The Next Generation X-Ray Observatory

N.E. White, R. Petre, E.A. Boldt, S.S. Holt, P.J. Serlemitsos, F.E. Marshall,
C.K. Stahl, R. Kelley, K. Arnaud, A.E. Szymkowiak, R.F. Mushotzky, Y. Soong,
N.A. Gehrels, A. Parsons, K. Jahoda, J.H. Swank, T.R. Kallman, K. Mukai,
S. Drake and I.M. George

Laboratory for High Energy
Astrophysics

SW 9543

Goddard Space Flight Center
Greenbelt, MD 20771

The Next Generation X-ray Observatory

N.E. White, R. Petre, E.A. Boldt, S.S. Holt, P.J. Serlemitsos,
F.E. Marshall, C.K. Stahle, R. Kelley, K. Arnaud, A.E. Szymkowiak,
R.F. Mushotzky, Y. Soong, N.A. Gehrels, A. Parsons, K. Jahoda,
J.H. Swank, T.R. Kallman, K. Mukai, S. Drake, and I.M. George.

Laboratory for High Energy Astrophysics,
NASA Goddard Space Flight Center,
Greenbelt, MD 20771.

Paper presented at the SPIE 40th Annual Meeting in San Diego '95,
EUV, X-ray, and Gamma-ray Instrumentation for Astronomy VI.
To appear in the Conference Proceedings Vol 2518,
Ed. O.H. Siegmund and J.V. Vallerga

Abstract

We are studying a Next Generation X-ray Observatory, NGXO, that will provide a high resolution spectral capability with large collecting area, at a relatively low cost. The mission consists of two co-aligned telescope systems that provide coverage from 0.3–60 keV. One is optimized to cover the 0.3–12 keV band with 2 eV spectral resolution using an array of quantum calorimeters with a peak effective area of 2,000 cm². The spectral resolution will be five times better than the calorimeter planned for Astro-E, with more than a ten-fold increase in effective area over previous high resolution X-ray spectroscopy missions. The second telescope will be the *first* focusing optics to operate in the 10–60 keV energy range, and will have arc minute angular resolution with 500 cm² collecting area at 30 keV. The sensitivities of the two telescopes are matched to make possible many thousands of high quality X-ray spectral observations, from an available population of more than one million galactic and extragalactic X-ray sources.

The NGXO mission is capable of addressing new astrophysical problems which include: determining the mass of a black hole, neutron star or white dwarf in binary systems from X-ray line radial velocity measurements; determining the 0.3–60 keV X-ray spectrum from AGN and determining their contribution to the X-ray background in this energy band; measuring Compton reflection spectra from cold material in accretion driven systems; determining the Hubble constant using resonant line absorption of QSO spectra by rich clusters; searching for a hot 10 million degree intergalactic medium; mapping the dynamics of the intracluster medium; mapping the ionization state, abundance and emission from supernova remnants on a 15 arc second angular scale; and measuring mass motion in stellar flares and the dynamics of accretion flows.

Keywords: X-ray Astronomy, spectroscopy, calorimeter, grazing incidence optics, multilayers, mission concept.

1. Introduction

The Astrophysics Division of NASA's Office of Space Science recently issued a call for proposals for new Astrophysics missions, with the aim of funding concept studies directed toward missions that fly after the year 2000. This paper describes one of four X-ray astronomy mission concepts accepted as part of this study. Our concept is a high spectral resolution, large throughput, broad band pass X-ray astronomy mission that utilizes next generation detector technology to provide a major breakthrough in capability.

The three major new X-ray observatories AXAF, XMM and Astro-E, that begin operation around the turn of the century, will herald a new era in X-ray astronomy. The workhorse instruments on these observatories are CCD cameras providing a spectro-imaging capability with an energy resolution of ~ 100 eV over the 0.4–10 keV band. The ASCA mission, launched in Feb 1993, carried the first X-ray CCD cameras and has been the pathfinder for the coming X-ray observatories. The first ASCA results (*see Ap J Letters vol 436 no 1, pt 2*) amply demonstrate the capabilities of X-ray CCD detectors to observe all classes of objects from nearby stars to high-redshift quasars. The larger throughput and improved angular resolution of AXAF, XMM and Astro-E will result in tens of thousands of high quality CCD X-ray spectra from objects of all classes. All of these missions carry higher spectral resolution devices (gratings on XMM and AXAF and a micro-calorimeter on Astro-E) and these will gather detailed spectra of the brighter sources.

In Figure 1 we show for these three missions the expected spectral resolution ($R = E/\Delta E$) as a function of energy and the effective area for the best spectrometers ($R > 250$). Both XMM and AXAF use grating spectrometers to obtain higher resolving power. The two sets of gratings on AXAF have $R \sim 500$ –1000 from 0.1–2.0 keV, with an effective area ranging from 3 to 180 cm². The peak effective area of the reflection gratings on XMM is slightly higher, ~ 280 cm² (combining two telescopes and the 1st and 2nd orders). They cover the energy range 0.3 to 2.0 keV, with $R = 200$ –800. The imaging crystal spectrometers planned for Spectrum-X Gamma (not shown) will give resolving powers of 1,000–3,000 narrowly centered on the Fe, S, Ar and O K lines, with an effective area of 2–5 cm². The X-ray Spectrometer, XRS, originally to be flown on AXAF, and now to be included as part of the Japanese Astro-E mission, utilizes an array of micro-calorimeters with an energy resolution of 10 eV, across the 0.3–8 keV band, which includes the K lines of most of the important medium-Z elements. The XRS has superior spectral resolution to the AXAF gratings above 3 keV, and with a relatively constant effective area of ~ 300 cm², comparable to that of the AXAF CCD detectors.

While these new capabilities offer a major increase in performance, they have some serious limitations that must be addressed by a follow-on X-ray observatory. The AXAF and XMM gratings cannot be used to study extended sources because the spatial extent of the X-ray emission will hamper their sensitivity to line emission by creating confusion between spatial and spectral features. This is unfortunate because supernova remnants and clusters of galaxies are among the most line-rich X-ray sources. The Astro-E XRS will be able to observe extended sources, but the ~ 10 eV resolution is insufficient at 1 keV to fully resolve many of key line complexes required for plasma diagnostics. The collecting areas of the grating spectrometers are factors of 5–10 less than the CCD cameras on their respective missions and will require long exposures of 10^5 – 10^6 s to obtain high quality spectra, even on the brightest *point* sources. On AXAF the gratings must share the observing time with the imaging experiments and the Astro-E XRS has a limited 2–3yr lifetime, because of the need for cryogenic cooling.

Another limitation is that the current generation of imaging X-ray telescopes have an upper energy threshold of 8–10 keV, above which the effective areas drop precipitously. The only possible exception is the Spectrum-X Gamma mission, whose telescopes have a limited ~ 60 cm² effective area up to ~ 20 keV, with arc-minute angular resolution. Observations above 20 keV are currently limited to using collimators or masks that have spatial resolutions ranging from arc minutes to degrees. The large size of the detectors means that these observations have been severely limited by background. The first results from ASCA are showing that sensitive observations of the >10 keV band are necessary to constrain the continuum spectra of many classes of X-ray source. This is crucial in highly absorbed sources and sources where the Compton reflection of X-rays from cold material is present. Extended energy coverage is also necessary to differentiate between thermal and non-thermal emission.

Figure 1: *Top:* The resolution as a function of energy for the spectrometers to be flown on AXAF (METG, HETG), XMM (1st order), Astro-E and that proposed for NGXO using a 2 eV micro-calorimeter array. *Bottom:* The effective area of the AXAF, XMM, Astro-E and NGXO spectrometers as a function of energy. For clarity only the AXAF medium and high energy gratings and first order XMM reflection grating spectrometers (RGS) are shown.

The Next Generation X-ray Observatory, NGXO, mission concept we are proposing utilizes expected advances in X-ray instrumentation to address the shortcomings of using dispersive spectrometers, and to provide a new hard X-ray capability.

2. The Baseline Instrumentation Payload

In the baseline concept we use two telescope systems, to cover the 0.3–12 keV and the 12–60 keV bands. There is a natural break point at ~ 12 keV because the atomic line transitions from the most abundant elements fall below this energy. Except for rather broad cyclotron features, the > 12 keV spectrum should be devoid of lines until nuclear line transitions start to appear around 60 keV. The low energy system is optimized for High Throughput X-ray Spectroscopy, HTXS, and maximizes spectral resolution. The higher energy system will be the first Hard X-ray Imaging Telescope, HXIT, and is optimized to give the maximum imaging and spectroscopic capability possible in this band. The baseline NGXO mission concept is sized to fit a *Delta* launch vehicle. The estimated end-to-end mission cost is \$399M (including \$75M MO&DA for an assumed 5 yr mission lifetime and a 20% contingency).

2.1 The High Throughput X-ray Spectrometer, HTXS

The micro-calorimeter array to be flown on Astro-E is the first flight of a new generation of X-ray spectrometer. Compared to an equivalent dispersive device it has a much higher quantum efficiency, and a larger dynamic energy range. This allows the simultaneous measurement of all the relevant emission lines and the continuum over a broad band. This device also facilitates spatially resolved spectroscopy, limited only by the instrument field of view and angular resolution. The 10 eV resolution of the Astro-E XRS is not the limiting resolution of this technology. An advanced micro-calorimeter array is currently under development that promises to give a resolution of ~ 2 eV, a factor of 5 improvement. Over the 0.3–12 keV band this corresponds to $R \sim 400$ –5000, which at 1 keV is comparable to the resolution to be attained with the XMM gratings (Figure 1).

Micro-calorimeters for X-ray spectroscopy were invented 10 years ago and determine the energy of an absorbed X-ray photon by measuring the resulting increase in temperature. The energy resolution is independent of photon energy over the energy band for which a calorimeter is optimized. The essential components of a calorimeter are an absorber, in which the energy of the X-ray is converted to heat, and a thermometer, which provides the signal. The device is connected to a heat sink by a weak thermal link to allow recovery of the base temperature after a photon is detected. In the Astro-E XRS detectors, an ion-implanted silicon thermistor serves as the thermometer, and a 12 micron HgTe layer serves as the absorber. The intrinsic limit on the resolution of the XRS calorimeter design, 3–5 eV for a heat sink temperature of 65 mK, comes from the Johnson noise associated with using a resistive thermometer and from the magnitude of thermal fluctuations (determined by the device heat capacity and temperature). Devices similar to those to fly on Astro-E have been fabricated with resolution at 5.9 keV around 12 eV; a resolution of 7 eV has been measured using a calorimeter with a lower heat capacity.

To study the iron K line the absorber must be thick enough to provide good quantum efficiency at 6 keV, and up to 12 keV, if possible, to cover all the available atomic line transitions. Because the resolution scales as the square root of the heat capacity, simply reducing the absorber thickness can improve the energy resolution, but at the loss of high energy efficiency. In order to improve the resolution to 2 eV, we need to reduce the device heat capacity without compromising quantum efficiency, or to replace the thermistor with a non-resistive thermometer, which would not suffer from Johnson noise which limits the current thermometer design. We have identified several possible approaches in both cases and expect substantial progress towards our 2 eV goal in the next two years.

The planned mission duration for NGXO requires a 5 yr lifetime for the cooler, which is required to maintain a heat sink at 65 mK. Astro-E will use a three stage cooler. In the outer stage, solid neon cools an inner volume to 15 K. A central insert is in turn cooled by pumped liquid helium to 1.2 K. Finally, an adiabatic demagnetization refrigerator is used to cool the detector heat sink to 65 mK. We anticipate a similar cooling apparatus for HTXS. Optimal choice of the cryogenics and other design issues which balance lifetime, robustness, cost, and mass against each other are issues for study. A five year lifetime is possible,

within the baseline mission parameters.

The spectrometer will be placed at the focus of a 1 m diameter foil X-ray telescope with a peak effective area of $\sim 2,000 \text{ cm}^2$ with an angular resolution of < 15 arc second half power radius, HPR. The field of view is limited by the dimensions of the micro-calorimeter array, and is baselined to be 3 arc-minutes, with 100 pixels. The combined telescope and instrument effective area is shown in Figure 1. The effective area up to 12 keV is kept relatively constant using a four-reflection grazing-incidence foil mirror with an 8 m focal length. This combination has a factor of 5 higher throughput and resolution than the Astro-E XRS and a factor of two better spatial resolution.

The combination of high quantum efficiency, with high throughput X-ray optics, gives a much faster spectrometer than the currently planned instruments (Figure 1). The spectral resolution is superior above ~ 2 keV, and with a much higher overall grasp. Below ~ 0.4 keV, the performance is no longer competitive with the AXAF or XMM gratings. However, this is not a major concern because the interstellar medium causes the vast majority of X-ray sources to be cut-off around this energy.

Experience with ASCA shows a minimum of 3000 counts are required to obtain a good quality spectrum. If we take $\sim 10^5$ s as a typical observation time, then for a typical AGN spectrum, the weakest observable source will have a 0.3–10 keV flux of $6 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ (twice the flux in the Einstein IPC or ROSAT PSPC band). The sensitivity to line emission is given by considering a narrow line detected at 4σ (~ 20 counts) in 10^5 s. This gives a line flux of $2 \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$, which corresponds to the Fe K 6.4 keV line emission from an AGN with a flux of $1 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (equivalent width ~ 150 eV).

The logN-logS for extragalactic sources shows that over 10^6 sources are available above a flux of $3 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the ROSAT band (~ 20 sources degree^{-2}). ROSAT images obtained with 25 arc second spatial resolution demonstrate that even at a deeper 0.1–2 keV flux of $\sim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ source confusion is not an important issue. Using the ROSAT logN-logS value and a 15 arc second radius gaussian beam gives a confusion level for NGXO of $\sim 5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.2–2 keV band.

2.2 The Hard X-ray Imaging Telescope, HXIT

Previous or planned instruments in the > 20 keV band utilize either collimated or coded mask detectors. A focusing optic provides a dramatic improvement in sensitivity because of its *focusing advantage*, which places a large fraction of flux falling over the aperture area onto a relatively small spot on the focal plane. This is unlike coded mask systems which have a *multiplex advantage* because each detector element can see many points on the sky. The reduction in particle and sky background in a focusing system represents a significant advance.

Multilayer coatings have been successfully used in the XUV region to enhance reflectivities in wavelength regions and for angles of incidence where simple materials with useful reflectivities are not available. The basic principle uses thin film interference to enhance reflectivity, similar to Bragg reflection. Two materials of different refractive indices are alternately deposited in a quarter wave stack (where $d = \lambda/4$). The number of layers can be up to several hundred and is optimized, along with the deposition thickness, to maximize the reflectivity at the desired wavelength. In the UV and soft X-ray domains, the trick is to use materials that are not highly absorbing. In the hard X-ray domain, where it is possible to use absorption-free materials, a multilayer coating can be designed with a very broad bandwidth, by layering coatings of different thickness. The incident radiation is transmitted until it reaches a resonant layer and is reflected.

The Hard X-ray Imaging Telescope, HXIT, in our baseline mission uses multilayer coatings on conical foil mirrors to enhance its high energy efficiency. In Figure 2 we show the effective area curves predicted for a W/Si (Tungsten-Silicon) multilayer design with a focal length of 15 m. The effective area at 30 keV is 500 cm^2 . The ragged appearance of the multilayer effective area curve is a consequence of the use of interference to reflect X-rays. The interfaces within the multilayer stack must be smooth; otherwise a loss of reflectivity will occur. Current deposition techniques can achieve thickness errors of $< 0.1 \text{ \AA}$ per layer with accumulated thickness errors of $< 0.5 \text{ \AA}$ over 100 layers. The combination of W and Si yields the smoothest multilayer, and provides excellent response up to 60 keV, where the response is ultimately limited by the W K-edge. It is interesting to compare these with the effective area curves for the conventional, gold-coated foil mirror

Figure 2: The effective area predicted from ray tracing for a 4 m four reflection gold coated foil, a 15m two reflection gold coated and a 15m two reflection Tungsten/Silicon (W/Si) multilayer foil telescope.

and a four-reflection 4 m design is also shown in Figure 2. Utilizing a four-reflection design with multilayers would be a powerful combination and should give an effective area curve comparable to a 15 m 2-reflection system, but with an 8-m focal length. The field of view will be strongly dependent on energy, decreasing from 30 arc minutes at 10 keV to a few arc minutes at 60 keV.

A hard X-ray detector must have good efficiency throughout the 10–60 keV energy range. Since there are no narrow atomic lines expected in this region, energy resolution is less of a concern. The required pixel size is 200 microns to provide about 5 resolution elements within the ~ 1 mm (half-power diameter) mirror point spread function. The fine position resolution required in this hard X-ray detector suggests the use of fine pitch semiconductor strip detectors. There are many semiconductor materials to choose from such as the relatively new material cadmium zinc telluride (CdZnTe) as well as the more familiar silicon (Si) and germanium (Ge) materials.

For NGXO, we baseline a CdZnTe strip detector. CdZnTe is a wide band gap compound semiconductor that shows great promise for hard X-ray astrophysics. With a high Z ($Z_{Te}=52$; $Z_{Cd}=48$) and high density (5.9 g cm^{-3} ; 2.5 times that of Si), the absorption efficiency for a 2 mm thick planar CdZnTe detector is 100%. The wide band gap (1.55 eV) allows room temperature operation. A CdZnTe detector development effort is underway at Goddard to develop strip detectors with 100 micron pitch. With the current technology, the energy resolution of CdZnTe devices at 30 keV is about 2–3 keV for room temperature operation: cooling the detectors to -20°C increases the resolution to <1 keV. At 5 keV, we can currently achieve 0.9 keV resolution. We expect the resolution to improve in the future with the development of strip contacts and electronic signal processing techniques such as pulse shape discrimination methods.

The detector background (sky and particle) will be very low with $\sim 10^{-5} \text{ count s}^{-1}$ and can be neglected. Requiring that 20 counts be observed from a source (a 4σ detection) in a 10^5 exposure of a 5 keV band centered at 30 keV, then for an effective area of 500 cm^2 at 30 keV the continuum sensitivity is $\sim 2 \times 10^{-7}$

$\text{ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$, or $20 \mu\text{Crab}$. This is ~ 100 times more sensitive than the INTEGRAL X-ray monitor (which will require exposure times of 10^6 s) and 50 times better than XTE (but with much better spectral resolution). A typical AGN with a flux in the 0.3-10 keV band of $\sim 1.0 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (or $\sim 5.0 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the Einstein IPC) will give 1,000 counts between 20 and 50 keV in 10^5 s , sufficient for a spectral measurement. There are $\sim 10^4$ AGN available at or above this flux level. Sources a factor of 50 fainter will be detectable by this telescope.

In the above example while the HXIT detects 1,000 counts between 20 and 50 keV, the HTXS will gather about 60,000 photons at lower energies. In spite of this factor of 60 difference, the sensitivities of the two co-aligned telescopes are in fact well matched. This is because HTXS will require many more photons to determine line parameters in great detail, whereas in the line-less hard X-ray band, 1000 counts is sufficient to constrain the high energy continuum.

2.3 Mission Parameters

Preliminary estimates of the size and mass of the spacecraft and instrumentation have been made based on scaling from components of missions with similar payloads. These estimates have been used to baseline the Delta II 7925 as the launch vehicle. As part of the study, these estimates will be refined; power, telemetry, thermal and attitude control requirements will be defined; and additional detailed spacecraft characteristics will be developed.

Dimensions: To reduce the size of the fairing and thus the launch costs, we intend to employ an extendible optical bench (EOB). An EOB was used on ASCA, and they will be used on both Spectrum-X Gamma and Astro-E. The required degree of extension depends on the size of the spacecraft fairing. The Delta launch vehicle comes with 9 1/2 foot and 10 foot fairings. Because the top of the experiment needs to be wide enough to hold both mirror assemblies ($\sim 1.83 \text{ m}$ across), the 10-foot fairing is preferred. Based on the Astro-E dewar design with a diameter of 0.99 m, a length of 1.43 m, and the detector 30 cm inside the dewar surface, we obtain a length for the HTXS of 4.17 m without extension. This also assumes the mirror assembly is 0.88 m deep. An 8 m focal length can be achieved with an extension of less than 100%. Squeezing the experiment into the 10-foot fairing with the third stage motor needed for a high orbit allows an unextended length of only 2.47 m. The technical challenge will be to extend to an 8-15 m focal length.

Mass: Our overall mass estimate is 2075 kg, based primarily on current designs for ASCA and Astro-E. The baseline HTXS mirror will require approximately 170 kg of reflectors, and a housing with about the same mass. The HXIT mirror will have about 50 % of the frontal size of the HTXS (a 70 cm diameter), but might require 2-3 times thicker foils to provide a rigid substrate for the multilayers. A first approximation is that both mirrors will have the same mass. The EOB in the Astro-E design has a mass one-third to one-half as much as the mirrors. Summing these together, the total mass of the optical system will be about 1020 kg. Based on Astro-E, the combined calorimeter and cooler mass will be approximately 330 kg. We estimate the CdZnTe detector mass to be about half that of the 4 CCDs on Astro-E, approximately 25 kg. A rough estimate of 700 kg for the spacecraft mass can be obtained from the current Astro-E allocation of 500 kg, which does not include the attitude control system.

The weight, size and overall cost of the instrumentation rule out NGXO as part of the SMEX and MIDEX programs. However, they are consistent with a Delta II launch to keep the cost to a modest level. The Delta II costs about \$50M. Larger launch vehicles, such as the Atlas, are considerably more expensive. A high earth orbit provides additional observing efficiency as well as long, uninterrupted viewing intervals at the penalty of reduced weight and size. The Delta II 7925, which contains a third stage, can place a 1556 kg spacecraft into a $1,000 \times 70,570 \text{ km}$ orbit with a period of 24 hr. Our weight estimate, which does not include any contingency, exceeds by more than 500 kg the amount that can be put into this orbit. A low earth orbit with inclination of 28 degrees provides the maximum weight to orbit and additional space in the Delta nose cone (the third stage motor is not needed). Since the Delta II 7920 can place $\sim 4500 \text{ kg}$ into a 600 km circular orbit, it can easily accomodate the estimated weight of NGXO.

A preliminary estimate for the mission cost, based on actual ASCA, XTE, and Astro-E development, is given in Table 1. The baseline mission can be launched within a budget envelope of \$325M (in FY95 \$), which includes a 20% contingency. Operations and data center costs for a five year mission, and funding for guest

Table 1: Mission cost estimate, in FY95 dollars

Item	Basis	Cost (\$M)
Launch (Delta II)	Actual	50
HTXS mirrors	Astro-E	15
X-ray Spectrometer + cooler	XRS	75
HXIT optics	Astro-E	20
HXIT detector	-	5
Spacecraft	XTE	70
Integration	XTE	20
Operations preparation	XTE	15
20% Contingency	-	45
Prelaunch Total	-	324
5 yr operations	0.5×XTE	25
Guest Observer Funding	-	50
Total	-	399

observer research grants bring the total end-to-end mission to \$399M. This is a conservative estimate, and during the study phase we will aggressively pursue options to reduce costs.

3. Science Drivers

3.1 Plasma Physics

The iron K line emission and absorption complex from 6.4–9.1 keV is particularly important because iron is one of the most abundant elements, the physics of the emission process is fairly well understood and the line is isolated from other emission features. It is a sensitive probe of the conditions in plasmas with a temperature range from 10^7 – 10^8 K, typically found in supernova remnants, clusters of galaxies, accretion columns and stellar coronae. It also seen in fluorescence or recombination when an X-ray source illuminates nearby material. Figure 3 shows simulated spectra centered on the Fe K He-like complex at 6.7 keV for the nearby bright stellar coronal source AR Lac. The Astro-E XRS, and the NGXO HTXS spectra are for an 80,000 s exposure. These simulations use the ASCA results which show two temperatures of 7 and 24 million degrees and abundances one third the solar photospheric value. With 2 eV resolution, and high throughput, the NGXO HTXS spectrum fully resolves the density sensitive He-like complex of lines, whereas the Astro-E XRS cannot resolve the complex of satellite lines centered on 6.65 keV. The classical forbidden, resonance and intercombination line diagnostics of the He-like transitions gives a direct density diagnostic.

The iron L line complex around ~ 1 keV is sensitive to lower temperatures of 10^6 – 10^7 keV. Figure 3 also shows the same AR Lac spectrum, this time centered at 1 keV for a simulated 80,000 s observation by one XMM RGS module (for the 1st order), and the NGXO HTXS. In this region the line emission spectrum is dominated by the 7×10^6 K component. With 2 eV resolution the NGXO HTXS delivers comparable spectral resolution to the XMM RGS, but with a factor of 10 increase in effective area (compared to two XMM RGS modules). All the important Fe L shell blends from Fe XVII through FeXXIV are resolved (Figure 3). These Fe L lines are often the strongest seen in celestial plasmas from stars, clusters and galaxies.

There are other K line complexes available in the 0.3-10 keV band including N, O, Ne, Mg, Si, S, Ca, Ar, and Ni, and these will also be available at far greater sensitivity. Each line has a different temperature sensitivity, and together they can be utilized to map the overall emission measure distribution and individual abundances. Table 2 lists some examples of the lines that can be observed, along with the temperatures and densities around which they are most sensitive (Pradhan and Shull 1981; Gabriel and Jordan 1969). The satellite lines of the higher Z elements like Ca and Fe are also ionization and temperature sensitive. For CaXIX, XVIII the typical separation of the temperature sensitive satellite lines ($k=3.865$, $w=3.901$, $q=3.872$ keV) is 5–7 eV. We conclude that 2 eV resolution is sufficient to provide the full range of density diagnostics. The NGXO HTXS will cover all the major K shell transitions, whereas the S, Ca, Ar, Fe and

Table 2: Representative density sensitive He-like transitions.

Ion	E_i (eV)	E_f (eV)	ΔE (eV)	T(MK)	$\text{Log}n_e$
OVII	568	561	7	2	10.5
NeIX	915	905	10	4	11.8
MgXI	1342	1330	8	6	12.7
SiXIII	1852	1839	13	9	13.6
SXV	2449	2439	10	14	14.8

Ni lines are above the threshold of the currently planned XMM RGS, and are at poor resolution and low collecting area for the AXAF gratings (Figure 1).

3.2 Dynamics

The natural widths of the K-resonance transitions are < 0.1 eV, however, it is doubtful that this would be detected in an astrophysical setting because of line broadening. The thermal Doppler width, ΔE_{th} , of an ion is $\Delta E_{th} = 1.5eV(T_7/Z_{Fe})^{1/2}E_{6.7}$ eV. For temperatures $> 10^7$ K thermal broadening of the Fe and Ni lines may just be detectable with 2 eV resolution, which will yield an independent measure of the gas temperature directly from the line shape. However, in many astrophysical situations line broadening and shifts introduced by bulk or turbulent gas motions will dominate. The FWHM broadening expected is $\Delta E_{bulk} = 2.2v_{100}E_{6.7}$ eV, where v_{100} is the gas velocity in units of 100 km s^{-1} and $E_{6.7}$ the line energy in units of 6.7 keV. The NGXO HTXS will be to detect bulk turbulent velocities $> 100 \text{ km s}^{-1}$ using the iron K lines, $> 600 \text{ km s}^{-1}$ from the iron L lines at 1 keV, and intermediate velocities for the Si, S, Ca and Ar K lines. To achieve 100 km s^{-1} at 1 keV requires a resolution of ~ 3000 , which is well beyond the currently planned capabilities.

The centroid of a bright line can typically be measured to 10% of its width. This means using NGXO we will be able to make radial velocity determinations using X-ray lines from binary systems where the orbital velocities are $> 10 \text{ km s}^{-1}$. This encompasses most CVs and X-ray binaries as well as stellar coronae systems. Because the velocity sensitivity scales linearly with energy, the iron K line is most sensitive for these measurements. The NGXO HTXS will give a factor of five improved sensitivity over that possible with the Astro-E XRS. This latter point is important when determining orbital parameters for systems with periods of a few hours, which are predominantly cataclysmic variables and X-ray binaries.

The resolution required for absorption features is almost identical to that for emission. The difference is that for resonant absorption lines it is essential that some line broadening is present, otherwise the measured equivalent width becomes negligible. In low surface brightness objects and the interstellar/galactic medium it is fruitful to study the lines in absorption when they are viewed against a strong continuum source, such as a distant quasar.

3.3 Compton Reflection

The spectrum reflected from relatively cold material near an X-ray source has features imprinted on it by photoabsorption, iron fluorescence and Compton scattering. The strength, shape and broadening of this spectrum is a diagnostic of the geometry, ionization state and iron abundance of the accretion flow. The Compton reflection spectrum creates an increase in the continuum above 10 keV, that depends on inclination. Around the iron K line and edge there are several narrow features from fluorescence on the accretion disk surface. It is a major objective of the proposed mission to simultaneously measure the Compton reflection spectrum, the overall continuum, line emission and absorption edges. The spectrometer will resolve the iron K line and edge emission, while the hard X-ray telescope will determine the magnitude of the reflection component. These measurements can be made for any accretion driven system, including AGN, cataclysmic variables and X-ray binaries.

We have simulated a spectrum using NGXO for a 10^5 s observation of an AGN at a flux of $5.0 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (over the 0.1–4.0 keV band). The simulation, shown in Figure 4, included a Compton reflection spectrum

Figure 3: *Top:* A simulated XMM RGS spectrum based on an 80,000 s observation of AR Lac. This is a two temperature model spectrum with 7 and 24 million degrees, one third solar abundance model derived from spectral fits obtained by ASCA. A single XMM RGS 1st order spectrum is shown. *Bottom:* A simulated NGXO HTXS (2 eV calorimeter) spectrum of AR Lac. This used the same input model and 80,000 s exposure time. The resolution of the XMM RGS and NGXO are comparable and adequate to resolve density diagnostic lines. But notice that the use of a non-dispersive calorimeter on NGXO yields a count rate that is twenty times higher.

Figure 4: *Top:* This Astro-E XRS (10 eV calorimeter) AR Lac simulation shows the iron K He-like blend at 6.7 keV. The model and exposure are the same as used in Figure 3. *Bottom:* This shows an 80,000 s NGXO HTXS (2 eV calorimeter) observation of AR Lac, using the same model as Figure 3. Notice how the increased spectral resolution and sensitivity of NGXO compared to Astro E fully resolves and brings up the iron K satellite lines.

Figure 5: A simulation of an AGN spectrum, including the effects of Compton reflection, for a 100,000s NGXO exposure of a source at a flux of $5.0 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (over the 0.1-4.0 keV band). This was for a cold disk, with an inclination of 10 degrees. The simulation included the reflection spectrum; the model fit shown is for a simple power law, and the residuals in the lower panel demonstrate the significance of the reflection bump at higher energies.

for an inclination of 10 degrees. The fit is to a simple power law model to illustrate the significance of the reflection spectrum, which is clearly detected above 20 keV. It will be possible to map the reverberations in the strength of the Compton reflection spectrum, in response to changes in the central luminosity of the X-ray source.

3.4 Non-Thermal Processes

Non-thermal processes (such as inverse Compton emission and synchrotron radiation) start to dominate the X-ray emission in most astrophysical systems above 10 keV. In several classes of objects such as the interstellar medium, stellar flares, elliptical galaxies and clusters of galaxies, non-thermal phenomena are quite weak and are only visible above the dominant thermal component at high energies. The maximum temperatures in these systems rarely exceed 10 keV, and X-ray observations over the entire 1-60 keV band produce a sensitive method of searching for high energy tails, which may indicate the presence of non-thermal processes.

4. The Study Phase Objectives

The goal of our proposed two year study is to develop a conceptual design for an NGXO mission (instrumentation, spacecraft and operations) that achieves our stated scientific objectives at a minimum of cost and technical risk. Many of the required components utilize technology currently under development at GSFC as part of the NASA SR&T program. This study will serve as a catalyst to demonstrate the viability of the proposed technology.

A large part of the new science possible with NGXO rests on the expectation that the spectral resolution

of a microcalorimeter can be improved by a factor of five. Based on the expertise gained by the LHEA in the development of the first X-ray micro-calorimeter, this seems an achievable step. At the end of the study phase it will be demonstrated that 2 eV resolution is feasible. The field of view of the spectrometer is limited by the maximum number of pixels that can be reliably fabricated and contacted electrically. The trade-offs between the array size, the science goals and the spacecraft pointing requirements will be investigated to determine the optimum array size.

For both telescope systems it is desirable to maximize the focal length, to achieve the highest possible throughput at high energies. The choice between a two- and a four-reflection system depends primarily on the focal length allowed by an extendable optical bench (EOB) and the launch vehicle. Based on studying the cost and technical trade-offs between the launcher capabilities, the EOB, and the focal length of the mirror system, a recommendation will be made regarding the optimum telescope configuration. For focal lengths up to 10 m, a four-reflection mirror in effect doubles the focal length by providing shallower grazing angles. But this is at the expense of efficiency and possibly spatial resolution from the additional reflections. For focal lengths greater than 10 m a two-reflection mirror provides the required collecting area without the additional cost of fabricating and aligning two more reflection stages.

To achieve the required reflection efficiency, the Hard X-ray Imaging Telescope requires the application of a multilayer coating on its conical mirror surfaces. This approach offers great promise as a means of producing a high throughput, low weight, low cost system that can deliver both arc minute spatial resolution and considerable effective area up to 60 keV. While multilayer technology has been successfully applied to enhance the performance of mirrors in narrow bands, it has not yet been fully developed for a hard X-ray telescope. During the study phase a program to study the feasibility and cost of applying multilayers to foil optics will be pursued. Other approaches to high energy imaging optics will be investigated, including the use of micro-channel plates as hard X-ray optics.

The CdZnTe detectors currently represent the most promising technology for the hard X-ray imaging spectrometer. As part of a NASA-funded Gamma-ray SR&T program, LHEA is already carrying out a development program for these detectors, and by the end of the study phase we will be able to demonstrate the feasibility of building a flight system. In parallel, we will investigate the use of alternate semiconductor materials, both previously used for hard X-ray spectroscopy (such as Si and Ge) and as yet unexploited (such as InSb). The performance of these solid state devices will be compared with that of more traditional gas filled detectors.

The period of this two year study started in March 1995. We plan to make regular progress reports at relevant meetings, and to publish the final report in late 1996/early 1997.

5. Acknowledgements

We thank George Fraser, Bob Warwick, Finn Christensen, Herb Schnopper and P. Giommi for useful discussions.