CONSTELLATION-X

RESPONSE TO
STRUCTURE AND EVOLUTION O F THE UNIVERSE (SEU)
ROADMAP TECHNOLOGY
SUBCOMMITTEE QUESTIONS

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RESPONSE TO SEU TECHNOLOGY ROADMAP SUBCOMMITTEE QUESTIONS

1.0 INTRODUCTION

The report was prepared by the Constellation-X project in response to a request for information from the SEU Roadmap Technology Subcommittee appointed by the National Aeronautics and Space Administration Headquarters.

1.1. Purpose

The purpose of this document is to provide a response to the seven questions submitted by the SEU Roadmap Technology Subcommittee:

1. **What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.**
2. **What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?**
3. **For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?**
4. **What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?**
5. **What is status of each metric --- i.e., compare the current capability with the required capability?**
6. **Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?**
7. **Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.**

1.2. Document Organization

The responses to the SEU Subcommittee's questions are organized into nine sections (Sections 2.1 through 2.9). Section 2.1 responds to Question 1, for the entire mission. The remaining sections, organized by technology, provide answers to all question specific to each of the eight technologies.

2.0 RESPONSE TO QUESTIONS

2.1. Top-Level Response to Question 1

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The key Science Objectives for the Constellation-X Mission are:

I. **Measure the X-ray spectra of the faintest sources in the Roentgen Satellite (ROSAT) Deep Surveys and the Chandra deep fields in less than 10^5 seconds.**

II. **Test General Relativity in the strong gravity limit by mapping the inner emission regions of black holes.**

III. **Search for the "dark matter" or "missing baryons" from observations of the Intergalactic Medium (IGM)**

IV. **Study the interchange of matter and energy between stars and the Interstellar Medium (ISM), and the enrichment of the IGM and Intracluster Medium (ICM) and the evolution of clusters of galaxies.**

As part of the mission definition effort, a series of specific science goals were developed to help define the specific mission requirements. A few examples of these observations are:

- Determine the rotation rate and mass of the black holes using Doppler shifts, relativistic broadening, and reverberation analysis of iron K lines from the innermost regions of the accretion disks.
- Determine the geometry of the accretion flow in Active Galactic Nuclei (AGN) by observing Compton reflection, partial covering, and absorption by inflowing and outflowing material.
- Measure the gravitational redshift at the surface of white dwarfs in magnetic cataclysmic variables (CVs) using the iron K fluorescence lines.
- Investigate the evolution of clusters by determining the abundance, density, and temperature structure for a large sample of clusters at low and high redshifts ($z > 0.5$).
- Directly map the velocity profile of cooling flows and determine their relationship to the dominant central galaxy.
- Constrain cosmological parameters by measuring X-ray line absorption through hot gas in clusters of galaxies using background active galactic nuclei.
- Set limits on the cosmological density of a hot diffuse intergalactic medium via an X-ray Gunn-Peterson test using edge and line opacity in the soft X-ray band.
- Investigate the evolution of the intergalactic medium by determining the chemical abundances at a large window of redshifts.
- Use non-thermal signatures to identify sites of cosmic ray acceleration in young supernova remnants.
- Map the intergalactic magnetic field strength by measuring inverse Compton scattering of the cosmic microwave background from relativistic electrons in AGN jets.
- Study chemical enrichment of galaxies through the dispersion of nucleosynthesis elements by supernova explosions and stellar winds.

- Investigate the formation and evolution of magnetic dynamos in young and pre-main sequence stars buried deep in molecular clouds by observing their X-ray coronal activity at high spectral resolution.

Science requirements flow down directly from the above Science Objectives and science goals, taken both individually and collectively, to each of the Constellation-X technology areas. These technology areas are primarily the optics and detectors, though the flowdown to all of the mission technologies (including the ground segment) have been evaluated. Many of the science flowdown requirements impact several technologies simultaneously. For example, the first of the science objectives above is a requirement on high sensitivity, which places simultaneous requirements on the telescope optics and its associated detector(s). Many of the science requirements must also be placed simultaneously on the optics and detectors, and take the interaction of the two into account, and resulting in a system-level requirement.

Below, we briefly present the science requirements for each of the key technology areas.

2.1.1 Spectroscopy X-ray Telescope (SXT) Optics

There are three primary science driven requirements on the SXT mirror system: effective area, angular resolution, and bandpass. These requirements are developed in conjunction with presumed detector performance and other telescope losses.

X-ray throughput is the first primary requirement on the SXT optics, derived from Science Objectives I through IV, and is for high throughput, yielding at least 1000 counts in 10^5 s for a flux of 2 x 10^{-15} ergs cm^{-2} s^{-1}. These requirements led to system effective areas that have been specified at 0.25, 1.25, and 6.4 Kilo Electron Volts (keV) of 1,000, 15,000 and 6,000 cm^2, respectively. This requirement must be implemented in conjunction with an understanding of the quantum efficiency (QE) of the detectors.

Angular (spatial) resolution is the second primary requirement on the SXT optics, and derives equally from two different requirements: spectral resolution and flux sensitivity. Again, these are derived from considerations of Science Objectives I through IV. First, the SXT optics must provide for high spectral resolution from 0.25 to 10, which requires consideration of the detector systems. While the calorimeter provides the necessary spectral resolution independent of the optics spatial resolution, the gratings place a requirement on the SXT optics for spatial resolution to achieve the specified system minimum resolution (R=300). Second, the spatial resolution must also be adequate to avoid source confusion at the faint source limit. These requirements yield a spatial resolution requirement of 15 arc seconds Half Power Diameter (HPD) for the mission, which is consistent with 10 arc seconds HPD for each SXT mirror

The bandpass from 0.25 to 10 keV is developed by consideration of the dual telescope system on Constellation: the SXT and Hard X-ray Telescope (HXT) bandpasses must overlap to allow adequate cross-calibration of the continuum x-ray fluxes.

2.1.2 X-ray Calorimeter

The primary science requirements that flow to the calorimeter are for spectral resolution, bandpass, count rate and, in conjunction with the SXT optics, field of view.

The X-ray calorimeter is a non-dispersive instrument, and the top-level requirement for resolving power is R=3000 from 6 – 8.5 keV; i.e., 2 Electron Volt (eV) energy resolution. The minimum spectral resolution anywhere over the line-rich 0.25 – 10 keV bandpass is set by the conditions that 1) there be sufficient resolution to separate the important density-sensitive He-like triplets (resonance, forbidden and intercombination lines) arising from the O, N, Mg, Si and S ions and 2) the majority of the individual spectral lines in this bandpass be resolved. For the X-ray calorimeter in particular, the spectral resolving power in the 6.0 –8.5 keV bandpass must be high enough to 1) distinguish the lithium-like satellite lines from the overlapping helium-like transitions, and 2) achieve a velocity resolution of at least 20 km s-1 in the Fe K lines.

A minimum field of view of 2.5 arc minutes has been specified to allow for studies of extended objects. In addition, the detector must critically sample the SXT point response function. The combination of these requirements yields a requirement for at least a 30 x 30 pixel array.

A bright source requirement imposes a count rate of 1,000 counts per second (cps) per pixel over 3x3 pixels or 10,000 cps over the detector.

2.1.3 Adiabatic Demagnetization Refrigerator (ADR)

There are no direct science requirements that flow to the ADR. The ADR requirements flow from the X-ray calorimeter requirements. Hence, the ADR must provide adequate temperature control (absolute temperature and temperature variations) that permits 2eV resolution in the calorimeter. These calorimeter science requirements result in engineering requirements on heat rejection at the hot stage of the ADR, and tight control over the temperature stability of 10 micro Kelvin (rms) at the cold stage.

2.1.4 Cryocooler

The direct science requirements that flow to the cryocooler are based on the required lifetime. Indirectly, the cryocooler requirements derive from the ADR cooling requirements (which are in turn driven by the calorimeter array size and the readout electronics). The mission lifetime requirement has been set at a minimum of 4 years of normal mission operations, with consumables sized for a minimum of 6 years. The array size is driven by a science requirement on the calorimeter to provide a field of view of at least 2.5 arc minutes with 5 arc seconds pixels (i.e., at least a 30x30 array). The readout electronics and their heat loading is driven by the science requirement on the calorimeter to allow for count rates of 1000 cps/pixel, or 10,000 cps averaged over the detector array, on a single telescope. This flows down to a cryocooler with a cooling capability of at least 7.5 milliwatts at 6K.

2.1.5 Gratings and Charged Coupled Devices (CCDs)

The science requirements that flow to the gratings and CCDs need to be considered together, though because the technology developments are substantially different, we consider them separately in the following section. The key requirements are effective areas, energy resolution, and bandpass.

The primary top level science requirement that flows to the grating/CCD is, in combination with the SXT optics, to achieve specified effective areas with a resolving power of $R > 300$ from 0.25 to ~1keV. The minimum spectral resolution anywhere over the line-rich 0.25 – 10 keV bandpass is set by the conditions that 1) it be sufficient resolution to separate the important density-sensitive He-like triplets (resonance, forbidden and intercombination lines) arising from the O, N, Mg, Si and S ions, and 2) the majority of the individual spectral lines in this bandpass be resolved, and that a velocity resolution of < 100km/sec can be achieved.

The second top level science requirement that flows to the gratings is to cover the bandpass from 0.25 to ~1 keV. Use of gratings for the low end of the bandpass follows from the fact that, for calorimeters, ΔE is constant, thus $\lambda / \Delta\lambda$ falls linearly with energy and is insufficient at energies less than ~0.6 keV. In addition, the X-ray calorimeter efficiency is limited at low energies due to the incorporation of long wavelength blocking filters. For a dispersive spectrometer, $\Delta\lambda$ is approximately constant, so $\lambda/\Delta\lambda$ rises inversely with decreasing energy. For reflection gratings, the efficiency also increases at low energies due to increasing reflection efficiency.

2.1.6 Hard X-ray Telescope (HXT)

The primary science requirements that flow to the HXT (optics plus detectors) are bandpass, energy resolution, and sensitivity.

A broad bandpass is required to address Science Objectives I – IV. Many cosmic sources exhibit spectral features over a broad range of energies. These include Active Galactic Nuclei (AGN), in which Compton reflection off surrounding cold material produces a continuum spectrum at energies above 10 keV; stellar flares, in which a hard, non-thermal impulsive continuum above 10 keV can accompany the thermal emission produced during coronal heating events below 2 keV; and Supernova Remnants (SNRs), in which the synchrotron radiation generated by cosmic ray electrons accelerated at the shock front can produce a high energy tail in addition to the thermal component. At the high energy end, the HXT must be capable of reaching 40 keV. The requirement at the low energy end is set at 6 keV such that there is sufficient overlap with the calorimeter to allow for cross-calibration of x-ray continuum spectra.

The energy resolution requirement derives from the ability to determine the form of the X-ray spectrum above 10 keV. A requirement on the energy resolution of $\Delta E/E < 10\%$ is adequate to achieve this goal, and has been placed on the HXT, which is sufficient to characterize the continuum emission.

The effective area requirement is set by the need for the HXT system to provide a good S/N spectrum in the same time (10^5 seconds) as the SXT observations of the faint sources noted in Science Objective I. This places a requirement of 1,500 cm^2 at 40 keV

As with the SXT, the HXT angular resolution requirement is set to allow confusion-limited observations of the faintest source populations to be studied. For the harder X-ray sources, this requires a telescope HPD of 1 arc minute.

2.2. Spectroscopy X-ray Telescope (SXT) Optics

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

There are four primary requirements on the SXT mirror system. Three are science driven, and one is mission driven:

Effective area - from the top level flux sensitivity requirement, the SXT needs to provide sufficient collecting area so the observatory collecting area for high resolution spectroscopy meets or exceeds 15,000 cm^2 at 1.25 keV and 6,000 cm^2 at 6.4 keV. Accounting for detector quantum efficiency, the SXT mirror must provide 30,000 cm^2 at 1 keV and 7,500 cm^2 at 6.4 keV.

Angular resolution - from the top level flux sensitivity and spectral resolution requirement (in conjunction with grating dispersion), the Half-Power Diameter (HPD) of the entire telescope must be smaller than 15 arc seconds. The SXT mirror must provide an HPD better than 10 arc seconds.

Bandpass - from the top level science requirement, the SXT must have a band pass of 0.25-10 keV.

Mass (mission driven) - observing time requirement leads to the need for a high altitude orbit. This in turn limits the spacecraft mass. Given this spacecraft mass, four identical spacecraft are baselined to meet the effective area requirement.

Implementation: The Reference Configuration for Constellation-X entails four identical spacecraft and sets of instrumentation. Each of the four identical SXT mirrors is a Wolter I grazing incidence mirror with a 10 m focal length and a 1.6 m diameter. The mirror is composed of many (100-250) nested Wolter 1 reflectors. The SXT optics utilizes a segmented approach. Instead of consisting of a complete surface of revolution, each mirror will be constructed as a set of identical azimuthal segments. In the current design concept, reflectors with diameter smaller than 0.8 m will consist of 8 azimuthal segments, and larger reflectors will consist of 16. The parabolic (primary) and hyperbolic (secondary) reflectors will be constructed separately. Reflector segments are composed of thin (0.4 mm) glass, thermally formed to the correct figure, and provided an X-ray reflecting surface via epoxy replication from a precise mandrel. Reflectors within a module (an azimuthal portion of the mirror) are aligned using a combination of optical means and accurate metering via etched Si microstructures.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

The fundamental challenge is constructing a mirror with the required angular resolution. The other requirements - mass, bandpass, and collecting area - are easily met by the current approach.

A second challenge is establishing an approach for mass production of reflectors and rapid accurate alignment of the reflectors within a module. This challenge arises from the Constellation-X development time line that requires completion of the SXT mirrors at an approximate rate of one per year.

3. For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

The metric for angular resolution is the half power diameter in X-rays (10 arc seconds) of a mirror assembly.

The metrics for mass production is the rate at which reflectors are produced, and the time necessary to assemble and align a module.

4. What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?

Ground tests are sufficient for demonstrating the SXT mirror performance. We will build a progression of prototype mirrors, each with a more flight-like configuration than its predecessors. For each of these, we will demonstrate via X-ray test that HPD meets the mission requirement before and after environmental tests. The first such performance demonstration, for the Engineering Unit, should take place by the end of 2003.

The phased development of the prototypes also provides a means for developing and demonstrating of reflector mass production and module alignment. The mass production and alignment approach should be demonstrated by the end of 2005.

5. What is status of each metric --- i.e., compare the current capability with the required capability?

The best segmented lightweight optical system that has flown—Astro-E, had angular resolution of ~100 arc second HPD. These mirrors were fabricated using a far less precise approach.

We have shown that most of the key components of a mirror system meet their requirement (as specified in an error budget), and the remainder are close. For instance, the Si alignment bars meet their requirement for accuracy and repeatability, and replication mandrels similar to those currently being fabricated have exceeded the Constellation-X requirement. The figure of formed glass substrates is approaching the required accuracy. We are assembling the components into a module that will establish a baseline for system-level angular resolution. We are also addressing the optics development at the system level by developing the assembly design.

Process development is still underway for the mirror components, reflector fabrication and alignment in particular. As these are defined, it will be possible to address the facility requirements for mass production, and the time necessary for alignment.

6. Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?

While the angular resolution requirement for Constellation-X is significantly better than that achieved with the previous (Astro-E) approach, the groundwork had been laid for most of this advance, so the required capability is now an extension of the existing approach.

The mass production and alignment will draw heavily from the Astro-E approach, but will incorporate the different reflector fabrication technique and a more accurate alignment approach.

The table below summarizes how the some of the component fabrication and alignment technologies used for Astro-E mirrors are being modified to meet the Constellation-X requirements.

Component	Astro-E	Constellation-X
Substrate	Thermally & mechanically formed Al foil	Thermally formed glass foil
Forming mandrel	Off-the-shelf quartz cone	Precisely figured quartz cone
Replication mandrel	Durant cylindrical glass tubing	Figured and polished Zerodur (Wolter I surfaces)
Surface production	Epoxy replication	Epoxy replication
Alignment structure	Electric Discharge Machining (EDM) aluminum combs	Si microstructures
Alignment method	Gang mechanical/optical alignment of full module	Optical alignment of individual reflectors or groups of reflectors; mechanical alignment using microstructures if possible
Alignment light source	Collimated optical beam	Chandra Centroid Detector Assembly

7. Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.

The development of this large area, light weight X-ray optics technology enables future X-ray missions; e.g., XEUS and Generation-X. Thus, there is synergy with efforts in other bands to produce lightweight optics (Large Telescope Space Initiative).

2.3. X-ray Calorimeter

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The requirements for energy resolution, high sensitivity, maximal field of view and detector read out speed are traceable to the specific scientific requirements of the mission as described in Section 2.1. The X-ray calorimeter provides the capability for high spectral and high quantum efficiency over a large energy bandwidth, without degradation due to finite source extent, and can deliver this resolution up to counting rates in the 100-1000 Hz range (with calculable dead time.) This makes these devices an ideal choice for spectroscopy of weak sources, including extended sources.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

The detector array requirements for Constellation-X are significantly more challenging than the performance characteristics of the X-ray calorimeters currently in use. The key areas for technology development are a spectral resolution of several eV out to ~ 8 keV, smaller pixels to allow appropriate matching to improved mirror point spread functions, larger arrays (e.g., > 30 x 30 elements) to subtend reasonable fields of view, and high spectral and quantum efficiency uniformity over the array.

What's been demonstrated: An energy resolution of 2 eV at 1.5 keV and about 4-5 eV at 6 keV has been demonstrated on single pixel devices. This resolution has been achieved at counting rates of up to a few hundred counts per second.

What need's to be demonstrated:

Spectral resolutions of a few eV on small arrays of simultaneously read out pixels. At present, the baseline pixel size for the Constellation-X calorimeter array is 250 microns. This is traceable to a 15 arc second HPD X-ray point spread function and assuming image over-sampling by a factor of three (i.e., 5 arc second pixels.)

Demonstrate read out schemes (either single string per pixel or multiplexed) that allow the full energy resolution of the array to be realized and which can be extended to full array sizes (e.g., up to 32 pixel columns or rows). These must also be compatible with realizable dewar system designs.

Operate detectors at rates approaching 1000 Hz and quantify dead time effects.

3. For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

- Pixel size (area and thickness necessary for high quantum efficiency): 250 micron pixels and > 90% QE at 6 keV.
- Energy Resolution: 2 eV at 6 keV.
- Resolution uniformity: Assuming a resolution of 2 eV, a uniformity of ~ 1 eV over the array is desirable to allow co-adding of spectra from four arrays.
- Array filling factor. > 95%.
- Robust fabrication process to ensure high yields for four separate instruments, including spares and engineering models.
- Number of channels simultaneously read out.
- Detector Speed. Faster pulses obviously allow higher counting rates to be achieved with lower dead time. Since some amount of dead time is unavoidable, a metric will be to quantify the dead time effects at counting rates approaching 1 kHz, and devise pulse energy determination algorithms that maximize throughput for different resolution grades.
- Scalability of system design to full-sized arrays of 32 x 32 pixels (i.e., detectors, amplifiers, and analog and digital electronics.)

4. What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?

- Operating arrays of devices that implement basic requirements for pixel size, quantum efficiency, etc., simultaneously (e.g., 2 x 2 array). This permits the uniformity on small pixels to be assessed, as well as system issues (thermal and electrical cross talk.)

- Read out small but meaningful subsets of pixels (e.g., 4 x 4 or 2 x 8) to demonstrate viability of read out schemes, including multiplexed schemes.
- Demonstrate 3 x 32 calorimeter channels operated simultaneously.
- Operate these systems in real-world low temperature systems (in particular ADRs, with their associated magnetic fields.)
- Demonstrate that detector read out schemes produce heat loads compatible with likely cooling techniques.
- Demonstrate that detector technology and read out scheme are robust with respect to cosmic rays. This includes both radiation damage and radiation affect on detector performance (energy resolution and dead time effects.) This can be assessed to a large extent from ground tests, but simulating cosmic ray effects is difficult and nothing can compare with in-flight experience.

Ground laboratory testing and subsequent environmental testing of near flight-like configurations are all that is required to demonstrate technology readiness. No space-based demonstrator is required.

5. What is status of each metric --- i.e., compare the current capability with the required capability?

Parameter	Requirement	Present Capability
No. pixels operating and read out simultaneously	1000	1
Pixel size	250 microns	300 microns
Energy resolution	2 eV up to ~ 8 keV	2 eV at 1.5 keV 4-5 eV at 6 keV
Pulse time constant	100-500 microsecond	> 300 microsecond

6. Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?

There are two X-ray calorimeter technologies being supported by Constellation-X Research and Development (R&D) funding. These are devices with superconducting transition edge thermometers and doped semiconductor thermometers. Based on the promising single pixel results that have been obtained so far, the prospects for achieving the goals of Constellation-X should eventually be possible without fundamental breakthroughs. However, reaching the necessary level of technology readiness [i.e., Technology Readiness Level (TRL)-6] by the middle of this decade will require many areas of technology development to be carried out in parallel.

To achieve the goals of the Constellation-X mission, both technologies require significant advancement in order to demonstrate the flight readiness of each approach.

<u>Thermometer</u>: For semiconductor thermometers, characterize thermometer responsivity with geometry, implant dose, etc. For the transition edge sensor (TES) devices, develop robust fabrication process for repeatable transition temperature, Tc, sufficient critical current, etc. Evaluate performance on thermometer sizes required for 250 micron unit cells.

<u>Noise sources</u>: Both thermometer types exhibit a certain amount of noise in excess of simple phonon and Johnson noise. Determine how noise scales with device parameters by fabricating test devices to map out the noise dependence.

Absorbers:

For semiconductor devices, develop process for attaching Sn foil and dicing (e.g., by laser) to create uniform absorber size and spacing. For TES, develop process for directly depositing absorbers onto TES. Demonstrate high spectral resolution up to ~8 keV.

System:

- Evaluate thermal and electrical cross talk using small arrays.
- Assess system issues (thermal and mechanical) for implementing very large numbers of Junction Field Effect Transistors (JFETs) (running at up to 130K for minimum noise) and Superconducting Quantum Interface Device (SQUIDs).
- Develop Transition Edge Sensor (TES)/SQUID interface for 1000 pixel array.
- Develop multiplex chip and control electronics, including MUX design and layout, optimizing for speed, noise, power, and number of channels to MUX (32 or fewer?), etc.
- Develop digital signal processor system capable of handling 1000 pixel arrays within very tight power constraints. This is required for either sensor type.
- Carry out radiation hardness tests of JFETs and SQUIDs
- Design anticoincidence detector appropriate for each type of sensor.

7. Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.

To a large extent, the read out of large arrays of X-ray calorimeters is being paralleled in the development of large IR and mm-wave bolometer arrays for both ground-based and space-borne observatories. Many of the issues are the same, such as thermometer technology, detector mounting and interfaces to amplifiers (JFETs and SQUIDs). But there are very significant differences. The X-ray devices must be much faster in order to detect individual photons up to relatively high counting rates. They require thick absorbers to provide high quantum efficiency up to 8 keV or so. These absorbers must have a particular heat capacity, thermalize photons with high uniformity, and be compatible with the full fabrication process. The read out of these sensor technologies is indeed synergistic, but again, the higher speeds of the X-ray sensors requires specialized development of the detectors all the way out to the digital read out electronics.

2.4. Adiabatic Demagnetization Refrigerator (ADR)

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The 2eV calorimeter requires subKelvin, stable operational temperatures. ADR technology has been baselined to provide the calorimeter operational temperature. The hot end of ADR must interface with a 6K cryocooler.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

A flight qualified ADR with an operational temperature of 50 mK and hot end of 1 K has been developed for ASTRO-E. Finer cold end temperature stability, higher temperature hot end, and higher cooling capacity are required for the Constellation-X ADR.

Several Constellation-X ADR technical challenges have already been overcome and demonstrated by a three-stage laboratory model ADR. This model demonstrated the required cold end temperature and stability in a continuously operating system

The primary remaining technical challenge for the ADR is demonstration of the “hot” end stage(s), which extends from 1-2 K to 6K. The hot ADR stages require new magnets, power leads, magnet electronics, salt pills and integration materials. The subsequent remaining challenge will be integration of these stages with the proven 50mK to 1-2K stages into a system that meets the overall performance.

3. ***For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?***

The primary metrics to achieve are a hot end temperature of 6K and overall system cooling capacity of 5 microwatts while maintaining the cold end temperature of 50 mK and stability of 10 microKelvin (rms). The cold end temperature and stability have already been demonstrated.

4. ***What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?***

Ground testing in the relevant thermal vacuum and launch vibration environments is sufficient to demonstrate the ADR technology.

ADR technology has been baselined over the dilution refrigerator technology because the latter requires on-orbit (or other zero g) demonstration.

5. ***What is status of each metric --- i.e., compare the current capability with the required capability?***

Temperature control has been demonstrated to a level of 8 microKelvin (rms) at 50 mK by a three stage ADR with a hot end of 1-2 K and continuous cooling at the cold end. This meets the requirement of the first three stages. Additional stage(s) will extend the hot end to 6K.

The final stages require new refrigerant, magnets, and lead materials that function at 2 to 6K. Candidate materials are currently under investigation. A laboratory model of final stage going up to 4.5K liquid Helium temperature is expected to be completed by the end of Fiscal Year 2002. The next major development will be to integrate all stages going up to 6K and demonstrate the full system cooling by early Fiscal Year 2004. Finally, an engineering unit of the multistage ADR will be built for performance and environmental testing by the end of Fiscal Year 2006.

6. ***Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?***

In all areas, the required capability can be obtained as a reasonable extension of existing capabilities.

At a minimum, research is already underway that has shown a probable solution in each case. In the case of producing refrigerant materials in crystalline form, the capability to produce some materials of interest can be revived by funding.

7. ***Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.***

Cross Enterprise Technology Development Program (CETDP) and Commercial Technology Development (CTD) NASA offices are addressing the ADR development challenge for Constellation-X, SPIRIT, Sub millimeter Probe of the Evolution of Cosmic Structure (SPECS), Filled Aperture Infrared Telescope (FAIR), Sub millimeter and Far Infrared Experiment (SAFIRE), Space Ultraviolet Optical Observatory (SUVO), Extreme Ultra Violet (EUV) Solar and Microarcsecond X-ray Imaging Mission (MAXIM) applications.

2.5. Cryocooler

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The ADR cooling needs and long mission life requirements motivate the cryocooler technology development. Mission requirements that flow down to the cryocooler include a mass and power budget.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

The most significant technological challenge is to reach a cold end temperature of 6 K with sufficient cooling power to lift the ADR heat load.

The ADR cooling needs may be met by stored expendable cryogen systems that have limited life when cryogen mass is limited. This is the case for many space applications due to limited launch mass. To increase the life of future space missions NASA JPL is leading a common cryocooler technology development known as the Advanced Cryocooler Technology Development Program (ACTDP), which encompasses the requirements for Constellation-X, Next Generation Space Telescope (NGST) and Terrestrial Planet Finder (TPF).

Four contractors are currently participating in the ACTDP Study Phase, which will be followed by a Demonstration Phase to develop prototype units of two or three technologies. The technologies currently under contract are Multistage Pulse Tube System, Multi-Stage Proprietary TRW Cryocooler, Joule Thomson (J-T) Cooler with 3-Stage Stirling Pre-cooler, and Turbo-Brayton. Cryocooler.

The 6K cooling challenge is common to all projects. Also, there is an intermediate stage cooling requirement for the other projects of which Constellation-X will be taking advantage. The temperature of the intermediate stage cooling is 18K at 250 mW.

3. For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

The metric is to lift 7.5 milliwatt (mW) heat load at 6 K and 250 mW at 18 K for less than 150 W beginning-of-life input power and 40 Kilograms of mass.

Reaching a temperature of 6K is a big challenge. Providing the cooling powers at 6K and 18K requires good staging and good performance. The thermodynamic efficiency also influences the required input power.

4. What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?

A cryocooler system (cooler with Bread Board electronics) ground test demonstrating the 7.5 mW requirement will be completed and reported on by each of 2 or 3 ACTDP contractors by mid 2005.

An Engineering Model capable of withstanding launch and flight environments will be tested on the ground in 2006 to demonstrate the readiness of technology for Constellation-X flight. Ground testing will be sufficient; there is no requirement for space demonstration.

5. What is status of each metric --- i.e., compare the current capability with the required capability?

The proof of concept Multi-Stage Pulse Tube Technology has demonstrated less than 7K of cooling temperature with a mass of 26 Kilograms and power of 106 Watts. Others have yet to attain the low temperature. The intermediate stage is also not demonstrated yet. Current off-the-shelf capabilities for space borne cryocoolers are in the 30+ K temperature region, but several R&D efforts such as Multistage Pulse Tube and Stirling have attained (with varying degrees of qualification) cooling in the 10± K region.

6. Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?

The required capability is the reasonable extension of the current capability as each of the four contractors selected for the Study Phase have proposed a varied mixture of existing technology and next-step technology that is coming out of Internal Research and Development, SBIR or other funded work.

7. Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.

The ACTDP has active participation in setting requirements, program reviews and contractor selection from Constellation-X, NGST and TPF.

2.6. Gratings

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The top level science requirement that flows to the gratings is, in combination with the CCD detector, to achieve specified effective areas (>1000cm^2) with a resolving power of R > 300 from 0.25 to ~1keV assuming 10 arc second HPD optics.

Mission requirements that flow down to the gratings include a mass budget.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

The baseline technology for the Constellation-X gratings is a reflection grating that is an evolution of the design flown on XMM.

The key challenge for this approach is to develop grating substrates with the required groove efficiency while meeting the required mass density per unit area and required optical tolerances. Master gratings that meet Constellation-X requirements have been fabricated. Micro-roughness of blazed facets with photolithographic process on silicon is below 0.4 nm (compared to XMM: ~ 1.2 nm), and diffraction efficiency is excellent.

An alternate approach is an “off-plane” radial groove grating. The technological challenge to this approach is to achieve adequate groove efficiencies at the required ruling density and with the proper “radial” groove geometry and blaze angle, while maintaining adequate optical tolerances.

The technology to fabricate the grating master is the primary challenge for this alternate approach. However, it potentially offers advantages in terms of science enhancement as well as easing the fabrication requirements on the grating substrates. This approach requires exploration of several aspects to be compared with the baseline approach:

- Optical tolerances on the substrates
- Assembly and alignment tolerances;
- Spectral resolution;
- Ruling densities;
- Groove efficiencies and the total number of gratings;

3. For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

The driving metrics for the reflection gratings are:

- Substrate mass per unit area ≤ 0.2 g/cm
- Substrate flatness < 0.5 micro m
- The driving metrics for the off-plane radial groove gratings are:

Groove efficiency in radial groove geometry of 25%

The substrate mass and flatness, and assembly tolerances would be relaxed for the off-plane grating approach in comparison with the baseline.

4. What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?

Laboratory demonstrations and subsequent environmental testing of near flight-like configurations of the gratings are all that is required for either the baseline or the alternate approach. No space-based demonstrator is required.

5. What is status of each metric --- i.e., compare the current capability with the required capability?

Minimal funding has been devoted so far to the baseline approach. Accomplishments against the metrics listed above include:

Flatness of <1 micron on a 100 mm diameter wafer that meets the 0.2g/cm2 areal density requirement has been demonstrated with magneto-rheological figuring (MRF).

For the alternative approach: Plans are in place, but no hardware has been fabricated. A grant is in place to assess feasibility and generate specifications for holographic recording geometry by late FY 2002. A holographic grating with 5500 g/mm with the a parallel groove configuration at 30 degree blaze on a 58 mm x 58 mm (half size) substrate will be produced by start of CY 2003. Laboratory evaluation of grating performance follows prior to following step. Generation of a flight size 120mm square grating with >5500g/mm in a radial groove configuration will take place by summer 2003, followed by laboratory evaluation of the grating later that year.

6. Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?

The required capabilities for the baseline approach are reasonable extensions of current grating fabrication techniques. The gratings will be directly fabricated using interference lithography on graze-cut silicon wafers. If a replication process is chosen instead, extrapolating from XMM/Newton Reflection Grating Spectrometer experience, high fidelity grating replication from a single master may require production of 7th generation replicas in a complex replication tree. A uniform ruling density master (38mm diameter) was fabricated and tested to provide proof of concept and verification of groove efficiency for the anisotropically etched gratings with flat, smooth facets Si(111) plane orientation. Extrapolation to include a radial groove on a large size wafer (200mm) appears to be reasonable extension of current technology.

The required capabilities for the alternate approach require improvements in ruling techniques to simultaneously achieve the groove density, groove geometry and groove efficiency. High density, blazed gratings have been fabricated for use in deep UV, e.g. for COS on Hubble Space Telescope (HST). Change of ruling geometry and evaluation of x-ray performance is required, but no new technology. Off-plane geometry allows higher separation between gratings so substrates may be thicker, which makes it easier to achieve the required flatness. Standard thin plate replication technology may be employed, but needs demonstration with holographic master gratings. This alternate approach may also allow the mass constraints to be met without significant technological advance, and should require fewer gratings to be manufactured (perhaps by a factor of 2).

7. Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.

Lightweight gratings and flat substrates are of use to many programs. Holographic high ruling density aberration-corrected gratings in use for COS and for future UV missions such as SUVO.

2.7. Charge Coupled Device (CCD)

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The key science driver for the CCD is, in conjunction with the gratings, to obtain the required effective area at a resolving power >300 from 0.25 to ~1keV. Energy resolution in the CCD is required to separate grating orders. CCD pixel sizes are driven by the required spectral resolution.

Additional mission requirements that flow to the CCDs are low power, radiation tolerance, high production yield and a mass budget.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

The baseline technology for the Constellation-X CCDs is a Resistive Gate CCD (RGCCD) approach that promises a low power, radiation resistant device. The significant technological challenge is to develop and prove the concept of the resistive gate structure.

An alternate approach to the CCD is an Event-Driven CCD (EDCCD). This approach has a number of potentially attractive aspects compared to the baseline approach:

- Significant reduction in the power required for the devices
- High frame rate which will enhance the science return and could relax the spacecraft stability and jitter requirements, and reduce the optical stray light requirement by at least and order of magnitude
- Reduced pile-up concerns
- Reduce the data volume that must be transferred to the ground
- Low power and the associated reduction mass savings on the spacecraft

The primary technological challenges are to develop the readout system for the EDCCD and to verify the Molecular Beam Epitaxy (MBE) back-side treatment process. The pixel array technology remains unchanged from existing CCDs. The MBE back-side treatment process will provide the improved low energy response of the CCDs below 0.5 keV. Studies of the MBE process are decoupled from the EDCCD geometry and electronics, and can occur in parallel. The demonstrated yield of the MBE process is already at least an order of magnitude above that used to provide the ACIS CCDs on Chandra.

A recommendation is being considered by the project to baseline the EDCCDs. The top level technology development roadmap and associated costs are needed before this decision will be made.

3. For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

For the RGCCDs, the metrics are:

- Frame rate 10 Hz
- Power: 10 times less than current devices
- QE: 25% at 0.25 keV
- Radiation hardness: 5x greater than Chandra ACIS CCDs

For the EDCCDs, the metrics are:

- Frame rate: > 50 Hz
- Power: 50 times less than current devices
- QE: 75% at 0.25 keV
- Radiation hardness: 10x greater than Chandra ACIS CCDs

Relatively high fabrication yield will be required by either technology to support production of the large number of CCD's required for the mission.

4. What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?

Laboratory demonstrations and subsequent environmental testing of near flight-like configurations of the CCDs are all that is required for either the baseline or the alternate approach. No space-based demonstrator is required.

5. What is status of each metric --- i.e., compare the current capability with the required capability?

The current technology is defined by the Chandra ACIS CCDs. The back illuminated devices have a QE at 0.25 keV of 25%, while the front illuminated devices only have a QE ~1% at 0.25 keV. The

Chandra CCDs have a frame rate of 0.3Hz. The power requirements and radiation hardness of the Chandra devices are taken as unity for comparison purposes with the RGCCD or EDCCD metrics.

No work is currently being funded on the RGCCDs. A single test lot was funded and fabricated in 1998. Basic functionality was demonstrated.

For the EDCCD approach, fabrication of the first set of devices began in February 2002, with completion planned for July 2002. This work is funded by internal MIT funds, and NASA ROSS2000. Device packaging and preliminary screening is planned for August 2002. Plans for FY 2003 include a run with a fully depleted, thinned CCD with high QE at 150eV.

6. Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?

While the RGCCD's required capabilities represents a new type of CCD, they are based on well-understood CCD fabrication techniques, and the first lot showed that the principle behind the RGCCD is sound.

The required capabilities for the EDCCD approach are straightforward extensions of current CCD fabrication techniques. The basic MBE process exists, and functioning devices with good X-ray energy resolution and low energy response have been fabricated.

7. Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.

EDCCDs are suited for surface inspections, contamination studies, and X-ray fluorescence studies for laboratory diagnostics; they are also suitable for use in large coded aperture systems. Many applications exist in general astronomy missions for high frame rate, radiation tolerant and low power CCDs.

2.8. Hard X-ray Telescope (HXT) Optics

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The primary science requirements that flow to the HXT optics are broad bandpass, spatial resolution, and sensitivity, as defined in section 2.1.6.

Additional mission requirements that flow to the HXT optics include a mass budget.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

The challenge is to demonstrate subarcminute angular resolution for low-mass, high-reflectance multilayer-coated optics.

To date, prototype multilayer mirrors have been fabricated which meet the reflectance requirement up to 50 keV using formed glass. The resolution must be improved and a full-sized flight prototype fabricated and tested. Replica Nickel optics have achieved the desired resolution, but multilayers have not been fabricated on the interiors of small-diameter shells.

3. For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

Technical readiness will be demonstrated by measuring the X-ray performance of a prototype optic consisting of at least 10 full shells. The measurement must demonstrate the reflectance at 10, 30, and 50 keV, and must show the angular resolution is less than 1 arc minute HPD.

4. What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?

Laboratory measurements of reflectance and resolution.

5. What is status of each metric --- i.e., compare the current capability with the required capability?

The current capability:

Glass optics: HPD 90 arc seconds, reflectance >45% to E=50 keV, can meet mass requirement.

Ni replica: single thin (low-mass) shells can be fabricated with <60 arc second resolution but multilayers have not been applied, so the reflectance has not been demonstrated.

6. Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?

The critical technologies are reasonable extensions of existing technologies, as described above.

7. Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.

There is significant synergy with a number of balloon SR&T programs (HEFT, InFocus), with explorer concepts. There is overlap with some balloon programs but none are driving the requirements in this way.

2.9 Hard X-ray Telescope (HXT) Detectors

1. What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

The primary science requirements that flow to the HXT detectors are broad bandpass, energy resolution, and sensitivity, as defined in section 2.1.6.

Additional mission requirements that flow to the HXT detectors include a mass budget.

2. What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

The challenge is to demonstrate high-quantum efficiency and 5 keV threshold for a 500 micron CdZnTe pixel detector/low-noise Application-specific Integrated Circuit (ASIC) hybrid.

To date, CdZnTe pixel sensors of appropriate dimensions and pixel size have been demonstrated at E>= 10 keV. The CdZnTe efficiency must be measured, and possibly improved upon for energies below 10 keV. Low noise ASICs with large numbers of channels must demonstrate the desired systematic threshold.

3. For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

Technical readiness will be measured by making low-energy X-ray scanning measurements of a prototype (at least 2 cm x 2 cm) detector. These must show the threshold to be below 5 keV, and the QE of the sensor to be above 70%.

4. What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities which can only be demonstrated in space?

Laboratory measurements with radioactive sources and X-ray generators.

5. What is status of each metric --- i.e., compare the current capability with the required capability?

Detectors and readouts with appropriate spatial resolution, energy resolution, and high-energy (E>10 keV) response have been demonstrated. The electronic thresholds are at ~8 keV, and low energy QE is unknown.

6. Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?

The critical technologies are reasonable extensions of existing technologies, as described above.

7. Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.

There is significant synergy with a number of balloon SR&T programs (HEFT, InFocus), with explorer concepts. Other missions requiring high-resolution CdZnTe pixel detectors (e.g., EXIST) are benefitting substantially from the low-noise readout development, and the high-quality CdZnTe sensor development.

There is overlap with some balloon programs but none are driving the requirements in this way..

LIST OF ACRONYMS

ADR	Adiabatic Demagnetization Refrigerator
AGN	Active Galactic Nuclei
AGN	Active Galactic Nuclei
ASIC	Application-specific Integrated Circuit
CCDs	Charged Coupled Devices
CdZnTe	Cadmium Zinc Telluroid
CETDP	Cross Enterprise Technology Development Program
CTD	Commercial Technology Development
CVs	cataclysmic variables
EDCCD	Event-Driven CCD
EDM	Electric Discharge Machining
EUV	Extreme Ultra Violet
EV	Electron Volt
FAIR	Filled Aperture Infrared Telescope
HPD	Half-Power Diameter
HST	Hubble Space Telescope
HXT	Hard X-ray Telescope
ICM	Intracluster Medium
IGM	Intergalactic Medium
IPT	Integrated Product Team
ISM	Interstellar Medium
J-T	Joule Thomson
JFET	Junction Field Effect Transistors
kbps	Kilobits Per Second
keV	Kilo Electron Volt
Khz	Kilo Hertz
LTSI	Lightweight optics

MAXIM	Microarcsecond X-ray Imaging Mission
MBE	Molecular Beam Epitaxy
Mhz	Mega Hertz
MRF	magneto-rheological figuring
ms	milliseconds
NGST	Next Generation Space Telescope
QE	quantum efficiency
R&D	Research and Development
RGCCD	Resistive Gate CCD
rms	route mean square
ROSAT	Roentgen Satellite
SAFIRE	Sub millimeter and Far Infrared Experiment
SBIL	Scanning Beam Interference Lithography
SEU	Structure and Evolution of the Universe
SNRs	Supernova Remnants
SPECS	Sub millimeter Probe of the Evolution of Cosmic Structure
SPIRIT	Space Infrared Interferometer Telescope
SQUIDs	Superconducting Quantum Interface Devices
SR&T	Scientific Research and Technology
SUVO	Space Ultraviolet Optical Observatory
SXT	Spectroscopy X-ray Telescope
TES	Develop Transition Edge Sensor
TPF	Terrestrial Planet Finder
TRL	Technology Readiness Level
UV	Ultraviolet