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AXSIO and the NASA X-ray Mission Concepts Study

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Abstract. The Advanced X-ray Spectroscopy and Imaging Observatory (AXSIO) focuses on the IXO science objectives ranked highly by the Decadal Survey: tracing orbits near SMBH event horizons, measuring BH spin, characterizing outflows and the environment of AGN, observing SMBH to z=6, mapping gas motion in clusters, finding the missing baryons, and observing cosmic feedback. AXSIOs streamlining of IXO includes reduction in the instrument complement to a calorimeter and a grating spectrometer, and relaxation of the angular resolution to 10 arc seconds. With 0.9 m^2 effective area at 1.25 keV, AXSIO delivers a 30-fold performance increase over current missions for high-resolution spectroscopy and spectroscopic timing. NASA has also undertaken a study of notional missions to determine lower cost approaches to accomplishing IXO objectives over the next decade. Three concepts were studied, which as a group encompass the full range of IXO science. The capabilities and architecture of these missions are summarized.

Key words. X-ray astronomy; X-ray spectroscopy; future missions

1. Introduction

The *International X-ray Observatory (IXO)* was a joint NASA/ESA/JAXA mission designed to address major astrophysics questions, including: *"What happens close to a black hole?"; "How and when did supermassive black holes grow?"; "How does large scale structure evolve?"; "What is the connection between supermassive black holes and large scale structure in the Universe?";* and *How does matter behave at high density? IXO* addressed these five questions through a combination of a very large area, high-resolution X-ray mirror and state of the art instrumentation, including a microcalorimeter, grating spectrometer and wide field imager (Bookbinder 2010, Barcons et al. 2011).

In *"New Worlds, New Horizons" (NWNH)*, the 2010 report of the US Decadal Survey of Astronomy and Astrophysics, *IXO* was described as *"a versatile, large-area, high-spectral-resolution X-ray telescope that will make great advances on broad fronts ranging from characterization of black holes to elucidation of cosmology and the life cycles of matter and energy in the cosmos"* (Blandford et al., 2010). Despite the perceived priority of the *IXO* science, the mission was ranked fourth among large NASA missions for this decade because of its projected cost.

IXO had also been proposed to ESA as a candidate for the L-1 opportunity in its Cosmic Visions program. Following the release of *NWNH*, the Planetary Science Decadal Survey, and the U.S. budgets in February 2011, ESA restructured its L-class program to allow ESA-only missions exclusively, resulting in the development of *Athena* and the termination of the *IXO* program.

Recognizing the importance of the *IXO* scientific objectives in the absence of a defined mission, NASA commissioned a study to identify approaches to fulfilling them at a cost more consistent with the available resources over the next decade. The primary study activity consisted of defining a set of notional missions and estimating their cost.

Prior to, and independent of, this study, the core US *IXO* team developed a concept for a mission that would address *IXO* science goals within the NWNH cost recommendation of ≤ \$2B. This mission was named the *Advanced X-ray Spectroscopic and Imaging Observatory (AXSIO)*, and featured prominently in the subsequent mission concepts study.

In this presentation, we briefly describe the study process and the notional missions that were defined.[1] Particular attention is focused on *AXSIO*, as the successor mission concept in the US to *IXO*.

2. The study process

The study was initiated by two NASA solicitations, one for white papers on mission or instrument concepts or enabling technologies that could be used for concepts that meet some or all of the scientific objectives of *IXO*, the other for membership on a Community Science Team (CST), whose function was to define a set of mission concepts for further study. These concepts were to represent various cost points between \$300M to \$2,000M. The Study Team members selected by NASA are listed in Table 1.

Based on the white papers and community input at a well-attended workshop, the CST defined three single-instrument "notional missions" that combined characteristics of various mission concepts from the white papers. These notional missions are: a calorimeter spectrometer (*N-CAL*), a gratings spectrometer (*N-XGS*), and a wide-field imager (*N-WFI*). In addition, the *AXSIO* was used as a representative large mission, based on the fact that it was conceived in direct response to the recommendations in *NWNH*, and because it had already undergone a feasibility and cost study using the same approach that was to be used for the notional missions.

The key properties of the four notional missions are summarized in Table 2. The single-instrument notional missions, taken together, address nearly the full suite of *IXO* science objectives (as does *AXSIO* by itself).

Each notional mission was subjected to a one-week GSFC Mission Design Lab (MDL) session. The goal of this effort was to apply a uniform process to the development of an initial concept design that would realistically meet the performance requirements set by the CST (i.e., a point design). Using standard cost estimating tools (most notably PRICE-H) and the same costing personnel for all estimates, the MDL then estimated the total mission lifetime costs. The cost goal and MDL estimate for each mission are included in Table 2.

Having studied the four notional missions, and the status of and prospects for the enabling technology, the study team came to the conclusion that it would in fact be possible to develop a mission that achieves a substantial fraction of the *IXO* objectives for \$1B. But developing a mission at this cost requires that the key technologies (optics, gratings, detectors) have reached sufficient technical maturity before the start of the mission so that they pose minimal technical risk. The study team also found that the critical instrument for achieving the *IXO* objectives is a calorimeter, echoing the conclusion in *NWNH*.

3. The notional missions

Below we briefly describe each notional mission, with emphasis on *AXSIO*. Important assumptions common to all four missions were an L2 orbit and a 3-year lifetime.

[1] The study report and all supporting documents can be found at http://pcos.gsfc.nasa.gov/studies/x-ray-mission.php.

Table 1. NASA X-ray Mission Concepts Study Team

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Study Scientist	R. Petre (GSFC)
Community Science Team	J. Bregman (Chair), M. Bautz, D. Burrows, W. Cash
	C. Jones, S. Murray, P. Plucinsky, B. Ramsey, R. Remillard
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Science Support Team	A. Ptak, J. Bookbinder, R. Smith, M. Garcia

3.1. Notional Calorimeter Mission (*N-CAL)*

The key performance requirements for *N-CAL* include effective area of 5,000 cm^2 at 1 keV and 2,000 cm^2 at 6 keV, a field of view of at least 4 arcmin, and angular resolution of 10 arcsec (HPD) or better. *N-CAL* would directly address all five of the *IXO* science goals. Specifically, time resolved, high-resolution spectra of the relativistically broadened Fe-K line in stellar mass or supermassive black holes would address *"What happens close to a black hole?"* Measurements of the mass and composition of clusters at z ¡ 2 through spatially-resolved spectroscopy would address *"How does large scale structure evolve?"* Measurements of the metallicity and velocity structure of hot gas in galaxies and clusters would address *"What is the connection between supermassive black hole formation and evolution of large scale structure (i.e., cosmic feedback)?"* The high spectral resolution of the calorimeter is the key enabling capability for meeting these objectives.

The *N-CAL* flight mirror assembly (FMA) utilizes a segmented design with precision slumped glass mirror segments. It has a focal length of 9.5 m, a diameter of 1.3 m, 178 shells, 20 cm segment length (each reflection stage), and a mass of 325 kg. The combined effective area of the FMA and the calorimeter, plotted in Fig. 1, provides more than an order of magnitude increase over the effective area of the *Astro- H* Soft X-ray Spectrometer. In addition, the FMA provides an order-of-magnitude improvement in angular resolution compared with *Astro-H* (1.0 arcmin HPD). The *N-CAL* calorimeter is a hybrid array that combines a

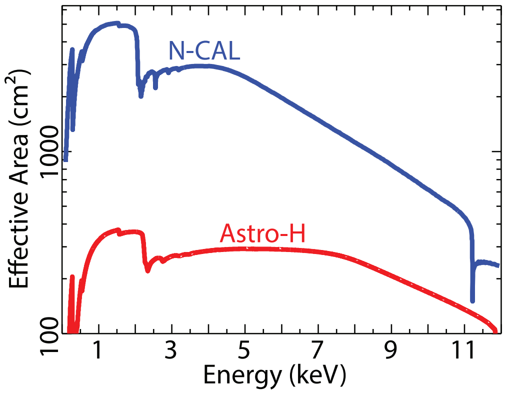

Fig. 1. Effective Area of *N-CAL* compared with the calorimeter on Astro-H.

small central point source array (PSA), with 16×16 pixels (1.5 arcsec pixels) optimized for higher spectral resolution and a fast readout for studying high count-rate point sources, with a larger array of single and multiple readout pixels, covering a total field of view of 4 arcmin on a side. This design is identical to that of *AXSIO* and is described below.

3.2. Notional Grating Spectrometer Mission (*N-XGS*)

N-XGS addresses the *IXO* science made possible by its X-ray Grating Spectrometer (XGS). Intended as a modest cost observatory dedicated to high-resolution soft X-ray grating spectroscopy, *N-XGS* would provide effective area of 450 cm^2 in the 0.31.0 keV band, a spectral resolving power $\lambda/\Delta\lambda \geq 3000$, and a spectroscopic capability far beyond current missions (Fig. 2). *N-XGS* would explore the

Table 2. Notional Missions

Mission	En. Range (kev)	Spectral Res.	Eff. Area m^2 @ keV	Ang. Res.	Field of View	Focal Length	Cost Goal	MDL Cost
N-CAL	0.2-10	≤3 eV (inner pixels)	0.5 @ 1 0.2 @ 6	10"	4'	9.5 m	≤$1B	$1.2B
N-XGS	0.2-1.3	$\lambda/\Delta\lambda$ ≥3000	0.05 @ 1	10"	n/a	4 m	≤$0.6B	$0.8B
N-WFI	0.2-10	150 eV	0.7 @ 1 0.2 @ 6	7"	≥24'	6 m	≤$1B	$1.0B
AXSIO	0.2-10 (XMS)	≤3 eV	0.93 @ 1 0.2 @ 6	10"	4'	10 m	≤$2B	$1.5B
	0.2-1.5 (XGS)	$\lambda/\Delta\lambda$ ≥3000	0.1 @ 1					

evolution of cosmic structure with unprecedented sensitivity to physical conditions in the WHIM, detecting absorption features with equivalent width as low as 5 mÅ (at 5σ significance in a 500 ks exposure) in 50 blazars. Deeper exposures of the brightest of these objects would be sufficiently sensitive to detect superwind-driven shells of outflowing matter around intervening galaxies. It would probe both the velocity and density, and thus, crucially, the mass outflows fed back from supermassive black holes to their host galaxies. *N-XGS* would look for atmospheric absorption features in the spectra of bursting neutron stars. If detected, these would constrain neutron star mass and radius, and thus their equation of state, via gravitational redshift and pressure broadening effects.

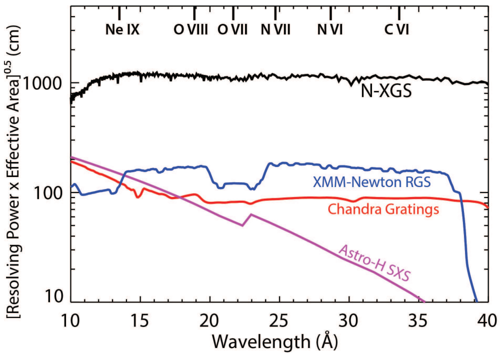

Fig. 2. *N-XGS* would provide at least a five-fold increase in sensitivity to key absorption lines (which is proportional to the square-root of the effective-area x resolving power product) over any current or planned spectrometer.

The *N-XGS* consists of two independent, objective-grating spectrometers that operate in parallel. Each spectrometer is illuminated by a set of four grazing-incidence mirror modules, which can be thought of as azimuthal sub-apertures of a circular mirror. Each module produces an astigmatic image, and the optical design maximizes spectral resolving power by dispersing the spectrum from each module separately and parallel to the narrow dimension of its image. The Line-Spread Function (LSF, characterized by its full-width at half-maximum, FWHM) is roughly a factor of three smaller than the half- power diameter of the full-aperture mirror (10 arcsec). For *N-XGS* a LSF with FWHM ≤ 3 arcsec is sufficient to achieve the required spectral resolving power ($\lambda/\Delta\lambda$ ≥ 3000). The astigmatic image produced by each 15 degree module of the FMA meets this requirement.

The *N-XGS* FMA modules use the same Wolter-I, segmented glass architecture adopted for N-CAL and *AXSIO*. Each 15 degree module spans 400 to 900 mm in radius. To minimize the spacecraft mass and volume, eight FMA sectors are arranged in a bow-tie configuration as shown in Fig. 3. Blazed objective gratings are mounted immediately behind each mirror module. Two distinct grating technolo-

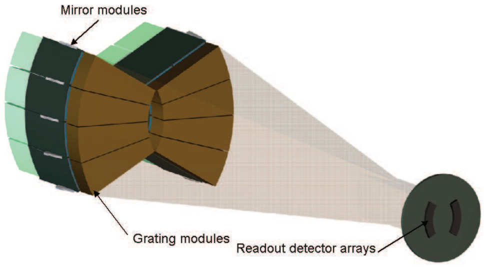

Fig. 3. Effective Area of *N-XGS* optical layout. Each of the two spectrometers consists of a wedge-shaped set of mirror modules spanning a 60-degree annular sector, associated objective grating modules and a readout detector array in the focal plane.

gies are under development for *N-XGS*: Off-Plane Gratings (OPG) (McEntaffer et al., 2011) and Critical Angle Transmission (CAT) gratings (Heilmann et al. 2011a, Heilmann et al. 2011b). The dispersed spectra are detected and recorded by arrays of X-ray photon counting, charge-coupled device (CCD) detectors.

3.3. Notional Wide Field Imager Mission (*N-WFI*)

The Wide Field Imager (*N-WFI*), is a sky survey instrument, with effective area 5,000 cm^2 at 1 keV and 2,000 cm^2 at 6 keV, $\leq$ 7 arcsec angular resolution across a field of view of at least 24 arcmin, and CCD spectral resolution (~150 eV at 6 keV). The *N-WFI* incorporates three identical telescopes, each consisting of a wide-field imaging mirror and a CCD detector.

N-WFI addresses three IXO objectives. Measurements of the mass and spatial distribution of clusters to z~2, along with the spatial distribution of AGN, would address *How does large scale structure evolve?* By measuring the luminosity function of AGN as a function of redshift (to z ~ 6), including obscured AGN often missed by other surveys, and determining the host galaxy properties and environment, *N-WFI* would answer the question *When and how did supermassive black holes grow?* The large numbers of clusters and groups of galaxies that *N-WFI* would study with good angular resolution would reveal the roles of AGN outbursts and how they change with redshift, addressing the objective *What is the connection between supermassive black hole formation and evolution of large scale structure (i.e., cosmic feedback)?*

N-WFI would conduct two surveys. A medium depth survey, with an average exposure time of 20 ks, would cover ~850 deg^2 (reaching a 0.5-2.0 keV point source 5σ flux limit of $\sim 4\times10^{-16}$ erg cm^{-2} s^{-1}). It would cover one or two large contiguous regions to enable spatial and angular correlation studies. A deep survey, with an average exposure time of 400 ks, would cover a total ~25 deg^2 spread over several distinct regions (reaching a point source 5σ flux limit of $\sim 7\times10^{-17}$ erg cm^{-2} s^{-1}). *N-WFI* would detect approximately 1.5×10^6 AGN in the medium survey and an additional 2.5×10^5 AGN in the deep survey. About 1.5×10^5 of these would have > 400 counts, and ~4,500 would have high N_H. *N-WFI*would detect ~10,000 clusters in the medium survey and an additional 750 clusters in the deep survey. A few hundred of these would have sufficient counts to map temperature profiles; many thousands would yield accurate temperature and mass estimates.

The *N-WFI* optics are Wolter-I type, with small design perturbations to reduce off-axis aberrations and enhance resolution across a broader field of view (Conconbi et al., 2010). The *N-WFI* design assumes full-shell fused-silica-based optics, with 71 nested shells in each of three 6-m-focal-length mirror modules. This design achieves the required sub-7-arcsec angular resolution to 18 arcmin off axis (Fig. 4) and better than 7,000 cm^2 effective area on axis at 1 keV and 1,800 cm^2 at 6 keV. Although the HPD exceeds 7 arcsec beyond 18 arc minutes off-axis, the field of view extends to 30 arc minutes off-axis. The detectors are 2×2 arrays of X-ray CCDs.

3.4. Advanced X-ray Spectroscopic and Imaging Observatory (*AXSIO*)

AXSIO retains most of the scientific power of *IXO* (Bookbinder , 2012). The *AXSIO* mirror provides nearly a factor of two more area at 1 keV than those of *N-CAL* or *N-XGS*, and provides the same effective area at 6 keV as *N-*

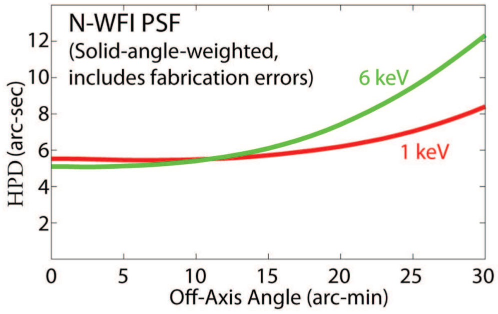

Fig. 4. Angular resolution (solid angle weighted) versus off-axis angle for *N-WFI* .

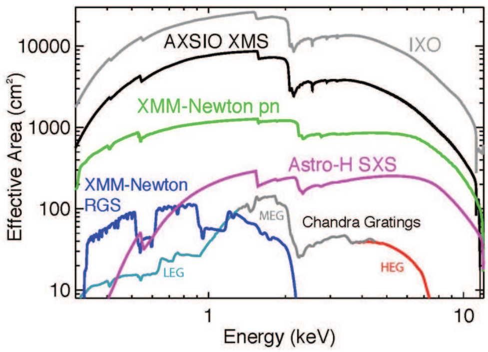

Fig. 5. Comparison of *AXSIO* effective area with those of *IXO*, *Astro-H*, and currently operating missions.

CAL (Fig. 5). Thus *AXSIO* could achieve all of both the *N-CAL* and *N-XGS* science objectives within the same three years simply using its larger effective area.

AXSIO would make significant advances on all five of the primary *IXO* science objectives. Unlike single-instrument missions, however, *AXSIO* also has unique complementary capabilities that are required to address some *IXO* (and *NWNH*) goals. Two examples demonstrate these synergistic efforts. The *IXO* science plan to address the question, *"How does large scale structure evolve?"* combines absorption spectroscopy using grating observations of background AGN and imaging spectroscopy of galaxy clusters. Similarly, understanding how black hole winds form and propagate requires high-resolution spectroscopy over a broad bandpass from 0.1 to 10 keV, capabilities only possible using both grating and calorimeter spectrometers.

The *AXSIO* FMA is based on a segmented Wolter-I design with precision slumped glass mirror segments, the same general approach as used for the IXO, *N-XGS* and *N-CAL* mirrors. The mirror has a 10 m focal length, a diameter of 1.8 m, and consists of 227 shells, each with two 20 cm long reflection stages. The *AXSIO* focus on spectroscopic science allows the angular resolution requirement to be relaxed to 10 arcsec: still over an order of magnitude improvement over *Astro-H*. The FMA provides 0.9 m^2 at 1 keV and 0.2 m^2 at 6 keV. The *AXSIO* effective area is plotted in Fig. 5.

AXSIO pairs an X-ray calorimeter spectrometer with an X-ray grating spectrometer. The calorimeter would have a hybrid array, combining an inner point-source array (PSA) consisting of smaller pixels, with higher spectral resolution and faster readout, with an outer array with larger pixels, slower multiplexed readouts and lower spectral resolution. The PSA would consist of 16 × 16 pixels with a spectral resolution of 2 eV covering a field of view of 0.4 × 0.4 arcmin (each pixel is 1.5 × 1.5 arcsec), requiring 256 Transition Edge Sensors (TESs) for readout. This improvement in the calorimeter configuration enables high count rate (15,000 cps, or 100 mCrab), high spectral resolution (2 eV) science, without the separate detector (High Time Resolution Spectrometer) that was needed on *IXO*. The outer array would complete the coverage of the 4 × 4 arcmin FOV with two types of pixels, each with a size of 6 × 6 arcsec. Surrounding the PSA would be 544 pixels, each with its own dedicated TES, to provide 3 eV energy resolution. The outermost part of the array would be populated by 1,040 pixels with 6 eV resolution. A single TES would provide the readout for four pixels, reducing the number of TESs required for this part of the array to 260. The total number of TESs (and hence individual signal lines) for the instrument would be 1,060.

The *AXSIO* retractable high efficiency X-ray grating spectrometer enables high-resolution spectroscopy of point sources, used either in tandem with the calorimeter or removed when observing diffuse sources. The grating spectrometer offers spectral resolution ($\lambda/\Delta\lambda$) of 3000 (FWHM) and effective area of 1000 cm^2 across the 0.3-1.0 keV band. The *AXSIO* design is compatible with both the CAT and the OPG. The gratings are mounted immediately behind the mirror module, with a mechanism to remove them from the beam if desired.

AXSIO is a facility-class observatory that would be placed via direct insertion into an L2 halo orbit; an Atlas V 521 provides substantial throw margin. The observatorys 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 L2 orbit facilitates high observational efficiency ($\geq$ 85 percent) and provides a stable thermal and radiation environment that simplified the overall mission architecture. All subsystems utilize established hardware with substantial flight heritage.

4. Future prospects

The X-ray Mission Concepts Study Report was submitted to NASA in July 2012. Subsequently, in January 2013, the NASA Astrophysics Division released an Implementation Plan, outlining how the next strategic mission after JWST will be selected. This mission would be selected by NASA in 2015, started in 2017, with an anticipated launch in 2022. One option described in the Plan is a ~\$1B probe class mission. An X-ray mission, like those described here, would be a strong candidate if NASA decides in favor of a probe class mission. Prior to the 2015 decision, a more thorough study will be made of AXSIO, with the goal of reducing estimate cost so that it can fall into the probe class.

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