NASA RFI NNH11ZDA018L
Concepts for the Next NASA X-ray Astronomy Mission

REDUX: A Flexible Path for X-ray Astronomy

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Category of response: Mission Concept; Other

Willing to participate in workshop: Yes

Sensitive or controlled information: No

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SUMMARY

A multi-spacecraft strategy could restore the core science of the IXO mission to the US program. Dividing the roles of the several IXO instruments onto separate platforms, each optimized for a different, complementary, decade of the X-ray spectrum, gives more observing time for each instrument, and a substantially greater utilization of each instrument. The specialization allows more modest cost missions, each in the small/medium class, or 'large Explorer' class, defined by the RFI. Dividing the capabilities onto separate spacecraft within a single mission allows for a flexible path: the missions need not be launched together, nor do they all have to be NASA-led, and their ordering can be decided both by competition and by budgetary constraints. We call this approach *Research Explorers for the Discovery of the Universe in X-rays*, or REDUX.

INTRODUCTION

X-ray astronomy has had an amazing run of success. By the 40th anniversary of the first detection of a celestial X-ray source [4], other than the Sun, in 2002, the field had become 1 billion times more sensitive than that first rocket-borne experiment [5]. That is equivalent to going from the naked eye to the Hubble Deep Field. It took optical astronomy 400 years to do that, so X-ray astronomy has truly galloped along. But, with IXO delayed until well past 2020, rapid progress in the field seems guaranteed to falter.

Five smaller X-ray astronomy missions will launch in the next 5 years: NuSTAR , ASTRO-H, GEMS, eROSITA and ASTROSAT. The prospects for new data in the field over this decade are actually good. It is the prospect that, by the end of the decade either or both of the current flagship missions, *Chandra* and *XMM-Newton*, which will be over 15 years old, might well cease operations. With no comparable or better replacement in sight, many X-ray astronomers are considering other career paths. Once expertise in a field is lost, it is hard to rebuild.

IXO was the flagship observatory for three agencies—NASA, ESA and JAXA -- sharing costs and technology development. Through its earlier incarnations as Constellation-X (NASA) and XEUS (ESA), the mission has been the primary focus of X-ray astronomers for well over a decade. During that time it was not really feasible to consider alternative approaches, lest they whittle away the science case for IXO.

However there are alternative designs for each capability of IXO. This is reflected in the variety of strong responses to this RFI. This abundance of options requires a strategy to decide how to proceed. One such approach is suggested here: dividing the components of IXO into separate, modest cost, spacecraft, while keeping the synergy of the whole mission available for use when demanded by the science.

REDUX: ONE DECADE AT A TIME

IXO was designed to span the full range of the X-ray band, from 0.1 - 100 keV, three full decades of the electromagnetic spectrum. This was an ambitious stretch. Other missions have tackled a more limited range, from ROSAT (0.2-2keV) in the 1990s to NuSTAR (~8-80 keV) to be launched early in 2012. By limiting their bandwidth these missions were able to be relatively modest in cost. Could a similar approach work for the post-IXO era?

A quick thought experiment -- transposing that range to optical and infrared wavelengths -- shows that spanning 3 decades might not be an optimal approach. A telescope that covers the ultraviolet (0.1microns) to the far infrared (100 microns) would have an observing program straining in opposite directions: the objects in the sky that are bright in the infrared are usually very dusty and cool. But dust absorbs ultraviolet light efficiently, and cool objects radiate only weakly in the ultraviolet. Such a mission would be as though the GALEX and *Spitzer* missions, which have few targets in common, were bolted together and forced to co-point. Such a mission would, mostly have its infrared instruments idle while observing the best ultraviolet targets, and vice versa.

Very much the same is true in the broad X-ray band: soft X-rays (<1 keV) are readily absorbed by cold gas, and cool sources (now meaning a 10^6 K, rather than $<10^3$K for the infrared) barely emit in hard (>2 keV) X-rays. Sources that are bright above 10 keV are often heavily obscured by gas and dust at lower energies, very often below 1 keV ($N_H \sim 10^{21}$ cm^{-2}), and commonly up to nearly 10 keV ($N_H \sim 10^{23}$ cm^{-2}).

The obvious solution is to split the IXO mission into three separate, specialized, spacecraft. Dividing IXO can be done quite naturally. The calorimeter, polarimeter and high time resolution detectors work best in the medium energy, 1-10 keV, range, while the gratings cover only the soft , 0.1-1 keV, range and the high energy detector covers only the hard 5-40 keV band.

Concentrating on a single instrument allows for optimization. As X-ray grazing incidence optics need focal lengths proportional to the photon energy reflected, each sub-band is best served by a very different mirror. This allows almost the same performance for a significantly reduced cost. The reborn IXO program would be a series of large Explorer-class missions. There are even possibilities for having greater capabilities than IXO in some areas – e.g. fast slewing.

An outline of "IXO redux" -- for which we can use the acronym REDUX *(Research Explorers for the Discovery of the Universe in X-rays*) -- is given in the following sections. The science case for X-ray astronomy is made very well in *New Worlds, New Horizons*. REDUX is a means of achieving that great science.

SOFT BAND: LOW ENERGY (<1 keV)

For low energies we take a lesson from ROSAT. The same diffraction gratings planned for IXO can be deployed on a short focal length mirror (~2-4 meters). This gives ~5 times the area/kg of IXO, so that a moderate cost mission could match the IXO collecting area with a modest diameter mirror. Using sub-aperturing this telescope could use ~5-10 arcsecond half power diameter (HPD) point spread function (PSF) and still reach a resolution of R~3000. R=3000 is a crucial resolution at which the thermal widths of atomic lines begin to be resolved. The slumped glass optics developed for NuSTAR are one existing low cost technology that meets this HPD requirement.

The 0-order imager needed for wavelength calibration on the Low Energy telescope will provide CCD-like energy resolution at the 5-10 arcsecond level over a wide, ~20 arcminute dia., field of view. The use of event-driven detectors will provide high time resolution. Fano-limited energy resolution, which would significantly improve low energy performance, is also possible.

It may be possible to include a polarimetric capability in this band, where X-ray photons are relatively plentiful in comparison to the medium energy GEMS band.

Being a short focal length mirror, the moment of inertia of this satellite is low. Following the lead of *Swif*t, it should be possible to include a rapid response capability for gamma-ray bursts, and other transients in which the X-ray sky abounds. IXO did not have this ability.

At least one such mission has been proposed in response to this RFI (*ÆGIS*, *An Astrophysics Experiment for Grating and Imaging Spectroscopy*, Bautz et al. 2011).

MEDIUM ENERGY (1-10 keV)

IXOs strengths in the medium energy band were high resolution spectroscopy and high time resolution. To find a lower-cost replacement one needs to realize that only rather bright sources (>~0.1mCrab) would ever give enough photons to make full use of either. But for such bright sources the 5 arscecond PSF requirement for IXO is overkill. A "big bad mirror" with an arcminute PSF is fully adequate to keep the background low, and to avoid having another bright source inside the PSF (i.e. source confusion).

That opens up the possibility of using a lightweight X-ray optics to achieve large areas at low cost. Foil mirrors can now reach 1 arcmin HPD. Even more lightweight are microchannel plate optics (MCPO). Per unit effective area MCPO weigh only 1% of the Suzaku foil optics. To achieve, or exceed, IXO collecting area at the crucial 6.4keV Fe-K line region is easier with a 20 meter focal length. Both foil and MCPO can MCPO are naturally rigid and thin and so are readily deployed in orbit. At this focal length the size of the spot made by a ~1 arcminute HPD X-ray beam would be about a centimeter.

A centimeter beam size is well matched to the microcalorimeter arrays developed for IXO. The broad PSF spreads the signal out over ~1000 pixels means the array can detect photons at a similarly faster rate before losing spectral resolution. That allows this mission is better than IXO by simultaneously giving high resolution spectra and timing in the same instrument, and allowing the brightest sources to be observed without pile-up.

At least one such mission has been proposed in response to this RFI (*Extreme Physics Explorer*, Garcia et al. 2011).

HARD BAND: HIGH ENERGY (10—100 keV)

Early in 2012 NuSTAR will be launched carrying the first ever mirrors to work in this energy range. Thanks to its 46 arcsecond PSF, NuSTAR will already be 100 times more sensitive than any predecessor, but the NuSTAR payload is remarkably small and, at some $110M, cheap. It is easy to imagine a larger version, with larger area, a smaller PSF, ~15 arcsec HPD, a higher energy cut-off, >100 keV, due to a longer focal length, and a lower energy monitor detector, as proposed for *Simbol-X* and NHXM. The smaller PSF and larger area will translate directly to an order of magnitude or greater sensitivity. The goal of resolving bulk of the X-ray background in the energy range in which it peaks could finally be realized with a telescope with this performance.

An example of such a mission has been submitted in response to this RFI (HEXP, Harrison et al. 2011).

IXO SCIENCE PROGRAM COVERAGE

Together these three REDUX telescopes would carry out a large fraction of the Primary IXO Science Objectives. The table from the RFI is reproduced below, annotated with the areas that the three REDUX telescopes cover: ***Low, Medium, High*** (Table 1).

The great majority of the topics are covered well by the three telescopes. The only major loss is of 5 arcsecond imaging above 1 keV, which is a limitation on measuring massive clusters of galaxies spatial temperature distributions, and on spatially resolving their turbulent velocities.

OBSERVING EFFICIENCY: By keeping the three spacecraft as part of a single mission, they can operate together when the science demands it. However, when the science does not require co-pointing, each can operate separately, observing up to 3 targets simultaneously, where IXO could only observe one.

A study presented to the Constellation-X Science Working Group in 2004, based on the Constellation-X Design Deference Mission, showed that ~50% more science observations per year could be completed by putting the instruments on separate satellites.

Table 1: Primary IXO Science Objectives

Science Question	**Measurement**	**Key IXO performance requirements**
What happens close to a black hole?	Time resolved high resolution spectroscopy of the relativistically-broadened features in the X-ray spectra of stellar mass and supermassive black holes	Spectral resolution of 2.5 eV at 6 keV; effective area > 0.65 m2 at 6 keV and 150 cm2 at 30 keV. ***Medium + High***
When and how did super-massive black holes grow?	Measure the spin in supermassive black holes; distribution of spins determines whether black holes grow primarily via accretion or mergers.	Spectral resolution of 150 eV at 6 keV and 1 keV at 30 keV; effective area of 3m2 at 1.25 keV, 0.65 m2 at 6 keV, and 150 cm2 at 30 keV; ***Low + Medium + High*** 5 arcsec angular resolution and 18 arcmin field of view at 2 keV. ***Low at 1-2 keV***
How does large scale structure evolve?	(i.) Find and characterize the missing baryons by performing high resolution absorption line spectroscopy of the WHIM over many lines of sight using AGN as illumination sources. (ii.) Measure the growth of cosmic structure and the evolution of the elements by measuring the mass and composition of clusters of galaxies at redshift < 2	(i.) Spectral resolving power of >3000; effective area > 1000 cm2 in 0.3-1.0 keV band. ***Low*** (ii.) Imaging spectroscopy with spectral resolution of 10 eV at 6 keV; 10 arcsec angular resolution **---** and 5 arcmin field of view across 0.3-7.0 keV band; effective area of 1 m^2 at 1.25 keV and 0.1 m^2 at 6 keV. ***Medium***
What is the connection between supermassive black hole formation and evolution of large scale structure (i.e., cosmic feedback)?	Measure the metallicity and velocity structure of hot gas in galaxies and clusters.	Imaging spectroscopy with spectral resolution of 2.5 eV at 6 keV; ***Medium*** 5 arcsec angular resolution ***Low*** and 2 arcmin field of view across 0.3-7.0 keV band; effective area of 3 m^2 at 1.25 keV and 0.65m2 at 6 keV; ***Medium*** total bandpass of 0.3-10 keV. ***Low+Medium***
How does matter behave at very high density?	Measure the equation of state of neutron stars through (i.) spectroscopy and (ii.) timing	(i.) Spectral resolving power >3000; effective area >1000 cm2 in 0.3-1.0 keV band. ***Low*** (ii.) Maximum count rate of 10^6 s-1 with relative timing accuracy of 10 μs and <10 percent deadtime over 0.3-10 keV band; spectral resolution of 150 eV and effective area of 0.6m2 at 6 keV. ***Medium***

PROGRAMATIC ADVANTAGES

LOWER FUNDING PEAK: The REDUX 3 telescope approach gives NASA the ability to spread the funding away from a single peak. The satellites don't have to be launched at the same time, in fact they might be spaced over several years. All of the telescopes are, in principle, long-lived. The cooling of the microcalorimeter array is a possible exception, but one that is being tackled. This flexibility in launch date aids in the financial planning. The ordering of the missions can be decided both by competition and by budgetary constraints.

EFFECTS ON MISSION DESIGN: In order to work together when the science demands it, the 3 REDUX telescopes would need to be in compatible orbits, and have power and heating constraints, designed so that their 'fields of regard' (the instantaneous region of sky they can observe) overlap substantially. They could also carry compatible transponders for rapid transmission of, e.g., gamma-ray burst (GRB) information to speed responses. To detect GRBs and other X-ray transients, it would be useful if one of the missions carried a simple all-sky monitor.

INTER-AGENCY OPTIONS: If NASA cannot afford to launch all three missions in this decade, then NASA, ESA and JAXA could build them all. ESA may choose to fly the medium energy ATHENA mission. JAXA may decide to continue its interest in the high energy capability of IXO via a high energy mission, possibly in collaboration with NASA. The powerful low energy mission is then well within NASA's financial resources. By cooperating the three agencies can reap the benefits that would have come from their collaboration on IXO, but lose much of the problems of working closely together. An advantage of the REDUX 3 telescope approach over IXO is that each agency can choose a satellite and build it with no financial or technology dependence on the others.

In order to get the synergy from having them work together, the agencies could agree to operate them for some fraction of the time, from 20% to 100%, as a single observatory.

Multi-spacecraft missions are not unusual in space science, or solar physics. The 1970s HEAO program was a set of three complementary high energy astrophysics satellites. Each was separately competed, within a NASA-defined science envelope. REDUX shares elements from each of these examples.

POSTSCRIPT: A High Angular Resolution Imager

The first rate IXO astrophysics that can be carried out with the three satellite REDUX mission, described above. However, it would be imprudent to put 100% of NASA resources in high energy astrophysics in RECUS alone. A long-term investment leading to a 'super-Chandra' -- large area sub-arcsecond imaging -- needs to be pursued in parallel.

True exploration of the sky in X-rays needs a powerful sub-arcsecond successor to *Chandra*. *Chandra's* high resolution images have been revelations, be it of moving filaments in the Crab Nebula, a pair of supermassive black holes in the nucleus of a galaxy, or a host of others.

Yet most of *Chandra's* images are heavily underexposed. It is the megasecond images that are the most impressive, because only these fill the small *Chandra* pixels with enough counts to exploit its full spatial and spectral resolution. But no more than 30 megasecond exposures can be done per year.

Clearly a much larger area telescope with *Chandra* or better angular resolution is central to the long term future of X-ray astronomy.

While *Chandra* has sub-½ arcseond HPD, IXO had a goal of only 2 arcsecond HPD point spread function (PSF), and the requirement was just 5 arcseconds. The minimum IXO beam area would have been 16 times larger than *Chandra*, and 5 arcseconds PSF would have been more than 100 times larger than *Chandra*. Much of the revealing detail, and sensitivity, we become accustomed to with *Chandra* would have been blended together with IXO.

Strangely, until recently, there was no program, world-wide, that aimed to build better X-ray optics for astronomy than *Chandra* already demonstrated. There are now programs that aim to use the adaptive optics approach employed by optical astronomers. This approach would allow lighter weight high resolution X-ray optics. Adapting this approach to the grazing incidence optics used in X-rays requires major modifications. While development of these optics is only beginning, it is essential to the longer term future of X-ray astronomy to aggressively pursue this technology. With a strong development program over the next 5 years or so, X-ray optics could even approach the 0.1 arcsecond level (beam area 1/25 of Chandra) of *Hubble* and JWST.

A response to this RFI has proposed an investigation of X-ray adjustable optics (Vikhlinin et al. 2011).

Neglecting to invest in adaptive grazing incidence technology would leave the NASA X-ray astrophysics program in a difficult situation, similar to the one it now faces, a decade in the future.