Constellation-X Options

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1 INTRODUCTION

Constellation-X is the most powerful X-ray astronomy mission planned for the NASA program and forms a central role in the 'Beyond Einstein' program of the agency. Constellation-X (Con-X) consists of four identical spacecraft each carrying telescopes that, combined, span three decades of the spectrum, from 0.1-100 keV. This wide coverage, equivalent to that from the ultraviolet to the far-infrared, enables the study of high energy processes around extreme objects such as black holes and magnetars, and cosmological investigations. Con-X achieves its power by emphasizing good spectral resolution and, particularly, large area mirrors.

With the recently announced delay[1] of the launch of Con-X to no earlier than (NET) 2016, the Con-X program faces two challenges and an opportunity. The first challenge is programmatic, and comes from the two other missions which have similar instrument payloads and are now due to launch on a similar schedule: the Japanese NEXT and European XEUS missions. The second challenge is scientific, and grows out of the extraordinary success of the *Chandra* mission. *Chandra* has produced a revolution in astrophysics over the past 5 years, and in doing so *Chandra* has altered, and has greatly expanded, the questions astronomers need to ask with the new generation of X-ray observatories.

The Con-X opportunity is to seize the 6 or more years before the commencement of phase B (§3.5) and couple them with advances in technology to reconfigure Con-X into a far more powerful observatory. To respond to the challenge of the post-*Chandra* era will need some 'thinking outside the box'. The ongoing studies of separate mirror and detector spacecraft for Con-X is a prime example of this new thinking.

This paper presents approaches to modifying the Con-X mission, concentrating on angular resolution. They offer the potential for significantly enhancing the science return of Con-X, yet keep within the basic parameters of the mission: launch weight, telescope and instrument suite and the constellation concept. The intention is to spur a constructive dialog about the Con-X mission at this critical juncture.

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[1] NASA budget site: URL http://www.nasa.gov/about/budget, click on 'Structure & Evolution of the Universe' for pdf file; space.com, URL http://www.space.com/news/nasa_budget_040130.html

Table 1: *Chandra* Breakthroughs

Chandra Observations		Implication	reference
X-ray background resolved to 10 keV*	→	accretion luminosity of the Universe	Giacconi et al. 2001
Dark Energy measured	→	new constraints on new physics	Allen et al. 2004
No cooling flows in clusters	→	20-year puzzle solved; AGN feedback	David et al., 2001
Cooling fronts in clusters	→	build up of galaxies, clusters	Vikhlinin et al. 2001
Warm-Hot Intergalactic medium*	→	'missing baryons' found	Nicastro et al. 2002
Ultra-Luminous X-ray Sources	→	intermediate mass black holes?	Fabbiano et al. 2003
Galactic center flares	→	Not so quiet Black Hole	Baganoff et al. 2001
Hot ISM abundances*	→	SN yields, ecology	Fabbiano et al. 2004
Optically dull/X-ray bright galaxies*	→	hidden active galaxies	Alexander et al. 2003
0.5c wisps in Crab	→	particle acceleration to near c	Hester et al. 2002

* exposure times approaching 1 Msec (2 weeks) needed to make the discovery.

2 CHALLENGES

2.1 THE CHANDRA REVOLUTION

Chandra's sub-arcsecond imaging and high resolution spectroscopy have produced profound advances in every field of astronomy (see Table 1 for a few examples). Even the hot gas in nearby clusters of galaxies which, as diffuse X-ray sources, were not expected to benefit from high angular resolution, have been shown to contain sharp 'cooling fronts', which allow completely new constraints on the formation of structure in the Universe. Similarly, spatially resolved spectral analysis of the rapid star forming galaxies the 'Antennae', have shown that lower angular resolution spectra encompassing the whole galaxy pair, were totally misleading. Far from having anomalously low abundances, these galaxies have high abundances which vary with position and constrain supernova yields. The lesson is that low angular resolution spectra do not give an average abundance, they give a *wrong* abundance - and by a large factor. Since the Antennae is our nearby laboratory for events at the peak epoch of star formation around $z \sim$1-2 (Madau et al. 1996) these results alter our understanding of the life cycle of matter in the Universe. The *Chandra* literature is packed with similar examples across all of astrophysics.

A large fraction of the *Chandra* breakthroughs required exposure times of a million seconds or so (Table 1). This demonstrates the science capability that comes when an observation has enough photons to give high dynamic range and spatially resolved spectra over a large, megapixel, field. It also demonstrates that *Chandra* is too small to fulfill the potential of arcsecond X-ray imaging. With its large collecting area Con-X would accumulate as many photons as *Chandra* in 1/10 the time. If Con-X had imaging quality comparable with *Chandra* then it would eclipse *Chandra's* accomplishments much as the VLA dominated over the Cambridge Ryle 5 km radio telescope. The Ryle telescope was the first to obtain 1 arcsecond imaging in it's band, but the larger area of the VLA quickly outshone the Ryle. But the baseline Con-X beam is 100 times larger, which smears out virtually all the *Chandra* discoveries. Without access to similarly fine angular resolution, with much larger effective area, the *Chandra* breakthroughs cannot be pursued further.

The science case for a much larger area X-ray telescope with at least *Chandra* resolution has been made before (Elvis & Fabbiano 1996). The Generation-X (Gen-X) mission concept, now under study by NASA[2] , is a response to this need. Gen-X is conceived as a 'mega-Chandra' with $\sim$1000 times the effective area and up to 10 times the angular resolution of *Chandra.* This is a very large step, and a reconfigured Con-X could serve as a stepping stone to Gen-X.

2.2 DISCOVERY SPACE OF NEXT & XEUS

It is a compliment to Con-X that the two other major space programs, those of Japan and ESA, have elected to use the same Con-X formula of emphasizing large area, bandwidth and microcalorimeter detectors for their next major X-ray astronomy missions, NeXT and XEUS. (Table 2 compares the missions.) However the result is that all three agencies and missions will be competing for essentially the same discovery space (Harwit, 1984) at about the same time. With NeXT having a NET 2011 launch date, the easy Con-X science will be picked off by this smaller telescope. With the launch of the first phase of XEUS hoped for in the first part of the 2015-2025 period this larger telescope will take the more challenging Con-X science.

To overcome this redundancy there are only three options: (1) cancelling a mission, (2) merging missions via interagency cooperation, or (3) reconfiguring a mission toward a different discovery space. No astronomer wants to cancel a mission, and interagency cooperation is difficult to achieve. Is there hope for expanding the discovery space of a mission?

Thanks to the choice of advanced mirror technologies being pursued for the large 0.5-10 keV Soft X-ray Telescope (SXT), it is Con-X that has the greatest opportunity for expanding the scope of its discovery space into the clearly desirable higher angular resolution regime. This higher angular resolution approach is the main one explored in this paper (§4), and it is enabled by finding ways to put much more mass into the SXT mirror assembly.

We explore also a second approach involving a change of the Con-X mission architecture into 3 energy band specialized spacecraft (§5). This design also puts Con-X into new discovery space: thermal limit (R=5000) spectroscopy and rapid (1 minute) response times. Moreover this architecture compensates for a loss of effective area introduced by the higher angular resolution option, and also leads to a more intensive scientific utilization of the observatory.

3 OPPORTUNITY

How is it possible to substantially increase the angular resolution of Con-X when so much work has already gone into meeting the 15" Half Power Diameter (HPD) requirement of the Con-X mission? Any changes to the mission must stay within the Con-X envelope of launcher capability, energy range and major instrumentation, and should retain the 'constellation' concept.

The heart of Con-X is the 0.5-10 keV soft X-ray telescope (SXT). The advantage that Con-X has over its ESA and JAXA competitors is that the SXT angular resolution is limited only by manu-

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[2] URL: http://generation.gsfc.nasa.gov

Table 2: Comparison of Con-X with NeXT & XEUS

Mission Characteristic	Con-X	NeXT[a]	XEUS (PERXEUS)
Lauch Date	NET 2016	NET 2011	NET 2015
Area (0.5 keV)	$0.1\mathrm{m}^{2b}$	$0.1\mathrm{m}^2$	$10\mathrm{m}^2$
Area (1 keV)	$1.5\mathrm{m}^{2b}$	$0.1\mathrm{m}^2$	$10\mathrm{m}^2$
Area (6 keV)	$0.6\mathrm{m}^{2b}$	$0.1\mathrm{m}^2$	$3\mathrm{m}^2$
Spectral Resolution (0.5 keV)	1000	250	250
Spectral Resolution (1keV)	500	500	500
Spectral Resolution (6keV)	3000	3000	3000
Angular Resolution (1-10 keV), HPD	5" -15"	30"	5"

[a] Ohashi et al., 2004.

[b] Includes losses due to grating efficiency, support structures.

facturing tolerances. The ASCA-derived foil mirror approach of NEXT (Ohashi et al. 2004) and the new micropore technology of XEUS (Bavdaz et al. 2004), both employ a conical approximation to the Wolter-I parabola-hyperbola optic. Con-X instead uses a true Wolter I design and so could have almost arbitrarily improved angular resolution.

The crucial limiting factor in beating down the manufacturing errors that determine the angular resolution of the SXT is the **mass/geometrical area ratio**. A well known plot (figure 1, e.g. Conconi et al. 2003) compares the angular resolution of X-ray telescopes against this ratio and finds a limiting line below which X-ray mirrors have not been constructed. Although this plot has no theoretical basis, including as it does X-ray mirrors made by several different techniques, it does seem that the line from *Chandra* through ROSAT to Con-X has some empirical validity: better angular resolution can be gained at the expense of greater mass. Con-X occupies an ambitious location in this diagram, and it is a tribute to the Con-X team that they are meeting the requirement of 15" HPD[3]. Thanks to the impressive work already undertaken for Con-X, we can reasonably expect from the Conconi et al. figure that a version of the Con-X mirrors with **eight times the mass/area to the SXT mirror assembly** (FMA) could reach 3 times the resolution at the baseline mass/area ratio. So starting with a low mass/area 10 arcsec HPD would give a resolution of 3.3 arcsec at high mass/area, and for a 5 arsec starting mirror (the Con-X goal) the HPD would improve to 1.8 arcsec, which approaches the *Chandra* territory. This mass factor would increase the SXT from the current 0.06 kg cm^{-2} up to 0.52 kg cm^{-2}, much greater than for XMM and approaching the 0.6 kg cm^{-2} of ROSAT. Of course such scalings are only a guide. New mirror manufacturing technologies may well be needed, such as the polishing of pre-slumped shells (Friedrich et al., 2004), and the tolerances on all components would have to be tightened correspondingly. But the added mass/reflector allows these technologies to be attacked with much relaxed constraints.

Increasing the mirror mass/area ratio opens up the design parameter space for the SXT. Merely increasing the thickness of the shells to 1 mm from 0.4 mm increases their stiffness 15-fold, simplifying support issues. This added freedom could well allow the Con-X SXT to attain 3 times better angular resolution, and so almost an order of magnitude more pixels in an image of any object.

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[3] Constellation-X Technology Readiness and Implementation Plan (TRIP) Report - Feb 3 2003, URL: http://conxproject.gsfc.nasa.gove/engn.htm

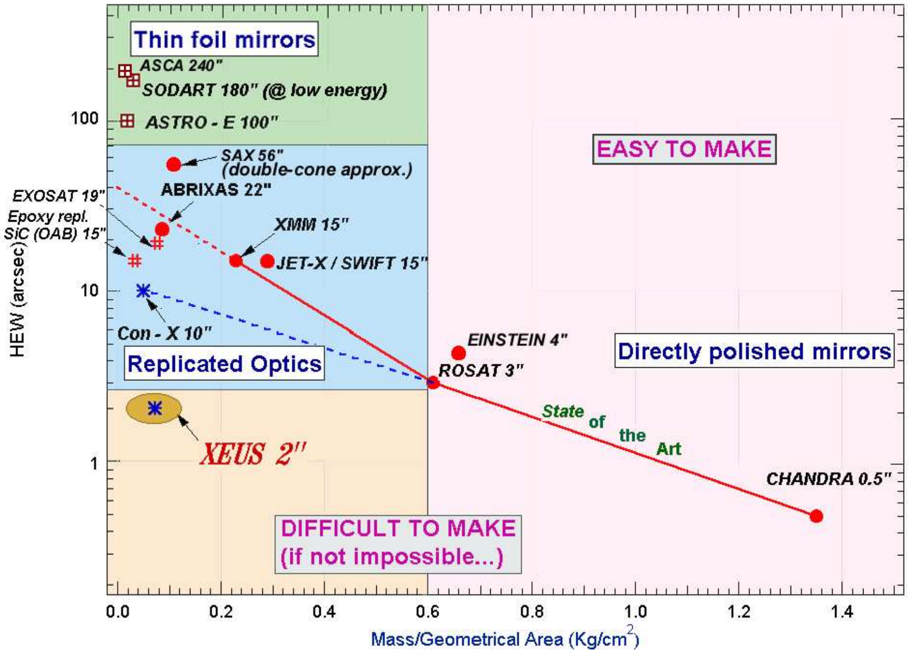

Figure 1: Mass/Geometrical Area ratio vs. Half Equivalent Width for X-ray mirrors (Conconi et al. 2003)

Such a gain would give a major boost to Con-X science, pushing it into new discovery space.

The next section describes two changes to Con-X that, when combined, allow such a large increase in SXT mirror mass/area ratio (Approach 1, §4), yet remains within the cost envelope of the baseline Con-X. We then look at alternate arrangements of the three Con-X instruments that can intensify their utilization, and provide new capabilities (Approach 2, §5). Throughout we keep to the constraint that the basic envelope of the Con-X mission is not violated. The two approaches are not alternatives, but complement one another.

4 Approach 1: INCREASED MASS/AREA IN THE SXT

4.1 ION ENGINES FROM LEO TO L2

Ion engines allow the mass of Con-X at L2 to be doubled, and the mass in the SXT mirror module to be quadrupled.

The rocket equation (e.g. Clarke A.C. 1960, eq.2.2):

$$\Delta V = v_{ex} ln(m_i/m_f)$$

relates change of velocity, ΔV to the ratio of initial to final masses (m_i/m_f) as a function of the exhaust speed, v_{ex} . So a factor 10 in v_{ex} buys a factor 2.3 in m_f, due to the lower propellant mass required.

Rockets are more often characterized by their specific impulse, I_{sp} sec $=v_{ex}/g$, where $g = 9.807$ m s^{-2}.

Low energy chemical bi-propellant engines (e.g. LOX/kerosene, N2O4/hydrazine) have I_{sp}=280-300 s, while high energy bi-propellants (e.g. LOX/LH2) have I_{sp}=400-450 s. By contrast ion engines, which electrically accelerate ionized gas to high speeds, have I=3800 s. By substituting the higher exhaust speeds of ion engines, the propellant mass becomes negligable, and the final mass to L2 can be doubled. Because ion engines need a high vacuum to operate they can be used only above normal LEO, so a higher transfer orbit is required, and this cuts into the full factor 2.3. We use a simple factor 2 as a reference value, increasing the total Con-X mass at L2 from 9904 kg to 19,808 kg.

Since there is no strong reason to increase the instrument or spacecraft systems mass on Con-X, all of this increased mass can be allocated to the mirror assembly. Since the SXT mirror assembly is currently $\sim$50% of the total Con-X mass the mass in this system could be *quadrupled.* Table 3a gives the mass budget for Con-X from the TRIP report, while Table 3b shows how the mass could be allocated given the additional mass available at L2 in an ion engine option.

Ion engines have been flight tested on several missions in the past few years. [E.g. Deep Space 1 (NASA, 1999), SMART (ESA, 2003), Nayabusa (=MUSES-C, JAXA, 2003)]. The NASA-Glenn/Boeing-Rocketdyne XIPS-25[4] is one system that has flown, though with some reliability issues, on many commercial comsats since 1997 (Boeing 601, 702 models). ‘XIPS’ is the ‘Xenon Ion Propulsion System’. Xenon is an inert gas and so poses no corrosion and few contamination issues.

The drawback of ion engines is their low thrust, $\sim$60 mN, and thus low acceleration, $\sim 10^{-5}g$ for a 5 t satellite. Since the ΔV from LEO to L2 is $\sim$3.2 km s^{-1}, the voyage will take $t = \Delta V/[NT/M]$, where N = number of ion engines, T thrust/ion engine and M the mass of Con-X. A transit time longer than 1 year becomes a significant fraction of the 5 - 10 year lifetimes of typical instruments and should be avoided. So setting t_1=1 yr, a M_{10}=10 t satellite, and ion engines with $T_{100} \times 100$ mN thrust and an on-time fraction ϵ, $t_1 = M_{10} T_{100} {\frac{N}{20\epsilon}}^{-1}$. I.e. N = 10/$\epsilon$ ion engines are sufficient.

Ion engines require electric power of 2-3 kW/ion engine. Con-X is currently scoped to have solar panels providing a total of 5.7 kW (with a 45% margin, TRIP report), implying an additional $\sim$20 kW of power for the observatory (if most systems are turned off during transit to L2). The mass of the additional solar panels and the added electrical system, scaling from the 67 kg/spacecraft for the power system on the Con-X baseline, would be $\sim$235 kg/spacecraft, almost exactly balancing the saving of 180 kg/spacecraft of propellant mass. Additional power could be valuable if larger focal plane instruments, or another focal plane instrument were to be added (see §3.6). The low acceleration points to only minor challenges to prevent the solar panels becoming detached during transit to L2.

4.2 TRADE AREA FOR RESOLUTION AND FIELD OF VIEW

A second path to improving the HPD of the SXT is to make a counterintuitive trade of effective area for HPD. Paradoxically this trade actually improves science/second for some major categories of Con-X science. A factor 2 more mass/reflector can be gained by *removing every other SXT mirror shell* at the cost of halving the SXT effective area. Before rejecting such an idea out of

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[4] URL: http://www.boeing.com/defense-space/space/bss/factsheets/xips/xips.html, and .../nstar.html

Table 3: Con-X Mass Budgets

Item	Mass (kg)*per Observatory*	Notes
A: **Current chemical engine baseline Con-X**[a]: Total mass to L2 = 9904 kg		
SXT RMA	642	
RGA	50	
RFC (RGA Focal plane Camera)	33	
HXT	151	3 units (incl. instruments)
XMS	147	
Thermal	297	
Integration & misc. materials	81	
Structure & mechanisms	454	
Spacecraft Bus	889	
TOTAL	2476	
TOTAL per launch	4952	wet or dry
Launch vehicle performance	6498	mass to L2 using chemical engines for transfer
Margin	34%	= 100x(launch vehicle performance - launch load)/dry launch load
B: **Ion engine option.** Total mass to L2 = 19,808 kg		
SXT FMA	2795	**4.3 x mass in current baseline, (a) above**
RGA	50	
RFC	33	
HXT	151	3 units (incl. instruments)
XMS	147	
Thermal	297	
Integration & misc. materials	81	
Structure & mechanisms	454	
Spacecraft Bus	709	as in option A, minus 180 kg of propellant
TOTAL	4952	
Total per launch	9904	
Launch vehicle performance	12,996	using ion engines from LEO to L2
Margin	31%	

a. Constellation-X Technology Readiness and Implementation Plan (TRIP) Report - Feb 3 2003,
URL: http://conxproject.gsfc.nasa.gove/engn.htm.

hand, recall that other Con-X requirements have been changed by a factor 2, even in the SXT, and even quite recently.We show below how this trade can be beneficial.

The Con-X field of view at 1 keV is already quite large, reaching 90% of the on-axis A_{eff} only at 8 arcmin off-axis. So removing the outer shells does not improve the field of view. Simply removing odd numbered shells will not be the optimal approach. Most likely the smaller inner shells can all be kept, preserving the high energy response. Most of the mass will be saved from the large, low energy reflecting shells. Vignetting is quite severe at 6 keV even 4 arcmin off-axis. This loss of area at high energies is due to rays from the inner primary shells falling off their corresponding secondaries. This can be remedied by lengthening the secondary at a ~25% cost in mass. (Geometrical obscuration is insignificant in the baseline Con-X, even 8 arcmin off-axis.)

A substantial fraction of the area sacrificed by removing shells can be recovered between ~1 keV and ~4 keV by applying a thin (~50 Å) carbon coating to the gold or iridium mirror surfaces (Conconi et al. 2003). This coating fills in the absorption edges in the high Z element reflectivities. For a mirror with a 7 m focal length and 1 m diameter, not too different from the SXT, Conconi et al. obtained a factor ~1.4 increase in area at 3 keV. Factoring in the factor 2 loss in the number of shells at this energy leads to a net area that is 70% of the baseline. The loss in area above the 0.28 keV C K-edge is quite modest, ~20% at 0.5 keV (G. Pareschi, priv. comm. 2004). More complex overcoating schemes may yield larger effective areas. New mirror manufacturing schemes may be more amenable to depositing overcoats on the high Z surface than epoxy replication. This same C-overcoating technique could of course be applied to the baseline Con-X, but the science case was made for the baseline Con-X, which does not have this feature. (See also §5.1, 5.4 for other options to regain low energy effective area.)

4.2.1 Science Gains from a Larger Field of View

This trade of area for field of view leads to performance improvements. For any observation that needs to cover more than the 4'x4' baseline FOV of the SXT a factor 4 larger useful field of view, means that fewer pointings are needed. Many targets easily fill the 8'x8' FOV of the *Chandra* ACIS-S3 chip, and for these targets the *same science goals can be accomplished in half the exposure time*, since the cost in collecting area was only a factor 2. Larger gains in field of view lead to even greater gains in efficiency.

We can quantify this gain by looking at the effect on the Design Reference Mission 3-year observing program (K. Weaver, 2004, priv. comm., see also Table 5). Studies of point sources will suffer a factor 2 loss[5] while studies of extended fields have a factor 2 gain [6], assuming an 8'x8' field of view. (Studies of stars are ambiguous as young stars lie in clusters (e.g. Orion), but older stars, and bright stars for grating spectroscopy, are isolated. We assume no net effect on the Con-X stellar program.) Weighting these factors by the exposure time for each area, the wide-field version of Con-X would be equivalent to 136.25 Msec, a gain of 57% over the baseline option.

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[5] I.e. Bright AGN, Other AGN, QSOs & IGM, X-ray Binaries, Black Hole Candidates, neutron stars. This assumes that the stellar mass compact objects being studied are in our Galaxy. Similar systems in external galaxies gain a multiplex advantage from a large field of view.

[6] I.e. Clusters, Ellipticals/Groups, Spirals/starbursts, SNR.

4.2.2 Relativistic Lines in AGNs

The loss of on-axis area will be felt primarily for studies of the time variability of sources in which background is unimportant and count rate is important. For this class of study longer exposure cannot make up for lost area. This category includes at least one of the primary Con-X goals: Fe-K line monitoring of AGNs, comprising ~10% of the DRM observing program (see Table 5). The zero redshift 6.4 keV line energy itself may suffer area loss in the proposed configuration. However, the most challenging part of the observation is the study of the redshifted part of the line at 3-5 keV, where the area is ~70% of the baseline, a signal-to-noise reduction of 1.2. This does not seem likely to change the science fundamentally.

The detection of broad features does not require the full spectral resolution of the SXT microcalorimeter, the XMS. (Narrow features, e.g. Turner et al. 2003, do require this resolution, but also require fewer photons to be detected.) As a result, the photons contributed by the HXT can be included in simulations, although to date they have not been used (C. R. Reynolds, 2003, priv. comm). The HXT has similar effective area to the SXT at 6 keV so, considered in this way, the wide-field Con-X proposed here will actually have double the collecting area so far considered for Fe-K reverberation studies with Con-X. The HXT detectors may not be sensitive at the highly redshifted energies of 3-5 keV however, so the science feasibility needs to be considered carefully for each goal.

4.3 SXT FOCAL PLANE DESIGN

A less vignetted SXT optical design is only useful if a large format detector can be put at the focal plane. A large format (megapixel) microcalorimeter with ~2 eV resolution (Figueroa-Feliciano, 2004) would be the best choice for a wide field focal plane instrument. This class of instrument would take X-ray astronomy straight to the 'integral field unit' capabilities that are now having a profound effect on optical astronomy (e.g. SAURON, Davies R.L. 2004).

However, in the event that such devices are not feasible for a 2016 Con-X launch (i.e. fully lab demonstrated by 2010), a back-up concept needs to be developed. Different microcalorimeters adopt different trades of spectral resolution versus high energy response or areal coverage. So a large area (1024^2, 15 arcminute on a side) microcalorimeter may well have to sacrifice the highest spectral resolution, which would compromise Con-X science goals. The focal plane of the SXT has a plate scale of ~20 arcsec/mm, so the baseline 4×4 arcmin field of view has a size of ~1.2 cm diameter. This is too small to fit more than one detector. The wider field of view proposed above would reach ~2.5 cm diameter, which is also tightly constrained.

A larger focal plane would allow the deployment of several specialized microcalorimeters: e.g. specialized for large field size, or high count rate, or high energy response, or higher spectral resolution at lower energies. Most likely the optimal choice from this variety of microcalorimeters will not come from a single hardware group, and a competition for focal plane space would result in several different designs being flown. This would be healthy for the US detector development effort.

There is a way to ease the space problem at the focal plane. Wide field variants to Wolter-I optics were first suggested for the WFXT mission (Burrows et al., 1992). WFXT had a 30 arcmin dia fov with a HPD=5". Recently these designs were revisited by Conconi et al (2003) who found a solution with a HPD=3" over a 50 arcmin dia. fov for a 7 m focal length. Changes in focal length with shell diameter were a key element of this design. Given the limited attention given so far to wide field designs it is likely that the ultimate wide field solution has not yet been found. A *Chandra* quality resolution design over a 30 arcmin field of view may yet prove feasible.

A 30 arcmin diameter field of view for the SXT has a 10 cm focal plane diameter. Within this space it is plausible that multiple instruments could be included, allowing the observer to choose the one most appropriate for the proposed science, and so getting more science done in the same time. In this option the Con-X focal plane would come to resemble those of the *Hubble* and *Spitzer* Space Telescopes. The additional solar power required for the ion engines (§4.1) would allow multiple instruments to be operated at once, and could enable the enhanced telemetry rate this implies. Thus a parallel program of surveys may be conducted along with all the pointed observations that use the small field of view microcalorimeters.

5 Approach 2: THREE SPECIALIZED SPACECRAFT

The current Con-X architecture consists of four identical spacecraft deployed via two separate launches. The main advantage of this approach is the avoidance of loss of mission in the case of a launch or spacecraft failure. (Cost savings were determined not to be important) While the identical spacecraft approach does provide additional redundancy, this redundency is only partial. Design or manufacturing errors that apply to batches of components are not guarded against by this means.

A new mission architecture could consist of three spacecraft that share the same bus design, but have instrumentation specialized by energy range. This approach still uses ion engines to get an increased mass from LEO to L2. The first launch would be of the SXT/XMS only, while the second launch would carry the HXT on one spacecraft and the RGA gratings (behind a new low energy telescope) on another. This architecture has several advantages:

1. Increased SXT area at low energies;
2. Lower cost 2nd launch vehicle;
3. Optimized designs for each energy band;
4. Greater instrument utilization;
5. New fast response capability at low energies (e.g. for GRBs);
6. Single focus SXT, giving weight savings and opening the potential for robotic servicing.

The three energy-band-specialized spacecraft would be:

1. A new, small, 'Low Energy Spectroscopic Telescope' (LEST, <1 keV) with R=5000 gratings;
2. The Soft X-ray Telescope (SXT ~0.5-10 keV) with much improved angular resolution;
3. The Hard X-ray Telescope (HXT, 5-60 keV) with optimized focal length.

Arranging the Con-X payload like this retains the key 'constellation' approach of Con-X, while increasing the science return of the mission. Let us consider each advantage in turn.

5.1 INCREASED SXT AREA AT LOW ENERGIES

The outer 89 of the 216 SXT mirror shells have objective reflection gratings (the RGA) behind them. These gratings divert 50% of the light from these shells onto a separate instrument to detect the dispersed spectrum. Half of the SXT mirror area below ~1 keV is thus lost to the imaging microcalorimeter in the current configuration. Removing the gratings from the SXT onto the LEST would thus double the low energy effective area of the microcalorimeter, recovering the loss from removing half the shells from the SXT design (§4.2). Combined with a ~40% 1-4 keV gain from carbon coating the mirrors (§4.2), this mirror would be close to the baseline Con-X area across the energy band.

5.2 LOWER COST SECOND LAUNCH

In Table 4 we show a mass budget for an energy-band-specialized Con-X, option 'C'. In this example we have put all of the additional mass enabled by an ion engine transfer to L2 into the SXT but only up to the limit imposed by putting all of the SXT into one launch. The new SXT now has 2.8 times the mass of the current configuration, a significant loss compared with the factor 4.3 of the simple ion engine option B of Table 3. This would result in an angular resolution a factor 2 better than the baseline Con-X, rather than a factor 3 in Approach 1, unless further area is traded for mass/reflector. The more intense utilization of the mission in this configuration (§5.4) could allow such a trade without loss of science for much of the DRM program. Table 4 required some assumptions. A single SXT focus, and so a single XMS, saves mass, but we have not allowed for the extendable boom connecting the mirror & detector units. Eliminating the HXT saves mass too. The mass of the structure (Thermal + Integration & misc. + structure & mechanisms) we have assumed to give a factor 2 savings over a 4 spacecraft architecture. There is no strong reason to suppose that the spacecraft mass needs to be increased for the SXT (other than adding larger momentum wheels to maintain the current slew rate). The increase in mass/area in this option is reduced to a factor 5.6 compared with a factor 8.8 in approach 1. In this scenario the hedge against a launch failure is removed.

The considerable advantage of this approach is that the masses of the two launches are quite different. Launch 2 has only 44% of the Launch 1 mass. This opens up the possibility of using a smaller, lower cost, launch vehicle for the second launch. A Delta 2 7920 (5100 kg to LEO) would be adequate. A typical Delta 2 launch costs >$ 50 M, while a Delta IV-M launch (13,500 kg to

Table 4: Con-X Mass Estimates: 3 Spacecraft Option

C: **3 Energy Band Specialized Spacecraft**		
Item	mass (kg)	Notes
Spacecraft 1. SXT: Launch 1.		
SXT FMA	7351	**2.8 × total SXT FMA mass in A.**
XMS	147	1 focus saves ∼441 kg
Thermal	594	savings of 50% of total of baseline SXT assumed
Integration & misc. materials	162	ditto
Structure & mechanisms	908	ditto
spacecraft	889	
Launch 1 TOTAL	9904	
Spacecraft 2. HXT: Launch 2		
mirror + instruments	604	
Thermal	175	scaled by mirror+instrument mass, i.e. factor 0.59
Integration & misc. materials	48	ditto
Structure & mechanisms	268	ditto
spacecraft	889	additional savings likely
S/C 2 TOTAL	1984	
Spacecraft 3. LEST: Launch 2		
Pharos mirror assembly	153	1.3 m dia.
RGA	50	using Table 3 A value
RFC	132	ditto
Thermal	297	
Integration & misc. materials	81	
Structure & mechanisms	454	
spacecraft	889	additional savings likely
S/C 3 TOTAL	2056	
Launch 2 TOTAL	4040	S/C 2 + S/C 3
MISSION TOTAL to L2	13,944	c.f. 19,808 in option B, ion engine

LEO) baselined for Con-X is projected to cost >§125 M [7] , so there are significant potential savings to the program from this 3 spacecraft approach.

Rather than saving almost 6 t of launch mass, a single focus SXT with the full factor 4.4 mass gain over the baseline Con-X could be achieved by separating the SXT detector system onto another spacecraft. This spacecraft would then be carried on the 2nd launcher, along with the HXT and LEST.

5.3 OPTIMIZED DESIGNS FOR EACH ENERGY BAND

With each instrument on a separate spacecraft the design of each spacecraft can be adapted to the demands of the technology of that energy band.

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[7] URL http://www76.pair.com/tjohnson/library.html

For example:

- Pointing stability and attitude reconstruction will be tighter for the ~2" HPD SXT than the ~20" HPD HXT.
- The HXT could use long, deployable, optical benches to achieve larger effective area at high energies than is possible when constrained to match the SXT focal length.
- The spacecraft for the HXT and low energy spectroscopy telescopes may be less massive than the 889 kg of the current Con-X design. Table 4 does not reflect this likely saving.
- The LEST can have a short focal length and so be compact, lightweight and agile.

At the same time the commonality of spacecraft bus systems will retain many of the Con-X economies. Note that there is value to having somewhat overlapping energy ranges to simplify telescope cross-calibration.

5.4 INTENSIFIED INSTRUMENT UTILIZATION

Con-X currently has 3 instruments all of which are permanently co-pointed at the same target. This approach guarantees simultaneous broad band coverage for all observations, a capability that has been hard to achieve with previous, separate, missions. This approach also has great scope for serendipitous discoveries of, e.g. hard X-ray emission from sources where it was not expected. However, there is a cost to this restricted operational flexibility. For any particular observation it is quite likely that at least one instrument's data will not be of astrophysical insterest. The most obvious case being grating (RGA) spectra of extended sources, such as supernova remnants and clusters of galaxies. The slitless design of X-ray grating spectrometers produces overlapping spectra in all extended sources, and so have inherent ambiguity in their interpretation.

We can make a rough quantification of the utilization rate of the 3 Con-X instruments: the grating spectrometer (RGA), the microcalorimeter (XMS) and the high energy system (HXT). A design reference mission (DRM) science program for the first 3 years of Con-X operation has been defined (K. Weaver 2004, priv. comm.). Table 5 shows the distribution of time for each scientific area in this program. This table also has columns showing the level at which each of the three instruments is involved in these observations: 'PRIME' indicates a major scientific use of data from this instrument for this science area and rates a 'utilization factor' of 1; '2nd' indicates a minor, or secondary, role for this instrument in this science area, and is awarded a utilization factor 0.5; '—' indicates that it is highly unlikely that data from this instrument will be useful in this science area, and is given a utilization factor of 0. For each area we then obtain a mean utilization factor by adding those for the 3 instruments and dividing by 3.

We can get a net utilization factor for the whole observatory by multiplying the mean utilization factors by the exposure time for each science area, and summing the results. As can be seen from the bottom line of Table 5, the Con-X DRM science program has a 58% utilization factor. I.e. roughly half of the instrument time theoretically available is not being used.

Table 5: Constellation-X Design Reference Mission (DRM) 3-year Observing Program

Category	total time (Msec)	fov/ area	SXT-XMS*	SXT-RGA*	HXT*	Utilization*	Util x time
Bright AGN	9.0	0.5	PRIME	PRIME	PRIME	1	9.0
Other AGN	5.5	0.5	PRIME	2nd	2nd	0.67	3.7
Clusters	10.8	2	PRIME	—	—	0.33	3.6
Ellipticals/groups	4.0	2	PRIME	—	—	0.33	1.3
QSOs and IGM	10.0	0.5	2nd	PRIME	—	0.5	5.0
Faint X-ray bkgd. sources	2	15.0	PRIME	—	2nd	0.5	7.5
Spirals/starbursts	2.4	2	PRIME	—	2nd	0.5	1.2
SNR	9.0	2	PRIME	—	2nd	0.5	4.5
XRBs	3.8	0.5	PRIME	PRIME	PRIME	1	3.8
BHCs	2.0	0.5	PRIME	PRIME	PRIME	1	2.0
Neutron stars	6.0	0.5	PRIME	2nd	2nd	0.67	4.0
stars	9.0	1	2nd	PRIME	—	0.5	4.5
solar system	.4	0.5	2nd	PRIME	—	0.5	0.2
TOTAL	86.9 (1.0)	136.25 (1.57)					50.3 (0.58)

* PRIME = major use of this instrument, Utilization = 1; 2nd = possible use of this instrument, Utilization = 0.5; '—' = unlikely use of this instrument, Utilization = 0.

Typically Table 5 shows that one energy range is dominant, and one is unused. For example: stellar coronae use the RGA intensively, but are uninteresting (in the main) for the HXT; then again, the cosmology probed by the large program on high redshift clusters of galaxies is completely an SXT project, with the gratings rendered useless by the angular extent of the clusters, and the HXT reduced to a serendipity mode search for non-thermal cluster emission. The SXT though is not a prime instrument for only ~22% of the program. Most of the gains will come from greater use of the RGA (now 39% Prime) and the HXT (now 17% Prime).

This energy band specialization in the DRM program suggests that re-arranging Con-X into three parts each dedicated to one band and instrument would create a mission a factor 1.7 times more efficient in carrying out the DRM science program[8].

Unlike the situation for completely separate missions the unified Con-X proposal system and a single operations control center would allow the 3 telescopes to work together whenever the science demanded co-pointing. Thus the science advantage of the 'constellation' concept is retained in this new configuration.

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[8] Allowances for changes in effective area at each energy, field of view, and higher angular resolution will complicate this result and will depend on which of the options proposed here are eventually selected.

5.5 FAST RESPONSE CAPABILITY AT LOW ENERGIES

The new element of this reconfigured architecture for Con-X is the separate telescope for low energies (<1keV), a Low Energy Spectroscopic Telescope (LEST). LEST takes additional mass over the current Con-X design, so the value of the proposal needs to be assessed carefully.

The configuration proposed is that developed for the 'Pharos' mission concept (Elvis & Fiore 2003). Pharos explores new discovery space in spectral resolution and in rapid response to transient events. The prime Pharos mission goal is to slew rapidly to gamma-ray burst (GRB) locations in order to use the Crab-strength X-ray afterglows they have 1 minute after the GRB as a means of 'X-raying' the intervening line of sight at high (R=5000) resolution. Such fast slewing has been demonstrated by other missions (Quickbird, Worldview, W. Purcell, priv. comm. 2004), and is planned for *Swift*. The slow slew speed of the baseline Con-X prevents Con-X from collecting the bulk of the fluence from GRB afterglows. (The relatively low spectral resolution of the *Swift* CCDs prevents the separation and detailed characterization of the absorbers.) For a mirror with HPD=5" the out-of-plane reflection gratings being considered for Con-X (Cash 1999) give $R = E/\Delta_E$=5000. R=5000 is a natural target resolution for the next generation of X-ray spectroscopy (Elvis 2001) as this just resolves thermal lines at 10^6K .

With this capability Pharos, or LEST, would expand the Con-X science into four areas of astrophysics that are new in the 21st century Pharos/LEST would measure the physics, abundances and dynamics of: (1) the Warm-Hot Intergalactic Medium (WHIM, Cen & Ostriker 1999, Nicastro et al. 2002, 2003, 2004); (2) galaxies at the peak epoch of star formation regardless of their dust content (using the GRB host galaxy); (3) the intimate environment of the GRB itself; (4) the epoch of 're'-ionization at z>6, for those bursts that originate from the explosion of the first stars.

Pharos exploits the fact that the large graze angles allowed for low energy X-ray reflection give larger effective area per unit mass than equivalent reflectors optimized for response up to 10 keV. By restricting the energy range of the LEST to below the 0.87 keV Ni-L edge, the excellent reflectivity of Nickel (~0.85 at 0.5 keV at a 2 degree graze angle) compared with Gold (~0.6 at 0.5 keV, 2 deg) or Iridium (~0.65 at 0.5 keV, 2 deg) gives a factor 2 advantage in effective area[9]. Thus a mirror made with Con-X technology could match the SXT A_{eff}(0.5keV) = 5000 cm^2 for a mass of 153 kg[10] This area requires a diameter of 1.3 m and a focal length of only 3.25 meters.

In order to have this 1 minute response capability to GRBs, LEST needs an autonomous on-board burst detection and location system. This can be achieved relatively modestly: a simple scintillator polyhedron to trigger on a GRB and provide ~1 deg positions, plus a small (~50 cm^2) coded aperture 0.5 - 10 keV system to provide ~arcminute positions would suffice.

A rapid slewing capability would also give the Con-X LEST a monitoring capability for other targets, e.g. AGN variability. Such programs would be overly costly to be widespread in the baseline Con-X mission. Yet they hold unique potential (e.g. for solving AGN winds, Elvis 2003)

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[9] For two reflections, $(0.85/0.6)^2$=2. The reflectivity of nickel is moreover almost constant in the 0.1-0.87 keV band (Zombeck 1990).

[10] Replacing the Nickel (ρ=8.9) of the Pharos design with the glass (ρ=2.1) of Con-X technology, and scaling by the area, and including a factor 2 for the mirror assembly. The shells are assumed to be 3 mm thick.

Since photons are typically more abundant at low energies, it may often happen that a short LEST observation is all that is needed to complement spectra taken at higher energies with the other two Con-X elements, giving further efficiency gains.

5.6 SINGLE FOCUS SXT

In option B the number of SXT focal planes remained at the baseline number of 4. However putting all the SXTs on one spacecraft opens up the option of having just one focal plane. This leads to savings of cost and weight from having only a single spacecraft and a single cryostat system (Table 4). With only one focal plane additional instruments also become more feasible.

The loss of redundancy may be alleviated, and an ability to upgrade instrumentation added, by robotic servicing coming of age. Recent developments in robotic servicing for HST suggest that the dangers of loss of part of the mission due to component failures could be guarded against with a design that simplifies robotic servicing (e.g. grappling fixtures, lidar transponders, modular instrument/spacecraft component design). Note too that a servicing mission would require a much smaller payload to L2 than the entire Con-X package, so that the costs of repair, or deployment of improved instruments, may not be prohibitive. New instruments now only beginning development, e.g. polarimeters, metallic magnetic microcalorimeters, then become options for refreshing the Con-X science capability, as on Hubble but at lower cost.

A single focal plane requires a doubling of the focal length, to 20 m. As the plate scale is also doubled the total detector area, and the background per HPD, would remain constant. The physical focal plane area would be 4 times larger.

6 BEATING 2 ARSEC: A SUPER-CHANDRA?

Why stop at 2 arcseconds HPD? The Gen-X mission concept (Reid et al. 2004) envisages beating the mass/geometric area limit by using actively controlled optics to correct the figure of every reflector surface once every 6-12 months.

With a NET 2016 launch phase the 3 year C/D construction phase of Con-X will not begin until NET 2013, and the 3 year phase B detailed design until NET 2010 (Con-X SXT FMA Pre-bidders Conference, 2003). That gives the project a minimum of six years to investigate active optics for Con-X.

A substantial effort in a joint Gen-X/Con-X program could plausibly put a first generation active optics system onto Con-X. Con-X might then achieve an imaging performance comparable to that of *Chandra*, but with over 10 times the effective area. A preliminary investigation in this area seems worthwhile.

Table 6: Con-X Re-configuration Options

Option	Advantage	Section
Approach 1:		
Ion Engines from LEO to L2	2 x total mass at L2 4 x SXT mirror assembly mass at L2 $\Rightarrow$ better angular resolution	4.1
Remove half of SXT outer reflectors	2 x mass/reflector in SXT $\Rightarrow$ better angular resolution 2 x wider field of view→1.7 x utilization No loss of 6 keV A_{eff}	4.2
Polynomial prescription for optics	Large focal plane area for multiple instruments	4.3
C-coating on SXT	1.4 x SXT A_{eff}, restores much of lost area	
Approach 2:		
3 energy-specialized spacecraft	1.7 x better utilization of instruments Fully restores SXT A_{eff} at E<1 keV Adds new fast response capability Cheaper 2nd launch	5
Approach X:		
1st generation active optics	Chandra resolution; Gen-X prototype	6

7 SUMMARY

As a response to the scientific and programmatic challenges to the Con-X program we have put forward two new approaches. These are designed (1) to increase the angular resolution of the SXT, expanding the Con-X discovery space; (2) to increase the intensity with which the Con-X instruments are employed, adding new flexibility without sacrificing the unique Con-X advantage of a co-pointing constellation. Table 6 summarizes the design changes and their advantages.

If all the advantages of the options presented here could be implemented, then Con-X would have moved into new volumes of discovery space untouched by any other missions. Con-X would have: (1) 2 arcsec imaging, with almost all the effective area of the baseline, four times the field of view and almost double the observing efficiency; (2) Multiple microcalorimeters would enable observations tailored to specific science goals, and with concurrent parallel survey observations being taken continuously; (3) grating spectroscopy at the thermal limit (R= 5000); (4) rapid response capability, catching gamma-ray bursts just a minute after their onset; Yet the whole mission could cost less, as the second launcher would be smaller than now planned.

The central subject of this paper has been the SXT. The SXT has been identified as the long lead item for the Con-X program (TRIP report pre-bid, 2003). For a launch in 2013 an industrial contract was due to be awarded in 2004, with a series of test mirrors culminating in a functional flight mirror module in 2007. The SXT options presented here will need to be investigated with some urgency, so that the industry study requirements can be modified to take advantage of those options that remain attractive after an initial evaluation.

The benefits of the approaches presented here to the Con-X mission are great. A large new discovery space volume is opened up to Con-X, while retaining the benefits of the constellation concept. The reconfigured Con-X would give a strong answer to the challenges posed by both parallel missions and by *Chandra*.

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