The International X-ray Observatory

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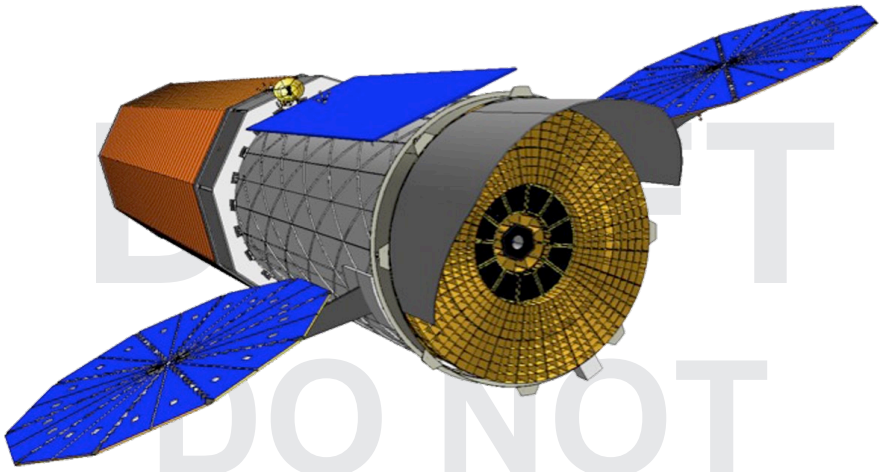

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and on behalf of the 69 members of the IXO Science Definition Team, Instrument Working Group, and Telescope Working group, whose membership is listed at http://ixo.gsfc.nasa.gov/people/

SUMMARY

The International X-Ray Observatory, a joint NASA-ESA-JAXA effort, is a next generation X-ray telescope that will answer many fundamental questions in contemporary astrophysics such as:

1) What happens close to the event horizon of a black hole?

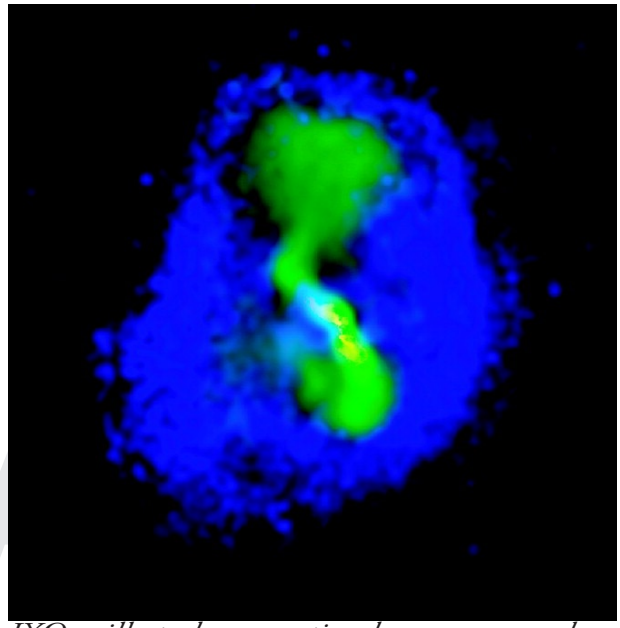
2) How do supermassive black holes influence galaxy and cluster evolution?

3) How do galaxy clusters evolve and how does this constrain dark energy and dark matter?

Chandra, XMM-Newton, and Suzaku are producing important discoveries now, but to address these questions, and many others, requires much more collecting area and often substantially higher spectral resolution. The hundreds of thousands of sources already detected tell us how to effectively use IXO's 1–2 orders of magnitude increase in throughput and up to 100-fold increase in spectral resolving power. The improvement of IXO relative to current X-ray missions is equivalent to a transition from the 200 inch Palomar telescope to a 20m telescope while at the same time shifting from spectral band imaging to an integral field spectrograph.

As a powerful astronomical observatory, IXO will address questions ranging from the neutron star equation of state to the distribution and dynamical state of intergalactic material. X-ray spectroscopy, polarimetry, and timing studies will provide detailed measures of abundances, temperatures, densities, magnetic fields and gravitational potentials, which simply are not possible until IXO flies. These measurements will be complementary to the next generation of observatories such as ALMA, JWST, and future ground-based optical-NIR telescopes. Previous experience assures us that unexpected discoveries will abound, and IXO is designed to produce breakthroughs in known areas and contribute to the understanding of new phenomena as they are uncovered.

The focal plane instruments will deliver up to 100-fold increase in effective area for high resolution spectroscopy from 0.3–10 keV, deep spectral imaging from 0.1–40 keV over a wide field of view, unprecedented polarimetric sensitivity, and microsecond spectroscopic timing with high count rate capability.



IXO will study energetic phenomena, such as the strong jets found in AGN, that can have a profound effect on the growth of structure in the universe. Non-dispersive spectral/spatial measurements with 2.5 eV spectral resolution will determine the temperature, ionization state, and velocities in the intra-cluster medium catching "feedback" processes in action. (Figure is adapted from Chandra/VLA study of Wise et al. 2007)

The heart of the mission is the lightweight X-ray optical system (which has an areal density more than an order of magnitude lower than Chandra and XMM). The mirror has a 20-meter focal length (a deployable optical bench enables this). Achieving the 3 m^2 collecting area with 5" angular resolution is the main technology driver. Two independent approaches towards 5" resolution are underway with well-identified paths to achieving the required performance levels.

IXO is planned for launch in the 2020–2021 timeframe and the spacecraft can be built using existing technology. It will launch on an Atlas V or Ariane V to an L2 orbit very similar to the JWST orbit.

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1. SCIENCE

Black Holes

In the past decade, we have come to appreciate that black holes are sites of enormous energy production that substantially influence their surroundings. Evidently, the immense energy liberated by growing black holes regulates the infall of gas in galaxies and clusters, while some analogous process, still poorly understood, ties the growth of black hole mass to a fixed fraction of its host galaxy's bulge—a two-way connection that has come to be called "feedback." IXO observations will elucidate these processes, leading to breakthroughs in understanding the energy generation mechanisms. IXO will measure the mechanical energy of the X-ray winds and jets that interact with the galactic and cluster environments. IXO will detect the accretion radiation from very distant AGNs, complementing the measurements of the reprocessed radiation (in the IR-millimeter regions) and providing a complete picture of the evolution of AGN over cosmic time.

Black Hole Astrophysics

IXO studies of black holes begin within a few Schwarzschild radii of the Event Horizon, in the strong field limit of General Relativity (GR). IXO will discriminate between Kerr and Schwarzschild spacetimes to measure the spin of the black hole in six independent ways, including relativistic disk line spectroscopy, reverberation mapping, disk hot spot mapping, disk continuum spectroscopy, disk polarimetry, and power spectral analysis (see Fig. 1-1). IXO observations of correlated changes in iron line intensity and energy from individual blobs of material orbiting in the accretion disk within a few Schwarzschild radii will explore the Kerr metric itself. These studies will require a sample of at least 10 bright Seyfert AGN and a larger sample of stellar-mass black holes.

The information in the black hole spin distribution changes with their mass. For stellar-mass black holes, the spin is set at birth, so the spin distribution reveals the angular momentum of the core of supernovae and gamma-ray bursts. In supermassive black holes (SMBH), the distribution of black hole spin parameters is a fossil record of the relative importance of black hole-black hole mergers versus accretion for a given black hole (see Fig. 1-2). Observations with IXO will deliver spin measurements in 200-300 SMBH, data not just about the history of a given galaxy and its central black hole, but on the whole nature of hierarchical merging and accretion-driven feedback (ionizing radiation, hot gas) between black holes and their host galaxies.

Black holes and galaxies put relativistic effects to work, sometimes with major impacts on host galaxy evolution. The process of disk accretion liberates ionizing radiation and supplies hot winds to galactic bulge regions. IXO's paradigm-changing spectroscopy will measure velocities and rotation—and thus angular momentum transfer—in hot X-ray disk winds. Such magnetocentrifugal winds are predicted by theory and known to be important in disk accretion in FU Ori and T Tauri stellar systems.

Feedback between Galaxies and SMBH

Both theory and observations suggest that AGN provide the essential link responsible for regulation of star formation in massive galaxies through the process of feedback. An understanding of this process requires that we measure the star formation rate (from UV through far-IR observations) and the energy input process as well. The energy comes from both stars and AGN, which are often hidden by the star-forming material. Current X-ray telescopes can detect these hidden AGN and have shown that the obscuring material is often not static, with massive outflows of

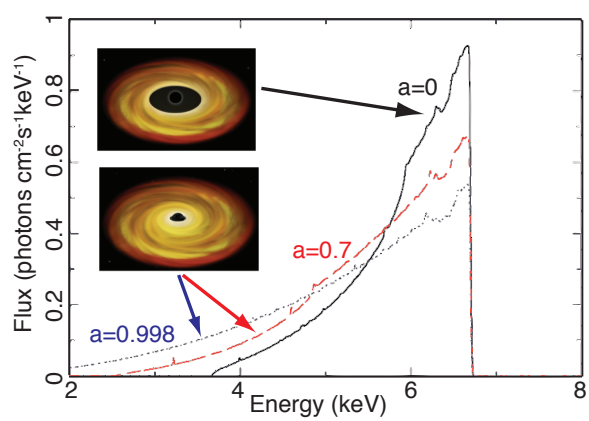

Figure 1-1. Spinning black holes broaden the iron lines seen from accretion disks.

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material seen in about 40% of AGNs (the broad absorption-line AGNs). Unfortunately, the X-ray absorption makes many of these AGNs dim, so few can be studied in depth.

With the enormous improvement in collecting area offered by IXO, existing modest detections of AGNs (e.g., 50 photons) will be transformed into spectral energy distributions from which one can derive the accretion energy, the amount of absorbing medium, and the mass and energy outflow. Spectral studies will be feasible for the most distant known AGNs (z ~ 6.3), since Chandra detected them in just a few tens of ksec.

The presence of the AGNs at z = 6–7 already challenges formation theories of SMBHs, so searches for even higher redshift AGNs should prove extremely important for understanding their formation histories and subsequent evolution. The existence of accreting SMBH at z = 7–10 remains a controversial topic, with model predictions differing by several orders of magnitude. However, if moderate luminosity AGN exist in this extreme redshift range, IXO has the sensitivity to detect such objects and define their accretion luminosities.

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Cosmology

It seems remarkable that X-ray astronomy probes not only the most compact of objects, but also the largest systems, the clusters of galaxies and the Cosmic Web of baryons that connects them. This occurs because gas, the primary baryonic component of the Universe, is heated to the characteristic temperature of collapsing or virialized dark matter structures. Both the properties of these structures and their evolution are particularly rich topics. A subset of this exciting science is discussed here, the evolution of galaxy clusters and the properties of the Cosmic Web.

Galaxy Cluster Evolution: Constraints on the Cosmological Models

Clusters of galaxies are of special importance for understanding the growth of structure in the universe, as they constitute the most massive virialized systems. A critical measure of galaxy clusters is their mass function, the space density of clusters as a function of mass. The shape of

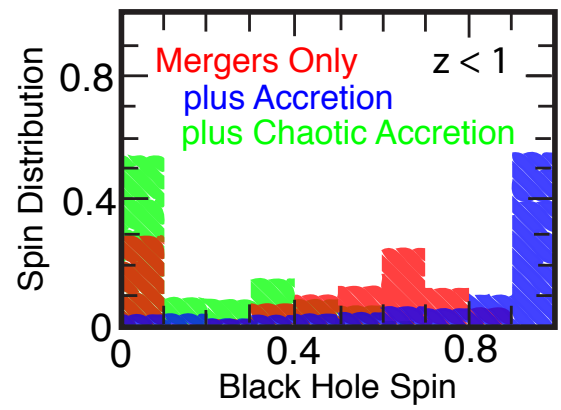

Figure 1-2. Three possible SMBH spin distributions, based on Berti & Volonteri 2008

this mass function, and the turnover mass evolves with the age of the Universe. Its evolution is sensitive to the characteristic densities of the Universe as well as to the expansion rate through cosmic time. Therefore, not only is the evolution of clusters fundamental astronomical data, these data constrain cosmological models.

Studies of cluster masses have improved enormously in recent years, as investigators used numerical simulations to identify combinations of X-ray observational quantities that lead to reliable and accurate results. It is through such efforts that the mass function of galaxy clusters is being increasingly well-defined at low redshift. A significantly more sensitive X-ray observatory, such as IXO, is required to extend these studies to higher redshift, from which we will determine their cosmological evolution.

A modest amount of IXO observing time, combined with lensing follow-up, will measure the perturbation growth factor from z = 0–2 with an accuracy comparable to, or possibly better than that expected from observations of cosmic shear with JDEM, and redshift-space distortions with EUCLID. The growth of structure data derived from clusters will significantly improve our knowledge of the dark energy equation of state and will aid in constraining non-GR models for cosmic acceleration, as shown in Fig 1-3. IXO observations of the largest, dynamically relaxed clusters will provide a powerful, independent measurement of the cosmological expansion history using the apparent $f_{gas}(z)$ trend. Systematic

and statistical errors from this technique are competitive with SNIa and baryon acoustic-oscillation studies, making the test extremely useful for improving the accuracy and reliability of the geometric cosmological measurements planned for LSST and JDEM. Only by employing a range of powerful, independent approaches can robust answers to puzzles as profound as the origin of cosmic acceleration be expected.

The Cosmic Web of Baryons

Less than 10% of the baryons in the local Universe lie in galaxies as stars or cold gas, with the remainder predicted to exist as a dilute gaseous filamentary network known as the Cosmic Web. Some of this gas is detected through Lyα and OVI absorption line studies, but half of the gas remains undetected. Simulations for the growth of structure suggest that these "missing" baryons have been shock heated in unvirialized cosmic filaments to temperatures of $10^{5.5}$–10^{7}K, and that the gas is chemically enriched by galactic superwinds. The study of this material probes the consequences of large-scale structure formation at overdensities that are significantly below virialized systems, a little-explored regime.

The first goal is to determine if the missing baryons really exist at these high temperatures. This measurement of mass as a function of temperature can be determined through X-ray absorption line grating spectroscopy of He-like and H-line ions of C, N, and O detected against background AGN. Another central goal is measuring the extent of the galactic superwinds, based on the proximity of absorption sites to galaxies and from the dynamics of the hot gas. The last goal is testing whether the hot gas is filament-like, using X-ray emission studies beyond the virial radii of galaxy clusters.

Intergalactic X-ray absorption lines are near or below the detection limit of current instruments, requiring order-of-magnitude improvements are in both spectral resolution and collecting area to make measurements routine. IXO is designed to provide these improvements to meet our goals with a feasible investment of observing time.

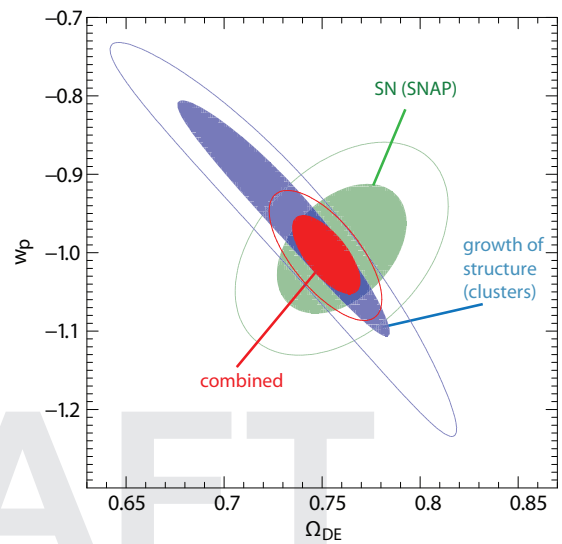

Figure 1-3. Measurements of Dark Energy from the growth of structure from galaxy cluster masses provide an orthogonal approach to standard candle methods such as Type Ia SNe.

The X-Ray Universe

In the past few decades, X-ray astronomy has grown into a discipline that touches every class of astronomical objects from the Solar System, through stars and galaxies to cosmology. There is good reason for the breadth of X-ray astronomy: the temperature that characterizes the potential well depth of most astronomical objects lies in (or near) the X-ray band. We present here a few representative examples of the broad range of IXO science, while white papers available on the IXO website cover more examples.

Neutron Star Equation of State

Neutron stars have the highest known matter densities, up to several times the densities in atomic nuclei, which is vastly beyond the densities produced in terrestrial laboratories. Quantum Chromodynamics (QCD) governs the physics, but there are conflicting predictions as to the nature of this high-density material (e.g., hyperons, Bose condensates of pions) due to poorly known parameters and the difficulties of calculating the relevant many-body interactions. These uncertainties lead to widely different equations of state. In turn, the equation of state determines the radius of a neutron star for a given mass. IXO will

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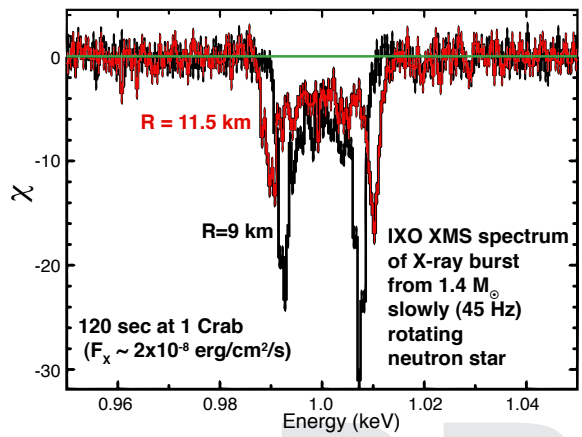

Figure 1-4. Doppler-shifted absorption lines in slow rotators directly reveal the neutron star radius while fits to the pressure broadening in the lines determines the mass.

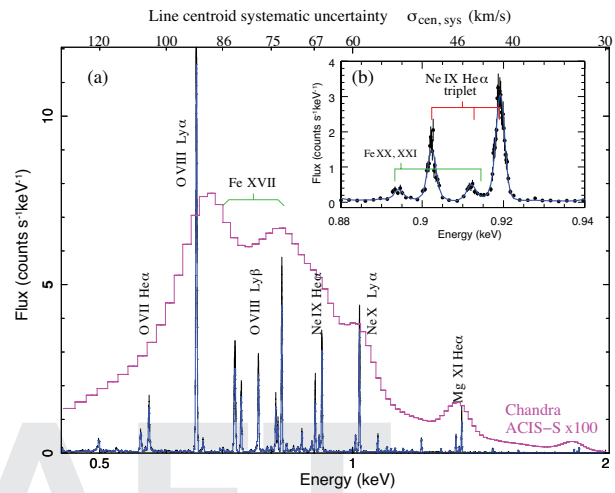

Figure 1-5. High-resolution X-ray spectra show both the metal abundances and the velocities in a starburst galaxy's superwind.

measure the mass-radius relationship for neutron stars, some of which should have masses well in excess of 1.4 $M_\odot$ due to ongoing accretion.

Time- and energy-resolved X-ray absorption lines from the neutron star's photosphere reveal the mass and radius in multiple ways. For a slowly rotating neutron star (see Fig. 1-4), high resolution spectroscopy with IXO will define the double absorption line profile of atomic lines. By modeling the effects of pressure broadening, along with special and general relativistic effects, excellent measurements of mass and radius will be achieved. For a rapidly spinning bursting neutron star (e.g., 400 Hz), the high time resolution spectroscopy offered by IXO will phase-resolve the Doppler broadening, leading to an absolute radius measurement and mass as well from the redshift of the line. This set of mass and radius measurements will constrain the equation of state and potentially rule out many of the current models.

Nucleosynthesis

The problem of understanding elemental creation and dispersal crosses all wavebands and astronomical objects. IXO will make major contributions to understanding supernovae and their nucleosynthetic yields, to precision measures of abundances in the Milky Way, to the dispersal of metals beyond galaxies, and to the evolution of galaxy cluster metallicites over cosmological time.

The dispersal of nucleosynthetic material from galaxies can occur as starburst galaxies drive out hot gas that is both heated and enriched by supernovae. This hot gas has been detected with current X-ray telescopes, but the critically important flow velocity cannot be measured directly. This velocity must be inferred from entrained cooler, denser optically-emitting gas that may be moving much slower than the hot material, leading to gross underestimations of the true outflow rate. As shown in Fig. 1-5, the actual hot gas flow velocity will be measured with IXO due to its exceptionally high-throughput spectroscopic imaging capabilities, representing a great advance in our understanding of galactic winds and the effects on their environments.

The processes of galactic winds over cosmological time may have led to the baryon-poor (relative to their dark matter content) galaxies of today. A variety of observations show that, relative to the cosmological ratio, most galaxies have lost more than 2/3 of their baryons. Basic considerations suggest that the missing baryons are hot, but they may have been either expelled as a galactic wind or preheated so that the gas never falls in. X-ray absorption lines seen with IXO will identify the location and metallicity of this missing gas from the line centroids and equivalent widths of hot C, N, and O ions, revealing a crucial aspect of galaxy formation.

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Table 1.1.

Science Topic	Typical Target	Flux (cgs)	# of Targets	Time/Tgt (ksec)	Area (m^2)	Resolution
SMBH	CDF-S	10^{-13}	5	400	1@6 keV	50 eV
Clusters	JKCS-041	2×10^{-14}	100	80	3@1 keV	2.5 eV
Starbursts	NGC 3628	4×10^{-13}	30	40	0.2@0.3 keV	2.5 eV
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Stars and Planets

Despite recent progress, questions about stellar X-rays remain, such as the connections between stellar flares, magnetic fields, and coronal heating. IXO's high resolution spectroscopy with 100 times larger throughput will enable a survey of "normal" stars out to ~5 pc, avoiding the bright "active-star" bias present in existing X-ray surveys. For example, the non-thermal kinetic energy ejected during flares from all types of stars may contain as much energy as is in thermal heating and radiation, but this is currently unconstrained. IXO has the resolution needed to determine both the Doppler-shifted bulk velocities and line-broadening from turbulence in the ejected matter.

X-rays and energetic particles from stellar flares will also irradiate protoplanetary disk gases and solids. They affect planet formation processes by heating the outer layers of the disk, producing reactive ion-molecular species and inducing disk turbulence via ionization. Chandra has seen disk fluorescence resulting from immense flares in stars in the nearby Ophiuici cloud, but IXO will observe to the far more common flares that are 10 to 100 times weaker, allowing correlations with ALMA and JWST observations to determine the properties of these systems.

Science Requirements

Achieving these results requires a flexible mission with a range of capabilities. Table 1.1 shows selected science topics and some of the requirements they place on the resolution, effective area, and lifetime of the mission; a complete table is available on the IXO website, http://ixo.gsfc.nasa.gov.

2. TECHNICAL OVERVIEW

Observatory Overview

The International X-ray Observatory (IXO) is a facility-class observatory that will be placed via direct insertion into an 800,000 km semi-major axis halo orbit around the Sun-Earth L2 libration point using either an Atlas V 551 or Ariane V launch vehicle. IXO is built around a ~3.3 m diameter grazing-incidence mirror assembly with a 20 m focal length. Flight-proven extendable masts allow the Observatory to fit into the launch vehicle fairing. The mission design life is five years, with consumables sized for 10 years. The observatory design is well defined, building on studies performed over the last decade by NASA, ESA, and JAXA, and has strong heritage from previous space flight missions.

Mission Performance Requirements derived from the science described in Section 1 are shown in Table 2.1. All are met or exceeded by IXO.

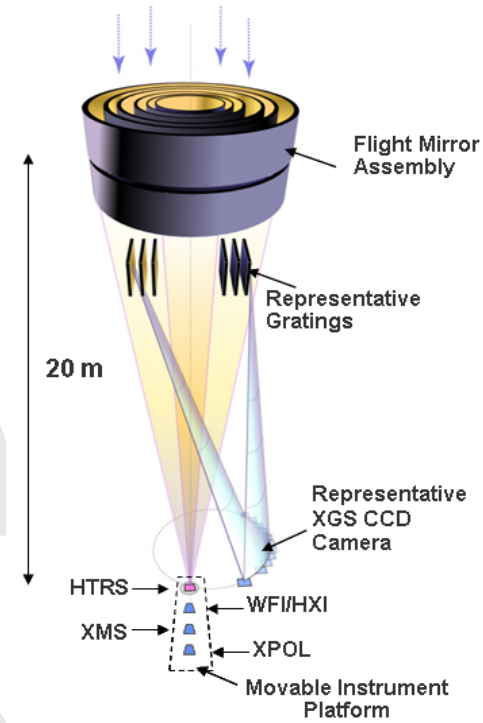

Figure 2-1. IXO Payload Complement.

Payload Overview

The IXO payload (Fig. 2-1) consists of i) the Flight Mirror Assembly (FMA), a large area, grazing incidence mirror; ii) four instruments mounted in the mirror focal plane on a movable instrument platform (MIP) which are exposed to the sky one at a time; and iii) an X ray Grating Spectrometer (XGS) that intercepts and disperses a fraction of the beam from the mirror onto a CCD camera, and which operates simultaneously with the observing MIP instrument.

The Flight Mirror Assembly design is driven by the following requirements:

- Effective area of 3 m^2 at 1 keV; 0.65 m^2 at 6 keV; 150 cm^2 at 30 keV (see Fig. 2-2)
- Angular resolution of 4 arcsec for E < 7 keV; 30 arcsec at 30 keV

Attaining the large effective area within the launch vehicle mass constraint requires a mirror with a high area-to-mass ratio. If the observatory is to have an overall angular resolution of 5 arc-

Table 2.1. Key Mission Performance Requirements

Mirror Effective Area	3 m^2 @ 1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV	Black hole evolution Strong gravity Strong gravity
Spectral Resolution (FWHM), over FOV, over band	ΔE = 2.5 eV, 2 × 2', (0.3–7 keV) ΔE = 10 eV, 5 × 5', (0.3–7 keV) ΔE = 150 eV, 18', (0.1–15 keV) $E/\Delta E$ = 3000, (0.3–1 keV)	Black hole evolution Black hole evolution Large scale structure Missing baryons
Angular Resolution	≤ 5 arc sec HPD (0.1–7 keV) 30 arc sec HPD (7–40 keV)	Cosmic feedback Black hole evolution
Count Rate	1 Crab with > 90% throughput.	Strong gravity, EOS
Polarimetry	1% MDP on 1mCrab, 100 ksec, 3 σ, 2–6 keV	AGN geometry, strong gravity

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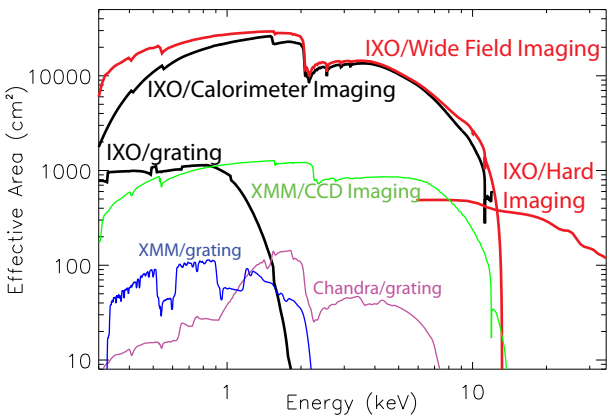

Figure 2-2. The IXO effective area will be more than an order of magnitude greater than previous X-ray missions. Coupled with this is an increase of approximately 1000 in spectral resolving power that will open up a vast new discover space for high-energy phenomena

sec half power diameter (HPD), the FMA angular resolution must be 4 arcsec HPD or better.

The mirror technology is well understood, but represents the most significant technical challenge for IXO (Section 3). Two technologies are being developed, thermally formed ("slumped") glass (by NASA) and silicon pore optics (by ESA). Both approaches lead to a highly modular design.

The NASA FMA concept incorporates glass slumped into a Wolter I optical design, with 361 nested pairs of concentric shells (Fig. 2-3). Each shell is divided into 12 or 24 azimuthal segments. Mirror segments are produced by slumping commercially available 0.4 mm thick Schott DeSag D263 glass onto figured, fused quartz mandrels. This technique is similar to, but more exacting than, what is being used to fabricate ~8000 mirror segments for NuSTAR.

Groups of radially adjacent segments mount into efficiently packed, wedge-shaped modules, constructed of Ti/Mo alloy, which closely matches the thermal expansion coefficient of the segments. The 60 modules are mounted in three rings into the FMA primary structure. The response above 10 keV is provided by a hard X-ray mirror module which mounts in the center of the FMA and has multi-layer coatings to enhance the high-energy reflectivity.

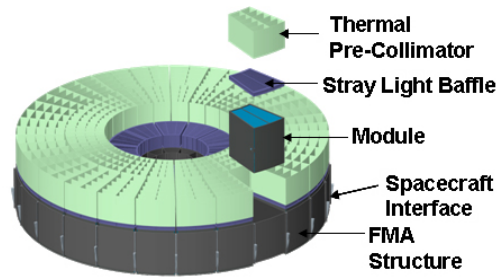

Figure 2-3. NASA FMA concept.

The ESA approach, Silicon Pore Optics, uses commercial high-quality silicon wafers as its base material. The mirror build up process is illustrated in Fig. 2-4. Wafers are diced, structured, accurately wedged, coated with an X-ray reflecting layer, bent azimuthally, and stacked. Two stacks are then assembled into a co-aligned mirror module. Each module is an annular segment of a group of tightly nested shells configured in a conical approximation of the Wolter I design. Hundreds of such mirror modules form a "petal" corresponding to an azimuthal segment of the full mirror. The petals in turn are mounted onto the spacecraft to form a complete X-ray mirror. Hard X-ray sensitivity is provided by coating modules at the innermost radii with multilayers.

Figure 2-4. Tested Silicon Pore Optics Petal.

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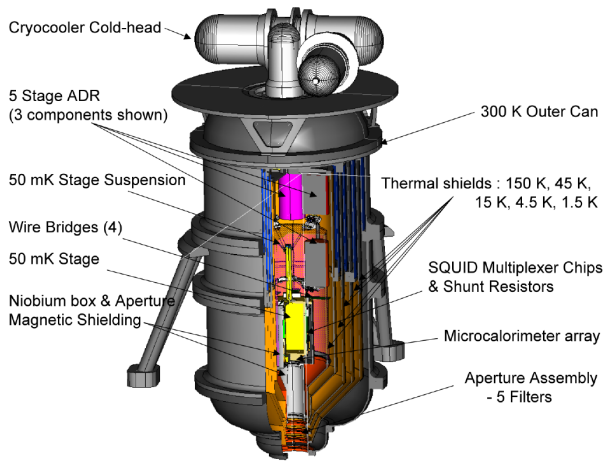

Figure 2-5. XMS CAD model.

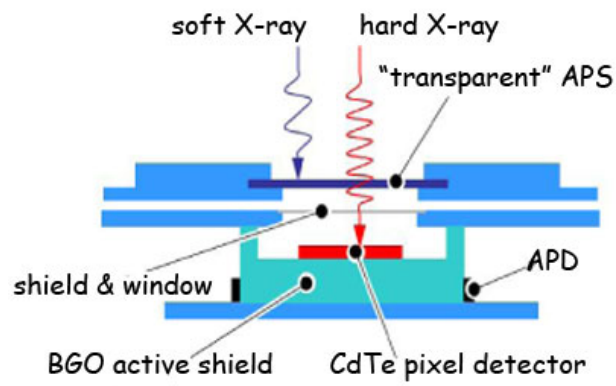

Figure 2-6. WFI/HXI Layout: The soft X-ray Active Pixel Sensor (APS) is in front of the hard X-ray CdTe detector.

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The X-ray Microcalorimeter Spectrometer (XMS) combines high spectral resolving power in a large array to provide non-dispersive imaging spectroscopy over a broad energy range. The driving performance requirements are to provide spectral resolution of 2.5 eV over the central 2 × 2 arcmin in the 0.3–7.0 keV band, and 5 eV over the entire 5 × 5 arcmin field of view.

The XMS is composed of an array of microcalorimeters, devices that convert individual incident X-ray photons into heat pulses and measure their energy via high precision thermometry. The microcalorimeters are based on Transition-Edge Sensor (TES) thermometers that use the extremely rapid change in electrical resistance in the narrow temperature range (< 0.001 K) of a superconducting transition. To achieve this performance, the detector must be cooled to 0.05 K and electrically biased into the superconducting transition at ~ 0.1 mK.

The focal plane consists of a 40 × 40 array of 300 × 300 μm pixels with spectral resolution of 2.5 eV. At 20 m focal length, these dimensions correspond a 2 × 2 arcmin field of view and 3 arcsec pixels. This core array is surrounded by an outer array of 52 × 52 pixels that are twice as large to extend the field of view to 5 × 5 arcmin with better than 10 eV resolution.

The arrays are fabricated using standard micro-electronic techniques. The pixels use Mo/Au bilayer superconducting films deposited on Si wafers with silicon nitride films. The X-ray absorbing elements are formed by electroplating Au/Bi films patterned so they only contact a small area so as not to interact electrically with the TES, but with high array filling factor (95%).

A Continuous Adiabatic Demagnetization Refrigerator (CADR) and a mechanical cryocooler provide cooling without expendable cryogens. Fig. 2-5 shows a CAD drawing of the full XMS instrument, including cooler.

The Wide Field & Hard X-ray Imager (WFI/HXI). The Wide Field Imager (WFI) is an imaging X-ray spectrometer with an 18 × 18 arcmin field of view (Fig. 2-6). It provides images and spectra in the 0.1–15 keV band. The pixel size of the WFI is 100 μm × 100 μm, corresponding to a viewing angle of 1 arcsec at a focal length of 20 m.

The WFI is a Silicon Active Pixel Sensor (APS), i.e., each pixel has an integrated amplifier. Compared with earlier CCD-type detectors, the APS concept has the significant advantage in that the information is stored and read directly in each pixel, rather than being transferred through hundreds or thousands of pixels before being read out.

The WFI's key component is the DEPFET (DEpleted P-channel Field Effect Transistor) device. The DEPFET is a p-type MOSFET on a depleted n-bulk and has the combined functionalities of both detector and amplifier. Signal electrons are collected and stored in a potential pocket underneath the transistor gate and can be read out on demand.

As shown in Fig. 2-6, the Hard X-ray Imager (HXI) is mounted directly beneath the WFI. It extends the energy coverage to 40 keV and enables simultaneous observations with both instruments. The HXI will have energy resolution better than 1 keV (FWHM) at 40 keV and cover a FOV of 12 × 12 arcmin. The HXI is a 7 × 7 cm wide Double-sided Strip Cadmium Telluride detector (DS-CdTe). Its 0.5 mm thickness affords nearly 100 % detection efficiency for 40 keV X-rays. To suppress background, an active anticoincidence shield is deployed around the imager. In addition, two layers of Double-sided Si Strip Detector (DSSD) are mounted above the CdTe to serve as particle background detectors and detectors of 10–30 keV X-rays.

The X-ray Grating Spectrometer (XGS) is a wavelength-dispersive spectrometer for high-resolution spectroscopy in the 0.3–1.0 keV band. Its key performance requirements are spectral resolution ($\lambda/\Delta\lambda$) of 3000 (FWHM) and effective area larger than 1000 cm^2 across its operating band.

The reference concept incorporates panels of gratings that intercept a portion of the converging FMA beam and disperse the X-rays onto a CCD array for readout. One implementation utilizes Critical Angle Transmission gratings. These gratings draw heritage from the Chandra High Energy Transmission Grating Spectrometer, but provide substantially higher efficiency. A second approach incorporates reflection gratings. The so-called "off plane" reflection gratings are ruled along the direction of incidence, rather than perpendicular to it, as was implemented on XMM-Newton.

The High Time Resolution Spectrometer (HTRS) will perform high precision timing measurements of bright X-ray sources. It can observe sources with fluxes of 10^6 counts per second in the 0.3–10 keV band without performance degradation, while providing moderate spectral resolution (200 eV FWHM at 6 keV). The HTRS is an array of 37 hexagonal Silicon Drift Diodes (SDD), placed out of focus so that the converging beam from the FMA is distributed over the whole array.

The X-ray Polarimeter (XPOL) is an imaging polarimeter, with polarization sensitivity of 1% for a 1 mCrab source in 100 ksec in the 2–10 keV band. XPOL utilizes a Gas Pixel Detector with a proportional multiplication counter finely subdivided to recognize tracks and measure the ejection direction of the primary photoelectron. Track analysis reconstructs the impact point with a precision of ~150 μm FWHM, allowing imaging with 7-arcsec angular resolution.

Observatory Overview

The Observatory consists of four major modules: Instrument, Deployment, Spacecraft, and Optics (Fig. 2-7). This architecture facilitates parallel development and integration and test.

The IXO spacecraft can be built using existing technology. Most components are "off-the-shelf." Resource tracking per AIAA standards shows that all IXO resource margins meet or exceed requirements.

The L2 orbit facilitates high observational efficiency and provides a stable thermal environment. The allowed attitude relative to the sun line is ±20° (pitch), ±180° (yaw); ±20° (roll). This range keeps detectors and radiators out of the sun while providing full solar illumination to the solar arrays throughout the mission.

The IXO system is robust. Full redundancy along with numerous failsafe mechanisms for contingency mode operations assure that no single failure will corrupt this mission. All spacecraft components and design solutions are traceable to space flight heritage.

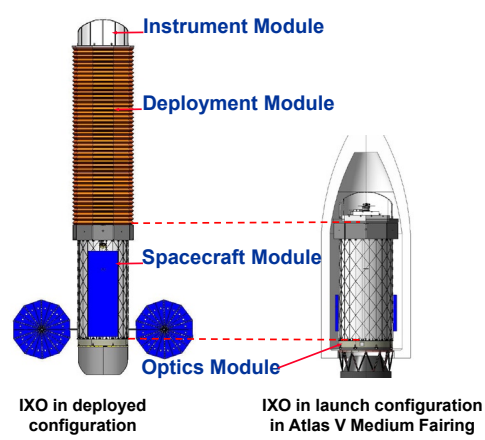

Figure 2-7. Observatory On-orbit and Launch Configurations.

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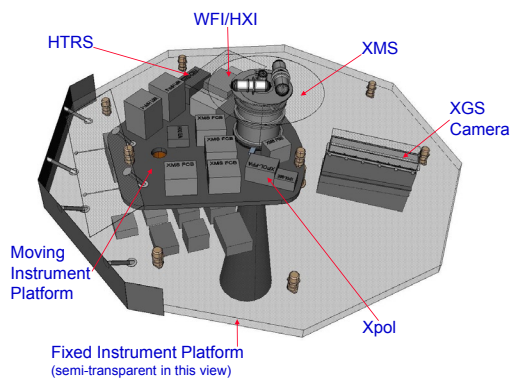

Figure 2-8. Instrument Module.

The Instrument Module (Fig. 2-8) accommodates the detectors. All detectors except the XGS CCDs mount to the MIP, which rotates to position instruments at the focus. Focus and translation mechanisms, coupled wth a metering structure metrology system, assure positional accuracy of instruments.

The Deployment Module is the extendable portion of the metering structure, which is deployed on orbit. It consists of three identical ADAM masts, similar to those on NuSTAR. High precision deployment accuracy/repeatability was proven with the 60 m ADAM used in space on the NASA's Shuttle Radar Topography Mission. As the masts deploy, they pull with them wire harnesses and two five-layer pleated shrouds that shield the instruments thermally and from stray light.

The Spacecraft Bus Module consists of a 6.6 m long × 3.3 m diameter cylindrical composite metering structure and a honeycomb deck. This module accommodates the bulk of the spacecraft systems for propulsion, RF communications, avionics, and power. Solar array wings, reaction wheels, propellant tanks, thrusters, and subsystem electronics boxes are also located on this module. All spacecraft subsystems utilize established hardware with substantial flight heritage.

The Optics Module holds the FMA, its sun shade and the star trackers, and mounts to the spacecraft bus module. It is designed to accommodate either the glass or the Si pore mirror.

IXO science and mission operations are relatively undemanding. A single daily 30-minute DSN contact is required for telemetry and orbit determination. Operations will be conducted from the IXO Science and Operations Center (ISOC), which will evolve from the Chandra X-ray Center (CXC) at the Smithsonian Astrophysical Observatory (SAO). The data system utilizes COTS hardware exclusively and COTS software to the extent possible. Routine operations are automated whenever possible and will be staffed by a single eight-hour shift seven days per week.

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Table 2.2 Resources Summary.

Mass			
Maximum expected mass (incl AIAA contingency) (kg)		Throw Mass (kg)	Margin
5530		6425	16%
Power			
BOL absolute min (W)	EOL absolute min (W)	Expected load (W)	EOL Margin
6600	5200	4200	15%
Data Rate			
Max 60 hrs. data volume (Gbits)		Storage capacity (Gbit)	Margin
200		400	100
Parameter		**Req't**	**Modeled**
Image aspect knowledge (arcsec, HPD)		1	0.54
Image position control (arcsec, 3σ)		10	1.54
Jitter (milliarcsec over 200 msec, 3σ		200	< 20

3. TECHNOLOGY DRIVERS

IXO X-ray Mirror Technology

The IXO mission places stringent requirements on the performance of the X-ray optics forming the core of the telescope. IXO optics must deliver an X-ray effective area-to-mass ratio of about 20 cm^2/kg (including structure), while at the same time retaining good angular resolution of 5 arcsec HPD. This is significantly better than provided by current technology. To meet these requirements, two technologies are being pursued; thermally formed (slumped) thin glass mirrors (NASA), and stacked, grooved silicon plates—Si pore optics (ESA).

Slumped glass mirrors have been fabricated with predicted performance of ~ 11 arcsec HPD. Mirror pairs measured with 8 keV X-rays achieved 15 arcsec HPD performance, including test conditions (alignment, mounting, gravity, etc). Performance (black circles) agrees well with metrology based predictions (solid red line, Fig. 3-1). Fabrication errors that dominate performance at present are: (1) mid-spatial frequency errors, contributed by the forming mandrel release layer, (2) mandrel low frequency figure, and (3) axial quadratic departure from nominal (sag, believed to be due to coating stress). Two different mirror mounting schemes are being investigated; an active, and a passive approach. The active approach has aligned mirrors to ~ 2 times coarser than requirements, but bonding has limited final results. The passive approach has demonstrated intermediate steps as good as can be measured (~ 1 arcsec HPD). Mounted slumped glass mirrors have been successfully vibration tested, and acoustically tested to Atlas V qualification levels.

Silicon pore optics represent a completely different approach to mirror fabrication. Stacks with as many as 45 plates have been made using a robotic process. X-ray imaging performance degrades as more plates of a stack are illuminated; full illumination of 4 plates yields ~ 17 arcsec HPD at 1.5 keV for the outermost stack of a 50 m focal length telescope. Many stacks have been assembled to form a full module.

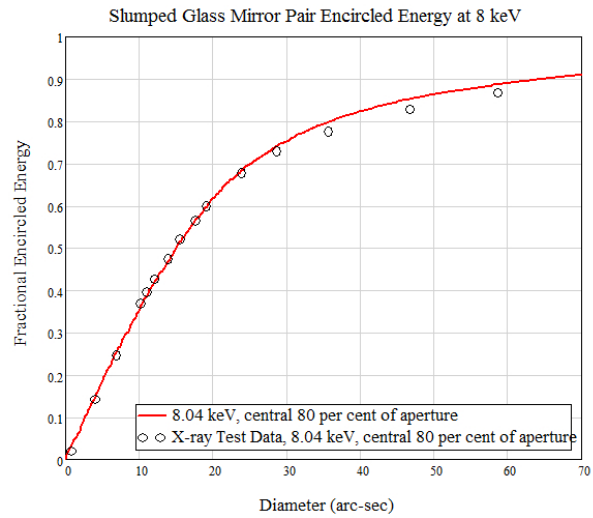

Figure 3-1. Slumped glass mirror performance.

What needs to be done?

1) To achieve TRL 6 for a 5 arcsec HPD Observatory in FY12, we have established a technology development plan that addresses the performance limiting items, described above. Several mandrel release layer treatments are being pursued to reduce mid-frequency error; polishing the boron nitride layer, and using sputtered platinum as a release layer. Better figured slumping mandrels (2 arcsec vs. ~ 7 arcsec HPD) are being produced using existing technology. Coatings that balance chrome and iridium deposition stresses are being investigated to reduce axial sag error due to coating stress. Improved bonding of mirrors in flight-like mounts are under investigation to achieve mounting and alignment error budget allocations.

2) Development is also required to demonstrate that silicon pore optics can meet the 5 arcsec HPD over a full stack of 45 plates: imaging performance degrades as more stacked plates are illuminated. This is believed to result from particulate contamination present during the stacking process producing distortions in the optical surfaces. Module development will focus on particle detection and removal during stacking, metrology improvement, and fabrication of inner radius modules (whose smaller radius makes stacking more difficult).

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X-Ray Microcalorimeter Spectrometer

The IXO XMS provides high resolution imaging X-ray spectroscopy. The instrument must achieve a spectral resolution better than 2.5 eV over at least a 2' field of view, and better than 10 eV out to at least 5', and provide this capability for at least five years. To meet these requirements, the XMS is base-lined to use a 4-kilo-pixel array of X-ray microcalorimeters with transition edge sensor (TES) thermometers. The array will be read out with a multiplexed SQUID array and the detector assembly will be cooled to 50 mK with a multistage ADR and long-life mechanical cryocooler. NASA, ESA, and JAXA are pursuing technology development in these areas. Two approaches are under development for the read out of the array, and there are several approaches for realizing the cryocooler technology.

What needs to be done?

For the array, 32 × 32 arrays are now being fabricated in the US and in Europe that will be used to measure energy resolution performance and quantify noise budgets, and provide a test platform for developing the multiplexed SQUID read out systems. Further, work is underway to implement multi-absorber TES devices to extend the field of view, and improving heat sinking so that kilo-pixel arrays can be fabricated that meet the energy resolution requirement with high uniformity across the array.

A prototype time-division-multiplexing (TDM) SQUID readout system has been successfully implemented and tested to evaluate its performance as a function of the number of channels read out. A project milestone was to read out two columns of 8 TES with better than 4 eV resolution, and a value of 2.9 eV was achieved with high uniformity. As the number of channels was increased, the SQUID MUX caused increasingly degraded performance as the number of multiplexed rows was pushed to 12, 16, and 20. In order to multiplex 32 rows of TES pixels with time constants similar to those of the 2 × 8 demonstration while meeting stricter energy-resolution requirements, we foresee the need for two straightforward improvements to the TDM system: lower SQUID noise and faster switching speed. First, reduction in SQUID noise will allow the coupling of the signal current to the SQUID to be reduced, which in turn will relax the amplifier slew-rate requirement. Such reduction will be achieved by better heat sinking of the multiplexer chip and by implementation of a new generation of quieter series-array (SA) SQUIDs placed on the 50 mK stage. Second, increasing the row-switching speed by a factor of four will allow 32 rows to fit in the same frame-time in which eight rows fit previously. At ESA and JAXA, Frequency Division Multiplexing (FDM) with Base-band Feedback is being pursued as an alternate approach and should be demonstrated later this year.

A five-stage continuous ADR (CADR) is baselined for XMS to provide the required cooling power within mass constraints. The prototype CADR for IXO achieves more than 10 times the cooling power of the XRS ADR, with about half the mass. Additionally, operating temperatures as low as 35 mK have been demonstrated, as well as the ability to reject heat at temperatures as high as 5 K. The next steps are to fabricate the two-stage ADR system and qualify it for the JAXA/NASA Astro-H project, and then similarly fabricate and environmentally test a prototype five-stage ADR system.

Cryocoolers with all of the essential component technologies for the XMS have flown in space since the early 1990s with very high success rate. Half of the cryocoolers have been operating continuously for 5–10 years, with some having outlived their instrument or mission. All of these applications required cooling between 50 K and 80 K, but the XMS requires significantly lower temperature cooling (< 6K). The JWST/MIRI 4He Joule-Thomson (JT) hybrid cryocooler, optimized for 6K, has recently been run in the 4K range and plans are in place to modify the cryocooler for use with ^{3}He for lower temperatures. Similarly, the Japanese SMILES instrument uses a ^{4}He JT cooler (~ 4K) and is awaiting launch to the ISS, and a 1.8 K ^{3}He JT cooler has been fabricated in Japan and just started undergoing life-testing.

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IXO X-ray Grating Spectrometer

IXO science requirements place stringent constraints upon the X-ray Grating Spectrometer (XGS) instrument; resolving power R ($\lambda/\Delta\lambda$) > 3000, and system effective area of 1000 cm^2 from 0.2 to 1 keV. Two grating spectrometers are under development to meet these requirements.

The first, using off-plane reflection gratings (OPRG), is being developed by the Universities of Iowa and Colorado. X-rays focused by the FMA are reflected by gratings with rulings in the plane of incidence, dispersing the X-rays onto a set of CCDs arrayed in an arc. Larger area OPRG have been flown on sounding rockets that have parallel rulings, rather than rulings which are arrayed radially from the system focus. This reduces the resolving power that can be achieved with the gratings.

The second—the critical angle transmission grating (CATG)—is being developed by MIT (Fig. 3-2) with heritage from the Chandra gratings approach. It behaves like a blazed transmission grating, and X-rays are dispersed along a linear array of CCDs. The required ruling density has already been achieved with the CATG. The CATG grating efficiencies were measured in synchrotron beamlines, and measured efficiencies are consistent with theoretical predictions.

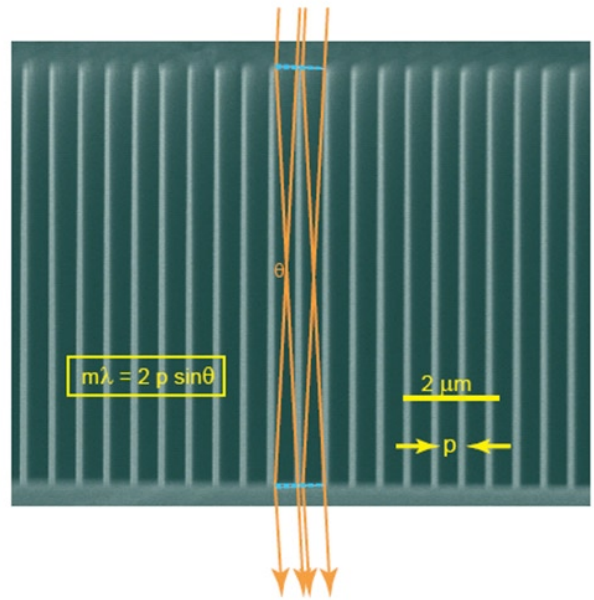

Figure 3-2. Cross-section scanning electron photograph of CATG.

What needs to be done?

The technology development plans for both approaches focus on improving the grating efficiencies and fabrication issues.

The first milestone for the OPRG will be a grating with the required ruling density in a radial radial pattern (the rulings must converge at the system focus), and a measurement of the resulting grating efficiency. Ensuring that flatness, alignment, and mounting tolerances of the grating plates are met will also be a development milestone. Subsequent milestones will be characterizing the polarization sensitivity of the grating efficiency.

Two key milestones for the CATG are (1) the increase in individual grating sizes (from mm to cm) in order to simplify the construction of the grating array, and (2) to increase the aspect ratio of the grating (which results in higher efficiencies) while simultaneously increasing the ratio of the grating "open area" to its structural support area,

The CCD detectors (common to both approaches) require very high quantum efficiency at the low-energy end of the XGS bandpass: the required optical blocking filters present a trade between X-ray transmission and out-of-band rejection. Techniques are being developed to deposit extremely thin (< 0.1 µm) layers with high uniformity directly onto the CCD surface. Higher CCD readout rates will also reduce the number of out-of-band photons detected per X-ray photon, helping to relax blocking filter requirements—thus higher-speed, low-noise readout techniques are planned.

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4. ORGANIZATION, PARTNERSHIP, AND STATUS

The International X-ray Observatory (IXO) mission will be implemented as a tri-agency partnership between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Japan Aerospace and Exploration Agency (JAXA). All three agencies have extensive expertise and experience in space science missions, spaceflight system development, and X-ray instrumentation. The agencies have partnered successfully in the past on astrophysics missions such as XMM-Newton (ESA-NASA), and ASCA and Suzaku (JAXA-NASA).

IXO is the result of merging the NASA Constellation-X (Con-X) and ESA/JAXA XEUS mission concepts in July 2009. Both mission concepts had been under study by their respective agencies for a decade. Con-X was the second priority major space initiative for the US in the 2000 Decadal survey. XEUS was recently selected as one of three candidate large missions in ESA's Cosmic Visions (CV) program.

NASA, ESA, and JAXA established the IXO Study Coordination Group (SCG) to oversee the mission concept development in preparation for Astro2010 and for the ESA CV selection process. The activities have focused on consolidating the science objectives, mission performance requirements, and observatory implementation. Three supporting international groups are the Science Definition Team (SDT), the Instrument Working Group (IWG), and Telescope Working Group (TWG).

ESA and NASA will define the mission leadership roles and responsibilities based on the output of the current studies, available funding, the selected mirror technology, and programmatic considerations. The modular nature of the IXO observatory provides clean and simple interfaces to facilitate sharing the development between international partners. The lead agency responsibilities will include spacecraft bus module development, mission systems engineering, observatory integration and test. The implementation must be compatible with an ESA-provided Arianne V or a NASA-provided Atlas V launcher. Both NASA and ESA are developing technologies for the Flight Mirror Assembly (FMA). The decision on the FMA lead agency will be made after the mirror technology milestones are demonstrated in 2012. The Instrument Module and its integration with the instruments, as well the Deployment Module can be separate well defined contributions.

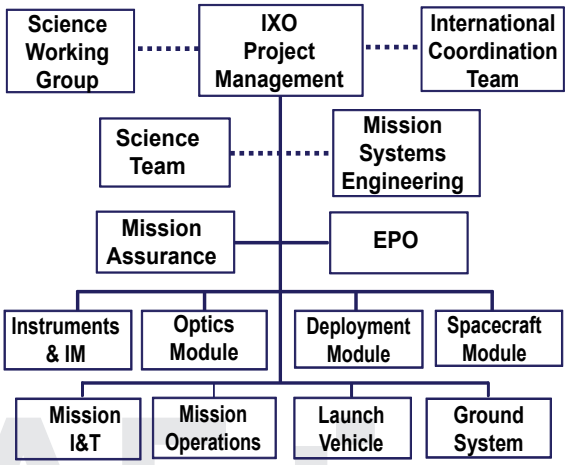

Figure 4-1. IXO Organization Structure

The current payload compliment is a straw person example used to define the overall mission. The final instrument payload will be selected via a multi-agency Announcement of Opportunity (AO) process. We note that there have been many successful examples of international cooperation in developing X-ray instrumentation, e.g., the gratings on Chandra and XMM-Newton. Within ESA it is typical for instruments to be multi-national consortia and there is heritage for JAXA/NASA collaborations.

A summary-level project organization chart is given in Fig. 4-1. The overall structure reflects the modular approach to the observatory development. Key stakeholders across the IXO team form the International Coordination Team that expedites resolution of issues across institutional boundaries. NASA's role in IXO will be managed by GSFC. NASA will competitively select any industry contractors for the spacecraft and/or FMA development. Elements of the observatory may be developed in-house at GSFC.

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5. SCHEDULE

The top level mission schedule is shown in Fig. 5-1. This schedule supports a May 2021 launch readiness, with 7 years and 2 months for development (Phases B, C, and D). Nine months of funded schedule reserve has been included on the critical path. Five years of mission operations after launch are nominally planned, with an option to extend the science mission to 10 years.

The schedule reflects the plan to capitalize on the modular nature of IXO. Each of the four Observatory modules (Optics Module, Instrument Module, Spacecraft Module, and Deployment Module) are developed and qualified in parallel, and then delivered for final Observatory Integration and Test (I&T). Milestones and key decision points consistent with NASA 7120.5D are used in the overall planning. Time has been allocated as appropriate for each of the processes for solicitation, selection and contract awards.

The critical path runs through the development of Flight Mirror Assembly (FMA) to Observatory I&T to the launch site operations and launch. A detailed mirror schedule reflecting lessons learned from NuStar mirror segment fabrication facilitization and initial production, IXO technology development, and Chandra mirror calibration and test has been rolled up into the summary schedule. Observatory I&T reflects activities, flows, and durations that have been developed based experience from other space observatories of comparable size and type.

A total of nine months of schedule reserve has been allocated on the critical path. Three months are currently allocated to the FMA development. Five months is held on the Observatory I&T line. Three additional weeks of reserve is held for launch site activities. Ample schedule reserve is also allocated for activities that are not on the critical path as indicated in Fig. 5-1.

Multiple industry studies for the mirror implementation will be performed in 2011 and 2012. A technology review and subsequent decision on which mirror technology to baseline will occur in mid-2012. NASA, ESA, and JAXA will finalize the responsibilities for each agency for IXO by the end of 2012.

In 2012 and 2013, Phase A parallel studies of the overall Observatory implementation concept and plans will be conducted by two or more industry contractors. At the end of these, a Request for Proposals (RFP) will be issued to select the observatory prime contractor, who will also provide the Spacecraft Module (SM).

The Announcement of Opportunity (AO) for science instrument teams will be released in late 2011 and instrument contracts awarded by the end of 2012. The instrument design reviews (Preliminary Design Review and Critical Design Review) will be timed to support instrument development instrument, and will occur prior to similar reviews at the mission level. All instruments will be fully tested and qualified prior to delivery to the Instrument Module (IM). After the instruments are integrated onto the IM, the IM will be tested and delivered for integration with the rest of the observatory in mid-2019. Performing IM I&T with the instruments prior to final Observatory I&T provides early verification of the instruments in their flight assembly, reducing overall schedule risk.

Spacecraft Module (SM) I&T will begin with delivery of the qualified primary structure and integration of the propulsion system onto the structure. After completion of SM I&T, Observatory I&T will commence with integration of the Deployment Module with the SM. Integration of the IM and the Optics Module will be next, followed by Observatory environmental and functional testing.

The development of the Ground System (GS), Mission Operations (MO), and science Data Analysis (DA) system will occur in parallel with the observatory development as with major reviews as indicated in Fig. 5-1. Phase E duration is five years.

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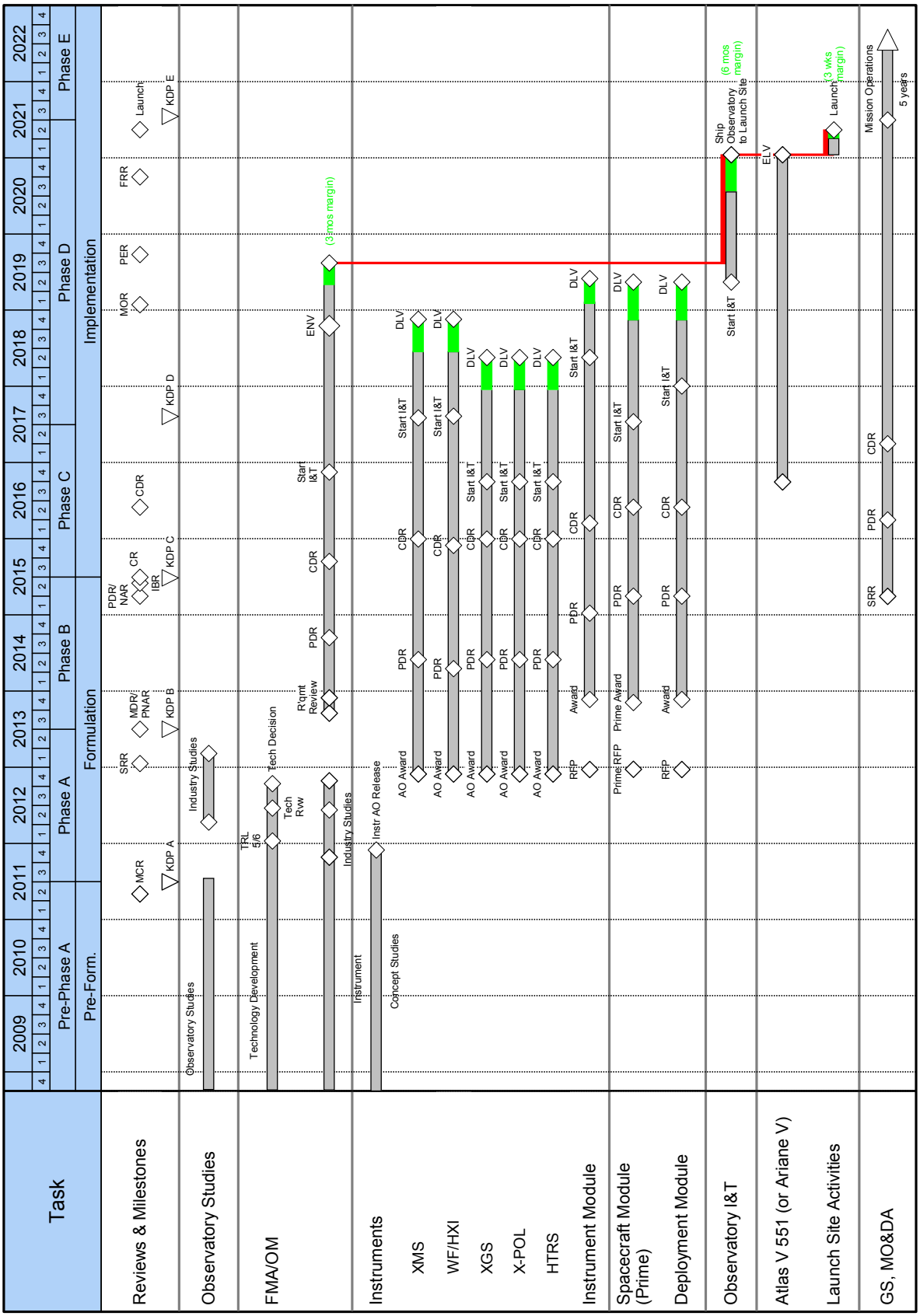
Fig 5-1. IXO Mission Summary Schedule



6. COST

The IXO cost to NASA is currently estimated to be ~$1610M (FY09 dollars), including $95M for grants to the US scientific community. This cost to NASA includes mission formulation, development and operational phases. This pre-liminary estimate has been generated based on an estimate of the full mission cost with deduc-tions for the anticipated contributions from inter-national partners including the European Space Agency (ESA), European member states, and the Japanese Aerospace and Exploration Agency (JAXA).

The mission cost estimates are preliminary and currently under development and refinement. An Independent Cost Estimate (ICE) has been initiated by Aerospace Corporation, as directed by NASA Headquarters. Final project cost estimates will be completed by summer 2009, after reconciliation with the ICE.

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Cost Estimating Process

Cost estimates for each element of the full mission are generated in FY09 dollars. Estimates are generated as 70% confidence where possible. For those elements, where explicit 70% confidence estimates do not yet exist, additional funds have been added to the estimate to account for the difference.

Initial estimates of the current IXO concept use a variety of methods including parametric cost modeling, analogy, and grass roots costs estimates. These cost estimates are initial iterations for the IXO configuration, and were generated over the period of time between June 2008 and February 2009. Updated cost estimates using the most current configuration information are underway. We expect the cost estimating process to continue in an iterative manner as we refine our understanding of the mission cost drivers and implement cost effective alternatives, where feasible. In addition, multiple methods of estimating will be incorporated, as possible, to provide additional validation and understanding of the costs.

Parametric Review of Information for Costing and Evaluation Hardware (PRICE-H) has been the primary tool for cost estimates of the majority of flight hardware systems. PRICE-H analyses for IXO have been performed by GSFC. A thorough Master Equipment List (MEL), currently with over 300 entries, has been used to generate the PRICE-H estimate. The MEL was generated by experienced engineers and includes catalog costs, where off-the-shelf units (such as star trackers, reaction wheels, etc) have been identified in the observatory design.

Some of the instrument costs have been generated using analogy to heritage spaceflight instruments accounting for difference in size and technology infusion. These analogy estimates have been provided by potential instrument providers, who have substantial involvement with the predecessor instruments. Validation of these costs is planned using PRICE-H or other means.

The Ground System, Mission Operations, Science, and Data Analysis cost estimates were generated by grass roots with strong analogy to similar activities for Chandra. These cost estimates were generated by the Smithsonian Astrophysics Observatory, which operates the Chandra X-ray Center under contract to NASA.

Cost Contributions

A summary of the preliminary cost contributions from the international partners on IXO are provided in Table 6-1.

Contributions from ESA, European member states, and JAXA are estimated on the basis of discussions among the participants taking into account the current cap of 650M Euro for Large Cosmic Vision missions. Specific division of responsibilities for the partners has not yet been defined by the agencies. European member states are likely to provide the WFI/HXI, HTRS, and X-POL instruments, as well as partner on the XMS, and these are reflected in the contribution summary. JAXA will likely provide the Hard

Table 6-1 IXO Mission Costs & Contributions.

Contributors	($FY09)M
NASA	1610
ESA	920
European Member States	300
JAXA	170
Mission Total	**3000**

Table 6-2 IXO Cost by Phase.

Funding Source	Mission Phases (M FY09$)				
	A	B	C/D	E	Total
NASA	$80	$190	$1,062	$278	$1,610
Contributions	$37	$362	$944	$47	$1,390
Total	$117	$552	$2,006	$325	$3,000

X-ray Imaging detector to the WFI/HXI, and may contribute to the Deployment Module and/or the hard X-ray mirror module of the FMA.

Cost by Phase

The estimates for cost to NASA are provided by major development phase (Phase A-D) and for operations (Phase E) in Table 6-2. The operations phase of $325M includes $95M in direct funding for the scientific community. No unusual costs at the end of the mission life are required.

The funding is phased so that approximately 22% of the total funds are in Phases A and B, not including costs for mission studies and technology development to date; 67% is required for Phase C/D; and 11% in Phase E.

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