer (XMS) provides high spectral resolution, non-dispersive imaging spectroscopy over a broad energy range. The XMS consists of an X-ray microcalorimeter array housed in a cryostat and associated electronics for the detector read-out and for controlling the cooler. Cryocoolers and a 3-stage adiabatic demagnetization refrigerator (ADR) cool the detector to 50 mK (Figure 8a). We have baselined a cooling system that has redundant cryocoolers to ensure extremely high reliability.

The microcalorimeter arrays utilize Transition Edge Sensors (TES) thermistors attached to X-ray absorbers consisting of gold or of a bismuth-gold bilayer. The XMS detector will be the only imaging detector on AXSIO, and so it must address the science requirements on the field of view (FOV), spectral resolution, and count rate capability leading to the AXSIO baseline of a central array for studying high count-rate point sources, surrounded by an array that extends the FOV to 4 arc-min, as shown in Table 4.

The microcalorimeter arrays are read out using SQUID amplifiers that are multiplexed in the time domain, i.e. each first stage SQUID attached to a single pixel is read out sequentially through a common second stage SQUID. Figure 8(b) shows the 3 eV energy resolution obtained from an array using two multiplexers that read out 8 pixels each[21]. The current TRL is 4-5; improvements to the architecture will allow us to increase the number of pixels per multiplexer to 32. Figure 8(c) shows a photograph of a prototype 32x32 array of 300 μm pixels that has demonstrated 1.8 eV single pixel performance. We have also fabricated arrays of 75 μm

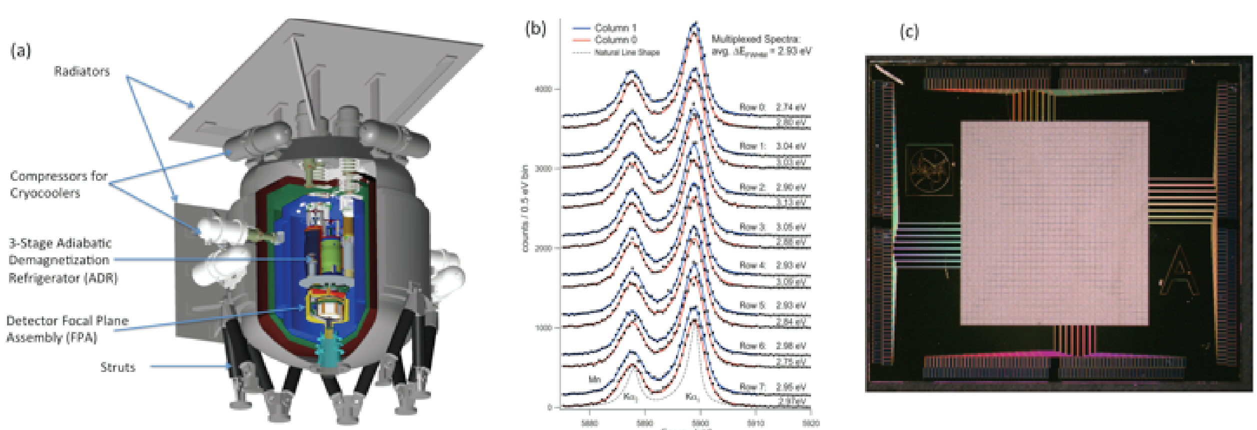


Figure 8. (a) Design of an XMS of the type baselined for AXSIO. (b) Performance of a microcalorimeter array with a 2x8 multiplexed read-out. (c) Photograph of a prototype 32x32 microcalorimeter array.

Table 4. XMS microcalorimeter array layout

Main Array	Inner Point Source Array
40x40 pixels, 6 arc sec each	24x24 pixels, 1.5 arc sec each
4.0 arc min FOV	36 arc sec FOV
300 µm pixels	75 µm pixel
80% throughput at 50 cts/s/pixel	80% throughput at 300 cts/s/pixel

pixels suitable for the inner array that have demonstrated 1.6 eV resolution, and allow count rates up to 300 cps/pixel.

The X-ray Grating Spectrometer (XGS) is a wavelength-dispersive spectrometer for high-resolution spectroscopy, offering spectral resolution ($\lambda/\Delta\lambda$) of 3000 (FWHM) and effective area of 1000 cm^2 across the 0.3–1.0 keV band. Two implementations have been studied in great detail: A Critical-Angle Transmission (CAT)[22] grating spectrometer and an Off-Plane reflection grating (OP)[23] spectrometer. Both implementations cover sub-sections of the mirror aperture (sub-aperturing) and take advantage of the resulting narrowing of the 1-D Line-Spread-Function (LSF) to increase spectral resolving power by orienting the grating dispersion direction perpendicular to the average plane of incidence for the corresponding mirror sub-aperture.

The CAT-XGS consists of two identical spectrometers, arranged as a pair of diametrically opposed CAT grating array structures (GAS) that cover the outer two FMA module rings over 30° in azimuth, and a readout camera offset from the telescope focus (see Fig. 9). CAT gratings combine the advantages of transmission gratings (light-weight, alignment and figure insensitive, transparent at higher energies) and blazed reflection gratings (high diffraction efficiency, use of higher orders). The removable GASs are placed just aft of the FMA for maximum dispersion distance and are passively temperature controlled through the FMA. Each GAS is populated by an array of ~60x60 mm^2 grating facets. The gratings for each GAS pair are blazed in the same direction and are therefore able to share a single readout array. Each camera contains a linear strip of eight modified MIT-LL CCID41 back-illuminated frame-transfer CCDs (1k×1k 24µm pixels each), extending from ~460 mm from focus radially outward. The CCDs are passively cooled to -90°C and their energy resolution sorts the spatially overlapping diffraction orders. The CAT-XGS is based on direct heritage from the Chandra HETGS (336 Au transmission gratings) and the ACIS and Suzaku/XIS cameras. Technology development is planned in the areas of grating size and throughput, efficiency, and integration. The CAT gratings are today TRL3 and expected to reach TRL4 in the next year; CCDs are TRL5.

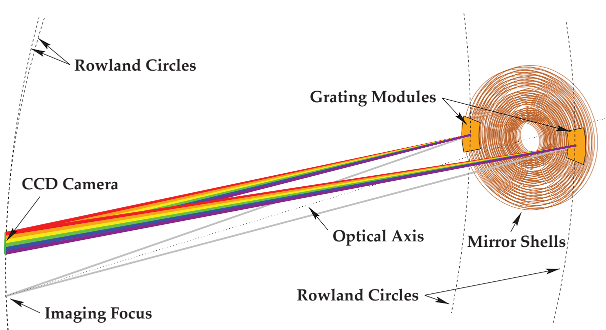


Figure 9. One (of two) CAT grating spectrometers.

An alternative implementation, the OP-XGS, uses thin reflection gratings in the conical diffraction, or off-plane mount. The OP grating array will intersect the outer FMA module rings and cover a similar portion of the telescope beam. The array consists of modules each housing a set of fanned grating substrates that disperse to a common focus. The groove profile is replicated onto each of the substrates from a single grating master per module. Reflection gratings have direct heritage from XMM and suborbital rocket flights, although OP reflection gratings displaying the required groove profile are TRL3. A current technology development program is aimed at increasing this to TRL5 over the next two years. The goals of this study include fabrication of a high fidelity master grating with the required groove profile and size, replication of this grating onto several substrates, alignment of these substrates into modules, and verification of system performance with X-ray and environmental testing. Similar to the CAT-XGS, the modules produce separate spectra at the focal plane allowing for spectral redundancy. The readout camera will be similar as well although organized in an azimuthal arc of CCDs rather than radially outward.

4. SCHEDULE AND COST

4.1 Schedule

The AXSIO top level mission schedule supports a June 2022 launch, including 8 months of funded schedule reserve on the critical path. The schedule reflects our ability to capitalize on the modular nature of AXSIO; the three Observatory modules (Optics Module, Instrument Module, and Spacecraft Module) are developed and qualified in parallel, and then delivered for final Observatory Integration and Test (I&T). Calibration activities take place at both the module and Observatory level. Observatory I&T reflects activities, flows, and durations that have been developed based on experience from other space observatories of comparable size and type with an emphasis from the Chandra development.

The development of the Ground System (GS), Mission Operations (MO), and science Data Analysis (DA) systems will occur in parallel with the observatory development. Five years of mission operations assuming 85% observing efficiency enables the science plan outlined in §1.

4.2 Cost

The AXSIO cost to NASA is currently estimated to be $1898.2M (FY12 dollars) including ~$132M for data analysis and science research (GO) grants to the US scientific community. This cost covers mission formulation, development, and operational phases (Phase A-E). The mission cost estimate is project-generated by NASA/GSFC and SAO, and is subject to ongoing development and refinement. Initial estimates of the AXSIO mission were derived using a variety of methods including parametric cost modeling, analogy, and grassroots costs estimates.

Costs estimates are generated for every element within the mission Work Breakdown Structure (WBS), and then rolled up into the overall mission level estimate. The estimates include the costs for the flight system, ground system, mission operations and data analyses, and technology development. They also include science, project management, mission systems engineering, safety and mission assurance, observatory integration and test, launch services, and education and public outreach. Cost estimates cover mission Phases A through E. Parametric Review of Information for Costing and Evaluation Hardware (PRICE-H) has been the primary tool for cost estimates of the majority of the AXSIO flight hardware, including all of the spacecraft costs. The inputs to the PRICE-H model are by component in the Master Equipment List (MEL) and include information such as mass, quantities, type of equipment, and technology readiness levels (TRL). The development schedule and planned engineering or qualification units are also factored into the PRICE-H estimates. The estimate assumes rates, including fees, consistent with this work being performed by a major aerospace industry contractor for the optics, and spacecraft.

The Flight Mirror Assembly (FMA) cost estimate was developed using PRICE-H and was based on a preliminary design supported by CAD, structural, and thermal optical analyses to determine material selection and sizing, and accounted for the modular nature of the FMA. The mirror segment production portion of the FMA cost estimate has also been based on NuSTAR experience-to-date that established mirror production facilities and fabrication of flight mirror segments.

Table 5: Cost breakdown by WBS

WBS	Description	Cost*	Reserve	Total
1.0	Project Mgmt	62.3	30 %	81.0
2.0	Systems Eng	62.3	30 %	81.0
3.0	Safety & MA	39	30 %	50.5
4.0	Science	260.4	7.4 %	279.7
	Mission Support	128.6		
	GO Grants	131.8		
5.0	Payload	521.3	30 %	677.7
	FMA	281.8		
	CAT XGS	56.5		
	XMS	183.0		
6.0	Spacecraft Bus	257.8	30 %	335.1
7.0	Mission Ops	61.7	30 %	80.2
8.0	LV	190.0		190.0
9.0	Ground Sys	43.8	30 %	56.9
10.0	Systems I&T	40.5	30 %	52.3
11.0	E&PO	13.5	0 %	13.5
	Totals	1362.4		1898.2

* in $M (FY12 dollars)

The CAT-XGS cost estimates were PRICE-H with pass-throughs. The XMS cost estimate was generated as a grounds-up current best estimate for items below the sub-system level, based on the current Astro-H cost data. The resulting total XMS cost is validated by comparison with the XMS cost estimate performed for the IXO mission using a PRICE-H model.

The Ground System, Mission Operations, and Science and Data Analysis cost estimates were generated by grass roots with strong analogy to similar activities for Chandra. These cost estimates were generated by the Smithsonian Astrophysical Observatory, which operates the Chandra X-ray Center under contract to NASA. Based on lessons learned from previous X-ray missions (Chandra and XMM) we have assumed that there will be a joint Science and Operation Center (AXSIO SOC, or ASOC) to maximize the science returns on the mission. For preliminary cost estimating purposes, we assume that the ASOC will evolve from, and be co-located with, the current Chandra X-ray Center, thereby leveraging significant NASA investments in existing facilities and expertise and minimizing risks.

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