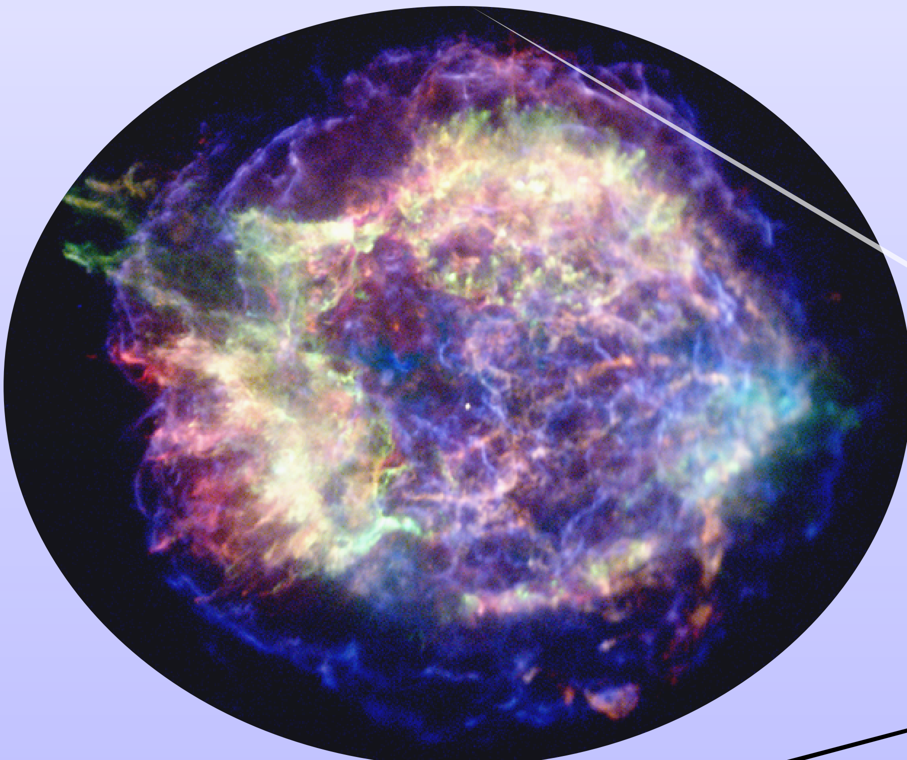
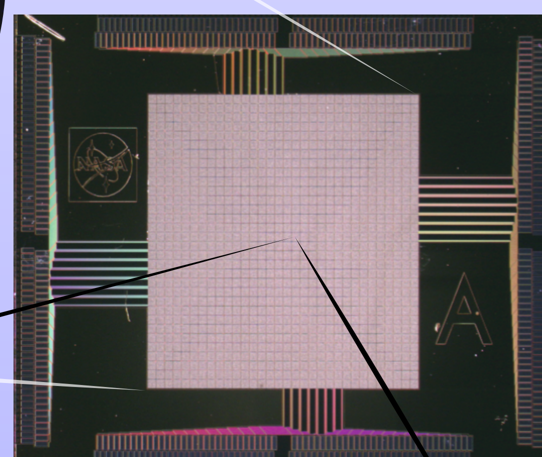
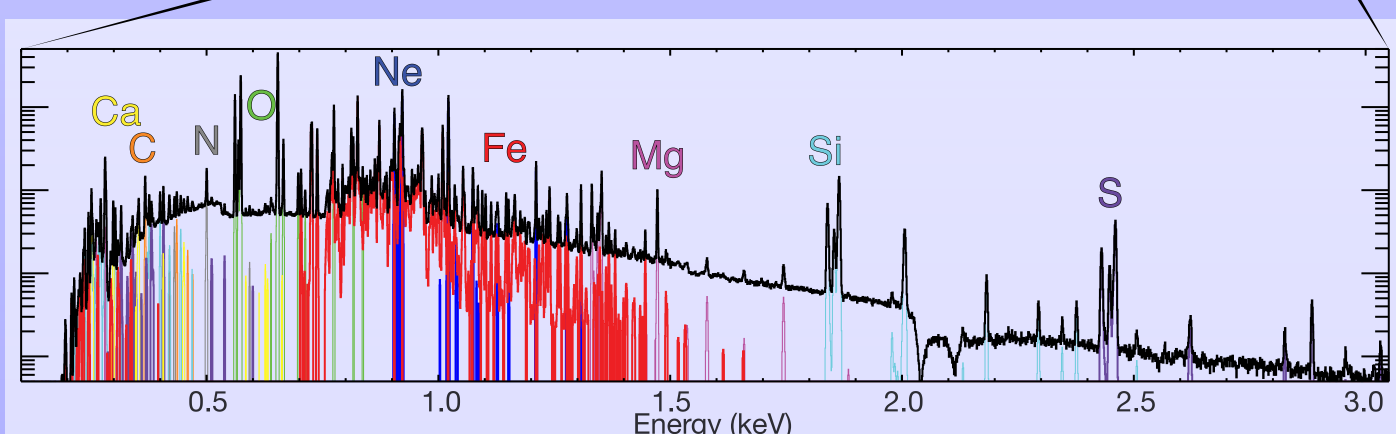
National Aeronautics and Space Administration

X-ray Mission Concepts Study

Project Report







August 2012

Cover Image: Chandra image of the supernova remnant Cassiopeia A (Credit: NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.). Photo: Prototype array of 32 x 32 transition edge sensors (TES) developed for IXO (Credit: NASA/GSFC). Spectrum: Simulation of high-resolution TES spectra showing emission lines from a range of elements (Credit: NASA/SAO).

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X-ray Mission Concepts Study Report

Submitted to

Astrophysics Division
Science Mission Directorate
NASA Headquarters

and

Physics of the Cosmos Program Office
Astrophysics Projects Division
NASA Goddard Space Flight Center

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X-ray Science Support Team
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1 Executive Summary

This study examines feasible NASA strategies to achieve the next great advance in X-ray astronomy. NASA stated the issue, "Following the termination of the NASA/ESA partnership in the *International X-ray Observatory* (*IXO*) mission, NASA's Physics of the Cosmos (PCOS) Program is developing alternative plans to address high priority *IXO* scientific objectives described in the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons* (NWNH)."

Key *IXO* science goals include: measuring black hole spin, a fundamental property that can reveal how supermassive black holes grow; tracing the orbits of accretion disk material close to the event horizon, one of the few opportunities to study astrophysics in the strong field limit; measuring the equation of state of neutron stars, giving new insights into particle physics; quantifying the growth of galaxy clusters, the largest gravitating structures in the Universe and a sensitive constraint on structure formation; carrying out absorption studies of the hot intergalactic medium, revealing the nature of the baryons missing from galaxies and from the baryon census; and determining the evolution of AGNs over cosmic time and feedback on their environment, which shapes the properties of galaxies and galaxy clusters.

To initiate this X-ray study, in Fall 2011 the NASA Astrophysics Division issued a Call for Letters of Application for membership in the Community Science Team (CST, to be assisted by a Study Team with specialized technical skills), and a Request for Information (RFI) of Concepts for the Next NASA X-Ray Astronomy Mission. The RFI states "Information being sought includes relevant mission concepts, instrument concepts, enabling technologies, or any aspect of flight, ground or launch systems architecture. … Mission concepts should range in cost from ~$300M to $2,000M (FY12)." There were 30 responses, which were also presented and discussed further at a workshop in December 2011. Following our charge, the CST and Study Team evaluated the RFI responses "for the degree to which they fulfill the *IXO* science objectives and for their degree of technical readiness" and to "identify a small number of concepts for further study based on input from the RFI and the workshop." Subsequently, a set of notional missions that have the collecting area, field of view, angular resolution, and instrument package to answer the key *IXO* science themes were developed. These notional missions should be feasible for a mission start toward the end of this decade, a timeline under consideration by NASA Headquarters.

We find that the extraordinary capability of a large-area X-ray calorimeter mission will address the greatest number of *IXO* science themes, so we developed a single-instrument Notional Calorimeter mission (*N-CAL*). A calorimeter array is a new generation imaging device where each pixel can produce a high-resolution spectrum to identify forests of emission and absorption lines, yielding fundamental physical quantities for many classes of objects (e.g., velocities, abundances, temperatures, and densities). Two other notional missions investigated were also single-instrument platforms (for simplicity) employing the other primary *IXO* instruments (both use CCD-type detectors). One is an X-Ray Gratings Spectrometer (*N-XGS*), offering superior spectral resolution for point sources in the energy band below ~1 keV and dramatically improving the detectability of the elusive "missing" baryons in the Universe. The other is a Wide-Field Imager (*N-WFI*) optimized for deep surveys that probe the nearby and high-redshift Universe. These missions will make critical scientific contributions but address fewer *IXO* science themes. AXSIO, a two-instrument package (calorimeter and soft gratings) developed in direct response to NWNH recommendations but before the study was initiated, was also considered along with the notional missions. *AXSIO* provides Doppler-limited spectral resolution across the entire X-ray band, combining the strengths of *N-CAL* and *N-XGS*. Each mission offers one to two orders of magnitude improvement over existing platforms or missions under construction (e.g., *Astro-H*) and will make major breakthroughs in central *IXO* science themes.

Mission cost estimates were generated from designs developed by GSFC's Mission Design Laboratory, including a consistent cost for *AXSIO*, and modeling based in part on actual costs of previous missions. The designs, and thus the costs, are not optimized, which would require additional study. The cost of the calorimeter-only mission (*N-CAL*) was $1.2B and for *AXSIO*, which has a larger mirror and a second instrument (soft gratings spectrometer), the cost was $1.5B. The least expensive mission was the gratings mission (*N-XGS*) at $0.8B, while the wide field imager (*N-WFI*) is $1.0B. Lower cost versions of these missions are possible through engineering optimization, foreign contributions, or descoping. These costs are reliable if the technologies are developed to TRL-6 prior to a mission start and if design stability is maintained, according to two GAO studies of NASA mission costs.

We identified the essential technologies to be brought to TRL-6 prior to the start of these missions. Lightweight optics are the central technological development that provides an order of magnitude more collecting area relative to existing observatories. It is fundamental to all of the notional missions as well as advancing X-ray Explorer-class missions in the near term. Progress in this area has been steady (now at TRL-4) given the available funding, but a more vigorous approach is warranted. Calorimeter detector technologies have advanced significantly through the development for *Astro-H* but further array development is needed for the notional calorimeter missions. Other important technologies for the notional missions are identified, such as gratings development.

These technologies enable longer-term goals. The next major goal in lightweight optics is to improve the angular resolution by an order of magnitude to the sub-arcsec level, a return to *Chandra* resolution but with much larger effective area. For detectors, the kilo-pixel calorimeters of *N-CAL* and *AXSIO* will be revolutionary, yet large field of view imaging at subarcsec resolution require megapixel calorimeters and possibly active pixel sensor images with more than 10 megapixels. To reach these ambitious longer-term goals, technology development is needed now, with the reward being another leap in scientific capabilities.

Chronic underfunding has hampered timely technology development in several areas, a problem that would be resolved by providing funding levels within the guidelines recommended in NWNH. Improved funding would enable multiple groups to explore technological solutions, a competitive approach that can lead to innovative technologies. Timely investment now is essential to enable a mission start this decade.

The study team identified simplified missions that capture most of the fundamental *IXO* science at a fraction of the *IXO* cost. These notional missions cost less than the current X-ray flagship missions (*Chandra*, *XMM*) yet will greatly outperform them in critical ways, producing breakthrough science around which the *IXO* concept was developed.

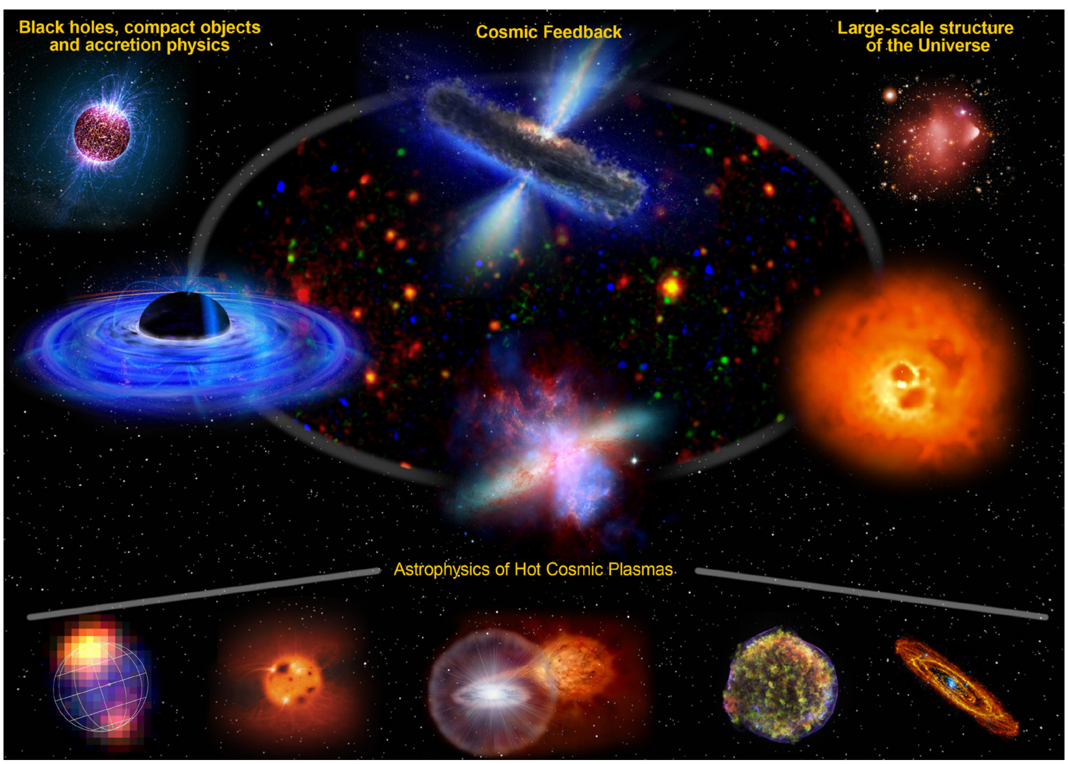

Figure 1-1. *Artist's illustration of IXO's science goals, including the physics of black holes, the growth of large-scale structure, and other regions near and far whose physics could be revealed by a new large X-ray mission (Figure courtesy Barcons et al. 2012, arXiv:1207.2745).*

2 Historical Background

In 1962, just 50 years ago, the first non-solar X-ray source, Scorpius X-1, was discovered by a team led by Riccardo Giacconi using an X-ray detector on a sounding rocket. The first imaging X-ray telescope, developed by Giacconi and his collaborators, made observations of the Sun in 1963. This X-ray telescope was about the same diameter and length as Galileo's 1610 telescope. From Galileo's telescope to the *Hubble Space Telescope*, the sensitivity improved by approximately 10^8, in a time interval of 380 years. A comparable increase in sensitivity was achieved between the first imaging X-ray telescope and *Chandra*, over a time of only 36 years. Yet even while *Chandra* was under construction, technological advances prompted considerations of new opportunities to leap forward. Here, we briefly review the achievements of the current flagship missions and the succession of efforts to define the next generation for high-energy astrophysics.

2.1 Current Flagship Missions

The *Chandra Observatory*, NASA's flagship X-ray mission, was launched and deployed by the Space Shuttle Columbia on July 23, 1999. At *Chandra's* heart is the highest angular resolution X-ray optic yet flown (Wolter type I, iridium coated, grazing incidence telescope) which allows sub-arcsec images to be made using either of two imaging detectors. In addition, very high resolution spectroscopy is achieved using either of two gratings, along with the imaging detectors. **Table 2.1-1** summarizes the mission characteristics. More than 12 years after launch, *Chandra* continues to operate well, with a high observing efficiency and all science instruments functioning. *Chandra* observations have revolutionized our views of the cosmos. They have had important impacts on nearly all areas of astrophysics from comets and planetary magnetic fields, to star formation and supernovae, to the most distant AGN and clusters of galaxies. As examples, astronomers using *Chandra* observations have shown that:

- repetitive outbursts and jets from supermassive black holes at galaxy centers quell star formation in elliptical galaxies;
- double nuclei show the presence of multiple supermassive black holes in the cores of galaxies;
- observations of the Bullet Cluster show that dark matter is not always coincident with luminous matter thereby ruling out alternative gravity theories as replacements for dark matter;
- measurements of the slow growth of galaxy clusters provide confirmation that the Universe is accelerating, independent of the results from Type Ia SN and cosmic microwave background measurements;
- the total (three-dimensional) velocities of galaxies and merging subclusters are directly measurable from jumps in the gas density and temperature distribution;
- the Cosmic X-ray Background from 2 to 8 keV is resolved into point sources and 60% is due to AGN at z<1;
- broadened iron emission lines in both AGN and X-ray binary spectra likely arise from reflections from the inner regions of the accretion disk around a rotating black hole (*Chandra, XMM-Newton* and *Suzaku*);

Table 2.1-1. Flagship Mission Characteristics

Mission	Detector	Band	Effective area (cm^2 at 1 keV)	FOV	PSF HPD arcsec	Resolution
Chandra	ACIS	0.2–10 keV	550	17' x 17'	0.5	ΔE ~ 150 eV at 6 keV
	HRC	0.1–10 keV	227	30' × 30'	0.4	ΔE ~ 1 keV at 1 keV
	HETG	0.5–10 keV	40	N/A	N/A	Δλ = 0.012 Å
	LETG	0.2–9 keV	17	N/A	N/A	Δλ = 0.05 Å
XMM	MOS	0.1–15 keV	922	33' × 33'	17	ΔE ~ 150 eV at 6 keV
	PN	0.1–15 keV	1227	27.5' × 27.5'	17	ΔE ~ 140 eV at 6 keV
	RGS	0.35–2.5 keV	105	N/A	N/A	Δλ = 0.06 Å

- young stars (less than 10 million years old) produce violent X-ray flares that can create turbulence in protoplanetary disks;
- strong stellar X-ray emission can evaporate significant amounts of mass from orbiting exoplanets;
- mixing of supernova ejecta in Cas A indicates the violent overturn of ejecta in some core collapse SNe;
- compact jet/torus structures in the inner regions of the Crab and other pulsar wind nebulae reveal the geometry of the rotating system and the magnetization of the wind;
- star formation can occur in the ram pressure stripped gas trails of galaxies falling into clusters; and
- shocks can be produced in the ISM in galaxies and groups by AGN outbursts;

The *XMM-Newton Observatory*, ESA's flagship X-ray mission has been operating well since it was launched on December 10, 1999, by an Ariane 504. *XMM-Newton's* large collecting area (three gold-coated Wolter type I telescopes with 58 shells; 4500 cm^2 total at 1 keV), good angular resolution (~15 arcsec) and large FOV (~30' × 30') allow detailed spectro-imaging studies of both point sources (stars to AGN) and extended sources (supernova remnants to the ISM in galaxies to clusters of galaxies) over the energy range of 0.1–15 keV, along with simultaneous optical monitoring. The mission characteristics are given in **Table 2.1-1**. Science highlights include:

- showing that AGN must inject energy to heat infalling gas in "cooling core" clusters (*XMM* and *Chandra*);
- the discovery of very distant (z >~ 1.5) X-ray bright clusters of galaxies;
- the detection of quasi-periodic oscillations in AGN;
- a reverberation-induced delay between the observation of a burst of Fe K emission from the corona of the SMBH in NGC4151 and its reflection by the accretion disk showed that the corona was separated from the accretion disk;
- detection of shock heated gas in merging clusters (*XMM* and *Chandra*);
- detection of hot gas in the filament between two massive clusters;
- the discovery of X-ray halos around spiral galaxies;
- the confirmation that charge exchange reactions with the solar wind ions produce X-rays in comets and in the heliosphere;
- the detections of jets and accretion shocks, from protostars as well as the hot plasma in star forming regions;
- constraints on the equation of state for white dwarfs and neutron stars; and
- the measurement of a multiyear precession of the axis of a neutron star.

2.2 *The Road from Chandra to the Present*

2.2.1 *Constellation-X*

While preparing for the launch of *Chandra* (then known as "*AXAF*"), planning began in the mid-90s for a mission to advance X-ray astronomy in the following decades. A mission called *Constellation-X* (or "*Con-X*") was created as the merger of three studies selected in response to a NASA announcement of opportunity for mission concepts. *Con-X* was conceived as a spectroscopy mission specifically aimed at studying strong gravitational fields around black holes, but with broad capabilities for many other areas of high-energy astrophysics.

Over the next decade, the *Con-X* mission implementation evolved as launch vehicle capabilities and costs changed and as technical progress brought new ideas and approaches into play. The science reach of *Con-X* relative to other space and ground-based missions was assessed and prioritized in 2000 by the *Astronomy and Astrophysics in the New Millennium* (AANM) Decadal Survey. In this survey, *Con-X* was ranked as the second highest priority large space-based facility (after *JWST*). The NRC study, *Connecting Quarks to the Cosmos* (2003), also assessed the capabilities of *Con-X* and called out the unique ability of the mission to address science at the intersection of astronomy and physics. The high scientific value of *Con-X* was reaffirmed by the mid-term review undertaken by the Committee on Astronomy and Astrophysics (reported in a letter to NASA HQ on February 11, 2005). The Beyond Einstein Program Assessment Committee (BEPAC) review in 2008 found that "*the Constellation-X mission will make the broadest and most* *diverse contributions to astronomy of any of the candidate 'Beyond Einstein' missions.*"

The configuration as presented to the BEPAC included four telescopes with 10 m focal length and 15 arcsec angular resolution (HPD) in a single spacecraft, feeding four calorimeters and grating spectrometers, complimented by a pair of hard X-ray telescopes that extended the energy range up to 40 keV. The calorimeter was expected to have an energy resolution of 2.5 eV, and the gratings a spectral resolution of E/δE = 1250 from 0.3 to 1.0 keV. Effective area was 0.1 m^2 for the gratings, 1.5 m^2 at 1.25 keV and 0.6 m^2 at 6 keV for the calorimeter.

2.2.2 The *International X-ray Observatory*

The science case for a large X-ray observatory had also been given priority in ESA's considerations of future programs. In the ESA *Cosmic Visions* plan, the *X-ray Evolving Universe Spectroscopy* (*XEUS*) mission (a joint ESA/JAXA effort) was selected in 2007 as one of three candidate Large Missions. In the spring of 2008, under the guidance and encouragement of ESA and NASA HQ, an effort began to determine whether *Con-X* and *XEUS* could be merged. The underlying rationale for this merger was the wide recognition that they had very similar science goals and therefore a merger might produce a higher science return. Despite the different implementation approaches, it was clear at the time that it would be cost effective to join forces. An ESA/JAXA/NASA coordination group was formed and met twice. Agreement was reached on a path forward, and was accepted at an ESA-NASA bilateral meeting on July 14, 2008. At this time, the *Con-X* and *XEUS* studies were replaced by a single tri-agency (including JAXA) study called the *International X-ray Observatory* (*IXO*).

A Study Coordination Group (SCG) was appointed by NASA, ESA, and JAXA, and independent mission studies were conducted with the explicit goals to develop a common set of science requirements and to submit the concept to the 2010 Decadal Survey (*New Worlds, New Horizons*, aka NWNH) in the U.S. and to the L1 selection review by ESA. The science goals and measurement requirements of *IXO* clearly reflected the merger of its two predecessors, and they are thus similar to, but not identical with, the *Con-X* objectives and requirements presented to previous NRC panels. The basic science goals of *Con-X* had remained unchanged from AANM to BEPAC with its emphasis on spectroscopy, but with the merger with *XEUS*, those goals were expanded to include imaging studies of AGN and clusters at high-z, polarization studies, and high count-rate science related to accreting compact objects in our Galaxy. Driven by the *XEUS* imaging science objectives, the angular resolution requirement for *IXO* was established as 5 arcsec half-power diameter (HPD). The *IXO* instrumentation consisted of a high-throughput mirror and six instruments: an X-ray Microcalorimeter Spectrometer (XMS), a Wide Field Imager (WFI), a Hard X-ray Imager (HXI), an X-ray Grating Spectrometer (XGS), a High Timing Resolution Spectrometer (HTRS), and an X-ray Polarimeter (XPOL).

The results of independent studies by NASA and ESA called for a very similar implementation approach. Each found that the *IXO* spacecraft could be built with technologies that were fully mature, and that any required technology development would focus primarily on the optics, with some additional efforts on the detector systems. The resulting studies were submitted to NWNH, and to *Cosmic Visions* 2015–2025, respectively.

In the 2010 NWNH report, *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*." The Electromagnetic Observations from Space (EOS) panel in particular ranked the *IXO* science very highly, stating that "*The key to keeping IXO's scientific priority is to feed a calorimeter with a much larger collecting area than has been done before.*" As part of their analysis, the panel evaluated the impact on some key science programs of a 30 percent reduction in mirror area—a substantial mass reduction—and angular resolution of 10 arcsec (approximately the state of the art) and found that "*the ability of the mission to meet its primary science goals would not be heavily compromised …*" The panel also recommended that the gratings spectrometer be retained in the context of a "*best effort*," but that it not be allowed to drive the cost of the mission in a significant way.

Despite the clear endorsement of the *IXO* science, its overall assessment as 4th priority among large programs by NWNH reflected its perceived technical and programmatic uncertainties. The *IXO* project's independent cost estimate was $3.5B total, with a U.S. contribution of ~ $2B. The independent cost estimate from the Decadal Survey study was $4.8B, largely due to uncertainties in the technology development and concerns about the complexity of the mission. NWNH presented two key recommendations: first, the cost to NASA of *IXO* should not exceed $2B; second, in recognition that *IXO* was unlikely to start in the current decade due to NASA's financial constraints, and because of *IXO*'s high scientific importance, a technology development program was recommended this decade with sufficient resources—estimated to be approximately $200 million—to prepare *IXO* for the next decadal survey. In recognition of the complexities of international collaborations, a third recommendation was that NASA find a "way forward" if ESA selected *IXO* as the L1 mission.

2.2.3 Post-*IXO* Developments

Following the release of NWNH, the Planetary Science Decadal Survey, and the U.S. budgets in February 2011, ESA announced revised plans for all three of the L-class missions under study (*IXO*, *LISA*, *EJSM*). Given that the U.S. Decadal surveys in astrophysics and planetary science had given none of these missions high enough priority to proceed, and taking into account the expected NASA budget constraints for the upcoming decade (i.e., flat for the next five years, with major U.S. contributions to these missions unlikely), ESA decided to cancel plans to develop these missions jointly with NASA. The structure of the L mission studies was revised in the context of a European framework, and each team was asked to restructure their mission concept and its science case to meet a scenario whereby, in the least optimistic case, a Europe-alone mission could be executed. Under this scenario, there would be, at most, relatively small international contributions, with an ESA cost cap of €850M for each (not including instruments).

In early April 2011, ESA appointed a Study Team (essentially augmenting the European *IXO* SCG) to develop an initial approach to implement the new ESA strategy. The charge to this group was to develop a new set of science requirements and a new mission configuration that would address as many of *IXO*'s science goals as possible, and to provide compelling science overall. In an open letter to the community, this study team proposed an ESA-only mission named *ATHENA* (*Advanced Telescope for High Energy Astrophysics*). With a total budget ~ €1B (including ESA member state contributions), the new concept was necessarily less ambitious—but retained many of *IXO*'s core capabilities by hosting two separate telescope systems, one feeding a WFI and one feeding a calorimeter. The *ATHENA* and other L1 studies were executed over a period of about nine months, culminating with a submission of a "Yellow Book" for each mission to ESA in December.

Essentially in parallel with the *ATHENA* study and prior to its dissolution in late 2011, the U.S. *IXO* team began to develop a mission concept that drew heavily on the *IXO* concept, but also responded directly to the Decadal recommendations, including a cap of $2B on the mission cost. This mission concept—named *AXSIO* (*Advanced X-ray Spectroscopic Imaging Observatory*)—had its performance specified by the IXO team and was developed through a one-week conceptual design session at GSFC's Mission Design Laboratory (MDL). From the science perspective, there were topics of changed emphasis, based on the report from the NWNH EOS panel. Specifically, emphasis was added on the following topics: impact of stellar flares on planet habitability, protostars, circumstellar disks, stellar formation, and Type Ia supernova progenitors, while there was less emphasis on high-z AGN and the neutron star equation of state. Key hardware changes from *IXO* included a reduction in mirror size, removal of the extendable optical bench, removal of four of six instruments (WFI, XPOL HXI, and HTRS), and removal of the instrument translation stage (needed for the WFI). The instrument suite on AXSIO therefore consists of the imaging calorimeter and the gratings.

The brief study of the *AXSIO* concept ended at about the same time that the NASA RFI for X-ray mission architecture studies (**Section 3** and **Section 4**) was written and released. This report includes *AXSIO* as a notional mission, along with three less expensive concepts described further in **Section 5**.

3 RFI Solicitation and the Nature of the Charge

On September 13, 2011, NASA released Request for Information NNH11ZDA018L, "seeking information that can be used to develop concepts that meet some or all of the scientific objectives of the *International X-ray Observatory* (*IXO*) [**Table 3-1**]. Information being sought includes relevant mission concepts, instrument concepts, enabling technologies, or any aspect of flight, ground or launch systems architecture." This RFI solicitation was based in part on the strong evaluation of *IXO* in *New Worlds, New Horizons* (NWNH) which ranked *IXO* as the 4th highest priority space-based project. The report noted:

> *"IXO is a versatile, large-area, high-spectral-resolution X-ray telescope that will make great advances on broad fronts ranging from the characterization of black holes to elucidation of cosmology and the life cycles of matter and energy in the cosmos. Central to many of the science questions identified by this survey, IXO will revolutionize high-energy astrophysics with more than an order-of-magnitude improvement in capabilities." (p.19, NWNH)*

The RFI requested 10-page responses due within six weeks (October 28, 2011). To evaluate these responses and write this report, a Community Science Team (CST) was appointed with the charge that "the CST will work with the astronomy community and the PCOS Program Office in reviewing all RFI re-

Table 3-1. Primary *IXO* Science Objectives

Science Question	*IXO* Measurement	Key *IXO* Performance Requirements
What happens close to a black hole?	Time-resolved high resolution spectroscopy of the relativistically-broadened features in the X-ray spectra of stellar mass and supermassive black holes.	Spectral resolution of 2.5 eV at 6 keV; effective area > 0.65 m^2 at 6 keV and 150 cm^2 at 30 keV.
When and how did supermassive black holes (SMBH) grow?	Measure the spin in SMBH; distribution of spins determines whether black holes grow primarily via accretion or mergers.	Spectral resolution of 150 eV at 6 keV and 1 keV at 30 keV; effective area of 3 m^2 at 1.25 keV, 0.65 m^2 at 6 keV, and 150 cm^2 at 30 keV; 5" angular resolution and 18 arcmin field of view at 2 keV.
How does large scale structure evolve?	(i) Find and characterize the missing baryons by performing high resolution absorption line spectroscopy of the WHIM over many lines of sight using AGN as illumination sources. (ii) Measure the growth of cosmic structure and the evolution of the elements by measuring the mass and composition of clusters of galaxies at redshift < 2.	(i) Spectral resolving power R of >3000; effective area >1000 cm^2 in 0.3–1 keV band. (ii) Imaging spectroscopy with spectral resolution of 10 eV at 6 keV; 10" angular resolution and 5 arcmin field of view across 0.3–7.0 keV band; effective area of 1 m^2 at 1.25 keV and 0.1 m^2 at 6 keV.
What is the connection between SMBH formation and evolution of large scale structure (i.e., cosmic feedback)?	Measure the metallicity and velocity structure of hot gas in galaxies and clusters.	Imaging spectroscopy with spectral resolution of 2.5 eV at 6 keV; 5" angular resolution and 2 arcmin field of view across 0.3–7.0 keV band; effective area of 3 m^2 at 1.25 keV and 0.65 m^2 at 6 keV; total bandpass of 0.3–10 keV.
How does matter behave at very high density?	Measure the equation of state of neutron stars through (i) spectroscopy and (ii) timing.	(i) Spectral resolving power >3000; effective area >1000 cm^2 in 0.3–1.0 keV band. (ii) Maximum count rate of 10^6 s^{-1} with relative timing accuracy of 10 μs and <10 percent deadtime over 0.3–10 keV band; spectral resolution of 150 eV and effective area of 0.6 m^2 at 6 keV.

Table 3-2. X-ray Mission Concepts Study Team

Study Manager	Gerry Daelemans (GSFC)
Study Scientist	Rob Petre (GSFC)
Community Science Team	Joel Bregman (Chair - Michigan), Mark Bautz (MIT), David Burrows (Penn State), Webster Cash (U Colorado), Christine Jones (SAO), Stephen Murray (JHU), Paul Plucinsky (SAO), Brian Ramsey (MSFC), Ron Remillard (MIT), Colleen Wilson-Hodge (MSFC)
Science Support Team	Andy Ptak (GSFC), Jay Bookbinder, Randall Smith, Michael Garcia (SAO)
Engineering Support Team	Tony Nicoletti, Gabe Karpati, Sharon Seipel (GSFC), Mark Freeman, Paul Reid (SAO), GSFC MDL and IDL engineers

sponses and defining mission concepts at various cost points between $300M to $2,000M."

The full study team is listed in **Table 3-2**. Additional support and guidance was provided by Ann Hornschemeier (PCOS chief scientist) and Jackie Townsend (PCOS Advanced Mission Concepts Manager), along with NASA HQ personnel Rita Sambruna (PCOS Program Scientist), Wilt Sanders (High-Energy Astrophysics Program Officer), and Jaya Bajpayee (PCOS Program Executive).

4 Response to the RFI

4.1 RFI Mission and Instrument Concepts

A total of 30 RFI responses were received. Submissions came from universities, industry, NASA centers, and federally-funded research labs. Fourteen responses described mission concepts, one response described a program strategy, 12 responses described enabling technology, and three described instrument concepts. The missions and instruments, and their basic characteristics, are summarized in **Table 4.1-1**. One-page summaries of the mission concepts were generated by the study team and are available on the Physics of the Cosmos Web site at **http://pcos.gsfc.nasa.gov/studies/xray/x-ray-summaries.php**.

Many of the missions emphasized high resolution spectroscopy, six using an *IXO*-like X-ray calorimeter (*AXSIO*, *EPE*, *SAHARA*, *SMART-X*, *WFXIS*, and *Xenia*) and four using dispersive X-ray gratings (*AEGIS*, *AXSIO*, *SMART-X*, and *WHIMex*). Three emphasized wide field imaging (*SMART-X*, *WFXT*, and *WFXIS*), six emphasized high energy science (*AXTAR*, *BEST*, *EREXS*, *HEX-P*, *BHT*, and *Xenia*) and/or all sky

Table 4.1-1. Instrument and Mission Concepts

Mission	Bandpass keV	Effective Area m^2@keV	Field of View arcmin	Ang. Res.* arcsec	Instrument(s)
AXSIO	0.2–10	0.9@1, 0.2@6	4	10	Calorimeter, Grating Spectrometer
SMART-X	0.2–10	2.3@1, 0.2@6	22	0.5	Calorimeter, Grating Spectrometer, Wide Field Imager
Xenia	0.2–5.0	0.053@1	84	15	Cryogenic Imaging Spectrometer, High Angular Resolution Imager, Transient Event Detector
AEGIS	0.25–2.0	0.14@0.6	19	10	Grating Spectrometer
EPE	0.3–10	0.5@1, 0.2@6	8	60	Calorimeter
EREXS	5–300	0.7@100	70°	20	Hard X-ray Imager, Infrared Telescope
SAHARA	0.2–3.0	0.3@1	8	5	Calorimeter
WFXIS	0.1–2.5	0.04@1	15	10	Calorimeter
WFXT	0.2–4.0	0.7@1	60	5	Wide Field Imager
AXTAR	2–30	3.2@6	60	60	Large Area Timing Array, All Sky Monitor
BEST	2–70	0.4@2, 0.3@6	12	10	Cadmium-Zinc-Telluride array, Polarimeter
HEX-P	0.15–200	0.8@6, 0.15@50	13	15	Silicon + Cadmium-Telluride array
SuperMon & BHT	2–60 0.5–30	3 × 0.04@10 5@10	4π 120	0.5°	Low Energy Proportional Counters, Silicon+Cadmium-Zinc-Telluride sandwich
WHIMex	0.2–0.8	.025@0.6	n/a	15	Grating Spectrometer
Hard X-ray Telescope	10–70	.025@30	12	22	Cadmium-Zinc-Telluride array
Soft X-ray Polarimeter	0.2–0.8	.03@0.4	n/a	n/a	Grating Polarimeter with Charge Coupled Device readout

The colors here represent estimated mission costs: >$1B (blue), $0.6B - $1.0B (green) and <$0.6B (pink). Rows that are white show instruments.

*Measured as HPD

monitoring (*AXTAR*, *EREXS*, *SuperMon*, and *Xenia*). One included a polarimeter (*BEST*). The *AXSIO* RFI submission benefited from a study that began prior to the release of the RFI, as a direct response by the existing *IXO* Study Team to the recommendations made in NWNH.

Based on estimates provided in the RFI responses, most of the missions fell into a cost bin between ~$600M and $1B, with six such missions indicated in green. Five missions fell into the <$600M cost bin, and three fell into the large cost bin of >$1B as indicated in blue. In general, the cost of a mission directly relates to the number of *IXO* science goals that can be well addressed. The most expensive, ~$1–2B class missions, address the majority of the *IXO* science objectives. The medium class missions address a substantial (but varying) fraction of the *IXO* science objectives, on occasion addressing all of the topics to a greater or lesser degree. The smallest missions typically address a single *IXO* science area. Some of the measurement approaches duplicate those that would have been taken by *IXO*, while other times novel approaches are suggested.

Representatives from each of the RFI response teams were invited to present their ideas to the science community at a workshop December 14–15, 2011. Over 100 astronomers attended, including the CST. These presentations and the ensuing discussion were critical in the CST forming the set of "notional" missions.

A series of technology talks made the case that none of these missions can proceed without a robust program that supports the cutting-edge technologies these missions would use. The level of effort needed for this technology program is discussed in **Section 6**.

The meeting showed that there is considerable concern about the future of the field and the planning of facilities beyond the notional missions discussed in this document. The prime "vision" was the desire to return to sub-arcsec imaging with a very large collecting area (tens of times greater than *Chandra*). Such a mission would extend X-ray investigations to the high redshift Universe, enabling the measurement of accretion in the earliest black holes, the studies of accretion and winds in early galaxy growth, the detection of proto-groups and the first clusters of galaxies, as well as advances in every area of X-ray astronomy. For future missions of this type, the relevant technologies will take years to develop and should be started as soon as possible.

It is clear that the wider community should be involved in charting the way forward. To that end, this X-ray Concepts study was discussed at a Town Hall during the January 2012 AAS meeting. The PhysPAG (*Physics of the Cosmos* Program Analysis Group) recommended formation of an X-ray SAG (Science Analysis Group) as a way to capture community insights and monitor the progress of mission concepts and technology.

4.2 Science Content of the RFI Concept and Instrument Submissions

The RFI focused on the five key questions from the *IXO* science case. These questions were acknowledged in *New Worlds, New Horizons* as compelling avenues for advancement in astrophysics. The RFI responses provided community input that would help the CST panel to define priorities and options for NASA to pursue these science goals within the prescribed levels of mission cost. The science content of the RFI submissions also provided the opportunity to refresh the *IXO* science case in terms of measurement goals and instrumental requirements that most effectively address the key science questions. The CST assessment of prioritized science applications provided a basis to define Notional Missions for detailed cost studies and to identify technology development that is vital to the science objectives.

During the RFI evaluation process, science summaries for each of the 14 mission concepts were prepared by members of the study team[1]. The summaries were organized in terms of the five key science questions. The summaries were made available on the X-ray study public web page, and RFI submission teams were invited to review them and comment. Then, at the Workshop on X-ray Mission Architectural Concepts (December 2011), each RFI submission was considered with an oral presentation and public discussion.

The science objectives of the RFI responses are summarized below, outlined for each of the key *IXO* science questions.

1 **http://pcos.gsfc.nasa.gov/studies/xray/x-ray-summaries.php**

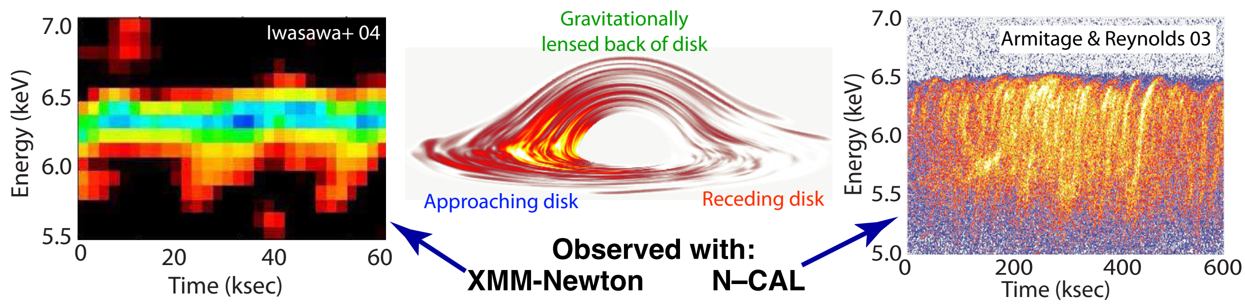

***Figure 4.2-1**. [Center] A time-dependent MHD simulation of an accretion disk around a BH (Armitage & Reynolds 2003) shows turbulent rings and hotspots which orbit the BH. [Left] : XMM-Newton may have detected such features, as shown in the time-energy contour diagram (Iwasawa et al 2004), but [Right] the large improvement in throughput and energy resolution will reveal weaker and narrower features on suborbital timescales, allowing us to map out the inner accretion flow.*

1) What happens close to a black hole?

The prime *IXO* technique to investigate strong gravity involves time-resolved spectroscopy of the relativistically-broadened Fe line from accreting black holes (see **Fig. 4.2-1**). *AXSIO*, *EPE*, and *SMART-X* propose to do this using calorimeters with high spectral resolving power (E/ΔE~2000 at the Fe-K line). The same application can be pursued with CCD resolving power (E/ΔE~50) with *HEX-P*, albeit with less precise modeling of accretion and absorption spectral features. RFI responses with bandpasses that cover the Fe-K line at 6.4 keV plus sensitivity to hard X-rays (*HEX-P*, *SuperMon*, and the HXT instrument) noted the capabilities to better define the underlying continuum and to include the continuum reflection bump in the analysis model. The gratings concepts, *AEGIS* and *WHIMex*, may investigate a relativistically broadened Fe-L line (at ~ 1 keV), as can the calorimeters combined with soft X-ray mirrors: *SAHARA* and *Xenia*.

Additional methods included gratings spectroscopy of accretion disk atmospheres and winds (*AEGIS*, *SMART-X*, and *WHIMex*). Strong gravity effects would be investigated for both black hole accretion disks and their jets, using time and energy-resolved X-ray polarimetry (*BEST*, *SuperMon*, and the SXP instrument). *WFXT* and *EREXS* would find and study tidal disruption events to investigate supermassive black holes. *AXTAR* focused on black holes in the Milky Way, with a goal to determine black hole spin values using three independent methods (X-ray continuum, Fe line, and high-frequency QPOs) applied to the same sources.

2) When and how did supermassive black holes grow?

With *IXO*, there were two methods to address this question. The distribution of black hole spin values, as measured with the relativistically-broadened Fe-K line from AGN, can determine whether black holes grow primarily by accretion or by mergers. This theme was invoked for several mission concepts with calorimeters: *AXSIO*, *EPE*, and *SMART-X*. Others would pursue this technique with CCD resolution: *HEX-P* and *SuperMon*.

The second technique involves deep imaging surveys of AGN to high redshift, providing statistical constraints on the formation history of supermassive black holes. AGN surveys in medium energy X-rays were advocated with *SMART-X* and *WFXT*, and in soft X-rays with *SAHARA* and *WFXIS*. Surveys with hard X-ray sensitivity can detect both obscured and unobscured AGN, as emphasized for *BEST*, *HEX-P*, and *EREXS*, and could be performed with the HXT instrument.

3) How does large-scale structure evolve?

This question is again tied to two measurement techniques. To find and characterize the missing baryons in the warm-hot intergalactic medium (WHIM), the gratings instruments (*AEGIS*, *SMART-X*, and *WHIMex*) would measure WHIM absorption lines and velocity profiles using AGN lines of sight as background illumination. The calorimeter instruments (*AXSIO*, *EPE*, *SMART-X*, and *Xenia*) would measure the same absorption lines as unresolved features. The power of spatially-resolved high-resolution spectroscopy is shown in **Fig. 4.2-2** which shows directly measuring outflowing superwind gas velocities in starburst galaxies.

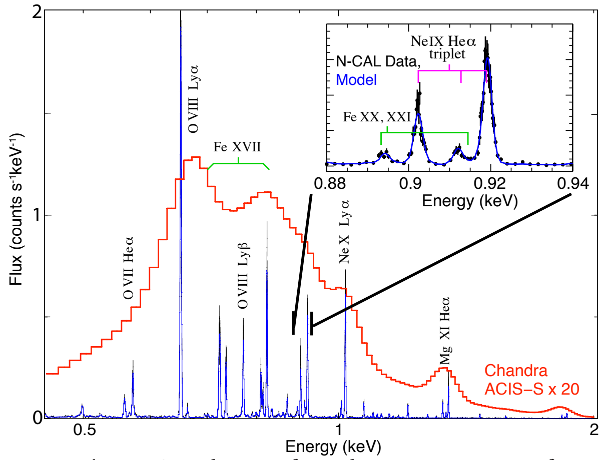

Figure 4.2-2. Simulation of a calorimeter spectrum from a ~1'×1' halo region in the starburst galaxy M82. With ~ 2 eV spectral resolution line diagnostics from He-like ion triplets, line broadening and Doppler shifts are deteable (blue line), which is not possible with CCD resolution spectra (red line).

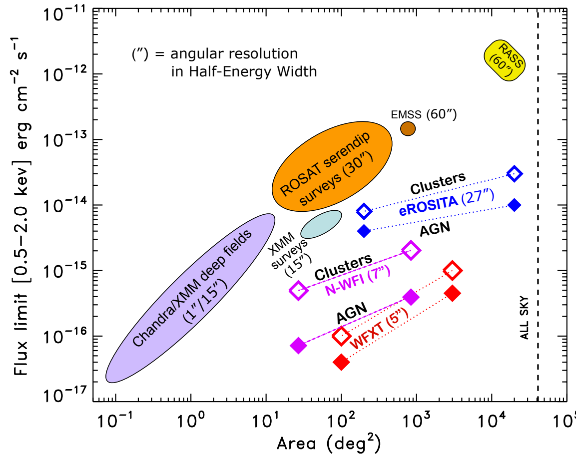

Figure 4.2-3. Effective flux limits and sky coverage for past and planned X-ray surveys with the surveys that would be performed by WFXT (Murray et al. 2011) and N-WFI (see **Section 5***) marked. The reduced survey sensitivity and solid angle of N-WFI relative to WFXT is a result of the decision to increase the effective area requirement at 6 keV for strong gravity science, which in turn resulted in an optical design with worse spatial resolution and increased vignetting. Also note that the mission lifetime of N-WFI (and the other notional missions) is three years while five years was assumed for WFXT.*

In the second technique, the mass and composition of clusters of galaxies is measured out to redshift ~ 2. *SMART-X* pursues this task with the best effective area and angular resolution, followed by *AXSIO*, *WFXT*, *SAHARA*, and *Xenia*. Mission concepts with fine imaging and hard X-ray sensitivity (*BEST*, *HEX-P*, and also the HXT instrument) would include surveys of nonthermal emission from clusters.

Additional methods were proposed. *BEST* proposes to cross-correlate their AGN survey with galaxy surveys to investigate large-scale structure. *EREXS* and *Xenia* trace primordial star formation and IGM absorption using gamma ray bursts.

4) What is the connection between supermassive black hole formation and evolution of cosmic structure (i.e., cosmic feedback)?

The *IXO* goal to measure the metallicity and velocity structure of hot gas in galaxies and clusters is carried forward with calorimeter observations of cluster cavities, bubbles, and AGN jets. *SMART-X* leads the way with its superior angular resolution, followed by *SAHARA*, *AXSIO*, and *WFXIS*. *Xenia* could make such measurements at low redshift. Instruments with hard X-ray sensitivity and good angular resolution (*HEX-P*, *BEST*, and the HXT instrument) would observe clusters and contribute knowledge of obscured AGNs and non-thermal components.

In related science, *WFXT* (CCD resolution) would survey clusters to redshift ~1 (see **Fig. 4.2-3**) and statistically investigate entropy, temperature, and metallicity as a function of redshift. *SMART-X* would detect AGN and dark matter halos out to redshift ~6, to investigate their co-evolution.

A second *IXO* approach to cosmic feedback involves measurement of the density and velocity of warm absorbers and other forms of outflow. This is done best with the gratings instruments (*AEGIS*, *SMART-X*, and *WHIMex*), while calorimeters can make useful contributions (*SAHARA*, *AXSIO*, *WFXIS*, and *EPE*).

Alternatively, *EREXS* proposed using deep surveys in both hard X-rays and IR wavelengths to compare SMBH and bulge masses and thereby investigate feedback on galactic dimension scales.

5) How does matter behave at very high density?

IXO had goals to apply different techniques to measure the Equation of State (EOS) of neutron stars (NS) via accurate determinations of their masses (M) and radii (R). In principle, R/M constraints can be obtained for a variety of NS conditions: accreting, quiescent/cooling, isolated, and during Type I X-ray bursts. Such efforts may involve observations of the X-ray continuum and/or line features.

The detection of gravitational redshifts in NS absorption lines, which has a direct impact on the determination of the EOS, requires a combination of high spectral resolution and large effective area that is far beyond the reach of current instrumentation. Weak absorption features are expected during X-ray bursts, but such features are modified by several affects: pressure broadening, beaming and Doppler effects, light bending, rotational broadening, possibly magnetic fields, and gravitational redshift. The feasibility to determine the gravitational redshift is improved for slowly rotating NS (e.g., the burster in Ter 5 rotating at 11 Hz), observed at early phases of the burst (when the illumination spot is small). Such investigations, which require high count rate capability and ms time resolution, are targeted with *AXSIO*, *EPE*, *SMART-X*, *AEGIS*, and *WHIMex*.

Alternatively, *AXTAR* and possibly *SMART-X* would combine large effective area and fast timing to model the continuum spectra during burst oscillations. The X-ray waveform evolution would be modeled at different photon energies, with full consideration of general relativity effects, as the nuclear burning spreads from the ignition spot to the whole surface of a rotating neutron star.

Other methods were advocated. Spin-phase resolved polarimetry of both thermally radiating and magnetized NS (with *BEST*, *SuperMon*, and the SXP instrument) would trace emission regions and viewing angles and constrain M/R with the help of light-bending terms in the models. *EREXS* would detect short GRBs and thereby support investigations of models for NS-NS or NS-BH mergers.

5 The Notional Missions

5.1 Overview

The Study Team was tasked with defining and assessing notional mission concepts at different cost points ranging from ~$300M to $2B to provide examples of which highly-ranked *IXO* science could be achieved at different cost points. As described in **Section 4**, the RFI responses offer a broad view of a variety of ways to approach *IXO* science. To focus the Study Team efforts on which missions to study, the CST considered missions currently under construction—with or without NASA participation—(**Tables 5.1-1a** and **5.1-1b**, respectively, list missions/relevant instruments) and the *IXO* science they address (summarized in **Tables 5.1-2a** and **5.1-2b**) along with the RFI responses. Two potential missions, *LOFT* (ESA) and *NICER* (NASA), currently in the study phase but not yet selected, are excluded from the tables. If selected, both will address neutron star EOS science, and *LOFT* will also investigate effects of strong gravity near accreting black holes.

Certain observational approaches to *IXO* science were clearly common to multiple RFI responses. Six responses included a calorimeter, four included gratings, two included a wide-field imager, and five included a hard X-ray telescope or hard X-ray detector; several were based on multiple instruments. The CST decided that instruments similar to the three main *IXO* instruments best addressed the most *IXO* science. A calorimeter was selected for study as it addresses the majority of *IXO* science objectives. A gratings instrument was also selected, as it addresses *IXO* science complementary to *ATHENA*. Finally, a wide-field imager was selected as it addresses several *IXO* science objectives that do not require high-resolution spectroscopy. Rather than select specific RFI responses for further study, the CST defined "notional missions" that combined characteristics of various mission concepts from the RFI responses. These notional missions are: a calorimeter (*N-CAL*), a gratings instrument (*N-*

Table 5.1-1a. NASA X-ray Missions

Mission/ Instrument	Energy Range	ΔE	Effective Area m^2@keV	Angular Resolution**	Field of View
NuSTAR	5–80 keV	0.5 keV @ 6 keV 1 keV @ 30 keV	0.07 @ 6 0.03 @ 30	50"	10'
Astro-H/SXS	0.3–12 keV	7 eV	0.02 @1–6	100"	2.8'
*GEMS**	2–10 keV	1 keV	0.05 @ 6	n/a	12'

**Measured in HPD

Table 5.1-1b. Non-NASA X-ray Missions

Mission/ Instrument	Energy Range	ΔE	Effective Area m^2@keV	Angular Resolution	Field of View
*ATHENA**/XMS	0.3–12 keV	3 eV	1 @ 1 0.5 @ 6	10"	2.3'
*ATHENA**/WFI	0.1–15 keV	150 eV	1 @ 1 0.5 @ 6	10"	24"
Spectrum R-G/ eROSITA	0.5–10 keV	130 eV @ 6 keV	0.23 @ 1 0.03 @ 6	15-20"	1°
Spectrum R-G/ ART	6–30 keV	900 eV	0.04 @ 6	60"	36'
Astrosat/LAXPC	3–100 keV	2 keV @ 20 keV	0.6 @10	1–5' (scan mode - collimated)	1°

* Not selected/canceled

Table 5.1-2a. ***IXO*** **Science with Upcoming NASA X-ray Missions**

Mission	Strong field General Relativity	Growing SMBH	Large Scale Structure	Cosmic Feedback	Neutron Star EOS
Astro-H	Orbit-integrated broad Fe-K lines	Fe-K line width for brightest AGN		Velocity broadening in clusters; Density and velocity of warm absorbers	
NuSTAR	Compton reflection above 10 keV in AGN and BHC	Detect ~100 obscured AGN in surveys			
*GEMS**	Polarization intensity and angle				

* Cancelled

Table 5.1-2b. ***IXO*** **science with non-NASA X-ray missions**

Mission	Strong field General Relativity	Growing SMBH	Large Scale Structure	Cosmic Feedback	Neutron Star EOS
*ATHENA** (ESA)	Test GR using Fe-K line reverberation mapping	Quantify SMBH growth; measure spin for 100s of GBH and AGNs	Formation and evolution of large-scale structure via properties of hot baryons in clusters of galaxies in the cosmic web	Physics of feedback from AGN and starbursts on all scales; velocity and metallicity flows	NS Atmosphere modeling; Emission line modeling; absorption lines during X-ray bursts
Astrosat (India)	High frequency QPOs in BH binaries				Coherent oscillations in X-ray bursts (like RXTE)
Spectrum R-G (Russia/ Germany)	Fe-K lines and Compton reflection in bright AGN and BHC	Detect ~3 × 10^6 AGN in survey	Detect up to 10^5 clusters	Detect up to 10^5 clusters	

* Not Selected

References:

Astro-H: **http://Astro-H.isas.jaxa.jp/si/index_e.html**

NuSTAR: **http://www.nustar.caltech.edu/for-astronomers**

ATHENA: **http://sci2.esa.int/cosmic-vision/AthenaYB_v4-2_final.pdf**

XGS), and a wide-field imager (*N-WFI*). The notional missions taken together address nearly the full suite of *IXO* science objectives, as does the multi-instrument *AXSIO* reference mission concept. This is shown in **Table 5.1-3**, which gives an overview of the primary *IXO* science objectives that would be accomplished by the notional missions assuming three-year mission lifetimes. In this table, [1] signifies essentially all IXO science can be acheived for this topic, [2] signifies that some of the IXO science can be achieved, and [3] signifies only a fraction of IXO science can be achieved. In the case of [2], the full IXO science can be achieved through an extended mission, while in the case of [3], the loss is not recoverable, for example due to inadequate spectral resolution. While *IXO*'s timing capability is partially retained by the *AXSIO* and *N-CAL* missions, *IXO*'s hard X-ray imaging and polarimetry capabilities are not available from any of the notional missions. A hard X-ray telescope was not selected because the CST decided that while hard X-rays are clearly important to the community and that there should be a future imaging hard X-ray mission, results from *NuSTAR* were needed before a future hard X-ray mission could be defined. Similarly, a polarimetry mission was not included in the notional missions because *GEMS* was still in Phase B. The cancellation of

Table 5.1-3. Primary IXO/Decadal Science Objectives Addressed by Notional Configurations.

Science Question	IXO Approach	AXSIO ($1.5B)	Notional Cal ($1.2B)	Notional Grating ($0.8B)	Notional WFI ($1.0B)
What happens close to a black hole where strong gravity dominates?	Measure the strong gravity metric via time resolved high resolution spectroscopy of stellar mass and ~30 SMBH at Fe-K and possibly Fe-L	Measure the strong gravity metric via time resolved high resolution spectroscopy of stellar mass and ~20 SMBH at Fe-K and possibly Fe-L [1]	Measure the strong GR metric via time resolved high resolution spectroscopy of stellar mass and ~ 10 SMBH at Fe-K [1-2]	Measure the strong GR metric via time resolved high resolution spectroscopy of stellar mass and ~ a few SMBH at Fe-L (speculative) [3]	Measure the strong GR metric via time resolved low resolution spectroscopy of stellar mass and ~ 10 SMBH at Fe-K [2]
When and how did SMBH grow?	Mergers and accretion impart differing amounts of spin to SMBH. Determine how SMBH grow via measuring the distribution of spin using >300 SMBH within z < 0.2 using orbit-averaged relativistic Fe-K lines	Measure how SMBH grow via determining the distribution of spin using ~60 nearby SMBH using orbit-averaged relativistic Fe-K lines [2]	Measure how SMBH grow via determining the distribution of spin using ~40 nearby SMBH using orbit-averaged relativistic Fe-K lines [2]	Measure how SMBH grow via constraining the distribution of spin using a few nearby SMBH using orbit-averaged relativistic Fe-L lines (speculative) [3]	Measure when SMBH grow via determining the census of AGN out to z~6; measure AGN power spectrum to infer the halo occupation density over a range in z [1-2]
How does large scale structure evolve?	(i.) Find the missing baryons and determine their dynamical properties via absorption line spectroscopy of the WHIM over >30 lines of sight using AGN as illumination sources.	Find the missing baryons and determining their dynamical properties via grating absorption line spectroscopy of the WHIM over >30 lines of sight using AGN as illumination sources. [1]	Find the missing baryons via absorption line spectroscopy of the WHIM over <30 lines of sight using AGN as illumination sources (speculative). [3]	Find the missing baryons and determining their dynamical properties via absorption line spectroscopy of the WHIM over >30 lines of sight using AGN as illumination sources. [1]	
	(ii.) Measure the evolution of the cluster mass function using ~500 clusters of galaxies at redshift 1-2	Measure the evolution of the cluster mass function using ~ 150 clusters of galaxies at redshift 1-2 [2]	Measure the evolution of the cluster mass function using 50-100 clusters of galaxies at redshift 1-2 [2]		Measure cluster mass function by detecting 5000 clusters, ~ 1000 at z>1 in surveys ; detection of protoclusters at earliest stages of formation (z~2) [1]
Connection between SMBH and large scale structure ?	Determine the energetics of SMBH outflows via measurements of the velocity structure of hot plasma in ~300 galaxies and clusters; measure the metallicity distribution in galaxies and their halos	Determine the energetics of SMBH outflows via measurements of the velocity structure of hot plasma in ~70 galaxies and clusters; measure the metallicity distribution in galaxies and their halos [2]	Determine the energetics of SMBH outflows via measurements of the velocity structure of hot plasma in ~50 galaxies and clusters; measure the metallicity distribution in galaxies and their halos [2]	Determine the energetics of SMBH outflows in ~ 30 AGN winds via ionization time variability; probe hot galaxy halos via background AGN absorption lines [2]	Measure metallicity distribution in ~ 100 clusters at z>1; measuring morphology of ~ 100 clusters at z > 1 [2]
How does matter behave at very high density?	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of ~ 30 bright neutron star X-ray binaries.	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of ~ 20 bright neutron star X-ray binaries [1]	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of ~ 20 bright neutron star X-ray binaries [1]	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of rare transient slow-rotator neutron star X-ray binaries [2-3]	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of a few bright neutron star X-ray binaries, using absorption lines in the burst rise and tails (speculative). [3]
	Measure the equation of state (mass and radius) of neutron stars via timing of ~ 30 bright neutron star X-ray binaries.	Measure the equation of state (mass and radius) of neutron stars via timing of ~ 20 bright neutron star X-ray binaries [1]	Measure the equation of state (mass and radius) of neutron stars via timing of ~ 20 bright neutron star X-ray binaries [1]		Measure the equation of state (mass and radius) of neutron stars via timing of a few bright neutron star X-ray binaries during burst rises and tails. [3]

Number grades and colors are assigned to give the degree to which the science topic is addressed, as discussed in the text. Lower numbers (darker colors) indicate greater ability to address the science question.

Table 5.1-4. Notional Missions

Mission	Energy range	ΔE	Effective Area m^2 @ keV	Ang. Res.*	Field of view	Focal length	Cost Goal	MDL Cost
N-CAL	0.2–10 keV	< 3 eV (inner pixels)	0.5 @ 1 0.2 @ 6	10"	4"	9.5 m	<$1B	$1.2 B
N-XGS	0.2–1.3 keV	λ/Δλ > 3000	0.05 @ 0.2–1.3	10"	n/a	4 m	<$600M	$0.8B
AXSIO	0.2–10 keV (XMS) 0.2–1.5 keV (XGS)	< 3 eV λ/Δλ > 3000	0.93 @1.25 0.2 @ 6 0.1 @ 0.3–1	10"	4'	10 m	<$2B	$1.5B
N-WFI	0.2–10 keV	150 eV	0.7 @ 1 0.2 @ 6	7"	>24'	6 m	<$1B	$1.0B

*Measured in HPD

GEMS was announced after the CST defined notional missions. Notional missions are listed in **Table 5.1-4** and described in detail below.

ESA's decision to select *JUICE* over Athena as its L1 mission had not been made when the CST defined the notional missions. The composition of the notional missions depended on whether or not *ATHENA* was selected, because *ATHENA* comprised an X-ray calorimeter and a wide-field imager (see **Table 5.1-1b**). If *ATHENA* had been selected, the CST denoted the grating mission (*N-XGS*) as the best complementary mission for addressing *IXO* science. Since *ATHENA* was subsequently not selected, the CST agreed that a calorimeter would achieve the most *IXO* science. This study therefore considered two calorimeter-based missions: *AXSIO*, the reference mission comprising a calorimeter and a grating that was defined prior to the start of this study, and the single-instrument calorimeter mission *N-CAL*. A third notional mission comprising only a wide-field imager (*N-WFI*) was also studied. In the following pages we discuss parameters and costing for the three single-instrument notional missions, as well as *AXSIO*. A discussion of trades follows, such as combining notional mission components, and cost impacts from changing capabilities.

5.2 Costing Methodology

The study team defined a set of notional missions, and each was subjected to a GSFC Mission Design Lab (MDL) session as described below. 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 study team (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, which can be used to compare missions, and which are current best estimates of mission costs. For the most complex of the instruments (the calorimeter), the GSFC Instrument Design Lab (IDL) was used to develop instrument concept costs that were then passed to the MDL. These labs arrive at instrument and mission costs using parametric models (where key parameters include mass and complexity), supplemented by bottoms-up estimates as appropriate.

The CST identified the key characteristics (e.g., collecting area, instrument type) for each notional mission. The X-ray study support team in partnership with an appropriate subgroup of the CST then developed an initial set of technical inputs, which were reviewed with the engineers in the respective design lab to ensure the inputs were sufficient to define a mission that could be costed. The CST subgroup worked closely with the X-ray study support and MDL/IDL engineer teams during both the review of the design lab inputs and during the actual one-week design lab run. This interaction included a number of face to face planning meetings, telecons, and attendance at GSFC during the design lab run.

The IDL and MDL provide an environment that facilitates multi-disciplinary, concurrent, space system engineering design and analysis activities, to allow rapid development of science instrumentation and mission architecture concepts. Staffed by over a dozen discipline engineers in a single facility, the IDL and MDL develop an internally consistent instrument or mission design, respectively, over the course of one week. The X-ray Study team, as the "customer," was integrated into the design lab process providing input and feedback as the instrument or mission design unfolded. Note that an MDL design represents a best effort to satisfy mission requirements for the lowest possible costs, but it is not optimized and only a few cost saving methods can be explored.

In one week, the design lab and its customer produce:

- Mission requirements and a baseline design with alternative design and trade studies identified;
- Functional block diagrams including interfaces;
- Detailed mass, power, and data rate estimates;
- Areas of technical risk, issues and concerns;
- Reliability analysis;
- Spacecraft bus Master Equipment List (MEL) for costing of the bus.

To the greatest extent possible, the costing approach for each mission design or delta mission design was identical. Specifically, the missions are all designated as high priority, low risk missions, with high to medium technical complexity and high to medium cost, and a minimum lifetime requirement of three years. This translates to being considered a NASA Class B mission[1], which imposes requirements with respect to mission assurance that significantly impact cost. These include the degree to which redundant systems are used, the depth and extent of a qualification test program (engineering models, engineering test and qualification units) and the pedigree of electric, electronic and electromechanical (EEE) parts. After consideration of factors involved in selecting a mission orbit (low-Earth, high-Earth, L2, etc.) for each mission, the study team determined that the science objectives for all missions could be met if placed in a Sun-Earth L2 orbit. This was merely a sufficient and not a necessary condition, but the short study periods did not permit detailed trade-offs between other possible orbits. Each design therefore includes propulsion, telemetry, orbit determination, etc., subsystems necessary for a L2 orbit. The launch vehicles, while not the same for each mission (due to differing throw weight requirements), were selected based on achieving this orbit.

Each instrument and spacecraft bus was costed using the same class EEE parts, the same level of qualification test programs, and the same philosophy of redundant vs. single string systems consistent with three years of mission operations. More specifically, all instruments were configured to meet a reliability of 90% probability of success after three years. Propellant tanks and solar arrays were sized to achieve five years of operations, thus allowing for the possibility of an extended mission. The notional mission total reliability requirement was at least 85% probability of success at the end of three years.

The costing approach for conceptual space flight missions at NASA/GSFC is to follow the NASA Cost Estimating Handbook (**http://www.nasa.gov/offices/ipce/CA.html**) on best practices, which for early concept development calls out the use of the PRICE-H modeler. The PRICE-H costing approach was applied to each of the notional X-ray missions. This is an industry-developed parametric costing system which considers the mass, complexity, TRL, type, quantity, qualification and testing approach, and procurement approach, of the various subsystems which make up a mission or instrument concept and also includes the system engineering and management and integration and procurement needed to develop a mission or instrument. PRICE-H draws on aerospace industry historical data for primitive structural and electrical elements like machined aluminum and analog electronics. It is periodically updated with the final costs for components from completed missions. The input for the PRICE-H cost modeler is a Master Equipment List (MEL). A significant effort was made to bring each notional mission's MEL to the same level of maturity to allow for comparative costing. The same personnel in the GSFC costing office performed all PRICE-H costing.

The technical inputs into the PRICE-H modeler are all current best estimates (CBE). As described in the GAO reports on NASA large missions (GAO-12-207sp, GAO-11-239SP), the way to ensure accurate cost estimates is to provide early development of key technologies to advance them to high readiness (TRL-6) prior to starting the mission. With this in mind, all PRICE-H costing of the instruments, mirrors, and spacecraft bus components, assumed a minimum of TRL-6 readiness. The technology needs for these mis-

[1] NASA document: NPR 8705.4 Risk Classification for NASA Payloads, (http://www.hq.nasa.gov/office/codeq/doctree/87054.htm) describes the procedure for determining mission risk classification, the distinguishing criteria between risk classes, as well as the commensurate recommended safety and mission assurance (SMA) program for each classification.

sions and estimates for the cost to achieve TRL-6 are discussed separately in **Section 6**. Even though the notional missions have had only a few weeks of definition work, this approach ensures that costings between the various missions remain comparable.

For each notional mission, the PRICE-H cost modeler was used to cost the spacecraft (WBS element 6) based on the MDL design, instrument (WBS element 5.1), and mirror (WBS element 5.2). The sole exception was the *N-WFI* mirror, which as discussed below was a bottoms-up estimate.

The MEL for the *N-CAL* calorimeter instrument was generated by the Instrument Design Lab (IDL), which started with the *IXO* X-ray Microcalorimeter Spectrometer (XMS) conceptual design, and updated it per the specifications called out by the CST. Lessons learned from the *Astro-H* Soft X-ray Spectrometer (SXS) development and the *ATHENA* studies were applied; the result is a substantially simplified design as compared with the Decadal *IXO* design. This MEL was also used in the re-costing of the *AXSIO* mission to ensure a uniform approach.

The study team generated the MEL for the *N-XGS* gratings instrument. While the off-plane grating design was used as the basis for the MEL, it is considered to be representative of grating spectrometers and thus the derived cost would be applicable to the alternative CAT grating design. This instrument MEL meets the specifications called out by the CST and was used for the notional gratings mission MDL run.

The MEL for the *N-WFI* instrument was generated using requirements from the *IXO* wide field imager and was derived from the MEL for the *Suzaku* X-ray Imaging Spectrometer (XIS) by the study team per the specifications called out by the CST.

The MELs for the mirrors for the *N-CAL* and *N-XGS* missions are derivatives of the MEL for the *AXSIO* mirror. The CST established the design parameters for each of these mirrors, while the same study team engineers who generated the *AXSIO* mirror MEL generated their respective notional mission MELs. The *N-WFI* mirror and mirror facilities costs were derived from an estimate included in the *WFXT* RFI response, and then reviewed and augmented by the *N-WFI* study team to include, for example, NASA Class B requirements.

Costs for the Project Management (WBS element 1), Mission Systems Engineering (WBS element 2), Safety and Mission Assurance (WBS element 3), Mission Level Integration and Test (WBS element 10) and Education and Public Outreach (WBS element 11) were generated as a percentage of the sum total of a mission's hardware costs, i.e., a percentage of the sum of instrument, its mirror and mirror facilities, and the spacecraft bus costs. This "wrap-factor" approach is typical for cost estimating at this stage of maturity.

Costs for Science (WBS element 4), Phase E Mission Operations (WBS element 7), and Ground Systems (WBS element 9) were provided by the study team and are based on experience gained during *IXO* pre-phase A activities, and were scaled for each mission accordingly, accounting for data volumes, mission operation complexity, etc. The Mirror Facilities (WBS element 5.3) costs were also provided by the study team and are based on experience gained during *IXO* pre-phase A activities (*N-CAL* and *N-XGS*) or prototype mirror development (*N-WFI*). The cost for the launch vehicle (WBS element 8) for each notional mission was provided by the MDL.

Cost reserves of 30% were added to the instrument and mirrors (WBS 5), spacecraft bus (WBS 6), mission operations (WBS 7) and ground data systems (WBS 9) as well as the wrap factors for WBS 1, 2, 3 and 10. Mission Science (WBS 4.1), had 10% cost reserves applied, while Education and Public Outreach (WBS 11), Launch Vehicle (WBS 8), and Science Grants (WBS 4.2), each had no cost reserves applied.

5.2.1 Confidence in Cost Estimation

At this early stage of mission design maturity, the generally accepted cost estimation methodology is based on parametric models such as PRICE-H, as discussed above. In one case, the *N-WFI* mission, the notional mission corresponds very closely to the *WFXT* mission concept that was submitted in response to the RFI (Murray et al.). In that response, a cost estimate based on a different parametric model (QuickCost 5.0) developed by J. Hamaker at MSFC was used. In Appendix B of the *WFXT* RFI response, the bottoms-up estimate by the *WFXT* team is compared by WBS element to the QuickCost model, and it was found that these two approaches are in excellent agreement (Bottoms-up cost $779M + launch vehicle; QuickCost $798M + launch vehicle). A similar comparison with the results of the *N-WFI* MDL cost estimate as described above compares very well with these two alternative cost estimates (MDL estimate $779M + launch vehicle). The agreement of these three estimates indicates that the MDL results are robust in generating early stage cost estimates.

As noted above, the recent GAO study concludes that if key technologies are mature, then estimates at confirmation are good predictors of mission cost. It is recognized that the current cost estimates are based on a much more preliminary stage of mission development. However, the assumption of technical maturity (to be accomplished outside of the missions) and the requirements for Class B missions have been factored into the study. In all four of the notional missions, the highest technical risk is with the X-ray optics, and therefore these are the source of the greatest cost uncertainly. For the notional missions, the mass and volume of the optics are well known; it is the cost of fabrication, assembly and alignment that are most uncertain (since TRL-6 has not been achieved). The telescope cost for large space missions is typically around 15% of the total mission cost, and this holds true for the notional missions of this study. Even a doubling of the cost of these optics, including the subsequent increases in other WBS elements that scale with cost, will only increase the total mission cost by less than ~10%—i.e., the costs are not particularly sensitive to the largest single uncertainty.

While it is difficult to assess quantitatively the final cost of a mission at this early a stage of design, the costing methodology has resulted in accurate relative costs for the notional missions, and also provides the best estimate for these mission costs at this time.

5.3 Calorimeter Mission (N-CAL)

As discussed below, calorimeter detectors under development would represent a fundamental improvement over the calorimeters on *Astro-H* and previous missions, particularly when coupled with a mirror with much higher effective area and a 10 arcsec HPD or better angular resolution. The improvement over CCDs is analogous to going from narrow-band imaging to integral field units. Calorimeters would measure the energy of a photon to 2–3 eV, about 30 times better than a CCD array, so that at 6 keV (a redshifted Fe Kα line), the resolution is 2000–3000, comparable to the Doppler width of the line. With a calorimeter, a pseudocontinuum of blended lines becomes a forest of lines that yield velocity, abundance, temperature, and sometimes density information.

5.3.1 *IXO*/Decadal Science Objectives Addressed

The CST determined that, of the single instrument missions, the notional calorimeter mission (*N-*

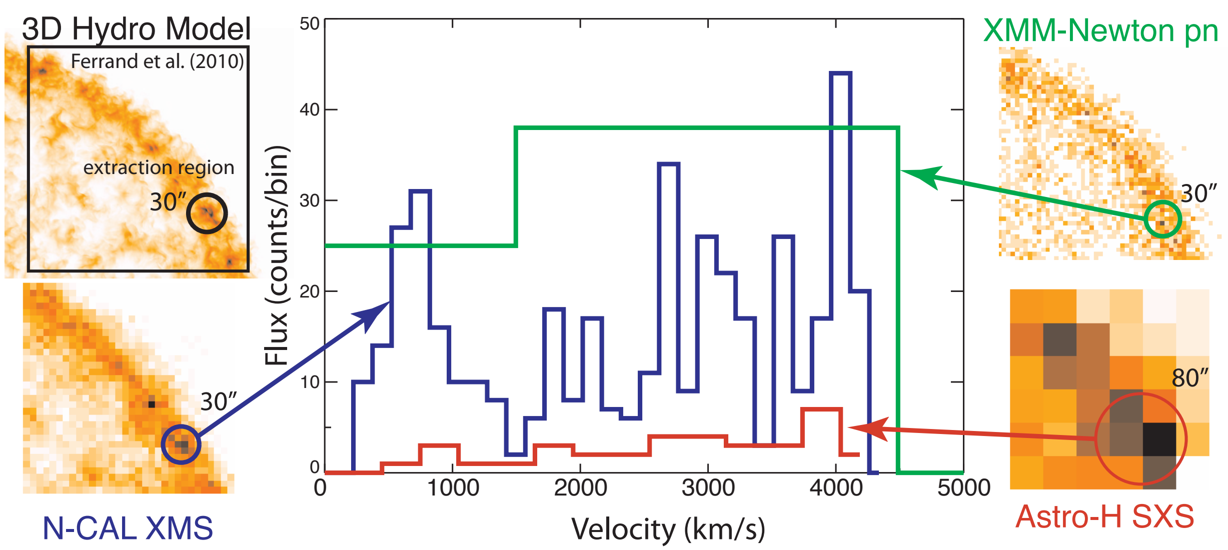

Figure 5.3-1*. N-CAL, XMM-Newton, and ASTRO-H simulations based on a model of Tycho's supernova remnant (top left; Ferrand et al. 2010). N-CAL observations will resolve the highlighted ejecta 'knot' and determine its velocity profile (derived here from Si emission lines), revealing the 3D dynamics of the supernova remnant and the underlying explosion mechanism.*

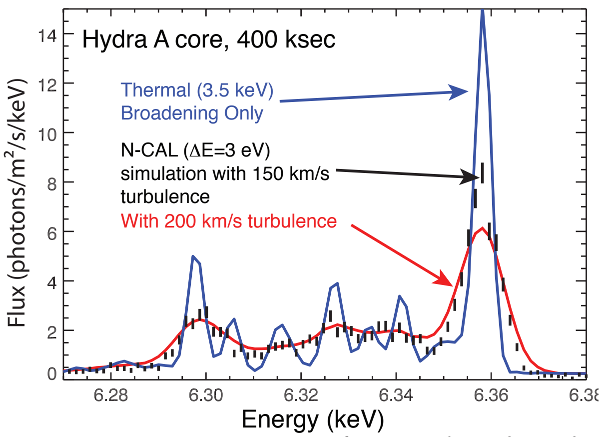

***Figure 5.3-2**. N-CAL spectrum of Fe XXV lines shows that turbulence as low at 150 km/s may be distinguished from thermal broadening alone. Simulated N-CAL data in black, models in color.*

CAL) addresses more of the *IXO* science objectives than the other two notional missions (see summary of science objectives in **Table 5.1-3**). A calorimeter with a spectral resolution of a few eV across the 0.5–10.0 keV bandpass is critical for many key *IXO* science topics. The CST specified requirements for a calorimeter-only mission are an effective area of 5,000 cm^2 at 1 keV and 2,000 cm^2 at 6 keV, a FoV of at least 4 × 4 arcmin, an angular resolution of 10 arcsec (HPD) or better, and an absolute time resolution requirement of 1 ms with a goal of 100 µs. Such an imaging high-resolution spectrometer would directly address all five of the high-priority science goals of *IXO,* as identified by NWNH, to varying levels of fidelity. Specifically, time-resolved, high-resolution spectra of the relativistically broadened Fe-K line in stellar mass or supermassive black holes would address the *IXO* science objective "*What happens close to a black hole?*" Measurements of the mass and composition of clusters of galaxies at redshift < 2 through spatially-resolved spectroscopy would address the *IXO* science objective "*How does large scale structure evolve?*" Finally, measurements of the metallicity and velocity structure of hot gas in galaxies and clusters with high-resolution spectra would address the *IXO* science objective "*What is the connection between supermassive black hole formation and evolution of large scale structure (i.e., cosmic feedback)?*" As an example of the quality of the data produced by a high-resolution calorimeter paired with a large collecting area mirror, **Fig. 5.3-2** shows a simulated spectrum from a 400 ks observation of the cluster Hydra A. The simulation shows the effect of turbulence on the observed spectrum and demonstrates that the high spectral resolution of the calorimeter can distinguish between no turbulence, 150 km s^{-1} turbulence, and 200 km s^{-1} turbulence.

The *N-CAL* mission would also partially address the objectives "*When and how did supermassive black holes grow?*" by measuring the spin of black holes

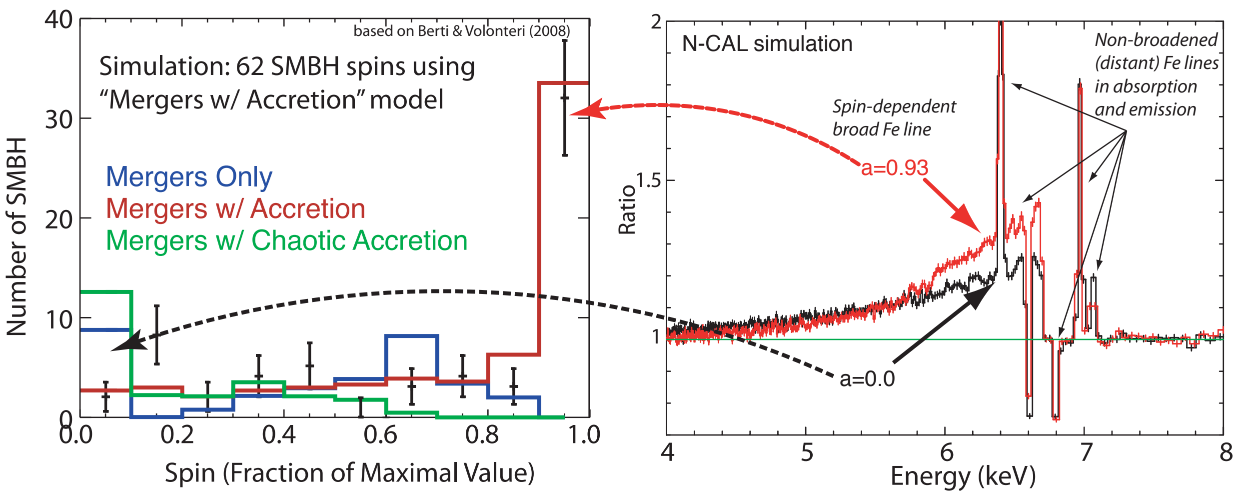

***Figure 5.3-3**. [Left] Three models for SMBH spin histograms in the nearby Universe based on different possible evolutionary scenarios for SMBH growth: via SMBH mergers only, via mergers plus gas accretion, or via mergers plus 'chaotic' accretion of smaller masses (from Berti & Volonteri 2008). By observing 62 SMBH spins, N-CAL will easily distinguish a mergers with accretion scenario from other models. [Right] Relativistically-broaded Fe K lines seen in a SMBH spectra of fast-spinning and a non-rotating SMBHs. The high resolution of the XMS calorimeter easily resolves narrow features which may be present but are far from the SMBH and thus not participating in the relativistic broadening.*

Table 5.3-1. *N-CAL* Instrument Parameters

Bandpass	FOV	Spectral Resolution	Timing Resolution	Angular Resolution	Eff. Area at 1 keV	Eff. Area at 6 keV
0.2–12.0 keV	4 × 4 arcmin	2–6 eV	100 μs	10" (HPD)	5,000 cm^2	2,000 cm^2

Table 5.3-2. *N-CAL* Detector Details

Array	FOV	# of Pixels	Pixel Size	Resolution	# of TESs
Inner PSA	0.16 $arcmin^2$	256	1.5 × 1.5"	2 eV	256
Outer #1	5.5 $arcmin^2$	544	6.0 × 6.0"	3 eV	544
Outer #2	10.3 $arcmin^2$	1040	6.0 × 6.0"	6 eV	260

from the relativistically broadened Fe line. The spin of a supermassive black hole (SMBH) depends upon its history: an accretion-dominated history leads to high spin and a merger-dominated one to low spin (see Berti & Volonteri 2008). With a sample of ~50 measured spins (see **Fig. 5.3-3**), one can begin to distinguish amongst the various growth scenarios proposed for SMBHs. Finally, the *N-CAL* mission would address the objective "*How does matter behave at very high density?*" by constraining the equation of state of neutron stars through gravitationally redshifted atmospheric absorption lines. The high spectral resolution

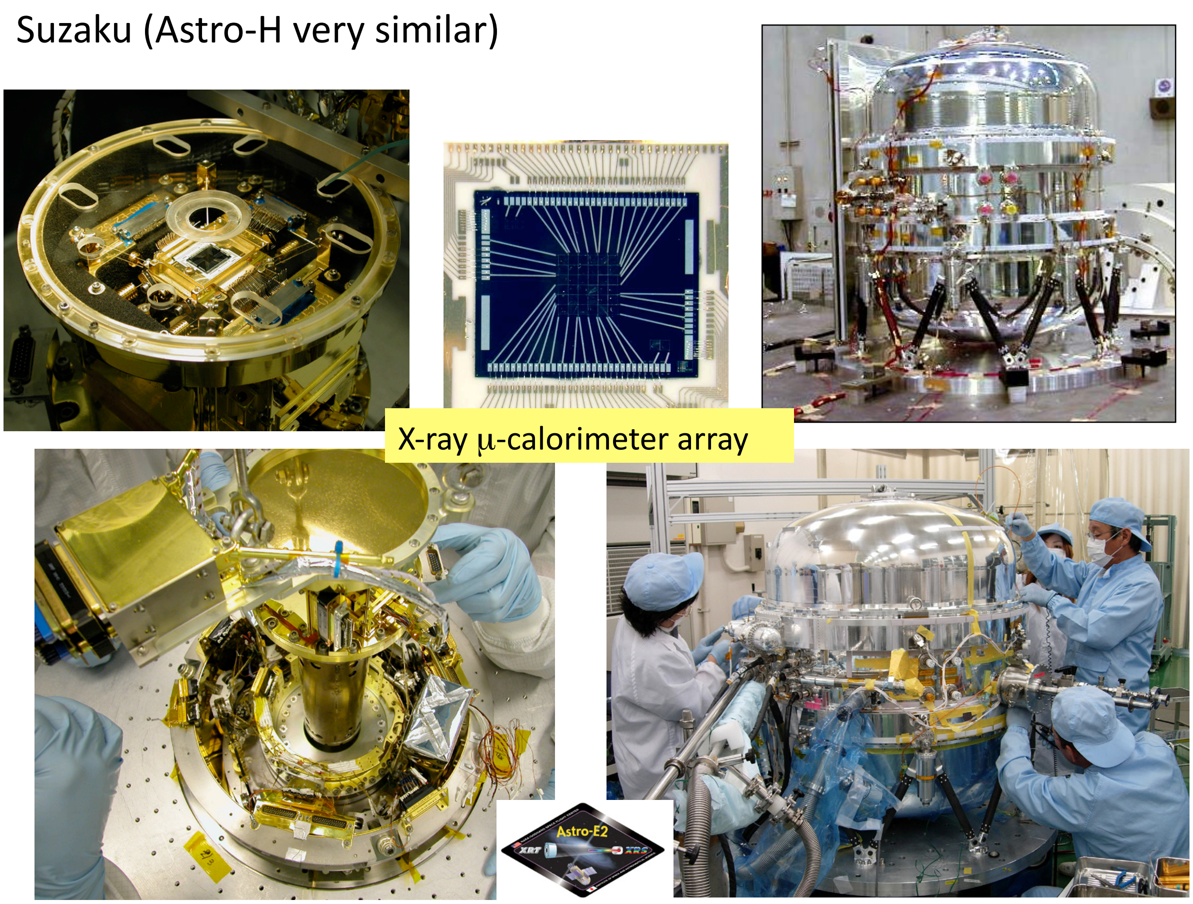

***Figure 5.3-4**. Several views of the calorimeter array and dewar developed for Suzaku.*

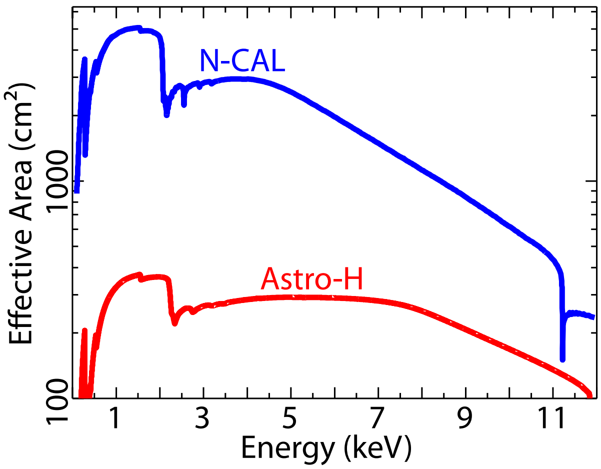

Figure 5.3-5. *Effective Area of notional XMS mission compared to the calorimeter on Astro-H*

of the calorimeter, with spectra of sufficient statistical precision, is the key enabling capability for all of these science objectives.

5.3.2 Description of instrumentation

The calorimeter design would be an updated version of the instrument built by the NASA/GSFC calorimeter team for *Astro-H* and similar to the instrument proposed for *IXO*. It would be a hybrid array consisting of an inner point-source array (PSA) consisting of smaller pixels, with higher spectral resolution and faster readout, and an outer array with larger pixels, slower multiplexed readouts and slightly lower spectral resolution. The PSA would consist of 16 × 16 pixels with a spectral resolution of 2 eV covering a FOV of 0.4 × 0.4 arcmin (each pixel is 1.5 × 1.5 arcsec), requiring 256 Transistion 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 extra detector (HTRS-type) that was used 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. There would be 544 pixels each with its own dedicated TES to provide 3 eV energy resolution surrounding the PSA. 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. **Tables 5.3-1 and 5.3-2** summarize the relevant parameters of the calorimeter instrument envisioned for this mission. **Figure 5.3-3** show several views of the calorimeter instrument developed for the *Suzaku* (known as *ASTRO-E2* before launch) satellite. The cooling for the calorimeter array would be provided by a combination of a cryo-cooler to achieve 4.5 K and a three-stage Adiabatic Demagnetization Refrigerator (ADR) to achieve 50 mK at the focal plane. Both cooling technologies are demonstrated at the TRL-6 or higher level. The three-stage ADR would provide approximately 24 hours of operations at 50 mK before needing a one-hour recycling.

The calorimeter 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 6.5-1** shows a photograph of a prototype 32 × 32 array of 300 µm pixels that has demonstrated 1.8 eV single pixel performance.

5.3.3 Optical Design

The mirror design would be based on the work of the NASA/GSFC mirror lab with segmented glass designs, also proposed for *AXSIO*, *IXO*, and the *N-XGS* mission. The flight mirror assembly (FMA) utilizes a segmented design with precision slumped glass mirror segments. The FMA has a focal length of 9.5 m, a diameter of 1.3 m, 178 shells, 20 cm segment length, and a mass of 325 kg. The surfaces of the mirrors are coated with Ir to provide the desired X-ray reflectivity. The combined effective area of the FMA and the calorimeter is plotted in **Fig. 5.3-5** compared

Table 5.3-3. *N-CAL* Mission Parameters

Mission Class	Lifetime	Orbit	Launch Vehicle	Field of Regard	Mass	Power	TLM Rate[1]
B	3 year Req. 5 year Goal	L2 Halo	Falcon 9 Block 2	± 25 degrees	1775 kg	1006–1127 W	76–1800 kbps

[1] The relatively large range in telemetry rates reflects the range in count rates from the sources expected to be observed.

Table 5.3-4. ***N-CAL*** **Mission Cost**

WBS Element		$M including Reserves
1.0	Project Management	50.0
2.0	Systems Engineering	50.0
3.0	Safety and Mission Assurance	31.3
4.0	Science	
	Science Team	49.4
	GO Grants	79.0
5.0	Payload(s)	
	Calorimeter	197.6
	FMA	71.2
	FMA GSE/Facilities	76.7
6.0	Spacecraft	303.2
7.0	Mission Operations System (MOS)	49.14
9.0	Ground System(s)	30.16
10.0	Systems Integration and Test	37.52
11.0	Education & Public Outreach	9.8
8.0	Launch Vehicle	140
	Total	1175.0

to the effective area of the calorimeter on *Astro-H*. The FMA provides the desired 5,000 cm^2 at 1 keV and 2,000 cm^2 at 6 keV, representing more than an order of magnitude increase over the effective area achieved with *Astro-H*. In addition to the order of magnitude increase in collecting array, the FMA also provides nearly an order-of-magnitude improvement in angular resolution compared to *Astro-H* (~1.0 arcmin HPD). This combination of effective area and angular resolution enables science projects that are out of reach for *Astro-H*.

5.3.4 *N-CAL* Mission Design

The calorimeter design was studied by the GSFC IDL in February 2012. The main objectives of the study were to incorporate an improved design for the cooling system and a consolidated design for the electronics that would reduce the number of electronics boxes (and hence weight and complexity). A successful design was achieved for the instrument with the hybrid calorimeter array being the lowest TRL item.

The calorimeter mission was studied by the GSFC MDL in March 2012, taking the output of the calorimeter IDL study as input and assuming a mirror design based on the slumped glass approach. A mission design was developed that succeeded in meeting all of the requirements for a Class B mission with a required mission lifetime of three years and a goal of five years. The final design had a payload mass, including contingency, of 1775 kg, an average/peak power consumption of 1006/1127 W, and an average/peak telemetry rate of 76/1800 kbps. A significant challenge of the study was to design a spacecraft with the mass and volume to accommodate the 9.5 m focal length that would fit within a Falcon 9 fairing that could be delivered to an L2 orbit. These basic mission parameters are summarized in **Table 5.3-3**. The one technical issue that was identified in the study was the challenge of achieving a 100 μs absolute timing requirement in an L2 orbit. A solution was found with currently available parts that are consistent with the capabilities of the Deep Space Network.

5.3.5 Cost Estimate

The point design cost estimate for the *N-CAL* mission, determined from the MDL study and assuming all technology is at TRL-6 or higher, is $1.2B. The costing assumptions, and reserves approach are summarized in **Section 5.2**. **Table 5.3-4** shows the *N-CAL* mission cost by WBS element, including reserves. The point design cost estimate for the calorimeter alone from the IDL study, assuming a TRL of 6 for the array, is $198M including reserves.

5.4 Notional X-ray Grating Spectrometer

5.4.1 *IXO*/Decadal Science Objectives Addressed

A compelling portion of *IXO* science was made possible by its X-ray Grating Spectrometer (XGS). With an effective area of 1000 cm^2 in the 0.3–1.0 keV band, and a spectral resolving power of $R \equiv \lambda/\Delta\lambda > 3000$, the *IXO* XGS addressed many of the fundamental questions tabulated in **Section 5.1** above. Sensitive absorption line spectroscopy of dozens of AGN promised to trace the location, quantity and physical state of the warm-hot intergalactic medium (WHIM), and

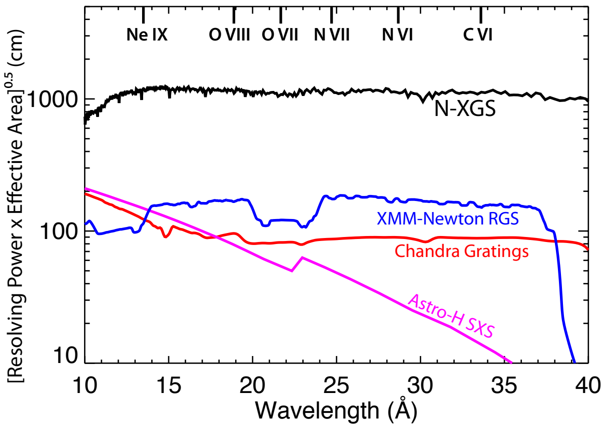

***Figure 5.4-1**. N-XGS would provide at least a five-fold increase in sensitivity to key absorption lines (which is proportional to the square-root of the effective-area x resolving power product) over any current or planned spectrometer.*

thereby probe the evolution of large scale structure. Spectra of background AGN would also have probed the hot baryons in galaxy halos, illuminating matter flows and feedback processes central to galaxy evolution. Absorption spectroscopy of the time-varying winds intrinsic to AGN could have provided both density and velocity of these outflows, thus quantifying the mass and energy fluxes connecting central black holes to the stellar systems that host them. Time-resolved spectroscopy of bursting neutron stars may even have provided mass and radius measurements for some of these objects, thereby constraining the behavior of matter at extremely high density. Finally, high-time-resolution stellar spectroscopy would have disentangled the effects of stellar winds, magnetic fields, and rotation in stellar coronae. The XGS was central to *IXO*'s scientific capabilities; no available calorimeter technology can provide the required spectral resolving power in the line-rich XGS passband.

The Study Team has therefore defined and evaluated a probe-class, notional X-ray Grating Spectrometer (*N-XGS*) mission that addresses most of these questions, and does so in many cases at least as effectively as the *IXO* XGS. The *N-XGS* is a moderate-cost observatory dedicated to high-resolution soft X-ray grating spectroscopy. For many astrophysical problems, the reduced effective area of *N-XGS* (~450 cm^2 at 0.6 keV), relative to *IXO* XGS, is more than compensated by the increased observing time available for grating spectroscopy in a dedicated mission. *N-XGS* will collect at least 60% more photons in its three-year nominal lifetime than *IXO* XGS would have in its five-year observing program shared with other *IXO* instruments. Moreover, *N-XGS*, with spectral resolving power equaling that of *IXO* XGS, will provide capabilities far superior to those of existing soft X-ray spectrometers. One of these is illustrated in **Fig. 5.4-1**, which compares the capability of *N-XGS* to detect faint absorption lines to that of other instruments. At the crucial K lines of O

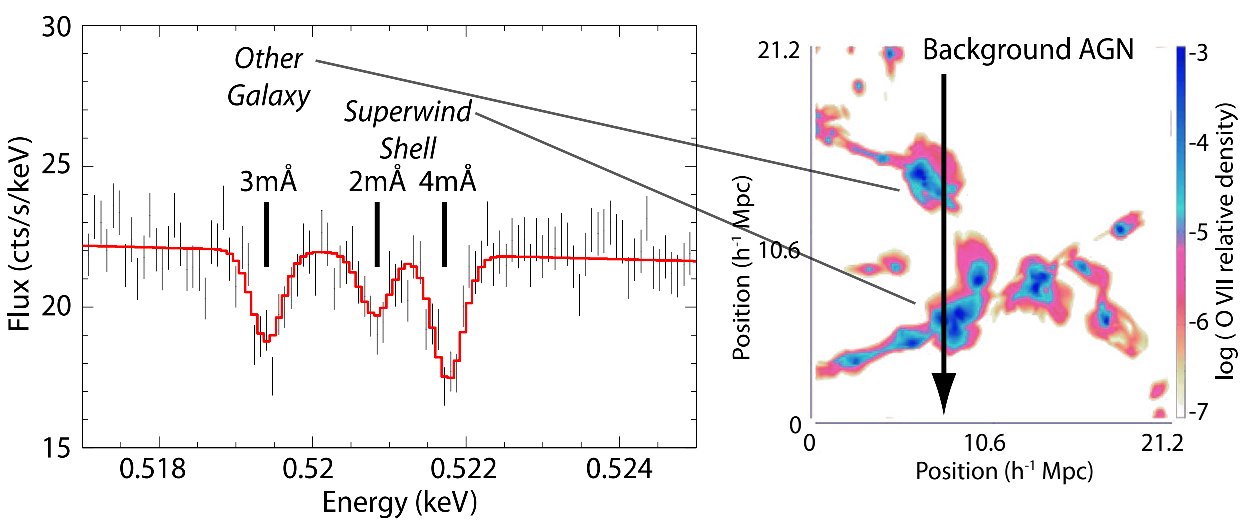

***Figure 5.4-2**. N-XGS 1 Ms spectrum of a background AGN (1.5x10^-11 cgs) going through a superwind shell ejected by a nearby galaxy (z=0.1) and through the halo of another galaxy 1200 km/s farther. Three O VII absorption lines are seen and resolved by the N-XGS (the two superwind shell lines are 600 km/s apart). Adapted from the simulation by Cen & Ostriker (2006) which is shown on the right.*

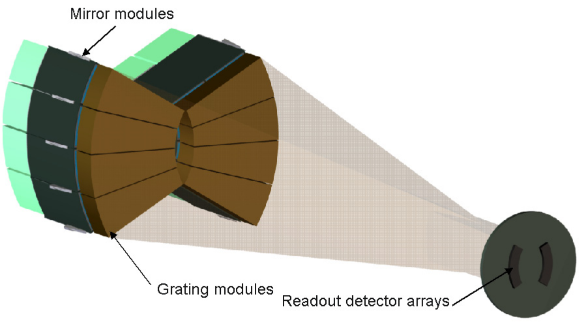

***Figure 5.4-3**. Notional XGS optical layout. Each of the two spectrometers consists of a wedge-shaped set of mirror modules spanning a 60° annular sector, associated objective grating modules and a readout detector array in the focal plane.*

VII and O VIII, for example, *N-XGS* is more than five times more sensitive than any previous spectrometer.

N-XGS will explore the 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 < 500ks exposure) in ~50 blazars. Deeper exposures of the brightest of these objects will be sufficiently sensitive to detect superwind-driven shells of outflowing matter around intervening galaxies (see **Fig. 5.4-2**). It will probe both the velocity and density, and thus, crucially, the mass outflows fed back from supermassive black holes to their host galaxies, although with less time resolution than would have been possible with the *IXO* XGS. *N-XGS* will look for atmospheric absorption features in the spectra of bursting neutron stars. If detected, these will constrain the mass and radius, and thus the equation of state in these super-dense objects, via gravitational redshift and pressure broadening effects. *N-XGS* will bring major advances to the study of stars, star formation and associated flows of matter. It will resolve the thermal line widths of coronal plasmas, distinguish the kinematics of and physical conditions in accreting and outflowing material, and characterize their angular momentum, disk irradiation and magnetic dynamos. These studies will be limited to a brighter and smaller population of targets than would have been accessible with the larger area of *IXO* XGS. Finally, *N-XGS* will bring the power of high-resolution X-ray spectroscopy to a broad range of other astrophysical problems, from the nature of the interstellar medium to the physics of black hole accretion and the baryon content of galactic halos.

Table 5.4-1. *N-XGS* Instrument Parameters

Parameter	Value	Units	Remarks
Performance (total for both spectrometers)			
Effective Area	450	cm^2	@ OVIII Lyα (653 eV)
E/ΔE	> 3000		0.3–1 keV
Flight Mirror Assembly			
Focal length	4	m	
Eff. Area FMA Only	1600	cm^2	@ OVIII Lyα (653 eV)
Ang. Res. (HPD)	10	arc sec	Full circ. aperture
Line-Spread (FWHM)	3	arc sec	2 × 15° modules
Mass	75	kg	
Power	65	W	Temp. cntrl.
CAT Gratings			
Periods	200, 230	nm	
Mass	3	kg	
Power	0	W	FMA temp. cntrl.
OPG Gratings			
Period	167	nm	
Mass	54	kg	
Power	50	W	Temp. cntrl.
Focal Plane Assembly			
Cameras	2		1/spectrometer
CCDs	12		6/camera
CCD Size Frame Rate	 50 × 25 15	 mm fr s^{-1}	MIT/Lincoln 24 µm pixels
Mass	64 (77 for OPG)	kg	
Power	74	W	

5.4.2 Description of Instrumentation

5.4.2.1 Optical Design

The *N-XGS* consists of two independent, objective grating spectrometers that operate in parallel. Each spectrometer is served by a set of four grazing-incidence mirror modules, which can be thought of as azimuthal sub-apertures of a circular mirror (see **Fig. 5.4-3**). 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° module of the flight mirror assembly (FMA) meets this requirement.

Blazed objective gratings are mounted immediately behind each mirror module. Two distinct grating technologies are under development for the *N-XGS*: Off-Plane Gratings (OPG) and Critical Angle Transmission (CAT) gratings. For concreteness, the Mission Design Laboratory study of the *N-XGS* focused on the OPG implementation, but showed that both the OPG and CAT implementations could be developed within the resource constraints deduced for the OPG version.

For either choice of grating, the dispersed spectra are detected and recorded by arrays of X-ray photon counting, charge-coupled device (CCD) detectors. The intrinsic CCD energy resolution separates the multiple spectral orders overlapping on the focal plane. The detectors are enhanced versions of those now operating on *Chandra* and *Suzaku*.

Table 5.4-2. *N-XGS* Mission Parameters

Parameter	Value	Units	Remarks
Payload[1]			
Mass	240	kg	
Power	190/205	W	Obs./peak
Telemetry	64/640	kbps	Avg./peak
Spacecraft Bus[1]			
Mass	386	kg	
Power	307/910	W	Obs./peak
Pointing Control Knowledge Jitter	 45 1.3 0.2	 arc sec arc sec arc sec	 over 200 ks 3 σ, per axis RMS, f > 15 Hz
Observatory[2]			
Mass	828	kg	At launch
Power	646/1451	W	Obs./peak
Downlink	10	Mbps	50cm HGA S/Ka
Storage	58	Gbit	Min. 72 hr
Mission			
Duration	3/5	yr	Prime/goal
Orbit	L2		800Mm halo
Launcher Vehicle Capability Margin	 Falcon 9 2530 1702	 kg kg	 Std. fairing To L2 205%
Comm.	1	pass/dy	DSN

[1]Current best estimates for payload and spacecraft bus
[2]Observatory values include 30% contingency

5.4.2.2 Flight Mirror Assembly

The *N-XGS* FMA modules use the same Wolter-I, segmented glass architecture adopted for the *N-CAL* and *AXSIO* missions. Each 15° FMA module consists of two radial sub-sectors together spanning 400 to 900 mm in radius. Key mirror parameters are listed in **Table 5.4-1**. To minimize the spacecraft mass and volume, eight FMA sectors are arranged in a "bow-tie" configuration as shown in **Fig. 5.4-3**. The small focal ratio of the mirror segments allows relatively large graze angles and, therefore, a relatively small number of mirror shells (51).

5.4.2.3 Gratings

As noted above, the *N-XGS* can be implemented with either of two grating technologies. Off-plane gratings (OPG) (McEntaffer et al. 2011a, 2011b; Cash et al. 2011) are reflection gratings arranged so that the dispersion direction is out of the plane of incidence (the plane defined by the direction of the incident radiation and the grating normal). Critical-angle transmission gratings (Heilmann et al. 2011a, 2011b, 2011c) are blazed transmission gratings. Details of each implementation are listed in **Table 5.4-1**.

The *OPG* are reflection gratings produced from holographic lithography onto a master substrate which is subsequently replicated onto flight elements to produce the requisite number of gratings. Their efficient packing geometry and blazed profile allow for high throughput while the high density, radial groove profile provides high spectral resolving power. This technology has heritage from the *XMM-Newton* RGS and suborbital rocket payloads. Each 15° *N-XGS* mirror module is associated with a 15° azimuth of gratings. Independent spectra at the focal plane allow for spectral redundancy and relaxed alignment tolerances. The effective area and resolving power requirements are met using orders 2 through 6.

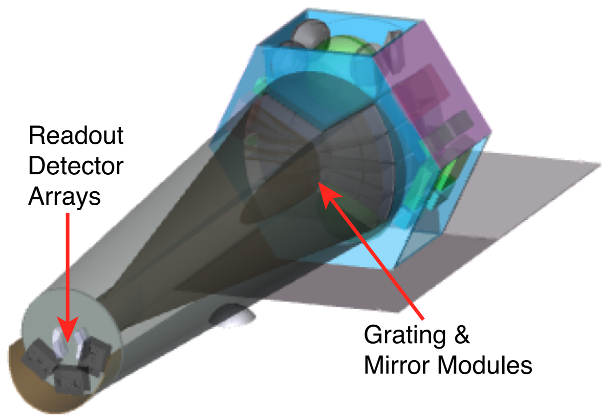

Figure 5.4-4. *Transparent view of the N-XGS spacecraft . The optical path is shaded in dark gray.*

The *CAT* gratings are produced from silicon wafers using nanofabrication techniques. They are lightweight, and combine the high spectral dispersion of blazed reflection gratings with the relatively relaxed alignment tolerances of transmission gratings. This technology is a direct descendant of the transmission gratings now flying on *Chandra*. In the *N-XGS* implementation, the two (adjacent) FMA modules of a given spectrometer are confocal, and are equipped with gratings with different grating periods, blazed on opposite sides of the undiffracted (0^{th} order) image. The CAT *N-XGS* uses a relatively broad range of diffraction orders (nominally 2^{nd} through 12^{th}), and two different grating periods are used to minimize the variation in effective area with wavelength.

5.4.2.4 Focal Plane Assembly

The focal plane assembly consists of two X-ray photon counting CCD arrays (one array for each spectrograph), a detector electronics assembly (DEA) providing analog signal processing and digitization, a digital processing assembly that identifies X-ray events in the data stream produced by the DEA, and a remote unit that serves as the interface between the focal plane assembly and the spacecraft. Each of the two detector housings is equipped with a (non-hermetic) door as well as a pair of focus actuators. The CCD detectors are high-quality back-illuminated devices derived directly from those now flying on *Chandra* and *Suzaku*. The detectors are passively cooled (via a dedicated radiator) to an operating temperature of -90° C. The CCD spectral resolution is adequate to separate the overlapping orders diffracted by the gratings. An optical blocking filter, consisting of 30 nm of Al and 10 nm Al_2O_3, is deposited directly on each CCD. Further details are listed in **Table 5.4-1**. Time resolution is determined by the 15 Hz CCD frame rate. Faster readout times are possible, but were not explored in detail here due to time limitations.

Table 5.4-3. ***N-XGS*** **Mission Cost**

WBS Element		$M including Reserves
1.0	Project Management	31.6
2.0	Systems Engineering	31.6
3.0	Safety and Mission Assurance	19.7
4.0	Science	
	Science Team	30.0
	GO Grants	26.2
5.0	Payload(s)	
	Gratings	101.1
	FMA	24.2
	FMA GSE/Facilities	40.3
6.0	Spacecraft	228.8
7.0	Mission Operations System (MOS)	50.3
9.0	Ground System(s)	30.2
10.0	Systems Integration and Test	23.7
11.0	Education & Public Outreach	6.4
8.0	Launch Vehicle	140
	Total	784.1

5.4.3 Mission Description

The *N-XGS* payload uses a compact, conventional spacecraft. Details of the mission are summarized in **Table 5.4-2** and the spacecraft configuration is illustrated in **Fig. 5.4-4**. *N-XGS* is launched directly into a Sun-Earth L2 halo orbit by a Falcon-9 vehicle. This orbit maximizes observing efficiency and simplifies some aspects of spacecraft design and operations. The nominal three-year mission provides more than 70 Ms of science exposure time, and the exposure-effective-area product exceeds that baselined for *IXO* by a factor greater than 1.6.

Communication with the spacecraft is via the NASA Deep Space Network (DSN). Daily contacts for commanding, ranging and science data downlink are envisioned. These will last 14–32 minutes, de-

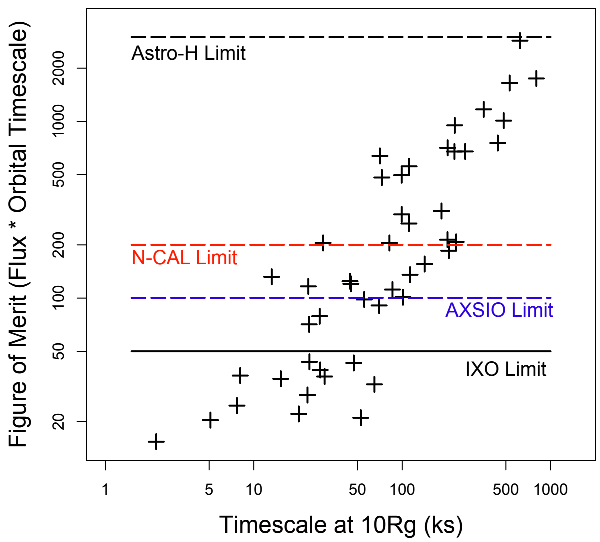

***Figure 5.5-1**. The orbital timescale at 10 gravitational radii vs. the figure of merit for measuring the orbitally resolved motions of hot spots in SMBH accretion disks. The figure of merit for each AGN is the product of the flux at the Fe-K(alpha) line and the orbital timescale, hence the correlation with orbital timescale. A longer orbital timescale allows a longer integration time. The limits for IXO, AXSIO, N-CAL, and Astro-H are shown. Any AGN with a figure of merit above the limit is reachable. For each AGN hundreds (or thousands) of hot spot orbits will be measured, allowing the gravitational metric for a range of radii to be accurately measured. Fluxes for the AGN are taken from the BAT 58-month catalog and limited to Seyfert 1s only, which provide the most unobscured view of the SMBH.*

pending on the flux of the sources. Onboard storage is sufficient for 72 hours of data collection, assuming observations totaling 60 hours of sources producing the nominal average count rate plus 12 hours of sources 10 times brighter. The mission operations model is identical to that used for the other notional missions.

5.4.4 Cost Estimate

The point design cost estimate for the N-XGS mission is $784M. **Table 5.4-3** shows the cost by WBS element, with reserves included. Costing was performed using the assumptions summarized in **Section 5.2**.

5.5 AXSIO

Following ESA's withdrawal from *IXO* and before IXO team was disbanded and the RFI issued, the *IXO* project office undertook a study of a reduced mission

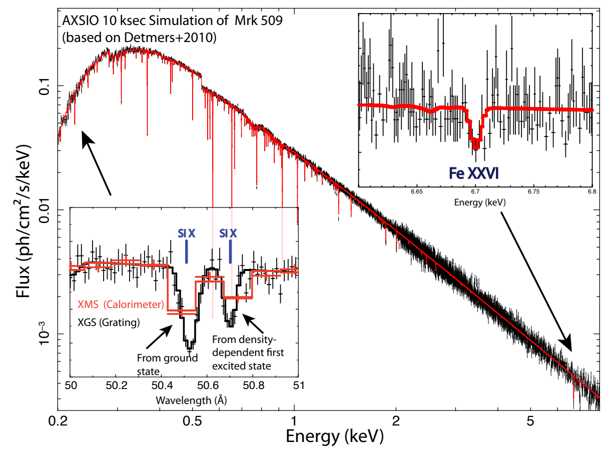

***Figure 5.5-2**. X-ray spectra can be used to determine the masses of warm clouds accelerated by a SMBH. This simulated 10 ksec AXSIO observation of Mrk 509 includes absorption from five different sources with a wide range of photonization parameters based on Detmers et al. (2010). The top right inset shows the weak Fe XXVI absorption that can only be detected by the XMS, while the lower left inset compares the density-dependent Si X lines from a cooler cloud observed with the XGS and the XMS; the higher resolution of the XGS at low energies allows the line profiles to be measured accurately. The X-ray flux of many SMBH show variation on timescales of 10–100 ksec and the timescales of the changing photoionization parameters will reveal both the column density and the local densities, allowing the cloud mass to be inferred.*

that would address *IXO* science goals. The study was aimed at developing a mission that would address the NWNH recommendation of costing less than $2B. This mission, *AXSIO*, has two instruments, a calorimeter and a dispersive grating instrument. *AXSIO* was reviewed again during the X-ray concepts study to verify that costing and design methodologies were consistent with those employed for the notional missions.

5.5.1 *IXO*/Decadal Science Objectives Addressed

AXSIO retains most of *IXO*'s scientific power thanks to a combination of the *XMS* and *XGS* in fixed position behind a rescoped mirror. Compared to the *N-CAL* and *N-XGS* missions, *AXSIO*'s mirror provides nearly a factor of two more area at 1 keV. All three missions were designed for a three-year lifetime, most of which would be spent observing bright sources not dominated by background. 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. As noted in **Section 6.7**, *AXSIO* can provide significantly more science than *N-CAL* for a delta cost of only $300M, slightly more than the cost of an Explorer mission and providing a significant increase in science per dollar.

Considering the capabilities of the two instruments independently, *AXSIO* will 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 0.1–10 keV, capabilities only possible using both grating and calorimeter spectrometers.

As described in **Section 5.4.1**, *N-XGS*-type spectroscopy will detect the missing half of the cosmic web via absorption spectroscopy towards bright AGN. Growth of structure simulations predict that these "missing" baryons are shock heated to 10^7 K in unvirialized cosmic filaments and chemically enriched by galactic superwinds. Most galaxies, in fact, have lost more than 2/3 of their baryons, relative to the cosmological ratio of baryons to dark matter. 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. In addition to detecting absorption features, *AXSIO* will also make high-resolution measurements that directly observe emission outside the virial radius of galaxy clusters and reveal gas just now falling into the cluster. On Galactic scales, *AXSIO* will identify the location and metallicity of these Local Group baryons from the absorption line centroids and equivalent widths of hot C, N, and O ions while also being able to detect diffuse emission from Local Group gas, setting direct limits on the density, size scales, and mass of this gas.

Another key *IXO* science question revolves around how the gravitational energy from a solar-system-sized SMBH can be effectively transmitted to the kpc and

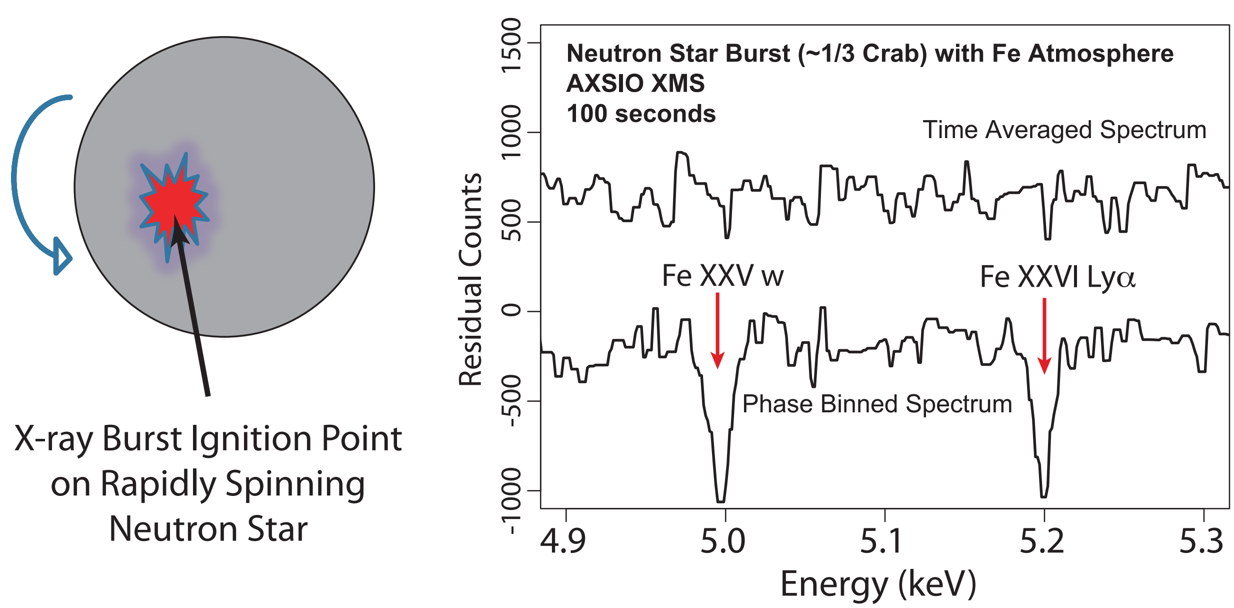

Figure 5.5-3. *X-ray bursts on neutron stars start in at a localized ignition points, as evidenced by the pulsations at the spin period seen during the burst rise. These pulsations decrease in amplitude during the burst as the ignition spreads over the surface of the neutron star, but also may continue throughout much of the burst decay for reasons that are not yet understood. Assuming the pulsations continue during the burst due to some azimuthal asymmetry in the emission, the Fe lines expected in the neutron star atmosphere will be Doppler shifted due to the rapid spin. The XMS has sufficient spectral and timing resolution to 'remove' the Doppler shift via phase binning the spectra on the spin period, and recover the lines which would otherwise be smeared out in the time averaged spectrum. Detection of these lines gives a robust and model-independent measure of both the mass and radius of the neutron star.*

Mpc scales of galaxies and clusters of galaxies. Although the process surely involves jets and the absorbing clouds observed around SMBH, it remains unclear whether or not the energetics are dominated by direct radiation or accelerated clouds. Broad bandpass high-resolution X-ray spectroscopy of these SMBH can answer this question by directly determining the mass of the clouds that are photoionized and accelerated by the SMBH jets. These clouds exhibit a wide range of photoionization, depending upon their density and distance from the SMBH as well as its flux. In particular, the rate of change in a cloud's photoionization after a change in the SMBH flux will reveal its density. As shown in **Fig. 5.5-2**, with one short observation the XMS can measure photoionization rates of highly-ionized clouds, while the XGS will be sensitive to the effect in less ionized clouds. An additional approach can be used with the XGS to measure density-dependent ions such as Si X in absorption.

AXSIO's science program will, however, be somewhat modified compared to *IXO*. *AXSIO*'s effective area and lifetime will support a survey of 60 rather than *IXO*'s 300 supermassive black hole spin measurements, but this will still reveal whether mergers or accretion dominates the SMBH growth. Some objectives now use a subset of the measurement approaches planned for *IXO*. *AXSIO* will measure matter at high density by observing absorption edges in bursting neutron stars using calorimeter and possibly grating spectroscopy, but approaches using polarimetry and quasi-periodic oscillations at high count rates were dropped. Similarly, the growth of black holes will be studied via their spin distribution with a deep wide-field survey for high-z SMBH.

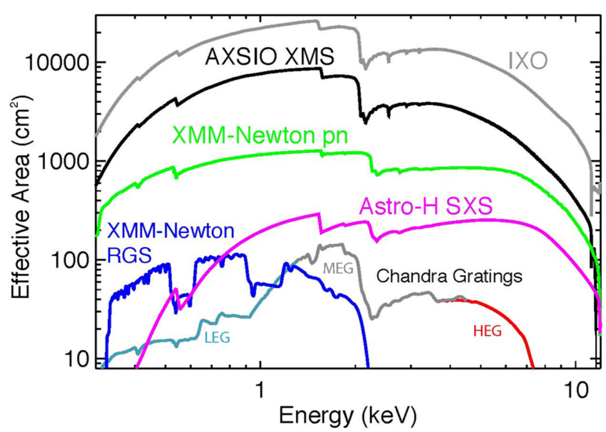

Figure 5.5-4. *Comparison of AXSIO effective area with those of IXO, Astro-H, and currently operating missions.*

5.5.2 Description of instrumentation

The AXSIO configuration considered here differs slightly from the AXSIO RFI submission in that the revised calorimeter design for N-CAL is used. The number of readouts are lower in the current configuration with the main consequence being that the outermost pixels have lower spectral resolution. However the FOV is the same (4' × 4').

Optics: *AXSIO*'s flight mirror assembly (FMA) is based on a segmented Wolter-I design with precision-slumped glass mirror segments, and is the same general approach as used for the optics of *IXO*, *N-XGS* and *N-CAL*. The optic has a 10 m focal length, a diameter of 1.8 m, and consists of 227 shells, each with a length of 40 cm (P+H). This shorter focal length compared with *IXO* removes the need for an extendable optical bench, while the smaller diameter requires many fewer shells than the *IXO* mirror. The *AXSIO* focus

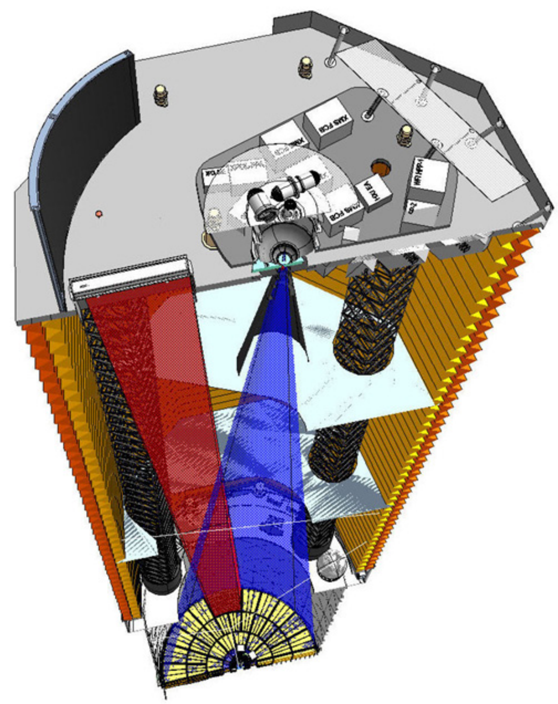

Figure 5.5-5. *The segmented optic is shown at the bottom. The primary X-ray path (Blue) focuses on XMS. When the gratings are deployed, a portion of X-ray beam that passes through the grating (Red) creates a dispersed spectrum on the XGS camera. Mission operations assumed that dual operations (shown in figure) mode (gratings deployed) will be used ~ 25 % of the time. Note that this schematic is showing the original IXO configuration of instruments but is intended to show an example optical layout for a combined grating plus calorimeter system.*

on spectroscopic science allows the angular resolution requirement to be relaxed to 10 arcsec (with a 5 arcsec goal)—which is still over an order of magnitude improvement over *Astro-H*. Taken together, these modifications to the mirror from the *IXO* configuration, along with the reduced number of shells, significantly reduce the difficulty and cost of fabrication. The mirror effective area is shown in **Fig. 5.5-4**, this FMA provides 0.9 m^2 at 1 keV (about a factor of two larger than the *N-CAL* mirror) and 0.2 m^2 at 6 keV (essentially the same as the *N-CAL* mirror). The total mirror mass, with support structure and thermal control system, is 524 kg.

To accommodate the grating instrument, the CAT implementation was selected for study and costing, though the OPG is a fully viable alternative. The CAT gratings are mounted immediately behind the mirror module, with a mechanism to remove the gratings from the beam when required (**Fig. 5.5-5**).

Instruments: *AXSIO* combines two instruments, an X-ray calorimeter spectrometer (XMS) with an X-ray grating spectrometer (XGS). *AXSIO*'s prime instrument is a calorimeter array that provides high-resolution spectroscopic imaging; a modest re-configuration of *IXO*'s calorimeter focal plane has allowed for recovery of much of the science that would have been accomplished by *IXO*'s High Time Resolution Spectrometer (HTRS) by using multiple pixel sizes. The *AXSIO* baseline (essentially identical to the *N-CAL*) is a hybrid array that consists of a 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. **Table 5.5-1** summarizes the instrument parameters as envisioned for *AXSIO,* with more detail given in the instrument sections for *N-CAL* and *N-XGS* (**Sections 5.3** and **5.4**).

AXSIO's retractable high efficiency X-ray grating spectrometer (XGS) enables high-resolution spectroscopy of point sources, used either in tandem with the calorimeter or removed when observing diffuse sources. The XGS is a wavelength-dispersive spectrometer, 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 detail: A Critical-Angle Transmission (CAT) grating spectrometer and an Off-Plane reflection grating (OPG) 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 dispersed spectra are detected and recorded by arrays of X-ray photon counting, charge-coupled device (CCD) detectors. The intrinsic energy CCD energy resolution separates the multiple spectral orders over-

Table 5.5-1. *AXSIO* Instrument 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	ΔE < 6 eV (FWHM) $E/\Delta E$ = 3000	Cluster Evolution, Missing Baryons	XMS – outer array XGS
Angular Resolution	10" HPD	Cosmic Feedback, Cluster Evolution	XMS
Field of View	4 arcmin	Cluster Evolution	XMS – outer array
Bandpass	0.2–10 keV 0.2–1.5 keV	Growth of SMBH, Cosmic Web	XMS XGS
Count Rate	15,000 cps, <10% deadtime	Neutron Star, Equation of State	XMS – point source array

Table 5.5-2. AXSIO Mission Parameters

Mission Class	Lifetime	Orbit	Launch Vehicle	Field of Regard - Pitch	CBE Wet Mass	CBE Power	TLM Rate
B	3 year Req., 5 year goal	L2 Halo	Atlas V-511	± 45 deg	1847 kg	1558 W	205–3085 kbps

lapping on the focal plane. The detectors are enhanced versions of those now operating on *Chandra* and *Suzaku*. Details of these two designs are discussed in more detail in **Section 5.4** of the *N-XGS* mission, and so are not repeated here.

5.5.3 Mission Design

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; an Atlas V-511 provides substantial throw margins. While the original *AXSIO* mission design life was five years, with consumables sized for 10 years, to ensure comparable costing with the notional missions this was reduced during the delta-MDL run to a three-year mission with five years of consumables. Essential parameters derived from the science are shown in **Table 5.5-1** and the mission parameters are summarized in **Table 5.5-2**. The *AXSIO* mission was studied by the Mission Design Lab (MDL) in October 2011, and a delta MDL was conducted in April 2012 to re-cost the mission with the updated calorimeter mass and costs developed in the IDL, and utilizing the same assumptions as the other notional missions to enable mission-to-mission comparisons.

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 L2 orbit facilitates 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). This field of regard is substantially larger (now ±45°) compared to *IXO* (±20°), significantly improving its ability to execute Target of Opportunity investigations.

As with the other notional missions, communication with the spacecraft is via the NASA Deep Space Network (DSN). Daily contacts for ranging and science data downlink are planned, with weekly uploads for the observing plan. Onboard storage is sufficient to accommodate two consecutive missed passes.

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 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 arcsec (3σ, radial), with post-facto aspect reconstruction accuracy of 1.3 arcsec (3σ, radial); these accuracies are achievable with adequate margin.

5.5.4 Cost Estimate

A revised cost estimate for *AXSIO* (**Table 5.5-3**) was generated based on the assumptions used for the other three missions, to ensure consistency, but resulting in a cost that differs from the estimate given in the Bookbinder et al. RFI submission. These common assumptions, as well as methodology and reserves approach, are discussed in **Section 5.2**. As with all of the notional missions, TRL-6 is assumed for the X-ray mirrors and the focal plane detectors. The total cost for *AXSIO* including reserves is $1.5B.

5.6 WFI Notional Mission (N-WFI)

5.6.1 *IXO*/Decadal Science Objectives Addressed

Sensitive X-ray surveys have been limited to small areas of the sky due to the intrinsically small field of view of Wolter-I X-ray optics, whose angular resolution degrades with the square of the off-axis angle. By contrast the *N-WFI* optics allow 5–10 arcsec weighted mean angular resolution over a wide (up to 1 degree) field of view as shown in **Fig. 5.6-1**. We note that while the *N-WFI* requirement is a 24 arcmin FoV with HPD < 7 arcsec, the preliminary mirror design actually provides a much larger, 1-degree, FoV as seen in **Fig. 5.6-1**. Good angular resolution achieves a low background for source detection, minimizes source confusion, and distinguishes point from extended sources. For comparison, in the survey mode *eROSITA*'s HPD at 1 keV is ~25 arcsec. Factoring in the expected *N-WFI* background and effective area, the sensitivity of the *N-WFI* mission for detecting faint point sources will be > 20 times that of *eROSITA* in the deepest surveys. While the *Chandra* deep surveys have covered relatively small solid angles, the combi-

Table 5.5-3. *AXSIO* Mission Cost

WBS Element		$M including Reserves
1.0	Project Management	66.8
2.0	Systems Engineering	66.8
3.0	Safety and Mission Assurance	41.8
4.0	Science	
	Science Team	63.6
	GO Grants	78.6
5.0	Payload(s)	
	Gratings	78.0
	Calorimeter	197.6
	FMA	105.7
	FMA GSE/Facilities	140.4
6.0	Spacecraft	337
7.0	Mission Operations System (MOS)	49.1
9.0	Ground System(s)	39.8
10.0	Systems Integration and Test	45.9
11.0	Education & Public Outreach	13.1
8.0	Launch Vehicle	230
	Total	1,554.2

nation of the *N-WFI* effective area which is ~8 times larger than *Chandra*'s at 1 keV, and the improved angular resolution within 30 arcmin off-axis, allows deep and moderate surveys to be performed by a *N-WFI* mission more than an order of magnitude faster than with *Chandra*. Similarly, *N-WFI* is more sensitive than *XMM* due to its combination of larger area and better angular resolution. While *XMM* carries out large area surveys of tens of square degrees, the surveys are limited in depth due to source confusion, and *XMM*'s 17-arcsec resolution is too large to study high redshift clusters, particularly to exclude cluster cores from spectral analysis.

N-WFI will touch on all five *IXO* science goals, strongly addressing three of them. In particular, measurements of the mass and spatial distribution of clusters of galaxies to redshifts of 2, along with the spatial distribution of AGN will definitively address the *IXO* science objective "*How does large scale structure evolve?*" By defining the luminosity function of AGN as a function of redshift (to z ~ 6), notably including obscured AGN often missed by other surveys, and determining the host galaxy properties and environment, the *N-WFI* surveys will answer the *IXO* questions of "*When and how did supermassive black holes grow?*" The large numbers of clusters and groups of galaxies that *N-WFI* will study with good angular resolution will reveal the roles of AGN outbursts and how they may change as a function of redshift which will address the *IXO* science objective "*What is the connection between supermassive black hole formation and evolution of large scale structure (i.e., cosmic feedback)?*"

N-WFI will also study the growth and evolution of clusters of galaxies by carrying out sensitive large-area surveys with sufficient depth to detect clusters and groups to redshifts of at least 2–3. The angular resolution of *N-WFI* will permit cluster recognition and allow the cores to be excised for measurements of cluster properties, the most important of which is total cluster mass. This is measured through several mass proxies: gas mass, gas temperature, X-ray luminosity and Y_X (the product of the density and temperature), all measured in the outer cluster region from 0.15 R_{500} to R_{500}; where R_{500} is the radius where the density is

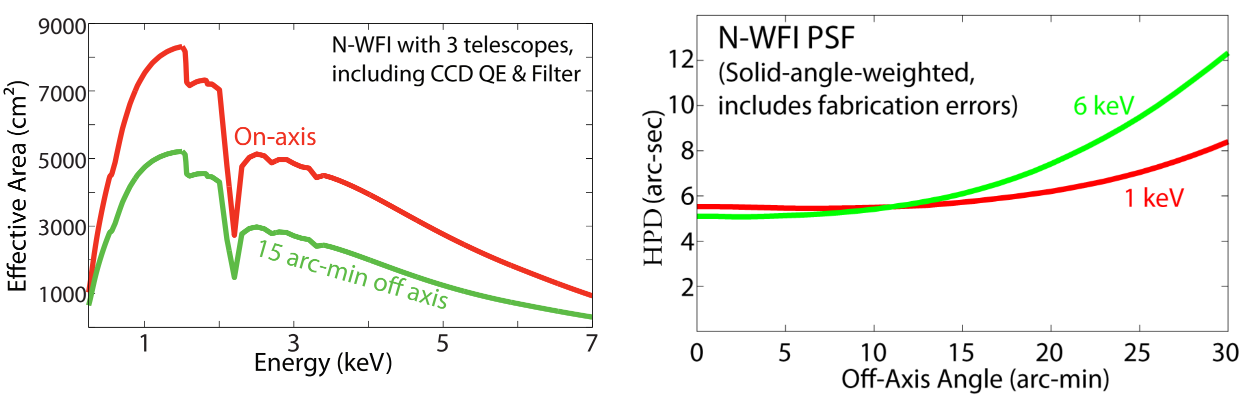

***Figure 5.6-1**. Left: Net effective area versus energy for the N-WFI payload. Right: Angular resolution (solid angle weighted) versus off-axis angle for the N-WFI telescope.*

500 times the critical density of the Universe. The detection of groups at high redshifts will inform the merger history of clusters and their growth. The impact of environment on galaxy evolution (e.g., inside or outside of clusters and groups) will be studied using the very large samples obtained in the *N-WFI* surveys. Based on a three-year mission lifetime, and setting aside about ½ year for the pointed (on-axis) studies of specific bright sources (AGN, NS, etc.), *N-WFI* will conduct two surveys. A medium depth survey, with an average exposure time of 20 ksec, will cover about 850 deg^2 and take about 1.5 years (reaching a point source 5σ flux limit of ~4×10^{-16} erg cm^{-2} s^{-1}, 0.5–2.0 keV). A deep survey, with an average exposure time of 400 ksec, will cover about 25 deg^2 and take about one year (reaching a point source 5σ flux limit of ~7×10^{-17} erg cm^{-2} s^{-1}, 0.5–2.0 keV). The medium survey areas will be one or two large contiguous regions to enable spatial and angular correlation studies. The deep survey will be several smaller regions, 5–10 deg^2 each, and will be spread over time in 40 ksec exposures to permit time domain studies on a variety of scales.

The *N-WFI* will detect approximately 1.5×10^6 AGN in the 850 deg^2 medium survey and an additional 2.5×10^5 AGN in the deep survey areas. Of these about 1.5×10^5 will have more than about 400 counts, and ~4,500 will have high column density. A large number of AGN will be detected at high redshift ($z > 6$), although predictions vary by orders of magnitude. The *N-WFI* sensitivity and survey area will be able to resolve this issue. Similarly, *N-WFI* will detect approximately 10,000 clusters in the medium survey and an additional 750 clusters in the deep survey areas. A few hundred of these will have sufficient counts to map temperature profiles, many thousands will have accurate temperature and mass estimates that can be used to address cosmology and dark energy parameters.

5.6.2 Description of Instrumentation

5.6.2.1 Optical Design

Wide field optics can be considered essentially Wolter-I but with small perturbations to their design to reduce off-axis aberrations and enhance resolution across a broader field of view. These design changes can include slight modifications to the figure of the mirror and varying the mirror shell lengths as a function of radius.

For the MDL run, full-shell fused-silica-based optics were considered, with 71 nested shells in each of three 6-m-focal-length mirror modules. The shells range in diameter from 0.3 m to 0.96 m and vary in total reflector length (parabolic plus hyperbolic sections combined) from 300 mm to 480 mm, smaller diameter mirrors being shorter in length. This design achieves the required sub-7-arcsec angular resolution out to ±18 arcmin off axis and better than 7000 cm^2 effective area on axis at 1 keV and ~1,800 cm^2 at 6 keV (see **Table 5.6-1**). Although the HPD exceeds 7 arcsec beyond 18 arcmin off-axis, the field of view covered

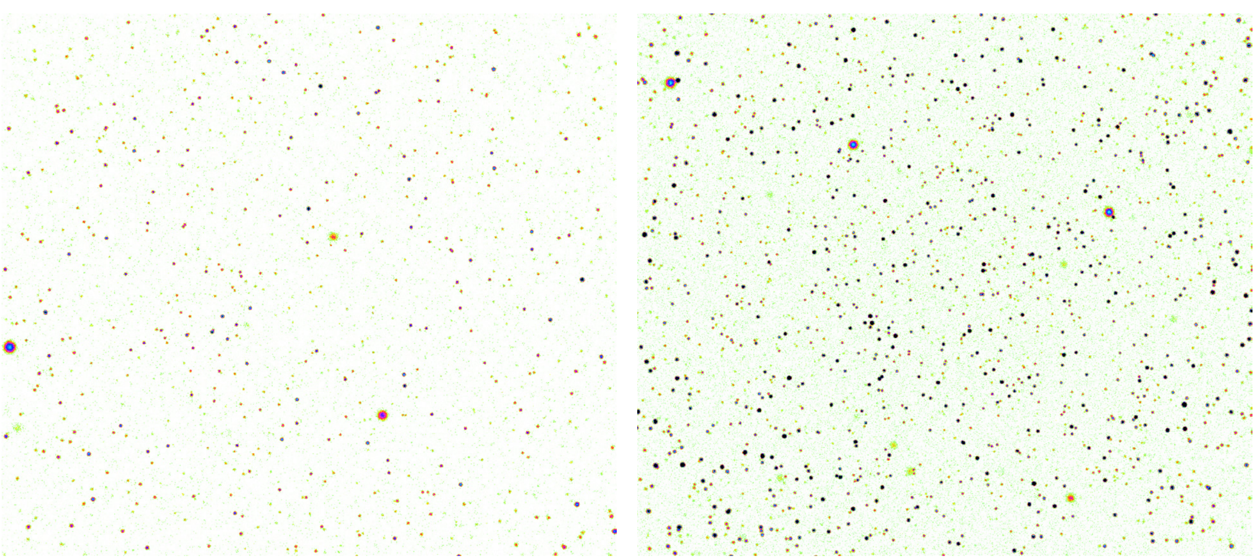

Figure 5.6-2. *Simulation of a typical medium (right) and deep survey field (left).*

Table 5.6-1. ***N-WFI*** **Instrument Parameters**

General		
	Effective Area (cm^2)	~ 8,000 cm^2 @ 1.5 keV
		~ 1,800 cm^2 @ 6.0 keV
	Bandpass	
	Angular Resolution	< 7" HPD solid angle weighted across the 24 arcmin field of view
	Field of View	>24 arc minutes (i.e ± 12)
	Spectral Resolution	60 eV at 0.5 keV 135 eV at 5.9 keV
	Timing Resolution	0.3 sec (imaging mode) 0.3 msec (timing mode)
Optics	**Number of Modules**	**3**
	Focal Length	6 m
	Number of Shells per Module	71
	Shell material	Fused silica
	Outer Shell Diameter	0.96 m
	Inner Shell Diameter	0.30 m
	Inner/Outer Shell Thickness	1.5 mm / 2.6 mm
Detector	**Type**	**CCD**
	Number per Telescope	4
	Pixels per CCD	2048 x 2048
	Pixel size	24 µm
	Depletion depth	75 µm
	Plate scale	1 pixel ~ 0.8"

by the focal plane extends to 30 arcmin off-axis and provides significant increased solid angle coverage.

5.6.2.2 Detectors

The detectors for the *N-WFI* mission are 2 × 2 arrays of X-ray CCDs. The baseline device is an MIT/Lincoln Laboratory CCD similar to those in operation on *Chandra* (launched in 1999) and *Suzaku* (launched in 2005). These are frame transfer devices, with low noise (2–3 electrons rms) performance resulting in nearly Fano-limited energy resolution over the *N-WFI* bandwidth. The CCD operating temperature is -90° C. As with *Chandra*, each array of CCDs is passively cooled via a 0.25 m^2 radiator, and trim heaters are used to adjust the temperature as needed. The CCDs are read out at 3 frames per second (with 2 × 2 pixel on chip binning) and X-ray events are identified by a digital processor that records position, amplitude, and frame time for transmission to the ground and post-facto image reconstruction. The CCDs have directly-deposited thin aluminized optical blocking filters to protect against scattered light. Based on *Chandra* experience, there is a two-position filter wheel in front of each CCD array. The closed position shields the CCDs from low energy protons from solar storms, eliminating this cause of CTE degradation.

5.6.3 Mission Description

The *N-WFI* mission operates in two general modes. As a pointed observatory, it will study specific targets with good angular resolution and high throughput. As a survey telescope, *N-WFI* will map large contiguous areas of the X-ray sky with nearly uniform sensitivity (medium and deep) to conduct a census of X-ray sources (mainly AGN and Clusters/Groups of Galaxies) to create a legacy database for community use. The three-telescope design approach allows for a compact mission (focal length of 6 M) while achieving large effective area up to 6 keV. The wide field prescription and short focal length keeps the focal plane small while covering up to 1 deg^2 solid angle per pointing, yielding

Table 5.6-2. N-WFI Mission Parameters

Orbit	L2
Mission Lifetime	3 year (5 year consumable lifetime)
Launch Vehicle	Atlas V (411)
Overall Mass / Payload Mass	2190 kg / 1173 kg
Total Observatory Power	1144 W
Telemetry rate	44 kbps average (354 kbps high)
Field of Regard	± 30 degree
Attitude Control	2–3"
Mission Class	B

a high grasp for efficient surveying as compared with the standard Wolter-I telescope design.

Each of the independent X-ray Telescope/Instrument assemblies includes an embedded aspect camera that provides the pointing information for that telescope. This arrangement relaxes the mechanical alignment tolerances of the spacecraft to reduce complexity and cost. Specific mission requirements on the spacecraft for *N-WFI* are a relatively relaxed pointing requirement of ~30 arcsec, due to the large field of view, and a pointing knowledge requirement of 2 arcsec. Additionally, the pointing stability (or jitter) requirement is 0.8 arcsec per 0.33 seconds (one CCD pixel per frame time). The data from the three telescopes are properly co-added during ground processing to produce the science data products for the mission. This technique is standard for X-ray missions. The multiple telescopes and focal planes provide for graceful degradation paths in the (unlikely) event of failures. Loss of a single CCD in one telescope would be a 1/12-th loss in total throughput—significant but not fatal.

The science payload mass and power requirements are accommodated by the bus structure design and sizing of the solar arrays. The CCDs are passively cooled using individual small radiators co-located with the focal planes. The spacecraft provides the closeout tubes and optical benches for the mirrors and detectors, as well as a deployable front cover/sunshade as depicted in **Fig. 5.6-3**. The CCDs are passively cooled using individual small radiators co-located with the focal planes. The spacecraft provides the closeout tubes and optical benches for the mirrors and detectors, as well as a deployable front cover/sunshade as depicted in **Fig. 5.6-3**.

Table 5.6-3. *N-WFI* Mission Cost

WBS Element		$M including Reserves
1.0	Project Management	37.1
2.0	Systems Engineering	37.1
3.0	Safety and Mission Assurance	23.2
4.0	Science	
	Science Team	35.3
	GO Grants	30.0
5.0	Payload(s)	
	WFI Instrument	83.3
	FMA	84.5
	FMA GSE/Facilities	16.3
6.0	Spacecraft	279.9
7.0	Mission Operations System (MOS)	50.3
9.0	Ground System(s)	30.2
10.0	Systems Integration and Test	27.8
11.0	Education & Public Outreach	7.4
8.0	Launch Vehicle	210
	Total	952.4

5.6.4 Cost Estimate

The cost estimate for *N-WFI* is broken down by WBS element in **Table 5.6-3**. The assumptions, methodology and reserves approach entering into this estimate are discussed in **Section 5.2**. As with the other notional missions, TRL-6 is assumed for the X-ray mirrors and the focal plane detectors. The total mission cost is $952M. For *N-WFI* Flight Mirror Assembly (FMA) an exception was made from the standard costing methodology. Since producing a MEL for the full shell design was beyond the Study Team resources, the FMA cost used is a best-effort pass-through. The cost is based on a bottoms-up estimate provided by the optics group at INAF/Brera, adjusted by the Study Team as appropriate to meet NASA requirements (e.g., quality assurance, reporting, U.S. labor costs).

5.7 Combined vs. Stand-Alone Missions

Three of the four missions considered by the study team are configured with a single instrument. The incremental cost of adding a second instrument to any

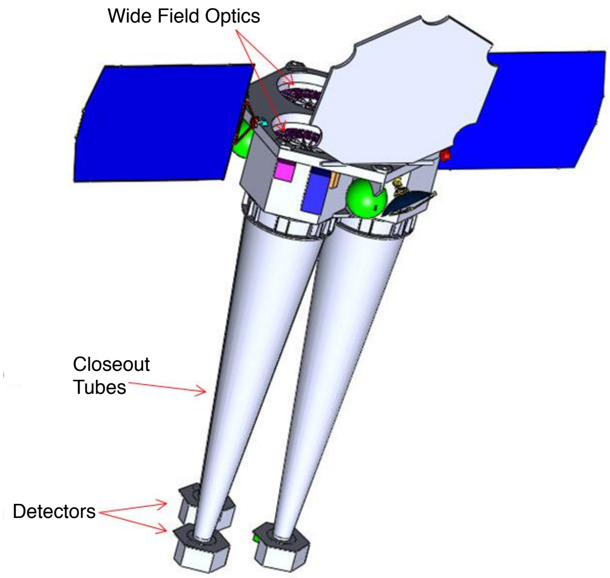

Figure 5.6-3. *N-WFI Observatory Configuration. The mirror assemblies are embedded in the spacecraft with optical bench closeouts providing the support structure for the CCD X-ray cameras and their cooling radiators. The front of the spacecraft has a deployable cover/sunshade to protect the telescopes on the ground and during launch, and when opened provides a sun shield to block stray light from entering the telescopes. The solar panels provide power. Star trackers mounted in the centers of the telescopes provide precision aspect information used for image reconstruction on the ground and for control of the spacecraft pointing.*

of these missions is a small fraction of the mission cost, while achieving a configuration closer to that of *IXO*; the study team investigated several such options. Foremost in these considerations are science, cost and risk.

Science: Adding a second instrument clearly enhances a mission's scientific capability, allowing a broader range of science goals to be fulfilled, and making possible synergistic observations between the two instruments. It also provides opportunities for cross-calibration that, for example, have been crucial in understanding *Chandra*'s calibration over time.

Cost: While the incremental cost of adding an instrument is modest compared with the total mission cost, it is not trivial. The increase of cost depends on the specific instrument added (i.e., whether additional elements such as a focal plane translation stage are required). Optimizing the observing program for a finite mission lifetime could be more challenging than for a single instrument mission, again, depending on which two instruments are chosen. Simply increasing the mission lifetime to fully accommodate the programs of two distinct instruments adds mission operations costs. In addition to the cost of operating a mission longer, requiring a longer lifetime increases reliability requirements, which translates into need for higher quality components and added redundancy. Nonetheless, as the current study has made clear, incorporating the capabilities of two missions into one is dramatically less expensive than developing two separate missions.

Risk: Adding a second instrument provides an important measure of risk reduction in that the mission is not lost if one instrument fails. This reduction must be weighed against the increased cost and technical risk associated with added complexity. The increase of complexity depends on the specific instrument added. For instance, adding a grating spectrometer (with a fixed grating array) to *N-CAL* can be accomplished in a straightforward fashion because the gratings cover only a portion of the mirror area and can be retractable. By contrast, adding a WFI would require incorporation of a focal plane translation stage, and thus be more complex.

The time and resource limitations of the study precluded a comprehensive examination of the many possible instrument combinations. *AXSIO* serves as an example of a well-integrated multiple instrument mission (calorimeter plus grating) and demonstrates that a multiple instrument mission is far more cost effective than two single instrument missions (*N-CAL* + *N-XGS*).

The following additions to the notional missions might be considered. The incremental costs quoted are very rough estimates based on study team past experience. They include the cost of the second instrument plus the expected increase in systems and operations costs.

5.7.1 *N-CAL* plus a Grating Spectrometer

This is effectively the *AXSIO* configuration, but with a smaller mirror.

Science gain: Extends high-resolution spectroscopic capability into the 0.2–1 keV band. Addition of this capability enriches observation of all point-like sources, particularly the search for missing baryons since the grating substantially increases the sensitivity to WHIM absorption features, and neutron star equation of state studies relying on spectroscopy.

Complexity: Mounting a fixed grating behind a portion of the mirror is straightforward but slightly reduces the low energy effective area of the calorimeter instrument. The more complex implementation of a removable grating could be considered, as was done on *AXSIO*. It is straightforward to add a grating camera to the focal plane, without substantial growth of the instrument support plate. For the spacecraft, the maximum data rate approximately doubles, and the overall mission power increases slightly. Integration becomes more complex. The ground system has to handle operation of a second instrument, and data processing and analysis tools must be produced and maintained for two instruments.

Cost: The $63M (with reserves) cost of a grating spectrometer from the *N-XGS* represents a lower limit for the increased cost. The most significant cost contributors from the spacecraft are avionics to handle the higher data rate, solar panel area for the increased power required, increased mission I&T, and ground systems commanding and processing software. The total increase is estimated to be $30M. Thus the estimated cost of *N-CAL* with an added grating spectrometer is ~$1.26B, consistent with it representing a smaller version of *AXSIO*.

5.7.2 *N-CAL* plus a WFI

This entails the addition of a focal plane translation stage to *N-CAL* to swap a WFI for the calorimeter. Note that in contrast the *ATHENA* concept entailed having both the WFI and calorimeter operating simultaneously (each using its own mirror).

Science gain: The primary objective of the *IXO* WFI is restored: deep surveys to locate the earliest black holes ($z \geq 5$), although at least 7 arcsec HPD imaging quality would be needed.

Complexity: The mass and power of the WFI instrument represent incremental increases. The primary source of added complexity is the need for a focal plane translation mechanism to interchange instruments at the mirror focus. Integration of the focal plane becomes more complex. The ground system has to handle operation of a second instrument, and data processing and analysis tools must be produced and maintained for two instruments.

Cost: The cost of one WFI camera is estimated to be $32M with reserves. The most significant additional cost item is the focal plane mechanism; this is estimated to cost $50M. Cost increases in other subsystems are small. Thus the estimated cost of *N-CAL* with an added WFI is $1.3B

5.7.3 *N-WFI* plus a Grating Spectrometer

A fixed grating spectrometer could be added to one (or more) of the three telescopes of the WFI mission, covering a small fraction of the mirror area with a grating configuration similar to that shown in **Fig. 5.3-3**.

Science gain: The objectives associated with the grating and WFI instruments are strongly complementary. Addition of a grating spectrometer makes possible the search for missing baryons and study of the neutron star equation of state via high-resolution spectroscopy. For the most part, the observation programs for the two instruments are disjoint.

Complexity: The three WFI telescopes are no longer identical; the focal plane of one must accommodate the grating detector. The addition of a grating spectrometer to the *N-WFI* mission is similar to adding one to the *N-CAL* mission: design, systems engineering, and I&T become more complex, and the ground system must accommodate the operation of a second instrument. Again, the ground system must accommodate the operation of a second instrument.

Cost: The cost increase will be similar to that of adding a grating spectrometer to the calorimeter notional mission: approximately $93M. Thus the estimated cost of *N-WFI* with an added grating spectrometer is $1.04B.

5.8 Costs and Benefits of Reduced Capability Notional Missions

The costs of the notional missions are a fraction of those of *IXO*, yet even these may exceed the funding available for such missions at the end of the decade. The study team examined whether the costs to NASA can be reduced for each mission and sought paths that NASA might pursue.

There are two approaches to reducing cost that should be pursued before considering reducing a mission's scientific capability. First, all four notional missions represent point designs; there was neither time nor resources for optimization. Considerable savings, possibly 5–10 percent, could be realized by a more thorough and internally consistent design. Additional savings of similar magnitude might be realized by developing a modified Class B, wherein some reliability requirements are relaxed. Second, the simplest way to reduce total cost to NASA is through partnership with a foreign space agency (e.g., ESA or JAXA).

5.8.1 *N-CAL* Reductions

If JAXA were to provide the cooling system (~$100M) and ESA the launch ($140M), the cost to NASA would be below $1B, even considering the added cost of managing international interfaces. If it is necessary to reduce the capability of *N-CAL* to substantially reduce the total cost (i.e., if the approaches discussed above are insufficient), then only a few options are available. These would necessarily involve a sacrifice of performance and thus of science reach. These include reduction of the mirror collecting area and/or angular resolution, narrowing the energy range (by reducing focal length), or making the calorimeter less capable. The possible reductions and their implications for cost and science are captured in **Table 5.8-1**.

Reduced effective area: A 25 percent reduction of the overall mirror area would largely preserve the scientific objectives, with the primary change being the need for longer exposures. If only outer shells are removed, then the black hole science, which relies on the area around 6 keV, is preserved. This reduction saves mass, reduces the mirror fabrication cost and reduces the demands on the spacecraft. A cost reduction of ~$100M is likely to be realized.

Reduced angular resolution: A foil mirror technology as used in *Astro-H* was suggested in the *Extreme Physics Explorer* (*EPE*) RFI response, which potentially reduces mirror costs by nearly an order of magnitude but reduces the angular resolution from 10 arcsec to ~1 arcmin (0.5 Mpc at z~1). Virtually all spatially-resolved spectroscopy would be compromised. In particular, much of the galaxy cluster science is lost. In addition to the reduced cost of the mirror, due to lower requirements on both the precision of mirror components and assembly, there are also reduced requirements on spacecraft systems; these allow for substantial savings. The cost reduction could be as much as $250M.

Reduced focal length: Reducing the focal length of *N-CAL* from 9.5 m to 5 m reduces the mirror mass by ~ 40%, as fewer nested shells are needed to fill the aperture. The primary consequence is a severe reduction of the effective area at 6 keV. This is the approach suggested in the *SAHARA* RFI response, with an effective area at 6 keV of 300 cm^2, comparable to that of the *Astro-H* SXS. Such a reduction would sacrifice some hard X-ray observations beyond the capability of *Astro-H*, most notably temporally-resolved observations of broad Fe-K lines. The reduced mirror cost coupled with the savings associated with a smaller spacecraft could result in cost savings of as much as $250M.

Simplified calorimeter: For uniform size pixels in the calorimeter, one gives up angular resolution near the center of the field of view or reduces the field of view, depending on the pixel size selected. For instance, if a uniform array of 6 arcsec pixels were introduced without reducing the total number of TESs, the field of view would be decreased from 4 arcmin to 3.3 arcmin, and the angular resolution near the center of the field of view would drop from 10 arcsec HPD to 11.5 arcsec. Both of these changes would affect extended object studies (especially higher-z clusters). Some timing capabilities would also be lost in this case, which affects some compact object science, and the spectral resolution will be reduced for bright sources. None of *N-CAL*'s objectives would be seriously compromised. On the other hand, the savings are minimal, $3.5–6.0M over the *N-CAL* design, largely due to simplified layout, and reduced assembly and testing costs.

Cooling System: The *N-CAL* cooling system does not have redundant coolers, as reliability of U.S. cryocoolers is thought to be high. Removal of the redundant control electronics might save $7M, but adds risk, especially for a single-instrument mission. The replacement of the cryocooler with a stored cryogen system reduces hardware costs, but the savings may be offset by the additional servicing required, including through launch preparations and especially complications associated with launch holds and potential recycling of the dewar. In general, stored cryogen dewars have lower reliability (*WIRE*, *NICMOS* Solid N2, *Suzaku*). Savings in going to a cryogen-based system would be approximately $10M.

Table 5.8-1: Possible reductions of *N-CAL*

Reduction Strategy	Estimated Cost Savings	Science Loss
25% effective area reduction	$100M	Exposures increased by 33% (except for black hole physics targets)
Optical quality reduction to 1' HPD (foil mirrors)	$250M	Galaxy cluster science compromised
50 % focal length reduction	$250M	Black hole physics compromised
Uniform size calorimeter array	$3.5M–$6M	Loss in cluster science and compact object timing
Reduced capability cooler	$7M-$10M	Possible loss of extended mission capability

5.8.2 *N-XGS* Reductions

The N-XGS mission was defined in such a way that either of the two grating technologies, CAT or OPF, could be used. This led to inefficiencies in the conceptual design. Substantial cost savings, possibly on the order of $50M–100M, could be realized if the mission were defined using a specific grating technology. If it were necessary to reduce costs further, then the spectrometer would have to be made smaller. Given the fact that the *N-XGS* concept has the minimum capability required to fulfill comprehensively the related *IXO* science objectives over a three-year duration, reducing the instrument would require a decision about which *N-XGS* science objectives to de-emphasize. A low cost data point is provided by the *WHIMEx* RFI response, which presents an Explorer class gratings mission (class D rather than class B) with ~ half the effective area of *N-XGS* but similar bandpass and spectral resolution in low earth orbit (and therefore with lower observing efficiency) at a cost of $350M (without launch vehicle).

5.8.3 *N-WFI* Reductions

The most plausible reduction of the WFI mission is removal of one telescope. The benefit is a reduction by one third of instrument mass, power and telemetry rate, allowing for reductions in the spacecraft systems. The primary consequence is a 33 percent reduction of the net area-exposure product. For a three-year mission lifetime, either the sky area covered by the surveys would be reduced by one third, or the depth of the surveys would be reduced by a third. The estimated cost savings would be $250–300M depending on whether the launch can be on a Falcon 9 instead of an Atlas V.

6 Technology Development for X-ray Astronomy

6.1 Introduction

GAO assessments of large-scale NASA projects conducted in 2011[1] and 2012[2] found patterns of cost and schedule growth (exceeding 14% and eight months, respectively, for 14 major projects excluding *JWST* that were assessed in 2012). The 2011 report points out that cost growth was even larger (averaging 55% for 13 projects) when compared against original projections, rather than against re-baselined costs determined in response to a 2005 statutory requirement. The 2011 assessment attributes some of this growth to a lack of technology maturity at project inception, pointing out that 83%, 71%, and 63% of NASA projects moved into the Implementation Phase with immature technologies at the PDR in 2009, 2010, and 2011, respectively. They state:

> *Our best practices work has shown that a technology readiness level (TRL) of 6—demonstrating a technology as a fully integrated prototype in a relevant environment—is the level of maturity needed to minimize risks for space systems entering product development. For NASA, projects enter development following the project's preliminary design review and confirmation review. NASA's systems engineering policy states that by the preliminary design review a TRL of 6 is desirable prior to integrating a new technology in a project. Technology maturity is a fundamental element of a sound business case, and its absence is a marker for subsequent problems, especially as the project begins more detailed design efforts.[3] … Proceeding into implementation with immature technologies increases a project's risk of cost and schedule overruns.[4]*

1 GAO Report to Congressional Committee: NASA – Assessments of Selected Large-Scale Projects, March 2011, GAO-11-239SP (**http://www.gao.gov/assets/590/589016.pdf**)

2 GAO Report to Congressional Committee: NASA – Assessments of Selected Large-Scale Projects, March 2012, GAO-12-207SP (**http://www.gao.gov/assets/320/316257.pdf**)

3 GAO-11-239SP, p. 15

4 GAO-11-239SP, p. 17

Part of the charter of the X-ray Concepts Study is to evaluate technology needs for future X-ray astronomy missions designed to achieve *IXO* science goals. In developing cost models for the notional missions discussed in **Section 5**, the Study Team assumed that all required technologies were developed to TRL-6 prior to mission start. This requires that technology funding must be made available over the next several years to advance key technologies to TRL-6 in preparation for mission starts. These key technologies can be broken down into two broad topic areas: optical systems including lightweight, high-throughput X-ray mirrors/telescopes and high resolution ($\lambda/\Delta\lambda > 3000$) gratings; and detector systems including calorimeters, their cryogenic support systems, and wide-field imagers.

The Study Team has drawn heavily on the RFI responses to assess program needs for these core technologies. In particular, the cost estimates for technology development were taken from RFI responses. No assessment of underlying assumptions nor independent determinations of costs, such as were made by the MDLs for the notional missions, could be made with the resources available. In the following, the RFI technology responses are summarized in **Section 6.2**, the key technologies needed for the notional missions are addressed in **Section 6.3** (Optics), **Section 6.4** (Gratings), **Section 6.5** (Calorimeters), and **Section 6.6** (Wide Field Silicon Detectors), and the technology development needs for the notional missions are summarized in **Section 6.7**. In **Section 6.8**, longer-range technology needs are discussed.

6.2 RFI Technology Submissions

Fourteen white papers on technology needs were submitted in response to the RFI that either focused on technology needs or addressed them in the context of a notional mission. These papers highlighted technology developments in optics (5), gratings (2), calorimeter detectors (1) and adiabatic demagnetization refrigerators (1), active pixel sensors (1) and fast readout technology to support them (1), extendable optical benches (1), large diamond turning machines (1) and high speed communication (1). These responses are summarized below:

i. **X-ray optics**: Most of the mission concepts for "near term" consideration rely on a few key optics technologies. High resolution, lightweight optics are absolutely critical for future X-ray astronomy missions, but a significant amount of technology development is necessary to achieve resolution equal to or better than 10 arcsec in flight mirror systems. RFI responses in this area include:
   a. Zhang et al. (2011a) propose developments needed to improve slumped glass segments to achieve angular resolution of 5 arcsec. This technology is assumed for a number of the mission concepts submitted in response to the RFI, and is the starting point for several of the arcsec/sub-arcsec technologies proposed. This paper also discusses sub-arcsec resolution using polished monocrystalline Si mirrors.
   b. The *WFXT* mission RFI response submitted by Murray et al. (2011a) describes the development of intermediate mass full-shell mirrors to achieve 5 arcsec angular resolution across a 1-degree field of view by grinding and polishing fused quartz cylinders into polynomial prescriptions that are small deviations from Wolter-I designs.
   c. The *SMART-X* mission RFI response submitted by Vikhlinin et al. (2011) suggests the use of piezoelectric films on slumped glass thin-shell optics to produce adjustable mirrors intended for sub-arcsec imaging.
   d. Ulmer (2011) suggests using magnetostrictive films to modify X-ray mirror surface profiles towards arcsec imaging performance.
   e. Ramsey et al. (2011) suggest differential deposition on mirror surfaces to correct figure errors to levels necessary for arcsec imaging performance.

ii. **Gratings developments**: RFI responses for both Critical-Angle Transmission Gratings (Heilmann et al. 2011c) and Off-Plane Reflection Gratings (McEntaffer et al. 2011b) were submitted. Both approaches have the potential for meeting *IXO*-like resolution and efficiency requirements.

iii. **Calorimeter arrays**: Several mission concept RFI responses rely on cryogenic calorimeter detectors to achieve high spectral resolution in an imaging array. Tremendous progress has been made in this technology over the past decade, but current detectors are limited in pixel size, count rate capability, and array size. Kilbourne et al. (2011) discuss technology developments required to meet the needs of future missions.

iv. **ADR improvements**: Improvements in flight-qualified Adiabatic Demagnetization Refrigerators (ADRs) are needed for the calorimeter instruments. Shirron et al. (2011) submitted an RFI response for development of a five-stage continuous ADR for use on future missions; such a device would permit continuous observations (cf. current designs that require a periodic down-time to recycle the ADR).

v. **Active pixel sensors**: Active pixel sensors (APS) are likely to replace X-ray CCDs in missions that need wide field imaging and have a start date after ~ 2020. A major advantage compared with CCDs is much lower sensitivity to on-orbit radiation damage, and greater readout speed. An RFI submission by Murray et al. (2011b) lays out the technology development requirements for these devices.

vi. **Fast readout technology**: Related to APS detectors is the need to develop technology for very high-speed readout and on-board processing of APS datastreams, which can be in the range of Gbps raw data rates for some proposed applications. Details are given in an RFI submission by Burrows et al. (2011)

vii. **Precision-deployable, stable optical benches**: Extendable optical benches are needed for missions with focal lengths exceeding ~10 m in order to allow the observatory to fit inside the launch shroud, but then extend on orbit to achieve the required focal length. An RFI submission by Danner et al. (2011) discusses the Northrup Grumman approach to this technology. An extendable optical bench is envisioned for a number of mission concepts submitted in response to the RFI. In the near term, however, none of the notional missions requires an extendable optical bench.

viii. **A three-meter-capacity diamond turning machine that can produce large mandrels for glass slumping**: An RFI submission by Cassteves (2011) discusses this technology in detail. However, the consensus of the Study Team is that this machine is not necessary for any of the technologies considered crucial for near-term X-ray astronomy missions.

ix. **High speed communication**: an RFI submission by McIntyre et al. (2011) discusses novel communications technology that permits very high data rates, even at L2 orbits. Since X-ray astronomy missions generally perform a lot of on-board data reduction and generate rather low bit rates, it is the consensus of the Study Team that this technology has low priority for future X-ray astronomy missions.

6.3 Optics Development

Nearly all of the mission concepts submitted in response to the RFI, as well as the four notional missions (*N-CAL*, *N-XGS*, *AXSIO* and *N-WFI*), require lightweight, low-cost per unit area X-ray optics. The initial technology development effort for these kinds of optics was directly funded by the *Con-X* and *IXO* projects, supplemented by APRA or more recently SAT grants. This funding resulted in raising the TRLs to 3 or 4, depending upon the approach.

However, in all cases, substantial development is required to continue to raise these mirror technology readiness levels to TRL-6. At present, optics technology development receives limited support from a few APRA and SAT grants. The current level of funding, substantially below the NWNH recommendations, makes progress to TRL-6 difficult within this decade.

In view of the critical importance of X-ray optics to achieving the scientific goals of *IXO* and PCOS, it is prudent to pursue multiple parallel paths of optics development.

The Study Team identifies two optics technology development efforts required for the notional missions: thermally-formed thin glass segmented mirrors with 10 arcsec or better imaging performance to satisfy the needs of at least three of the notional missions (*N-CAL*, *N-XGS*, and *AXSIO*), and full-shell mirrors with 7 arcsec performance across a wide field for N-WFI. Silicon pore optics developed in Europe has made significant progress towards 10 arcsec performance, and may be viable as a foreign contribution to a U.S.-led mission. However, the discussion here is restricted to technologies that appear to be feasible for development in the U.S. under NASA funding. The mirror developments outlined below are necessary not only for the notional missions, but also to lay the groundwork for the even more capable observatories needed in the next decade.

6.3.1 Slumped Glass Lightweight X-ray Optics

Lightweight optics, which can be densely "nested" (stacked within one another and made confocal) to achieve large collecting areas with moderate mass, are needed for nearly any conceivable future X-ray astronomy mission. The *N-CAL*, *N-XGS*, and *AXSIO* missions require collecting areas of several thousand cm^2 at 1 keV with 10 arcsec half-power diameter (HPD) angular resolution, using segmented slumped glass optics developed for *IXO*. Currently, optics made via thermal forming (or "slumping") of glass sheets can achieve better than 10 arcsec (HPD) for a single pair of primary and secondary mirror segments in flight-like mount (TRL-4). This performance must be maintained or improved for full modules and demonstrated at TRL-6, not only to meet the requirements of the notional missions but also to provide the starting point for future sub-arcsec developments. With slight changes to the optics prescription and improvement in the angular resolution (to 7 arcsec HPD), this approach could also be used for *N-WFI* (**Section 6.3.2**).

The process of making slumped glass mirrors is discussed by Zhang et al. (2011a, 2011b) and illustrated in **Fig. 6.3-1**. Thin (0.4 mm) sheets of glass are placed in contact with a mandrel, and then heated to above the "slumping temperature." At these temperatures, the glass slowly deforms to match the shape of the mandrel. The glass and mandrel are then slowly cooled back to room temperature to avoid introducing thermal stresses. When finished, the glass surface matches that of the mandrel and corresponds to a segment (15 –60 degrees in azimuth) of a full mirror shell. A high-Z coating is applied to provide high X-ray reflectivity, and segments of different radii are nest-

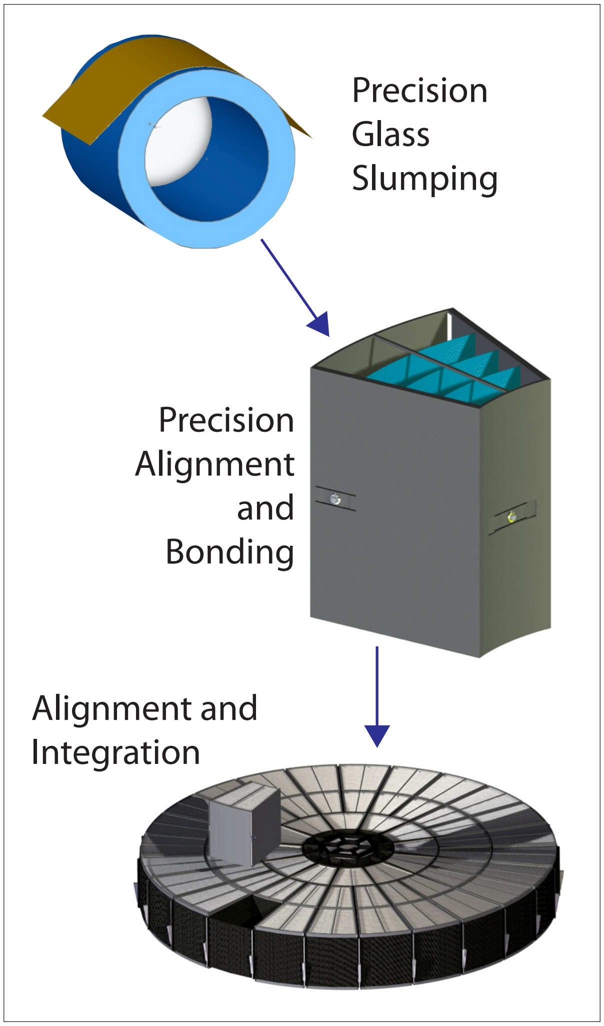

Figure 6.3-1*. Fabrication hierarchy of slumped glass mirrors. Glass segments are slumped onto a precision mandrel to give them the correct shape and are then assembled into modules. Modules are then assembled into full mirrors.*

Figure 6.3-2*. Prototype of a wide-field X-ray telescope fused silica shell, 50 cm in diameter, 20 cm long and 2 mm thick, in the final figuring and polishing machine. The shells are manufactured by Heraeus and ground to a conic approximation. Out-of-roundness corrections are made using a precision lathe prior to the final polishing and figuring.*

ed inside one another to fill the mirror aperture. The thin glass segments are lightweight relative to their collecting area; for example, the *IXO* slumped glass mirror design contained nearly 100 times as many mirror shells as *Chandra*, producing approximately 40 times the collecting area for the same mass as the *Chandra* High Resolution Mirror Assembly (HRMA).

6.3.1.1 Slumped Mirror Technology Development Plan

Technology development for thermally formed mirrors is required in several areas, including reduction of mid-spatial-frequency (0.5–5 cm^{-1}) figure errors, optimization of the release layer designed to prevent the glass segments from bonding to the mandrels during the slumping process, and low stress mounting of flexible mirrors. Several approaches exist for each of these areas (Zhang et al. 2011a), including optimization of the thermal forming temperature profile and development of smoother release layers (Romaine et al. 2010, 2011). Low distortion mirror mounting requires the development of low stress mounting technologies such as adjustable mounts, including the use of force or displacement feedback, and real-time metrology.

The estimated cost for this development program to achieve TRL-5 from the RFI is approximately $3M/year for two years. At least one additional year at this level will be needed to reach TRL-6.

6.3.2 Lightweight Optics for Wide Field Imaging Telescopes

Wide field optics are similar to Wolter-I optics but with small perturbations to their design to reduce off-axis aberrations and enhance resolution across a broader field of view (Burrows et al. 1992). These design changes include slight modifications to the figure of the mirror, optimizing the length of each mirror shell and by slightly offsetting the shells in the axial direction (Conconi et al. 2010). The net result of these small design changes is to flatten the angular resolution response across the field of view, degrading the on-axis resolution somewhat while significantly improving the resolution further off axis where most of the solid angle lies.

The fabrication challenges are essentially identical to regular grazing-incidence optics (the required changes to figure, for example, are at the μm level). An improved (due to the 7 arcsec HPD angular resolution requirement of the *N-WFI* mission) segmented optics approach could be considered. However, a full-shell approach using multiple telescope modules, shorter focal lengths and thicker shells (which can be polished directly) was assumed for the *N-WFI*. This approach has inherently stiffer shells that may also offer benefits in mounting and alignment.

Full-shell wide field optics have been under development at the Osservatorio Astronomico di Brera (OAB) in Italy, which is developing mirror shells made of fused quartz that are first ground to the approximate shape using a precision vertical lathe, and then directly figured and polished on a seven-axis computer-controlled polishing machine (Murray et al. 2011a) (**Fig. 6.3-2**).

6.3.2.1 Wide-Field Mirror Technology Development Plan

Although full-shell wide field prescriptions have not been developed to date in the US, several technologies with prior U.S. development work are amenable to these designs. A development effort similar to the Italian effort could be undertaken using direct polishing of either fused quartz or beryllium, for which a significant amount of expertise has been developed in support of *JWST*. The estimated development cost is roughly $4M/year for four years. An alternative is electroformed replication of nickel alloy mirror shells, which has substantial U.S. expertise. Initial development of nickel shells could be funded at a more modest level ($1–2M over two years) to determine feasibility.

A segmented optics approach would require a funding level of approximately $3M/year for approximately four years to improve the angular resolution to 7 arcsec, implement the polynomial figure prescription, and advance the technology readiness level of a complete mirror module to TRL-6.

6.4 Gratings

Both Critical Angle Transmission (CAT) Gratings and Off-plane Gratings (OPG) are potentially capable of meeting requirements for the notional X-ray spectrometer mission (see **Section 5.4** for more details). Each requires further development and each has its particular challenges: the CAT gratings in fabrication and the OPG in their mounting and alignment. Both approaches are discussed below as it not currently evident which would ultimately provide the better solution.

6.4.1 Critical-Angle Transmission Gratings

CAT gratings are blazed transmission gratings that combine the advantages of transmission (relaxed alignment, figure, and thermal tolerances, low mass, transparent at high energies) and reflection gratings (high broadband efficiency, blazing to higher orders) (Heilmann et al. 2011c). They are fabricated from <110> silicon-on-insulator (SOI) wafers. The architecture of a CAT grating is illustrated in **Fig. 6.4-1**. High-aspect-ratio CAT grating bars (40 nm thick and 6 μm tall) and a Level 1 (L1) support mesh are etched out of the few-μm thin device layer (wafer front side), and a coarser Level 2 (L2) support mesh is etched out of the ~0.5 mm thick handle layer (wafer back side). To date, the sub-nm-smooth grating bar sidewalls required for high efficiency have been achieved with a wet-etch process, but this unfortunately leads to broadened L1 supports and thus loss of area. A competing etch process, reactive-ion etching (DRIE), can minimize the L1 and L2 mesh areas, but this process results in rough sidewalls.

6.4.1.1 CAT Gratings Technology Development Plan

The current TRL for the CAT gratings is estimated to be 3. Among the tasks required to reach TRL-6 are refinement of the overall fabrication process to improve grating quality, throughput, and yield. In addition, improvements in the mechanical design are needed to ruggedize them for flight and testing must

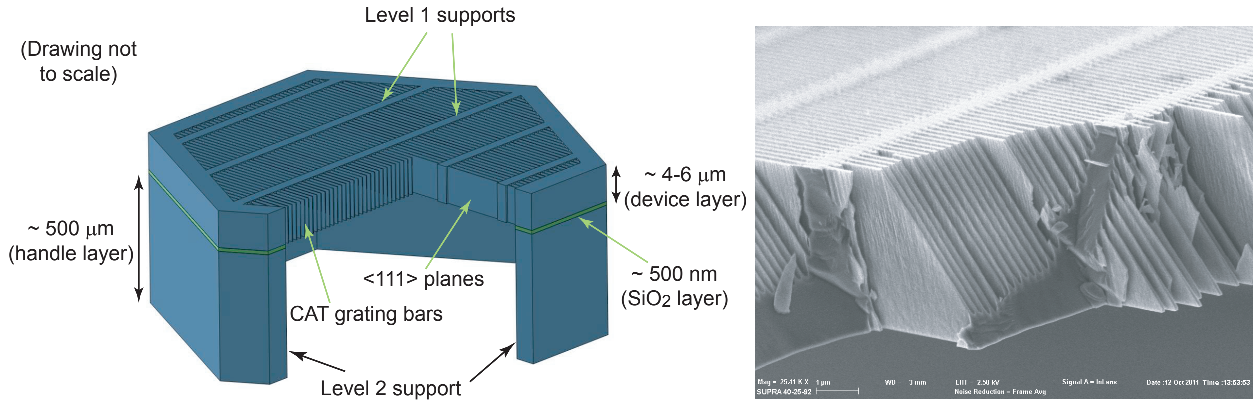

Figure 6.4-1*. Left: CAT grating configuration. The hexagon shown spans about 2 mm and contains a hierarchical structure to support the CAT grating bars. The bars are 40 nm thick and 4–6 μm tall and the bar period is 200 nm. A single CAT grating element, 60 × 60 mm in size, is a monolithic structure containing an array of such hexagonal cells fabricated from a silicon-on-insulator wafer. An array of elements is assembled to provide the full collecting area required by the observatory. Right: Cleaved section from a recently fabricated 25 mm CAT grating with the full structural complexity of a full-sized CAT grating, showing CAT gratings and supports etched all the way through the SOI device layer.*

be carried out on prototypes to confirm their ability to withstand launch and operational environments. The overall cost for CAT grating development to TRL-6 is estimated to be ~$8M over three years.

6.4.2 Off-Plane Gratings

Off-plane gratings are reflection gratings blazed at high orders to obtain high resolution (> 3000). The grating grooves are arranged to lie nearly parallel to the X-ray beam, diffracting in a direction out of the plane of the X-ray beam and grating normal. Gratings are fabricated by replication from a master grating produced by industrial processes using holographic imaging and ion etching to achieve high density radial grooves (5500 grooves/mm) blazed at 18–24°. A large array of thin-substrate gratings configured for a sounding rocket flight is shown in **Fig. 6.4-2**. The OPG gratings that were being developed for *IXO* are currently at TRL-3 (McEntaffer et al. 2011b).

6.4.2.1 OPG Technology Development Plan

Achieving a spectral resolution of 3000 requires that the substrates remain flat and aligned to a few arcsec level in flight. Furthermore, they must be densely packed behind the mirror arrays, so they must be thin (typically a few mm) and light. While the gratings are easily replicated onto thin substrates, technology development is needed to ensure that the flatness and alignment tolerances are met in an array of thin gratings. Further development work is also needed to achieve higher groove densities and improved groove profiles, and in the metrology needed to verify these. X-ray tests of masters and replicas must be carried out to confirm efficiency and spectral resolution. As with the CAT gratings, environmental tests must be carried out on prototype units followed by X-ray tests to verify expected on-orbit performance.

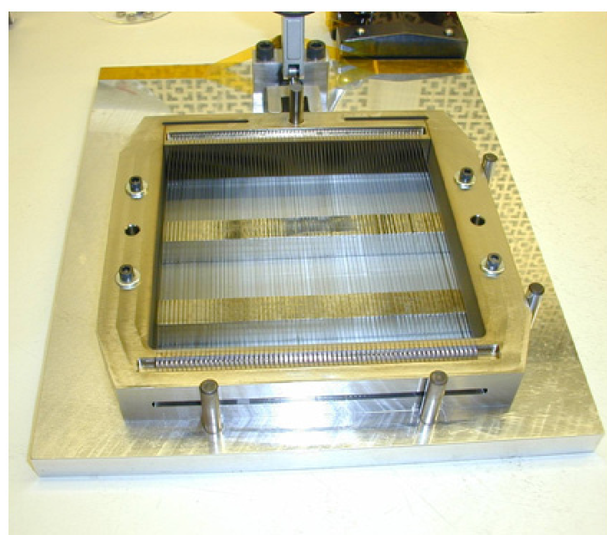

Figure 6.4-2*. This array of 104 off-plane gratings replicated onto 125 μm thick nickel substrates and tensioned flat has flown into space three times on the EXOS spectroscopy sounding rocket.*

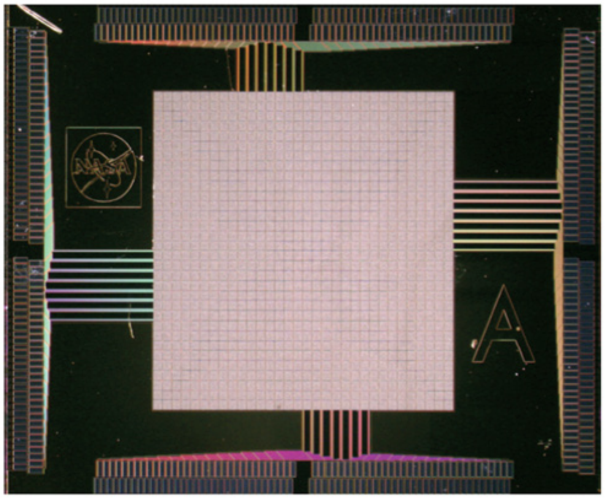

Figure 6.5-1. *Prototype 32 x 32 TES array developed for IXO/XMS.*

The overall cost for the OPG grating development program is estimated to be ~$3.5M over three years.

6.5 Calorimeters

The ability to perform broad-band imaging X-ray spectroscopy with high spectral resolution and moderate angular resolution was an essential capability of the mission concept for the *International X-ray Observatory*. Superconducting transition-edge sensor (TES) array technology was the basis of the *IXO* X-ray Microcalorimeter Spectrometer (XMS) instrument. Existing programs have brought the XMS detector system to TRL-4 and have laid much of the foundation for a TRL-5 demonstration of a 32 × 32 TES array readout via time-division multiplexing (see **Fig. 6.5-5**). Technology funding is essential to push this core technology toward TRL-6 over the next few years, and to develop advanced technologies that enable improvements in the scientific return (Kilbourne et al. 2011).

6.5.1 Calorimeter Technology Development Plan

The core technology areas that need to be developed are independent of the detailed requirements of any particular mission concept. The XMS detector system technology development roadmap developed for *IXO* consists of major milestones tied to significant demonstrations of the integrated detectors and readout electronics, each fed by supporting demonstrations of the detector and superconducting electronics components separately. These developments are relevant to several of the notional missions, and consist of gradual improvements in 32 × 32 pixel arrays (300 μm pixels) to multiplex ever larger numbers of the pixels while maintaining < 3 eV resolution at 6 keV. In parallel, developments of breadboard assemblies are needed to demonstrate the capability to handle the required number of signal wires while maintaining the necessary thermal environment and providing the necessary magnetic shielding. Also, developments of prototype particle veto systems on scales appropriate for full arrays are required.

These core technologies are essential for the most basic 32 × 32 pixel calorimeter array, in which all pixels have the same size. The *AXSIO* and *N-CAL* notional missions assume more complex calorimeter arrays, with multiple pixel sizes and a configuration designed to optimize the science return with a given number of TES sensors. Thus several additional technologies must be developed in parallel with the core technologies to realize these designs. These include fabrication of arrays with multiple pixel sizes (smaller, 75 μm pixels on-axis, surrounded by 300 μm pixels to obtain a larger field of view), and development of means of building arrays that are too large to measure the signal on every pixel directly. For these, a “hydra” approach has several detector pixels (up to nine) connected to a single output signal. Implementing different thermal coefficients between the pixels creates different rise times for photons landing on different pixels, allowing the absorbing pixel to be identified. Hydra designs need to be optimized for energy resolution in a pixel size-scale commensurate with the requirements of the target mission. Demonstration of the energy resolution of up to 32 multiplexed hydras is needed, while being able to identify the pixel of the incident photon for energies as low as 150 eV.

The estimated development cost of these calorimeter technologies for *AXSIO* and *N-CAL* is $20M over six years.

6.6 Wide-Field Silicon Imaging Detectors

At the detector level, wide field imaging needs are addressed by the size and number of pixels in the focal plane. The specific needs depend on the field of view and plate scale. With a 6 m focal length (*N-WFI*), the focal plane for a 1-degree diameter field of view would be 10.4 cm across. This is far beyond the capability of expected developments in calorimeter arrays over the next decade, leaving Si-based imaging arrays as the only viable detector option. Si-based detectors are sufficient even in the long range for a broad class of applications where very high spectral resolution is not required. They are less complex and cost less than large, cryogenic calorimeter arrays.

The typical pixel size for scientific X-ray CCDs is about 25 μm (with a range from ~5 μm to ~50 μm). Current "standard" (*Chandra* and *Suzaku*) X-ray frame transfer CCDs have been built with 1k × 1k pixels and can be laid out in a 2 × 2 array to cover about 5 cm × 5 cm. For the 1-degree field of view discussed above, a mosaic of four frame-transfer CCDs with 2k × 2k pixels would be needed. These are well within the current state-of-the-art for CCD manufacturers, but would need to be built and tested.

An investment of $2M would be needed to achieve TRL-6.[5]

6.7 *Summary of Technology Needs for the Near-Term Notional Missions*

The key technologies required by the four notional missions, *N-CAL*, *N-XGS*, *AXSIO,* and *N-WFI*, are summarized here. If funding is expected to be available to start one of these missions within this decade, then the key technology funding must be in place almost immediately. The key technologies are listed below, and **Table 6.7-1** gives a summary of the development cost estimates. These are rough estimates based primarily on the RFI responses supplemented by information obtained by the Study Team. These estimates are minimal in that they assume a single development effort, not a parallel one.

A. ***N-CAL***: a calorimeter-only mission, requires development of segmented, slumped-glass, 10 arcsec optics and 1840 pixel calorimeter arrays with 1060 TES output signals. Estimated development cost to TRL-6 is $29 M over six years.

B. ***N-XGS***: a gratings-only mission, requires development of segmented, slumped-glass, 10 arcsec optics and high resolution gratings, as well as enhancements in CCD detector readout speed. Both OPG and CAT gratings should be developed with a competitive down-select at an appropriate time in the mission schedule. Estimated development cost to TRL-6 is ~$24 M over three years.

C. ***AXSIO***: a spectroscopy mission with a combination of a calorimeter and a grating, *AXSIO* requires the combination of technology development needed for *N-CAL* and *N-XGS*. Estimated cost for TRL-6 development is $44 M over six years (less than the sum of *N-CAL* and *N-XGS* because both need the same optics development).

D. ***N-WFI***: a wide field imaging mission, requires development of 7 arcsec wide-field optics. NASA may wish to hold a competitive down-select between segmented optics and full-shell approaches. Estimated development cost to TRL-6 is $18 M over five years.

6.7.1 Technology Cost Estimates

Simultaneously pursuing the technology development for all of the notional missions would cost $57M. Note that the total cost column in **Table 6.7-1** sums to $61M since there are overlaps in the technology development needed for the individual missions (most notably in X-ray optics). These numbers are grassroots values, derived from the RFI submissions, and thus likely to be optimistic. Thus the values in **Table 6.7-1** are almost certainly underestimates. Moreover, a prudent technology development program aimed at minimizing risk warrants parallel efforts in key areas. It should be noted that NWNH recommended an expenditure of $200M during this decade to develop the same technologies for *IXO*. A reasonable range of actual development needs is probably between the estimate above and that of NWNH. While it is true that the technology development cost can be reduced if NASA selects a mission concept earlier rather than later, all these technologies are foreseen to play a role in future X-ray missions, on all size scales (from suborbital to Explorer and facility-class missions). Given the projected budgets for the next few years, the funding for X-ray technology is woefully inadequate.

6.8 *Longer-Term Technology Needs*

Although it is not clear at this point exactly what NASA's next X-ray observatory will look like, the future of X-ray astronomy is critically dependent on continued technological advances in optics and detectors. Of particular long-term importance are lightweight sub-arcsec optics, megapixel calorimeter arrays

5 This cost was estimated post-RFI submission

Table 6.7-1. Notional Mission Estimated Technology Development Costs

Technology	Current Performance	Goal	Applicable Missions	Cost per Year (M$)	# Years	Total Cost (M$)	Source
Calorimeters	16 pixels, TRL-4	1840 pixels	*AXSIO*, *N-CAL*	3.3	6	20	Kilbourne
Slumped glass optics	8.5", TRL-4	10"	*AXSIO*, *N-CAL*, *N-XGS*	3	3	9	Zhang, CST
Wide field optics	17", TRL-4	7"	*N-WFI*	4	4	16	CST
CAT gratings	TRL-3	TRL-6	*AXSIO*, *N-XGS*	2.7	3	8	CST/IXO Tech. Dev. Plan
OPG gratings	TRL-3	TRL-6	*AXSIO*, *N-XGS*	1	3	3	McEntaffer
X-ray CCDs for *N-WFI*	1k × 1k, TRL-9	2k × 2k	*N-WFI*	1	2	2	CST
X-ray CCDs for *N-XGS*	0.3 Hz frame rate	15 Hz frame rate	*N-WFI*, *AXSIO*	1.5	2	3	CST
Total				**16.5**		**61**	

and 10^7 pixel APS arrays. The NRC's newly released NASA Space Technology Roadmap states: "*Further development in grazing-incidence optical systems to improve spatial resolution by at least a factor of ten, without increasing mass per unit area, is critical for future X-ray astronomy missions. … Sub-kelvin coolers and high-sensitivity detectors are very high priority for future space astronomy missions and are strongly linked to the top technical challenge of developing a new generation of lower-cost astronomical telescopes.*"[6] Therefore, technology developments for near-term objectives should be funded in parallel with those needed for long-term objectives to ensure that a highly capable X-ray observatory can be presented to the 2020 Decadal Survey. Depending on the level of funding available for the mission and for technology developments, such a mission could include sub-arcsec imaging, large calorimeter arrays, and/or 10^7 pixel APS arrays.

6.8.1 Sub-arcsecond Optics

Breakthrough optics technology is required to produce lightweight mirrors with the imaging performance of *Chandra* and a manageable production cost. Several technologies discussed in RFI responses may be able to achieve this goal, including adjustable optics (Vikhlinin et al. 2011), magnetostrictive films (Ulmer 2011), differential coating deposition (Ramsey et al. 2011), and single crystal silicon mirrors (Zhang et al. 2011a).

Adjustable optics provides a possible game-changing technology for attaining and maintaining figure control of lightweight grazing incidence mirrors. The approach utilizes thin piezoelectric films deposited on the back of thin mirror segments (e.g., slumped glass optics) followed by an array of platinum electrodes that define cm-sized cells (see **Fig. 6.8-1**); application of a DC voltage to a given piezo cell develops a strain that deforms the mirror. By appropriately adjusting the voltage to each cell, the sum of the deformations can potentially compensate for figure errors to achieve sub-arcsec performance. Unlike conventional adaptive optics, these mirrors would be adjusted infrequently.

Magnetostrictive films use a similar approach (Ulmer 2011), but here the material strain is produced magnetically. A "magnetic smart material" film is sputtered onto a permanent magnetic material, and a position-dependent magnetic field is applied through a magnetic write head in order to deform the surface in a way that minimizes deviations from the desired figure.

6 NASA Space Technology Roadmap, "NASA Space Technology Roadmaps and Prioirites: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, Technical Area TA08, "Science Instruments, Observatories, and Sensor Systems". National Academies Press (2012)

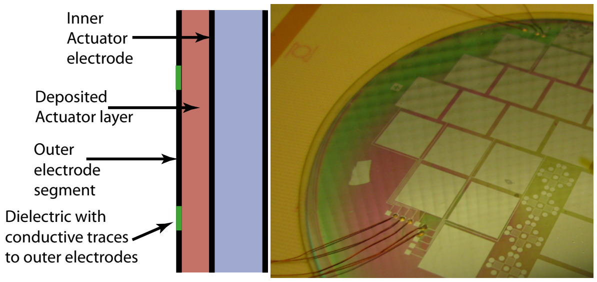

Figure 6.8-1. Left: Cross-sectional schematic of the PZT cell structure. Right: A photo of a flat test mirror with deposited PZT film and a pattern of the independently addressable electrodes.

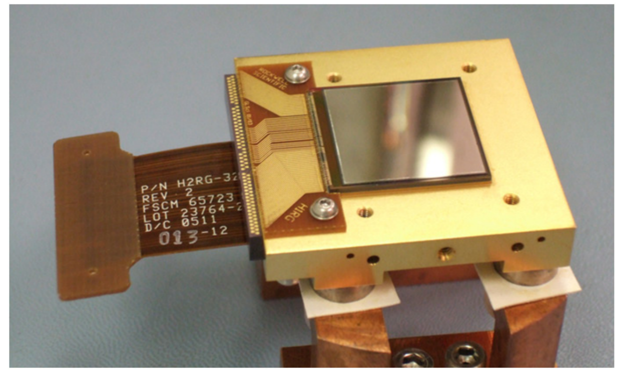

Figure 6.8-2*. 1024 x 1024 pixel hybrid CMOS X-ray APS detector developed by PSU/Teledyne. Devices using different technologies are being developed by MIT/Lincoln Lab and JHU/Sarnoff.*

An alternative technology to achieve high resolution is differential deposition. This technology is basically the inverse of computer controlled polishing. Rather than removing material selectively via a polishing lap, material such as nickel is vacuum deposited under computer control to improve the surface figure. Preliminary, proof-of-concept experiments have shown that slope errors can be at least partially corrected in test mirrors (Kilaru et al. 2011).

Single crystal silicon mirrors have been proposed as a substrate that could be polished directly to arcsec figure accuracy (Zhang et al. 2011a). The attraction of this material is that it has very low internal stresses and thus optics can be lightweighted without losing their figure.

Fabrication of lightweight sub-arcsec X-ray optics is a challenging technical endeavor, and none of the approaches described above is guaranteed to work. Specifically soliciting and funding multiple approaches at levels sufficient to allow rapid progress for the rest of this decade would maximize the chances of success. While some of these approaches assume the availability of precision slumped glass substrates, an order of magnitude estimate of the additional overall development costs can be projected from the RFI responses. This investment is approximately $10M/year for 7–8 years.

6.8.2 Megapixel Calorimeter Arrays and Associated Cryocoolers

The ultimate X-ray imager is a detector with spatial resolution adequate to support sub-arcsec imaging with sub-eV energy resolution, high quantum efficiency over a broad energy band, fast timing, and high count rate capability. Calorimeters currently provide the best approach to ideal performance, but are limited to small arrays with current technology. It is essential to improve multiplexing capabilities, with a goal of eventually achieving megapixel calorimeter arrays to provide reasonably wide fields of view with excellent energy resolution. This will require substantial developments in the area of multiplexing the signals from the pixels, as discussed by Kilbourne et al (2011). Readouts based on microwave multiplexing appear at this time to offer the best path to megapixel arrays. Several versions of this type of multiplexer exist, and the U.S. leads this effort, but significant additional development is needed. It is estimated that an investment of $5M/year for a decade or more will be necessary to achieve this goal.

To support the advanced calorimeters, similarly advanced cryocoolers are needed. These must be able to cope with much larger heat loads but within manageable cryocooler masses. Ideally, they will also be able to operate continuously (current systems must be "recycled" to offload heat that has built up) to provide the maximum observing efficiency. Continuous Adiabatic Demagnetization Refrigerators (CADR) appear to be capable of achieving these goals, providing one to two orders of magnitude higher cooling power per unit mass compared with current systems. A path for development of a flight scale, TRL-6 five-stage CADR system was presented by Shirron (2011). The cost for this was estimated in this RFI to be $1.3 M/year for three years.

6.8.3 Active Pixel Sensors

Active Pixel Sensors (APS) can potentially replace CCDs as future X-ray detectors. The APS has an amplifier for each pixel, as opposed to a CCD that typically has one or two amplifiers through which all the pixels must be read, and this offers substantial benefits in terms of readout speed and radiation hardness (since charges are not clocked over large distances). There are several design approaches for these detectors being pursued by different groups. The most advanced of these is the Depleted Field Effect Transistor (DepFET)(Struder et al. 2011) devices being developed at the Max Planck Institute's Semiconductor Laboratory in Germany. These devices have ultra-low noise levels and deep depletion depths, but the current pixel sizes (75–100 μm pixels in 256 × 256 arrays) are much larger than typical CCDs and are not appropriate for sub-arcsec imaging. U.S. efforts are concentrated on finer pixels.

APS detectors with large arrays of fine pixels are currently at the TRL-2 to TRL-3 and need substantial development as discussed in Murray et al. (2011b). It is estimated in this RFI response, that funding at the $3M/year level for about a decade will be necessary to realize devices with >10^7-pixels.

6.8.4 Longer-Term Technology Cost Summary

We note that the total technology development cost, if all of these items discussed in **Section 6.8** are pursued simultaneously, is about $18M per year for the next ~ decade, with a runout total of $170M in line with the recommended funding level of the Astro 2010 report ($200M) when near-term technology goals are included.[7]

7 Astro2010 Decadal Report, New Worlds, New Horizons, p. 214.

7 Relationship of the Notional Missions to the 2010 Science Plan for NASA's Science Mission Directorate

The IXO science goals are highly regarded both by NASA and by the community, as reflected in *New Worlds, New Horizons*. The challenge has been to achieve those science goals in a timely fashion and at an affordable cost, so here we emphasize suggestions from the "2010 Science Plan For NASA's Science Mission Directorate," although we raise additional important issues.

The opportunity for addressing leading astrophysical problems is usually driven by realizing large gains in observing capabilities, such as sensitivity or spectral resolution. In turn, such gains are made through technological advances, often in a particular wavelength region. History shows us these technology developments usually take decades of devoted effort, as evidenced by the development of X-ray CCDs and the *Chandra* optics. Consequently, a major mission about every two decades produces watershed science and transforms a field. For example, *Chandra* was launched about 20 years after the *Einstein Observatory* and *Fermi* was launched 20 years after *CGRO*. This success can be repeated. The rate of technology development in calorimeters and lightweight optics enables a mission in the 2020 time frame that will make enormous inroads for high energy astrophysics.

With the ESA decision not to select *ATHENA*, a mission with a calorimeter is needed because it can accomplish the largest number of the *IXO* science goals—goals that will not be achieved by any other planned mission. This could be a stand-alone mission (*N-CAL*), or it might include a second instrument, since the cost of adding a second instrument (e.g., *AX-SIO*) is small compared to flying a separate mission.

The MDL estimated cost of such an observatory is about $1.1–1.5B, but this can be reduced through engineering optimization, foreign contributions, or/and modest descoping, as discussed in Section 5.8. On the topic of cost containment, the "2010 Science Plan" offers two important suggestions. One suggestion is to "mature technologies through focused efforts prior to committing to implement missions that need them." Along these lines, we sought to identify the relevant technologies, and we find that the current NASA investment needs to be increased. Not only is it necessary to advance the technologies to TRL-6 (as assumed in this study), it is important to produce working instruments that are used, such as in suborbital flights (as has been done for calorimeters). This is a key strategy for remaining on budget and schedule, also identified in the GAO analysis of NASA missions (above). The necessary technology challenges are not daunting, so TRL-6 can be achieved by FY2017, a possible start date outlined by the NASA Astrophysics Division Director at the June 2012 CAA meeting.

Another suggestion from the "2010 Science Plan" is to "partner with other nations' space agencies to pursue common goals." This can cut costs to NASA, as Japan and the European nations have been developing relevant technologies. In past successful collaborations, one agency leads the project, with minority contributions from collaborators (e.g., *HST*, *Planck*, *GALEX*, *XMM*), so similar contributions to a X-ray mission could reduce NASA mission costs by ~10–30%.

There are major scientific issues beyond the IXO science goals that can only be addressed with a next-generation mission. For example, the study team envisions a mission having lightweight optics with sub-arcsec angular resolution and a large collecting area for imaging and spectroscopy to study the high-z Universe and extend our capabilities in almost every area of astrophysics research. One conceptual implementation was discussed in the *SMART-X* RFI response, but the path to success is challenging and various competing technologies will need to be developed and evaluated. The study team supports investment in key technologies for such a mission and in parallel with the technology support identified here for the notional missions. Moreover, the possibility of such a "vision" mission points out the need for long-term planning of high energy astrophysics within NASA, an activity that we hope NASA will continue with community input.

Appendix A. References

1. Astro2010 Decadal Report, New Worlds, New Horizons, p. 214.
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Appendix B. Acronyms

AANM	Astronomy and Astrophysics in the New Millennium
ACIS	Advanced CCD Imaging Spectrometer
ADR	Adiabatic Demagnetization Refrigerator
AEGIS	Astrophysics Experiment for Grating and Imaging Spectroscopy
AGN	Active Galactic Nucleus or Active Galactic Nuclei
APRA	Astronomy and Physics Research and Analysis
APS	Active Pixel Sensor
ATHENA	Advanced Telescope for High ENergy Astrophysics
ATK	Alliant Techsystems
AXAF	Advanced X-ray Astrophysics Facility
AXSIO	Advanced X-ray Spectroscopic Imaging Observatory
AXTAR	Advanced X-ray Timing Array
BEPAC	Beyond Einstein Program Assessment Committee
BEST	Black Hole Evolution and Space Time
BHC	Black hole candidate
BHT	Black Hole Tracker
C	Carbon
CADR	Continuous Adiabatic Demagnetization Refrigeratos
CAT	Critical-Angle Transmission
CCD	Charge Coupled Device
CfA	Center for Astrophysics
CGRO	Compton Gamma Ray Observatory
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial Off-the-Shelf
CST	Community Science Team
CTE	Charge Transfer Efficiency
CXO	Chandra X-ray Observatory
DepFET	Depleted Field Effect Transistor
DRIE	Dry Reaction Ion Etching
DSN	Deep Space Network
EEE	Electric, Electronic and, Electromechanical
EELV	Evolved Expendable Launch Vehicle
EJSM	European Jupiter System Mission
EOS	Electromagnetic Observations from Space
EOS	Equation of State
EPE	Extreme Physics Explorer
EREXS	Epoch of Reionization Energetic X-ray Survey
eROSITA	extended ROentgen Survey with an Imaging Telescope Array
ESA	European Space Agency
ESTEC	ESA Technology Center
EXOS	Extended X-ray Off-plane Spectrometer
FMA	Flight Mirror Assembly
FOV	Field of View
FWHM	Full-Width Half-Maximum
GALEX	Galaxy Evolution Explorer
GAO	Government Accountability Office
GBH	Galactic Black Hole

Gbps	Gigabits per second
GEMS	Gravity and Extreme Magnetism Small Explorer
GR	General Relativity
GSFC	Goddard Space Flight Center
H	Hydrogen
HETG	High Energy Transmission Grating
HEX-P	High Energy X-ray Probe
HPD	Half-Power Diameter
HRC	High Resolution Camera
HRMA	High Resolution Mirror Assembly
HST	Hubble Space Telescope
HTRS	High Timing Resolution Spectrometer
HXI	Hard X-ray Imager
HXT	Hard X-ray Telescope
I&T	Integration & Test
IDL	Instrument Design Lab
IGM	Intergalactic Medium
INAF	Instituto Nazionale di Astrofisica
ISM	Interstellar Medium
IXO	International X-ray Observatory
JAXA	Japan Aerospace Exploration Agency
JHU	Johns Hopkins University
JUICE	Jupiter Icy Moon Explorer
JWST	James Webb Space Telescope
LAXPC	Large Area X-ray Proportional Counter
LETG	Low Energy Transmission Grating
LISA	Laser Interferometer Space Antenna
LOFT	Large Observatory For X-ray Timing
LSF	Line Spread Function
M	Mass
MDL	Mission Design Laboratory
MEL	Master Equipment List
MIT	Massachusetts Institute of Technology
MOS	Metal Oxide Semiconductor
MOS	Mission Operations System
MSFC	Marshall Space Flight Center
N	Nitrogen
N-CAL	Notional Calorimeter Mission
NICER	Neutron Star Interior Composition Explorer
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NRC	National Research Council
NS	Neutron Star
NuSTAR	Nuclear Spectroscopic Telescope Array
N-WFI	Notional Wide-Field Imager
NWNH	“New Worlds, New Horizons”
N-XGS	Notional X-Ray Gratings Spectrometer
O	Oxygen
OAB	Osservatorio Astronomico di Brera
OP	Off-Plane

OPG	Off-plane Grating
PAG	Program Analysis Group
PCOS	Physics of the Cosmos
PDR	Preliminary Design Review
PhysPAG	Physics of the Cosmos Program Analysis Group
PN	Positive Negative
PRICE-H	Parametric Review of Information for Costing and Evaluation for Hardware
PSA	Point Source Array
PSF	Point Spread Function
PSU	Penn State University
QA	Quality Assurance
QPO	Quasi Periodic Oscillation
R	Radius
RFI	Request for Information
RGS	Reflection Grating Spectrometer
SAA	South Atlantic Anomaly
SAG	Science Analysis Group
SAHARA	Spectral Analysis with High Angular Resolution Astronomy
SAO	Smithsonian Astrophysical Observatory
SAT	Strategic Astrophysics
SCG	Science Coordination Group
SMA	Safety and Mission Assurance
SMART-X	"Square Meter, Arcsecond-Resolution X-ray Telescope"
SMBH	Stellar Mass Black Hole
SMEX	Small Explorer program
SOI	Silicon-on-Insulator
SQUID	Superconducting Quantum Interface Device
SXS	Soft X-ray Spectrometer
TES	Transition Edge Sensor
TOO	Target of Opportunity
TRL	Technology Readiness Level (see **http://www.hq.nasa.gov/office/codeq/trl/trl.pdf**)
WBS	Work Breakdown Structure
WFI	Wide-Field Imager
WFXIS	Wide Field X-ray Imaging Spectrometer
WFXT	Wide Field X-Ray Telescope
WHIM	Warm-Hot Intergalactic Medium
WHIMex	Warm-Hot Intergalactic Medium Explorer
WIRE	Wide Field Infrared Explorer
XEUS	X-ray Evolving Universe Spectroscopy
XGS	X-Ray Gratings Spectrometer
XIS	X-ray Imaging Spectrometer
XMM	X-ray Multi-Mirror
XMS	X-ray Microcalorimeter Spectrometer
XPOL	X-ray Polarimeter

Appendix C. RFI Solicitation

REQUEST FOR INFORMATION (RFI)

Concepts for the Next NASA X-ray Astronomy Mission

General Information

Solicitation Number:	NNH11ZDA018L
Release Date:	September 13, 2011
Response Date:	October 28, 2011
Recovery and Reinvestment Act Action:	No
Classification Code:	A -- Research and Development
Issued by:	Science Mission Directorate

Description

The National Aeronautics and Space Administration (NASA) and its Physics of the Cosmos (PCOS) Program is soliciting information through this Request for Information (RFI) pertaining to potential X-Ray astronomy missions. Specifically, NASA is seeking information that can be used to develop concepts that meet some or all of the scientific objectives of the International X-ray Observatory (IXO) (Table 1). Information being sought includes relevant mission concepts, instrument concepts, enabling technologies, or any aspect of flight, ground or launch systems architecture.

In accordance with FAR 15.201(e), the information requested is for planning purposes only and is NOT intended to bind the Government. This RFI is not expected to lead to a future procurement.

Background

The future mission portfolio of NASA's Astrophysics Division is constrained by budgetary resources. The Division is making a concerted effort to control cost growth of future strategic missions through a combination of improved early cost estimation, a more conservative posture of cost reserves, and a reinvigorated technology development program.

Since termination of the NASA/ESA partnership X-ray mission, IXO, NASA's PCOS Program is developing alternative plans to address high priority IXO scientific objectives described in the 2010 Astrophysics Decadal Survey, "New Worlds, New Horizons" (NWNH) (NRC 2010, http://www.nap.edu/catalog/12951.html).

The PCOS Program Office will work with the science community to develop new X-ray astronomy mission concepts satisfying some or all of the scientific objectives listed in Table 1.

Such scenarios might include one or more observatories. These scenarios will be presented to the National Academy of Sciences Committee on Astronomy and Astrophysics (CAA) for consideration. Recommendations from the CAA will subsequently be used to guide detailed development of scientific, technical, and cost information for some or all of these X-Ray mission concepts. Data from these concept studies will also be used to assess future technology needs for the Astrophysics Division. Information from the technology assessment will also be provided to the CAA.

This Request for Information (RFI) is the first step in this process. Through this RFI, NASA is seeking information relevant to an X-ray astronomy mission concept or mission concepts that will satisfy some or all the scientific objectives listed in Table 1. The RFI also requests standalone instrument concepts as well as relevant key enabling technologies for such missions or instruments. Mission concepts should range in cost from ~ $300M to $2,000M in FY12 dollars.

Science Objectives

NWNH identified a number of high priority science objectives that IXO could fulfill. These objectives are listed in Table 1. Also listed in Table 1, for reference, are the performance requirements of IXO driven by these objectives. More detailed information about IXO, its science objectives and its proposed instrumentation and configuration can be found at **http://ixo.gsfc.nasa.gov/.**

Table 1: Primary IXO Science Objectives		
Science Question	Measurement	Key IXO performance requirements
What happens close to a black hole?	Time resolved high resolution spectroscopy of the relativistically broadened features in the X-ray spectra of stellar mass and supermassive black holes	Spectral resolution of 2.5 eV at 6 keV; effective area > 0.65 m^2 at 6 keV. Spectral resolution of 150 eV at 30 keV.
When and how did super-massive black holes grow?	Measure the spin in >300 supermassive black holes within z < 0.2; distribution of spins determines whether black holes grow primarily via accretion or mergers.	Spectral resolution of 2.5 eV at 6 keV; effective area > 0.65 m^2 at 6 keV.

How does large scale structure evolve?	(i.) Find and characterize the missing baryons by performing high resolution absorption line spectroscopy of the WHIM over many lines of sight using AGN as illumination sources. (ii.) Measure the growth of cosmic structure and the evolution of the elements by measuring the mass and composition of ~500 clusters of galaxies at redshift < 2	(i.) Spectral resolving power of >3000 combined with effective area > 1500 cm^2 in 0.3-1.0 keV band. (ii.) Imaging spectroscopy with spectral resolution of 2.5 eV and 5 arcsec angular resolution across 0.3-7.0 keV band, and 5 arcmin field of view. Effective area of 3 m^2 at 1.25 keV and $0.65m^2$ at 6 keV.
What is the connection between supermassive black hole formation and evolution of large scale structure (i.e., cosmic feedback)?	Measure the metallicity and velocity structure of hot gas in galaxies and clusters.	Imaging spectroscopy with spectral resolution of 2.5 eV and 5 arcsec angular resolution across 0.3-7.0 keV band, and 5 arcmin field of view. Effective area of 3 m^2 at 1.25 keV and $0.65m^2$ at 6 keV.
How does matter behave at very high density?	Measure the equation of state of neutron stars through (i.) spectroscopy and (ii.) timing	(i.) Spectral resolving power >3000 combined with effective area > 1500 cm^2 at 0.5 keV. (ii.) Maximum count rate of 10^6 s^{-1} with <10 percent deadtime over 0.3-10 keV band.

Requested Information:

The response to this RFI will be in the form of a PDF document that is uploaded through NASA's NSPIRES system (see instructions below). The response should not exceed ten (10) pages in length.

The response should contain the following information:

- Name of submitter and contact information including all team members, institutional affiliations, and email addresses. Note that a lead submitter or point-of-contact must be identified (name and position, organization, email, phone number);
- Category of response: List all applicable and provide brief description of each in less than 20 words.
    - Mission concept,
    - Instrument concept,
    - Enabling technologies,
    - Other;

- Answer to these questions:
  - Will you be willing to participate and present your concept at the workshop if invited?
  - Does your organization have any sensitive or controlled information (e.g., export controlled, proprietary, competition sensitive) that might be useful for this exercise? If so, are you willing to discuss this information with NASA if proper arrangements can be made to protect the information?
- The information should be submitted in a format most effective for conveying the information (e.g., white paper, presentation charts, technical paper, other). The response should include, at a minimum, the following information:
  - A description of the concept or technology including a list of key performance and technical parameters. Performance parameters include sensitivity, bandpass, angular resolution, spectral resolution, and field of view. Technical parameters include mass, power, and dimensions. The technical readiness level (TRL) of key components should be listed. Sufficient technical detail should be provided so that the level of complexity and technical readiness can be assessed.
  - A description of how the concept or technology fulfills some or all of the IXO science objectives (Table 1).
  - A rough-order-of-magnitude (ROM) total cost, plus a brief explanation of how this cost was estimated. The ROM cost will be used to bin concepts into the following cost categories: small ($300-$600M), medium ($600M-$1B) and large ($1B-$2B).

Future Plans

Within two weeks of release of this RFI, NASA will release an open solicitation inviting members of the astronomy community to participate in an X-ray astronomy mission Community Science Team (CST). The CST will work with the astronomy community and the PCOS Program Office in reviewing all RFI responses and defining mission concepts at various cost points between $300M to $2,000M.

As part of the definition process, NASA will sponsor a workshop this Fall (2011) to present:

a) The latest information regarding the landscape and circumstances that surround formulation and implementation of the next X-ray astronomy mission (or missions)
b) A summary of the information received in response to this RFI
c) Potential mission scenarios for further study

All responders to this RFI, as well as the broader community, are invited to attend the workshop and participate in this process. The workshop will serve as a forum for receiving community input for mission concept(s) definition. The CST and the PCOS Program Office will use the RFI responses and the workshop input to define mission concepts at various price points. These concepts will undergo more detailed definition and cost estimation using NASA's mission design laboratories in collaboration with the study team consisting of CST members plus PCOS Program Office staff.

The final product of this effort will be a report describing scientific capabilities that can be achieved at various cost points as compared to IXO, the science achieved by Athena (if selected), and other science missions in the time frame of the proposed mission. The report will also describe each mission concept, its scientific capability, technical readiness and overall cost. In the Spring of 2012 the PCOS Program will release this study report to the community and present it to the CAA of the National Research Council's Space Studies Board.

Disclaimer

It is NASA's intent to publicly disclose information obtained through this RFI and to incorporate relevant portions into the workshop proceedings and the final study report. Responders shall not submit proprietary information, export controlled information (including ITAR restricted information) or confidential information in response to this RFI. It is emphasized that this RFI is NOT a Request for Proposal, Quotation, or Invitation for Bid. This RFI is for information and planning purposes only, subject to FAR Clause 52.215-3 titled "Solicitation for Information or Planning Purposes", and is NOT to be construed as a commitment by the Government to enter into a contractual agreement, nor will the Government pay for any information submitted in response to this RFI.

No solicitation exists; therefore, do not request a copy of the solicitation. If a solicitation is released it will be synopsized in FedBizOpps and on the NASA Acquisition Internet Service (NAIS). It is the potential Offeror's responsibility to monitor these sites for the release of any solicitation or synopsis. The Government reserves the right to consider a small business or 8(a) set-aside based on responses hereto. As part of its assessment of industry capabilities, NASA-GSFC may contact respondents to this Request for Information (RFI), if clarifications or further information is needed. Respondents will not be notified of the results of the evaluation.

Instructions

All responses submitted in response to this RFI must be submitted in electronic form via NSPIRES, the NASA online announcement data management system, located at http://nspires.nasaprs.com/. For this RFI, a response submission will take the form of a Notice of Intent (NOI) within the NSPIRES online announcement data management system. The RFI response itself will be a PDF-formatted document that is attached (uploaded) to the NSPIRES system.

You must be registered with NSPIRES to submit a RFI response. See registration instructions at http://nspires.nasaprs.com (select "Getting an account"). Neither institution registration nor an institution affiliation is required to respond to this RFI.

1. Log in to your account at http://nspires.nasaprs.com/.
2. Select "Proposals" from your account page.
3. Select "Create NOI" from your proposals page.
4. Click "Continue" on the next page.

5. Select "Request for Information: NNH11ZDA018L (Concepts for the Next NASA X-ray Astronomy Mission)" from the bullet list of announcements. Click "Continue".
6. Enter RFI response title ("NOI title" field will be shown).
7. Select "do not link at this time" for submitting organization page.
8. Click "Save" on next page.
9. It is not necessary to complete any of the "NOI Details"; all requested information must be included in the attached PDF document. Information which is entered into "NOI Details" but not included in the attached PDF document will not be considered.
10. Prepare your RFI response offline and save as a PDF document (note NSPIRES instructions on .pdf formats). The response document must include the respondent's Name, institution, phone number, and E-mail address so the file is self-contained. File names format should be "Respondent Last Name - First Name - RFI". The response should not exceed seven pages in length.
11. To attach (upload) your PDF document:
    a. Click "add" under NOI attachments section;
    b. Select "Proposal Document" from the drop down list;
    c. Browse to attach your PDF file;
    d. Select "Upload";
    e. Click "OK";
    f. Your RFI document has been uploaded to NSPIRES.
12. Click "Submit NOI" button. NOTE that this does not complete the submission process.
13. Ignore any warnings about incomplete NOI elements. Ensure that your NOI document is attached and click "Continue".
14. Click "Submit". This will take you to the NOI submission confirmation page, which provides you with the NOI/RFI number for your records.

Please note: You may delete and replace form fields and uploaded documents anytime before the submission deadline. Submitted NOIs cannot be deleted.

For Additional Information

For further information on this RFI, please contact Jean Cottam, PCOS Chief Scientist, at jean.cottam@nasa.gov. You may also contact the NASA HQ PCOS program officers, Jaya Bajpayee, PCOS Program Executive, at jaya.bajpayee-1@nasa.gov, and Rita Sambruna, PCOS Program Scientist, at rita.m.sambruna@nasa.gov. Please check http://pcos.gsfc.nasa.gov/ for the most up to date information on the PCOS Program.

Appendix D. RFI Responses

List of Submitted X-ray Mission RFI Responses
http://pcos.gsfc.nasa.gov/studies/xray/x-ray-mission-rfis.php

1. Bautz, Marshall
   ÆGIS—An Astrophysics Experiment for Grating and Imaging Spectroscopy [PDF]

2. Bookbinder, Jay
   AXSIO—The Advanced X-ray Spectroscopic Imaging Observatory [PDF]

3. Burrows, David
   Development of Fast Readout Technology in Support of Future X-Ray Astronomy Missions [PDF]

4. Cash, Webster
   The WHIMEx Mission Concept and Lessons Learned [PDF]

5. Casstevens, John
   Three Meter Capacity Diamond Turning Machine For X-Ray Telescope Components [PDF]

6. Danner, Rolf
   Precision-Deployable, Stable, Optical Benches for Cost-Effective Space Telescopes [PDF]

7. Elvis, Martin
   REDUX: A Flexible Path for X-ray Astronomy [PDF]

8. Garcia, Michael
   EPE: The Extreme Physics Explorer [PDF]

9. Gorenstein, Paul
   A Hard X-Ray Telescope for an X-Ray Spectroscopy Mission, Extending the Bandwidth [PDF]

10. Grindlay, Jonathan
    Epoch of Reionization Energetic X-ray Survey (EREXS) [PDF]

11. Harrison, Fiona
    The High Energy X-ray Probe (HEX-P) [PDF]

12. Heilmann, Ralf
    Critical-Angle Transmission Gratings for High Resolution, Large Area Soft X-ray Spectroscopy [PDF]

13. Kilbourne, Caroline
    Enabling Technologies for the High Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission: Options, Status, and Roadmap [PDF]

14. Kouveliotou, Chryssa
    Xenia: A Probe of Cosmic Chemical Evolution [PDF]

X-ray Mission Concepts Study Report

15. Krawczynski, Henric
    The Black Hole Evolution and Space Time (BEST) Observatory [PDF]

16. Lillie, Charles
    The Warm-Hot Intergalactic Medium Explorer (WHIMex) [PDF]

17. Marshall, Herman
    Soft X-ray Polarimetry [PDF]

18. McEntaffer, Randall
    Reflection Grating Spectrometers [PDF]

19. McIntyre, Todd
    Space Communication Rates at Multi-GBPS [PDF]

20. Murray, Stephen
    Wide Field X-Ray Telescope Mission [PDF]

21. Murray, Stephen
    Active Pixel X-ray Sensor Technology Development for SMART-X Focal Plane [PDF]

22. Mushotzky, Richard
    SAHARA: Spectral Analysis with High Angular Resolution Astronomy [PDF]

23. Ramsey, Brian
    Improving X-Ray Optics Through Differential Deposition [PDF]

24. Rao, A.R.
    Super Mon & Black Hole Tracker [PDF]

25. Ray, Paul
    The Advanced X-ray Timing Array (AXTAR) [PDF]

26. Shirron, Peter
    5-Stage Continuous ADR for Future X-Ray Missions [PDF]

27. Ulmer, Melville
    Concept for an orbiting wide field X-ray imaging spectrometer (WFXIS) [PDF]

28. Ulmer, Melville
    Improving the performance of X-ray optics with magnetostrictive films [PDF]

29. Vikhlinin, Alexey
    SMART-X, Square Meter, Arcsecond Resolution X-ray Telescope [PDF]

30. Zhang, William
    Next Generation X-ray Optics: High-resolution, Light-weight, and Low-cost [PDF]

Appendix E. December 2011 Workshop

In conjunction with the RFI, the PCOS Program Office hosted an X-ray Mission Concepts Workshop to bring together the X-ray astrophysics community with the study team to explore new mission architectural concepts. The workshop was held on December 14th and 15th at the Maritime Institute in Linthicum, Maryland.

Workshop on X-ray Mission Architectural Concepts Presentations
All presentations in a single archive zip file [408 MB]

Day 1 - Wednesday, December 14

- Morning
  1. **X-ray Agenda** [PDF]
  2. **R. Petre** [PPT]
  3. **R. Smith** [PDF]
  4. **C. Wilson-Hodge** [PDF]
  5. **M. Garcia** [PDF]
  6. **R. Mushotzky** [PDF]
  7. **M. Ulmer** [PDF]
  8. **A. R. Rao** [PDF]
- Afternoon
  9. **M. Bautz** [PPTX]
  10. **W. Cash** [PPTX]
  11. **S. Murray** [PPT]
  12. **M. Elvis** [PPTX]
  13. **P. Ray** [PDF]
  14. **H. Krawczynski** [PDF]
  15. **D. Hartmann** [PPTX]

Day 2 - Thursday, December 15

- Morning
  16. **N. White** [PPT]
  17. **J. Bookbinder** [PPT]
  18. **A. Vikhlinin** [PDF]
  19. **J. Grindlay** [PPTX]
  20. **F. Harrison** [PPTX]
  21. **W. Zhang** [PDF]
  22. **B. Ramsey** [PPTX]
  23. **M. Ulmer** [PDF]
  24. **J. Casstevens** [PPTX]
  25. **R. Heilmann** [PPT]
  26. **P. Gorenstein** [PPT]
  27. **R. McEntaffer** [PPTX]
- Afternoon
  28. **H. Marshall** [PDF]
  29. **C. Kilbourne** [PPT]
  30. **P. Shirron** [PPT]
  31. **D. Burrows** [PDF]
  32. **R. Danner** [PPTX]
      a. **R. Danner** [WMV]
      b. **R. Danner** [WMV]
  33. **T. McIntyre** [PDF]
  34. **J. Bregman** [PPTX]

Appendix F. IDL/MDL Items

http://pcos.gsfc.nasa.gov/studies/x-ray-mission.php

Instrument Design Laboratory (IDL) Studies

1. **X-ray Calorimeter** (February 13–17, 2012)

X-ray Mission Design Laboratory (MDL) Studies

1. **X-ray Gratings MDL** (March 19–23, 2012)
2. **X-ray Calorimeter MDL** (April 2–6, 2012)
3. **X-ray WFI MDL** (April 16–20, 2012)
4. **X-ray AXSIO Redux** (April 30–May 4, 2012)
5. **X-ray Gratings Redux** (May 2–4, 2012)