The Constellation X-ray Mission: Exploring the Mysteries of Matter in the Universe

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Abstract—The Constellation-X, a premier observatory for probing black holes and investigating the structure of the Universe, is planned for launch near the end of this decade. This observatory will consist of a constellation of identical space based X-ray telescopes, with a large total collecting area and sensitivity one hundred times previous missions. The current Reference Mission Configuration consists of four satellites, which are launched, two at a time, into operational orbit at the Sun-Earth libration point, L2. Development is currently underway to demonstrate several mission critical technologies including: large lightweight grazing incidence X-ray optics, improved X-ray detectors (microlcalorimeters, Charged Coupled Devices and CdZnTe detectors) with sensitivities from 0.25 to 40 kiloelectron volts (keV), sub Kelvin coolers for detectors, lightweight mass producible reflection gratings, and multi-layer coatings for X-rays up to 40 keV.

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1. INTRODUCTION

The Constellation-X will be a premier observatory for probing black holes and investigating the structure of the universe. It was ranked as the second highest priority major space based initiative for this decade by the National Research Council’s decadal Astronomy and Astrophysics Survey Committee. The Constellation-X is part of Cosmic Journeys, a new series of National Aeronautics and Space Administration (NASA) space science missions to explore the Universe. It consists of a constellation of space based X-ray telescopes, with total collecting area large enough to perform detail spectroscopy on celestial sources that current X-ray telescopes can barely detect. With sensitivity one hundred times previous missions, the Constellation-X will measure X-rays which emanate from near the event horizon of black holes allowing astronomers to observe the effects of General Relativity in a strong gravity environment as well as to investigate black hole evolution.

Figure 1 – The Constellation-X

The Constellation-X will complement the Chandra X-ray Observatory, each having its own unique way to view X-ray emission from the Universe. The Chandra, primarily an X-ray imaging telescope, has offered many captivating and astonishing observations, such as the structure seen in the image of the Crab Nebula powered by a rotating neutron star (depicted in the upper right hand corner of Figure 1). The Constellation-X will enable astronomers to build on the discoveries made with the Chandra and more fully investigate properties of the Universe that are only revealed through the spectral content of the collected X-rays. It will have one hundred times more collecting area at 1 keV than the Chandra, enabling more powerful diagnostic capability. Its ability to measure the energy of X-rays twenty five times more precisely will allow the Constellation-X to better measure variations in source conditions such as velocity and temperature. The Constellation-X band pass will extend up to 40 keV with one hundred times the sensitivity of the Rossi X-ray Timing Experiment.

Technology development and mission formulation activities are currently underway for the Constellation-X. The goal,
dependent on approval of the Cosmic Journeys initiative, is to begin mission implementation in 2005, launch the initial satellites in late 2008 and perform science operations through 2013. The mission formulation effort is led by the Goddard Space Flight Center (GSFC), with a project team comprised of both GSFC and Smithsonian Astrophysical Observatory (SAO) members.

This paper provides a brief overview of the Constellation-X science, mission design and technology development efforts. Further information and recent updates about this mission can be found at http://constellation.gsfc.nasa.gov/

2. SCIENCE AND MISSION REQUIREMENTS

The Constellation-X will change the way we look at the Universe. With its large collecting area and improved detectors, the Constellation-X will be able to observe and analyze celestial X-ray sources, that could previously be barely detected or not at all. It will provide detailed spectral information that can be deciphered into elemental composition, temperature, velocity and more to explore the mysteries of matter in the Universe.

Probing Black Holes

As material spirals into a black hole, it heats up emitting a trail of X-rays that will allow the Constellation-X to probe close to the event horizon, the point of no return for matter or light. The Constellation-X will use the ultra strong gravity environment of a black hole as a “laboratory” to study the effects of General Relativity, by measuring the spectral profile of material near the event horizon. By observing hundreds of black holes and determining properties such as rotation and mass, the Constellation-X will enable astronomers to investigate how black holes evolve. Many black holes may be hidden behind a torus or thick disk of material (Figure 2). These black holes may only be visible above 10 keV, where the Constellation-X will have unprecedented sensitivity and resolution.

"X-raying" the Cosmic Web

The Constellation-X will search for baryons that could point to a web of missing dark matter that weaves throughout the Universe, from galaxy cluster to galaxy cluster (Figure 3). The ionized gas trapped by gravity in the Cosmic Web will be detected by the absorption lines created in the spectra of background quasars.

Figure 3 – Searching for Baryons Against Background Quasar

Mission Requirements

The capabilities necessary to perform the mission science objectives are summarized below:

Mission effective area:
- 15,000 cm² at 1 keV
- 6,000 cm² at 6.4 keV
- 1,500 cm² at 40 keV

Where the effective area is a function of the overall mirror collecting area and all system efficiencies and losses including surface reflectivity, detector efficiencies, etc.

Band pass: 0.25 to 40 keV

Spectral resolving power:
- 300 from 0.25 to 6.0 keV
- 3000 at 6 keV
- 10 at 40 keV

Where spectral resolving power is the absolute electromagnetic energy divided by the energy resolution.

System angular resolution:
- 15 arc sec Half Power Diameter (HPD) from 0.25 to 10 keV
- 1 arc min HPD from 10 to 40 keV

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3 GSFC and SAO independently proposed large area spectroscopy X-ray missions in response to a NASA Research Announcement to study new space science mission concepts. Both proposals were selected and the two teams led by Dr. Nicholas White (GSFC) and Dr. Harvey Tananbaum (SAO) subsequently merged their concepts into the Constellation-X.
Field of view:
2.5 arc minutes from 0.25 to 10 keV
8 arc minutes from 10 to 40 keV

These top-level requirements flow down into a set of engineering implication and key technologies. The following two sections discuss these implications in further detail.

3. MISSION DESIGN

Approach
The overall mission approach is to utilize a constellation of identical satellites, each of which carries a portion of the total mission collecting area and simultaneously views the same celestial target. By splitting up the collecting area, the mirror assemblies on each satellite may be smaller, and much more practical for near term technology implementation, than for a single very large diameter mirror. This unique multi-satellite approach avoids “putting all of our eggs in one basket” by utilizing more than one launch vehicle and is robust against loss of any single satellite. The overall mission reliability can be high while judiciously using only selective redundancy, on each satellite. Finally, since all the satellites are identical, there is a cost and time advantage to be gained for multiple builds, learning curve, sparing, etc.

Basic Telescope Systems
Each satellite has two telescope systems to cover the full mission electromagnetic energy range: the Spectroscopy X-ray Telescope (SXT) from 0.25 keV to 10 keV and the Hard X-ray Telescope (HXT) from 6 to 40 keV. To achieve the required energy resolution and throughput across the SXT band, it is covered by two detector systems, which utilize a single common SXT optic. Reflective gratings and an array of CCDs are used for the lowest end of the band and an X-ray microcalorimeter is used from 1 to 10 keV. The hard X-ray telescope consists of multiple smaller diameter grazing incidence mirror assemblies that use depth graded multilayer coatings with CdZnTe detectors at their foci.

Orbit
A halo orbit around the Sun-Earth libration L2 point, 1.5 million kilometers from the Earth in the anti-sun direction, has been chosen for mission operations for several reasons (Figure 4). In that orbit, the entire celestial sphere can be observed over the course of each year, with a single side of the spacecraft oriented toward the Sun and the Earth. This orbit and orientation provide a stable thermal environment for the telescope and a constant view to deep space for the cooler. The L2 orbit allows for highly efficient operational viewing without target occultation by the Earth or the Moon.

Figure 4 – L2 Lagrange Point of the Sun-Earth

Reference Mission Configuration
A Reference Mission Configuration has been generated for the Constellation-X to convey one viable means to achieve the mission requirements. It demonstrates mission feasibility, and is used for requirements development and generation of cost estimates. The details of the Reference Mission Configuration will continue to mature and evolve along with the mission enabling technology during mission formulation.

The Reference Mission Configuration consists of four satellites. As shown in Figure 5, each satellite is modular, with separable Instrument and Spacecraft modules. This allows for parallel development of the two systems prior to a
relatively simple final satellite integration and test. To achieve the required mission collecting area, the SXT mirror on each satellite will have an outside diameter of 1.6 m and a focal length of 10 meters. The Hard X-ray telescope shares the same 10 m focal length. The SXT and HXT mirror assemblies will mount to a common structure and will be surrounded by the spacecraft bus components, a configuration that helps provide the necessary small temperature gradient and stable thermal control. The detectors, which generally require cooler operating temperatures, are mounted at the opposite end of the 10-meter Optical Bench. The Optical Bench structure will be graphite epoxy or similar material that is lightweight with a low coefficient of thermal expansion near zero.

The constellation of four satellites is launched two at a time on an Atlas V class launch vehicle. To meet the challenge of providing the required focal length yet fitting two satellites within a single Atlas V fairing for launch, two variations on the mechanical configuration have been studied. Both of these variations utilize the same exact SXT and HXT configurations, technologies and spacecraft subsystems except for the structure and optical bench.

One variation uses an extendible optical bench which collapses like a camping cup or spyglass for launch, and deploys for on-orbit operations. In this case two satellites fit one on top of the other in the fairing envelope as shown in Figure 6. A dual payload adaptor fitting, which includes a canister (not shown) that surrounds the lower satellite, provides a structural load path for the upper satellite. This option, in which each satellite fills the entire fairing cross section, allows ample room for packaging components around the large SXT mirror assembly.

Another option, shown in Figure 7, uses a fixed bench to achieve the 10 m focal length, and places the satellites side-by-side inside the fairing for launch. The satellites would be attached to each other near the top for launch, providing additional structural stiffness to the cantilevered payload. The fixed bench approach does not require the heavy dual payload adaptor and reduces the risks associated with a deployable bench.

The satellites will utilize lunar phasing loops and on-board hydrazine propulsion to get to the operational orbit at L2. Each satellite in the constellation will operate to view the same targets simultaneously. There is no requirement to maintain satellite formation with respect to each other. A single ground station with an eleven-meter antenna will be adequate and ground management strategies that optimize the efficiency of constellation operations will be necessary.

A number of technologies that will enable the Constellation-X are currently under development. The goal of the Constellation-X technology development program is to demonstrate all of the required new technologies by meeting the required performance and withstanding flight like environments.

Large Lightweight X-ray Optics Overview

X-rays are collected and focused by grazing incidence optics. To maximize the collecting area within a given diameter, the optics are nested, as shown in Figure 8. To achieve the required mission collecting area, the Constellation-X uses four mirror assemblies, each with an outside diameter of 1.6 m, 70 to 150 nested optics per mirror and mass no greater than 750 kg. Each optic has a Wolter Type I figure consisting of a paraboloid and hyperboloid surface. The mirror system angular resolution must be 10 arc seconds.

Two technologies represent the current state of the art for flight quality highly nested X-ray mirrors: replicated segments and replicated shells. Both technologies use
replication techniques to copy the optical figure and surface finish from a precision mandrel onto a substrate material, saving the time and expense of figuring and polishing each flight reflecting surface. Neither of these technologies currently meet both the Constellation-X requirements for both mass and angular resolution.

Figure 8 – Nested Grazing Incidence Wolter Type I X-ray Optics

Replicated Segments

This technology utilizes wedge-shaped segments to build up a fully circular optic as shown in Figure 9. Epoxy replication techniques are used to transfer a gold or platinum optical surface from a mandrel onto an optic substrate.

Figure 9 – Astro-E Replicated Segment Mirror Assembly

This technology, as developed for the Astro-E mission, meets the mass requirements for the Constellation-X, but requires a factor of ten improvement in angular resolution and a factor of four increase in diameter. The contributors that are being addressed to achieve the required resolution include:

(1) Precision figured and polished mandrels in place of extruded Pyrex cylinders
(2) Optical substrate material that better maintains its shape than aluminum
(3) Improved positioning and alignment of optical reflectors within their housing
(4) Wolter Type I figure rather than a conical approximation

Significant progress has already been shown at the component level. Thernally formed glass substrates have yielded a factor of four figure improvement over aluminum. Silicon etched alignment bars have demonstrated substrate-to-substrate positioning repeatability less than 1 arc second. Precision mandrels have been produced with figure better than 5 arc seconds. Efforts are currently underway to replicate Wolter Type I figure, to procure a meter class mandrel and to integrate the optimized components into an engineering model mirror assembly.

Replicated Shells

The shell technology uses complete shells of each diameter optic to build up the full mirror assembly. There are two variations on this technology. In the first, integral shell, the entire optical surface and substrate are formed on a precision mandrel. This technology, using electroformed Nickel shells, was flown on the X-ray Multi Mirror Newton Satellite. It has been demonstrated to nearly meet the angular resolution for the Constellation-X but requires a factor of 6 reduction in scaled mass. An increase in the outer diameter by a factor of 2.3 is also required. As shown in Figure 10, shells with 0.5 m diameter have now been produced from a new high micro-yield nickel alloy that meets the Constellation-X mass requirement. Optimization of the electroplating bath parameters are underway to lower the residual stress and improve angular resolution.

Figure 10 – 1 kg 0.5 m Diameter Replicated Shell (in ground support structure)

(1) Precision figured and polished mandrels in place of extruded Pyrex cylinders
(2) Optical substrate material that better maintains its shape than aluminum

4 The replicated segmented technology development team is led by Robert Petre, GSFC and includes partners from MIT, SAO and MSFC.
5 The replicated shell technology development team is led by Steven O'Dell, MSFC and includes partners from SAO and Osservatorio Astronomico di Brera (OAB)
The alternative replicated shell technology non-integral shells, uses pre-formed shell substrates and epoxy replication to transfer the optical surface from a precision mandrel. Shell substrates of various materials including silicon carbide, alumina and graphite epoxy have been fabricated and replication techniques are under development.

**X-ray Microcalorimeter**

An X-ray microcalorimeter, which detects X-rays by a rise in temperature upon photon impact and uses the quantitative thermal increase to determine the energy, will be used to detect photons from 1.0 to 10 keV. It must have 2 eV electromagnetic energy resolution and a 32 by 32 pixel array. This requires a factor of 10 improvement in electromagnetic energy resolution and factor of 30 in array size over the state of the art developed for the Astro-E mission.

Transition Edge Sensor (TES) microcalorimeter devices have shown great progress. The required electromagnetic energy resolution of 2.0 eV at 1.5 keV has been achieved for an aluminum silver TES with Bismuth absorber. Devices of molybdenum copper and molybdenum gold, which will lend themselves to be micro-fabricated, have demonstrated electromagnetic energy resolution approaching the Constellation-X requirement. An absorber scheme for a fully monolithic flight size array has been demonstrated and multiplexing techniques are in development.

**Cooling for the Microcalorimeter**

Long life cooling to 50 milli Kelvin (mK) must be provided to the X-ray microcalorimeter. This can be accomplished with a 6 to 8 Kelvin mechanical cooler, such as the turbo-Brayton, in series with a sub-Kelvin stage, such as an adiabatic demagnetization refrigerator.

A turbo-Brayton 70 Kelvin cooler was successfully flown in the Host Mission of the Hubble Space Telescope and a flight qualifiable 6 to 8 Kelvin cooler is under technology development. The last stage of an adiabatic demagnetizing refrigerator has been demonstrated to 100 milli Kelvin and further developments in the other stages, including heat switches, are actively pursued.

**Grating and CCDs**

Reflection gratings coupled with CCD detectors will provide coverage over the 0.25 to 1.0 keV band pass where it is expected that the microcalorimeter resolving power will fall below 300 and the throughput degrade. Gratings mount behind the outermost, highest diameter optics of the SXT mirror assembly in position such that they pick up a percentage of the photons that have been reflected through (Figure 11). The gratings disperse the X-rays creating a spectrum on a linear array of CCD detectors.

Thousands of gratings are required for the mission and it will be critical that, in addition to providing high resolution and throughput, they are light weight and are conducive to mass production. To improve these aspects of the gratings, over the XMM Newton heritage, fabrication techniques using anisotropic interference lithography on silicon wafers are being investigated. An efficiency of 23 percent at 1.5 keV has been measured on a prototype grating. Current efforts are concentrating on improving small scale flatness across the wafer.

Approximately eight CCDs will be required per satellite. It will be important to minimize the power per device, and improve the manufacturing yield experienced during production on previous missions. The resistive gate technology, for which a proof of concept has been developed.

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6 The X-ray microcalorimeter technology development team is led by Richard Kelley, GSFC, and includes partners from NIST, University of Wisconsin, and SAO.

7 The Constellation-X reflection grating spectrometer technology development is lead by Steve Kahn, Columbia University, includes partners from Massachusetts Institute of Technology and Pennsylvania State University.
demonstrated on an initial lot, is a candidate to make these improvements.

**Hard X-ray Telescope**

The Hard X-ray Telescope uses smaller diameter (40 cm) grazing incidence mirrors with depth-graded multilayer coatings to greatly enhance the reflectivity at high energies. Cadmium Zinc Telluride (CdZnTe) pixel detectors will provide the required spatial and spectral resolution at the higher electromagnetic energies.

CdZnTe detectors have demonstrated the electromagnetic energy resolution and efficiency required by Constellation-X. Several multilayer coating materials including Tungsten Silicon, Platinum Carbon will meet the Constellation-X requirements and a cross evaluation is underway.

5. **SUMMARY**

The Constellation-X with its high throughput, high spectral resolution X-ray sensitivity will take us on an “armchair” cosmic journey from black holes to the Cosmic Web, exploring the mysteries of matter in the Universe. A unique and robust mission constellation approach has been developed. The mission enabling technology is well defined and substantial progress has been made.

**REFERENCES**


Jeana Grady has been the Project Formulation Manager for the Constellation-X at GSFC for three years. For seven years prior, she was the Head of the Space Telescope Experiments Office, in the Laboratory for Astronomy and Solar Physics, where she managed the development of the Space Telescope Imaging Spectrometer which was installed into the Hubble Space Telescope (HST) during the second servicing mission in February 1997. She also managed the Repair Kit for the Goddard High Resolution Spectrograph, which was successfully installed on the first HST servicing mission. She has worked as an engineer on various projects at GSFC including Polar Orbiting Platform, International Space Station, Solar Maximum Repair Mission and the Cosmic Background Explorer. She earned a B.S. in Aerospace Engineering from the University of Maryland in 1979.

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