The Constellation-X Observatory

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ABSTRACT

The Constellation-X Observatory is currently planned as NASA's next major X-ray observatory to be launched towards the end of the next decade. The driving science goals for the mission are to: 1) Trace the evolution of Black Holes with cosmic time and determine their contribution to the energy output of the Universe; 2) Observe matter spiraling into Black Holes to test the predictions of General Relativity; 3) Use galaxy clusters to trace the locations of Dark Matter and follow the formation of structure as a function of distance; 4) Search for the missing baryonic matter; 5) Directly observe the dynamics of Cosmic Feedback to test models for galaxy formation; 6) Observe the creation and dispersion of the elements in supernovae; and 7) Precisely constrain the equation of state of neutron stars. To achieve these science goals requires high resolution ($R > 1250$) X-ray spectroscopy with 100 times the throughput of the Chandra and XMM-Newton. The Constellation-X Observatory will achieve this requirement with a combination of four large X-ray telescopes on a single satellite operating in the 0.25 to 10 keV range. These telescopes will feed X-ray micro-calorimeter arrays and grating spectrometers. A hard X-ray telescope system will provide coverage up to at least 40 keV. We describe the mission science drivers and the mission implementation approach.

Keywords: X-rays, Constellation-X, black holes, cosmic feedback, dark matter, neutron stars, X-ray spectroscopy

1. INTRODUCTION

X-ray astronomy requires space-based observatories since the Earth's atmosphere readily absorbs X-rays from astronomical sources. Current X-ray observatories, including the Chandra and XMM/Newton flagship missions, utilize technology largely developed during the 1980's. The science objectives discussed in this response are achievable as a result of ongoing instrumentation (optics and detectors) development that promises the next quantum leap in capability. High resolution X-ray spectra from the Chandra and XMM-Newton grating spectrometers are reaching a level of detail previously obtained in the UV/optical band, demonstrating the power of X-ray spectroscopy but limited by throughput to only a small number of bright X-ray sources. The 0.3 – 10 keV X-ray band contains the inner (K-shell) lines for all of the abundant metals from carbon to zinc as well as many L-shell lines from iron and heavier atoms. These atomic transitions provide plasma diagnostics that enable precise characterization of physical conditions in sources. However, separating the density and temperature-sensitive triplet lines of helium-like ions of oxygen through sulfur requires a spectral resolving power of at least 300. In the spectral region between 6 and 7 keV that covers the Fe K complex a resolving power of order 2000 is required to resolve the complex Fe K structure arising in the accretion disks of black holes. Resolving powers of 300-3000 provide absolute velocity measurements ranging from 100-1000 km/s which are found in many astronomical systems. Chandra's modest throughput means that today only the nearest and brightest examples of many classes of objects have useful spectra with $E/\Delta E > 1000$. Most X-ray spectra from most sources have only moderate resolution CCD spectra ($E/\Delta E < 30$), insufficient for the type of line diagnostics routinely available in other wavebands

The throughput of Constellation-X (more than 100 times the throughput of the Chandra and XMM grating spectrometers across the 0.6-10 keV band) and its high spectral resolution are essential for achieving the four science objectives described here:

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1. Black Holes: Measuring black hole spin and testing General Relativity.
2. Missing Baryons: Unambiguous detection of the hot phase of the Warm-Hot Intergalactic Medium (WHIM) at z>0.
3. Neutron Star Equation of State: Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter
4. Supernovae and the Creation of the Elements

In addition, the large increase in capabilities provided by the Constellation X-ray observatory will enable major advances covering all of astrophysics from solar system objects to distant quasars. The mission enables these science topics, but they do not create additional drivers on the performance of the observatory. We discuss some of these, including evolution of supermassive black holes and cosmic feedback as "non-driving objectives" and also describe a subset of the other science topics that would be considered “Observatory science”.

The scientific goals of Constellation-X require sensitivity for high-resolution spectroscopy that is a factor of 25-100 higher than previous missions. This sensitivity requirement in turn calls for an X-ray mirror system with ambitious performance goals. Adding to the challenge are the envelope and mass constraints, which drive the program toward innovative implementation. The resulting implementation approach is described, and a brief status of the mission is provided.

2. SCIENCE CASE & SCIENCE DRIVERS

2.1 Black hole evolution

Constellation-X will measure one of the fundamental parameters of black holes, the spin, constraining models of the growth of black holes. Accretion of matter onto a black hole, or the merger of multiple black holes, will cause them to spin up, spinning space-time along with it. Accretion occurs from co-aligned disks and should spin the black hole up to the theoretical maximum value. Conversely, mergers may have no preferred axis and would lead to a distribution of spin values. A major goal of the Constellation-X mission is to observe and quantitatively measure these effects, in particular to measure the black-hole spin with sufficient precision to rule out competing theories and investigate the relation between the spin and the properties of the black hole system[1,2]. For example, is black hole spin related to redshift (suggesting that the origin black hole growth changes over cosmic time), or to the Hubble type of the host galaxy, or to the presence of jets? Constellation-X will also investigate why the spins of galactic disks are misaligned with the central black hole spin, and is there a similar misalignment in X-ray binary black holes and the orbital plane? In order to answer these questions Constellation-X observers will need to be able to measure time-averaged Fe-line profiles for numerous AGN in reasonable exposure times. The shape of the Fe Kα line, blurred and broadened by rotation and GR effects, provides a direct measure of the black hole spin.

With the ‘calibrated’ time-averaged profiles in hand, one can measure the spin properties and therefore space-time structure in large numbers of AGN via model fitting, and determine the range and distribution of BH properties with cosmological time. The redshift of AGN with F_X(2-8 keV) ~ 10^{-14} erg/cm^2/s spans the range $0<z<4$ and has a mean z~1.0 [3].An effective area of 15,000 cm^2 at 1.25 keV allows measurements of the shape of the Fe line in these sources using reasonable (albeit long) deep survey exposure times of a few Msec to obtain 100,000 counts. The Fe lines originating in the reflection component from the accretion disk are often accompanied by complex and narrow absorption features (the so-called “warm absorber”). Current measurements of warm absorbers at soft energies (< 1 keV) show typical velocities of 100 - 200 km/s, requiring resolving powers of 1500 - 3000 to resolve these features, and determine the underlying continuum. A resolving power of 2400 further ensures that the various Fe ionization states are deblended, and that most warm absorber components will be resolved.

Key to measuring the Fe Kα line shape is determining the underlying continuum, which requires measuring the spectrum at energies above and below the line. An area of 150 cm^2, combined with an angular resolution of 30 arcsec to limit background, ensures that sensitivity from 10 - 40 keV is sufficient to constrain the high energy portion of the continuum. With this high energy constraint, the number of photons over the 2-10 keV band required to measure spin to ±5% is ~>100,000. If there is no collecting area above 10 keV, the required number of counts in the 2 keV – 10 keV bandpass increases significantly (by a factor of ~4). This sets our requirements for effective area and spectral resolution from 10 keV – 40 keV.

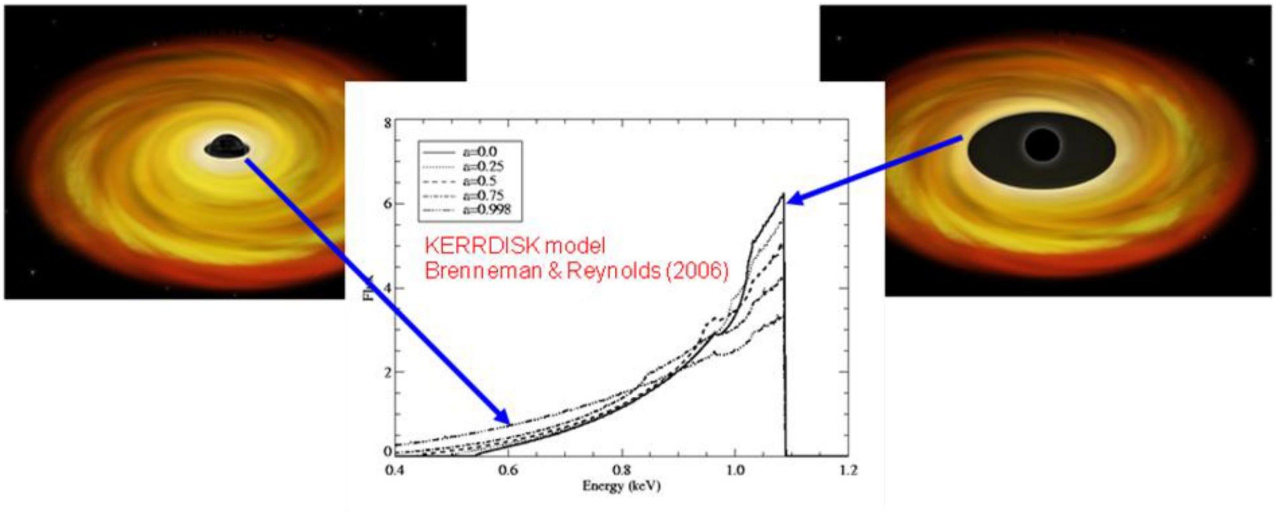

Figure 1: [Left] A rapidly spinning black hole creates a broader Fe K feature (dot-dashed line). [Right] A non-spinning black hole creates a narrower (solid) line. Figure courtesy of C. Reynolds.

General Relativity predicts black holes have only two interesting parameters: mass and angular momentum (significant charge cannot be sustained in a realistic astrophysical environment). While we cannot yet measure either of these with the precision that we can now achieve for cosmological parameters, the two Einstein Great Observatories, LISA and Constellation-X, will allow precision measurements of the two crucial black hole parameters (mass and angular momentum) in complementary ways. LISA will provide exquisite precision for a limited number of very special systems (stellar-mass black holes spiraling into 10^6 solar-mass black holes and mergers of supermassive black holes with masses < 10^7 solar masses). Constellation-X will measure mass and spin for a large number of accreting black holes, from stellar mass systems to the multi-billion solar mass black holes at the centers of giant elliptical galaxies. In addition, Constellation-X will further our understanding of how matter accretes onto a black-hole – a process which provides a huge, if not dominant, component of the radiant energy of the observable Universe.

2.2 Black holes testing General Relativity

Another related and driving Constellation-X science objective is to test General Relativity through observations of material falling into black holes, close to the event horizon where the strong field will dominate the observed properties. Ever since the detection of rapid X-ray variability over 20 years ago, it has been clear that X-ray observations of accreting black holes provide a window on the immediate vicinity of the black hole event horizon. The innermost regions of accretion disks require X-ray studies, since the last signal we receive from accreted matter, at this innermost stable orbit, is also where the disk is hottest.

Observing the broad iron fluorescence line seen in the X-ray spectrum of many accreting black holes has proven to be the most powerful technique for studying the inner accretion disk. This line is emitted by the surface layers of the thin, Keplerian accretion disks believed to extend nearly down to the event horizon, and possesses a highly broadened and skewed energy profile sculpted by the effects of relativistic Doppler shifts and gravitational redshifts.

Constellation-X will add a new dimension – time – to the study of iron lines. Its superior collecting area will enable detection of iron line variability on sub-orbital timescales (minutes to hours). The 6,000 cm^2 collecting area requirement at 6 keV ensures that there are at least 10 AGN targets accessible for these measurements. The fact that observations of the accretion flow can be used to probe the spacetime metric (and hence test GR) follows from the geometric and dynamic simplicity of accretion disks. In the luminous systems suitable for this study, the accretion flow is in the form of a thin, pancake-like disk of gas orbiting the black hole. Each parcel of gas has an orbit around the black hole that closely approximates a circular test-particle orbit. Deviations from test-particle orbits are due to radial pressure gradients that are typically less than 1% in such thin accretion disks. Any non-axisymmetry in the emission of the iron line will appear as "arcs" on the time-energy plane, each arc corresponding to an orbit of a given bright region. Evidence for similar features from outlying regions of the accretion disk (where the orbital timescale is longer and hence the features are easier to detect) has been seen in XMM-Newton observations of NGC 3516 and Markarian 766. GR makes specific predictions for the form of these arcs, and the ensemble of arcs can be fitted for the mass and spin of the black hole as well as the observed inclination of the accretion disk. Many such arcs will be observed and if GR is correct, then each of these arcs will have a form which matches the GR predictions for a given mass, spin and radius. There are two possible scenarios of different arc measurements: 1) yielding consistent spin measurements at different radii (consistent with GR) verses 2) a case where the arcs deviate (breakdown of GR). If the latter were the case, these measurements would provide a framework to examine alternate gravity theories or extensions to GR.

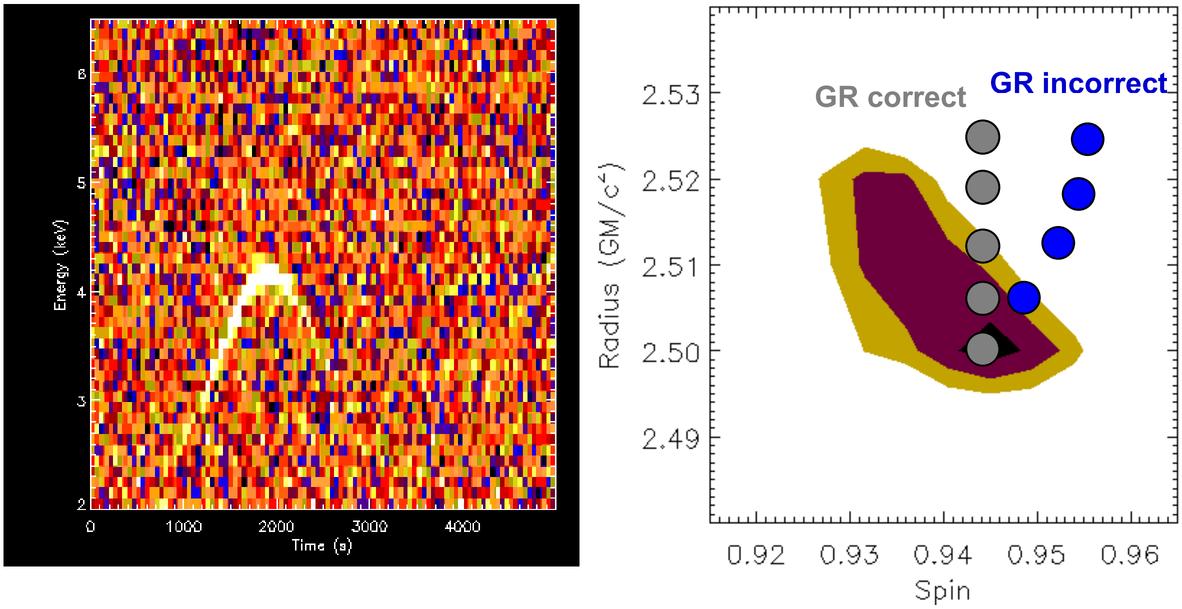

Figure 2: [Left] The track traces the orbit of an individual hotspot in an accretion disk as it spirals in towards the black hole, shown in the time-energy plane. [Right] If GR is correct, Constellation-X measured spin and mass should be independent of the radius of the hotspot. The Kerr metric can be tested by searching for consistency in the black hole mass and spin between fits to multiple individual tracks. Simulation courtesy of C. Reynolds

2.3 Missing baryons

For decades, it was thought that the dilute gas prevalent in the early Universe eventually formed into the galaxies that we see today. However, when a census was taken of the amount of the normal matter in the galaxies around us, only 10% of the baryons known to exist were found. Thus an extensive search for the missing baryons was begun, and studies found that the hot gas in galaxy groups and clusters, combined with the cold gas that produces UV absorption lines could account for up to 40% of the known baryon content. The remaining >60% of the normal matter was still undiscovered. Current cosmological simulations are in broad agreement that the majority of the baryons exist in the temperature range $10^5 - 10^{7.5}$ K, primarily in the overdense filaments that connect clusters and groups.

The high temperature of the Warm-Hot phase of the Intergalactic Medium (WHIM) fully ionizes both hydrogen and helium, while the dominant ions of the next most abundant element are O^{+6} and O^{+7}. These ions can only be detected via high-resolution X-ray spectroscopy. High spectral resolution studies with Chandra and XMM have shown the first evidence of detection of the WHIM within the Local Group and a suggestion of higher-redshift filaments. This detection comes in the form of OVII Ly-α absorptions lines obtained in long grating exposures of a bright background AGN. The detections are near zero redshift, so the absorbing material is either in the Galactic halo or the Local Group[4]. Accounting for the remainder of the WHIM remains a major goal of observational astrophysics.

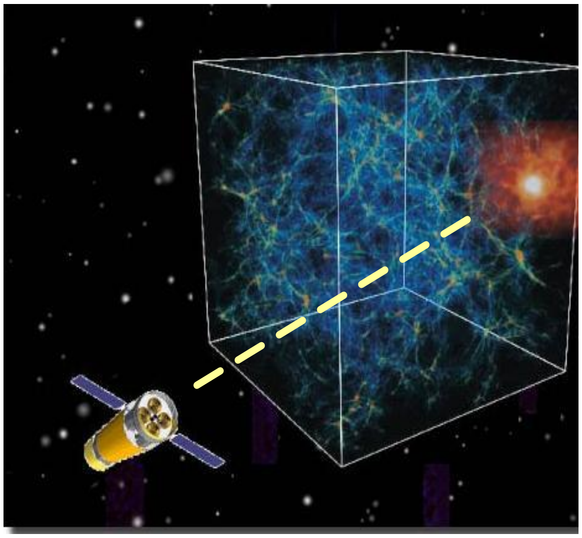

Figure 3: A simulation of the WHIM showing its filamentary nature and the illuminating background AGN. The WHIM is seen in absorption against the AGN.

Constellation-X will measure WHIM filaments in absorption along the line-of-sight to bright background AGN, constraining the hot baryon content of the Universe. With >100 filaments detected at z>0, this will provide the first unambiguous detection of the WHIM. The measurements will require high spectral resolution (R) at low energies, specifically R>1250 FWHM over the 0.3-1.0 keV band assuming 1000 cm^2 area over this band.

The most powerful tool for the measurement of the WHIM is through the absorption lines produced upon background continuum sources, such as AGN. Absorption lines created by the WHIM are in the low opacity limit so the equivalent width of the lines translates directly into a column density equal to the average ion density multiplied by the depth of the filament, providing a prime measure for the mass content of the hot gas. Measurement of the redshift of each filament places them in the Cosmic Web connecting all groups and clusters. The position and abundance of the filaments relative to the nearest galaxy, as well as the turbulent width of the line if it can be measured, are all sensitive to the gravitational shocks, and galactic superwinds that heat the WHIM.

To find the WHIM, we need reasonably bright background AGN (note that there are 50 AGN with F_X (0.1-2.4 keV) > 10^{-11} ergs cm^{-2} s^{-1} in the ROSAT All-Sky Survey and easily hundreds more just slightly fainter than this) and moderately dense filaments. Constellation-X must be able to detect the strongest absorption lines, which are the ground-state resonance lines of O VII and O VIII, with the possibility of deeper observations that can detect other transitions such as Ne IX and Ne X. The O VII ion is sensitive to gas at $0.5 - 3 \times 10^6$ K and is measured through the 1s-2p transition at 21.60Å (574 eV), while the O VIII ion can be found in the $1 - 7 \times 10^6$ K range through its Lyα line at 18.97 Å (654 eV). The ratio of these two lines is a temperature indicator. Other lines will permit more detailed characterization of the ionization state of the gas and will extend the temperature sensitivity to 10^7 K. If high spectral resolving powers are available, the lines will be resolved and effects of turbulent heating or ongoing collapse in the WHIM could be detected.

For good constraints of the WHIM, Constellation-X must detect these absorption features for ~100 filaments (with multiple detections/filaments per observed AGN expected) and should detect these filaments over the redshift interval $0< z < 0.5$ (with z=1 as a goal). Given that many bright AGN are at modest redshift (z<0.3), the redshift path length for a typical observation will be $\Delta z = 0.3$. If we set a target of observing filaments in the 30 nearest bright AGN, this requires three filaments per target ($dN/dz \sim 10$ for a path length $\Delta z = 0.3$). This establishes a target sensitivity of 1 mÅ, which may be achieved for several different combinations of collecting area and spectral resolving power.

2.4 Neutron star equation of state

At their cores, neutron stars harbor the highest matter densities in the Universe, up to several times the densities in atomic nuclei. The properties of matter under such conditions is governed by Quantum Chromodynamics (QCD), and the close study of the properties of neutron stars offers the unique opportunity to test and explore the richness of QCD in a regime utterly beyond the reach of terrestrial experiments. While terrestrial experiments (RHIC, LHC) explore the high-temperature, low-density regime, astrophysical studies will probe the opposite, low-temperature, high-density regime, where a multitude of novel phenomena associated with QCD phase transitions may take place. Observations of X-ray emission from neutron stars with Constellation-X have the potential of providing for an experimental determination of the 'Cold Equation of State' through measurement of the fundamental mass-radius relation of neutron stars.

X-rays from accreting neutron stars in binary systems provide two distinct opportunities to probe the structure of neutron stars. In such systems, a continuous supply of fresh metals such as Fe creates significant atmospheric abundances of line-producing elements, unlike isolated (non-accreting) neutron stars whose atmosphere should contain no metals. Accreting systems also show thermonuclear X-ray bursts, brief but bright flashes of thermal X-ray radiation that shine through the neutron star atmosphere and may be absorbed by the accreting metals. In addition to atmospheric absorption features, bursts create "hot spots" on the surface of the neutron star that can be used to measure the spin rate of the neutron star directly (so called 'burst oscillations").

Accurate masses for some neutron stars have been obtained from observations of young neutron star pulsars in binary systems, but essentially nothing is yet known about the radii. These accreting neutron stars have gained enough mass to probe the mass/radius relation in a different regime than the non-accreting binary radio pulsars. This leads to the possibility of obtaining mass-versus-radius curves for neutron stars, telling us a great deal about the state of matter at extreme densities. The science requirement for Constellation-X is to determine the radii and mass of several neutron stars to within several percent, providing strong constraints on the Neutron Star Equation of State. Since the measurements can only be done during X-ray bursts, this requires the observatory to operate at full capacity up to rates equivalent to 0.25 Crab flux units.

Constellation-X will be the first X-ray observatory with the capability of making simultaneous high spectral resolution and fast timing measurements of X-ray bursts. One may then simultaneously use several independent methods to constrain mass and radius, providing important checks on any systematic errors associated with either method.

2.4.1 Neutron star structure via absorption

As photons escape a neutron star's powerful gravitational field they are redshifted by an amount proportional to the stellar mass to radius ratio, GM/(c2R), also called the compactness. Cottam, Paerels & Mendez[5] found evidence of narrow, redshifted Fe absorption lines in co-added spectra of 28 X-ray bursts from the LMXB EXO 0748-676 with the XMM-Newton RGS. Their proposed identifications for these lines with the Hα transitions of Fe XXVI and XXV implies a surface redshift of $z = 0.35$ that is consistent with most modern EOS. The line widths are influenced by rotation of the star via the Doppler effect. Since the spin rates of many of these accreting neutron stars are known, the strength of this Doppler effect is directly proportional to the radius of the neutron star through the surface velocity. Accurate measurement of the line profiles can therefore determine the stellar radius. The relatively narrow lines inferred from EXO 0748-676 are consistent with the 45 Hz spin rate found from burst oscillations in this object[6], but present data do not have the statistical precision to tightly constrain the radius[7].

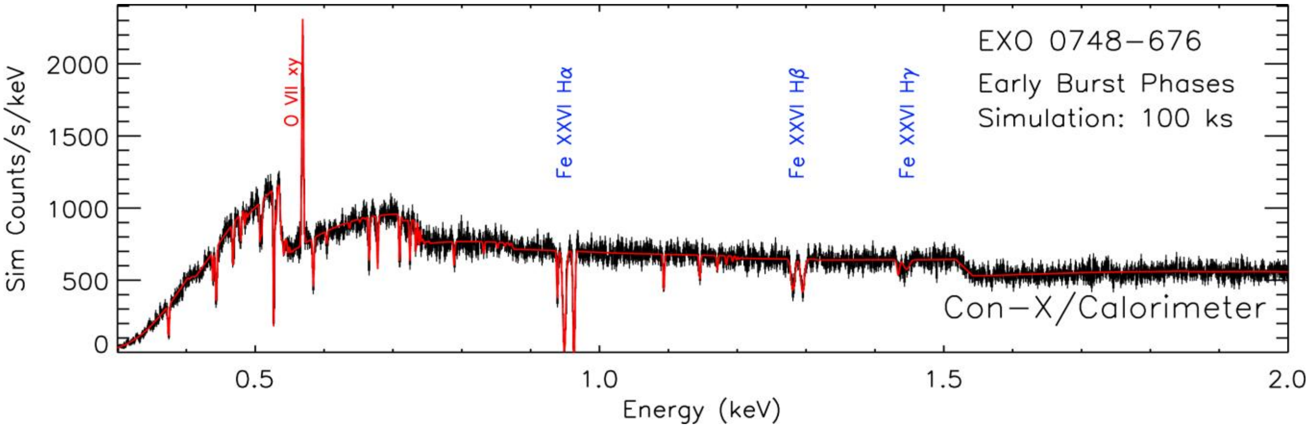

Figure 4. Absorption spectra provide a direct measure of gravitational redshift at surface of the star ($z \propto M/R$). The simulated spectrum of the early phases of the X-ray bursts from the accreting neutron star EXO 0748-676 (a 100 ks observation yields 1 ks of burst time). The blue labeled lines are gravitationally redshifted absorption lines from the neutron star atmosphere. The remaining spectral structure originates in the circumstellar material. The measured widths of the lines constrains the radius to 5-10% (compared to the best present constraints of 9.5-15 km for EXO 0748-676). Simulation courtesy of F. Paerels.

Constellation-X will measure the radius to within a few percent by measuring the widths of absorption lines with much greater precision for this burst source and others. Moreover, the much larger collecting area of Constellation-X (as compared to the XMM-Newton RGS) will enable far more sensitive searches for higher order transitions (for example, the Hβ lines of Fe XXVI ions). If several lines in the series are detected, their relative strengths can be used to provide a measure of the surface density. This quantity is proportional to $GM/(c^2R^2)$, which combined with the redshift measurement ($GM/(c^2R)$) also leads to unique determinations of both mass M and radius R.

2.4.2 Neutron star structure via burst oscillations

Constellation-X will also probe neutron star structure using the spin modulation of a non-uniform brightness pattern ("hot spot") generated on the neutron star surface by thermonuclear burning. Both the amplitude and shape of these pulsations encodes mass and radius information. For example, the modulation amplitude is influenced by gravitational light deflection in the strong gravitational field of the neutron star, which depends directly on the compactness. Fitting of the observed pulses to a physical model of surface emission from a rotating neutron star can provide constraints on the stellar mass and radius [8,9,10].

2.5 Supernovae and the formation of elements

Nucleosynthesis during the Big Bang created the initial cosmic abundances of Hydrogen, Helium, and Lithium. During a star's lifetime it creates and disperses some heavier metals, such as Carbon, Nitrogen, and Oxygen. However, the only known mechanism that could both create and disperse the heavier metals from Neon through Iron and beyond is a supernova explosion, either from a massive star (aka Type II) collapse or the thermonuclear burning of a white dwarf (Type Ia). The goals of supernova remnant (SNR) research are to understand the mechanisms of supernova explosions, constrain predictions of nucleosynthesis calculations, study the behavior of high-speed collisionless shocks, and investigate the injection of metals and energy into the surrounding ambient medium. X-ray studies offer a comprehensive picture of these high-energy processes in SNRs thanks to the high velocities involved, typically 100's to 1000's km/s, and the fortuitous fact that highly ionized species of the abundant elements from C through Ni produce emission lines in the energy range between 0.2 and 10 keV,

The capabilities of Constellation-X will open a new window into the physics of supernova (SN) explosions through a dramatic improvement in the quality of the observations of young, ejecta-dominated supernova remnants (SNRs). The dynamical timescales for SNRs are comparable to the collisional timescales needed for electrons and ions to reach thermal equilibrium or the ions to reach ionization equilibrium. As a result, determining the composition, temperature, ionization state, and velocity of the gas requires high-resolution spectra from each position in the remnant. This sets our requirement for non-dispersive high spectral resolution of Constellation-X combined with at least 15 arcsec angular resolution over a 5 arcmin square field of view.

Constellation-X observations of core-collapse SNRs will unveil new information about the core-collapse process by revealing the distribution and dynamics of nucleosynthesis products formed during the explosion, tracking the early evolution of SNRs, unveiling unshocked iron, and measuring the total mass of iron in SN ejecta. A prime target for studies of core-collapse supernovae is the well-studied Cassiopeia A (Cas A), because it is the brightest X-ray remnant with emission dominated by silicon and iron ejecta. The X-ray emission from Cas A is spatially complex, showing structure on scales from the remnant's full ~ 3 arcmin extent to knots and filaments ≤ 2 arcsec in size. Constellation-X will enable deeper investigations into the nature of the knots and other complex ejecta structures as its resolution approaches the goal of 5 arcsec.

One of the unsolved problems in SN research is the nature of Type Ia SNe (SN Ia) progenitor systems. Early Constellation-X observations of bright SN Ia (preferably before maximum optical brightness ~20 days after ignition) will constrain the progenitor's circumstellar environment. The cosmological importance of SNe Ia have inspired new surveys aimed at detecting early SNe Ia (2 days after the explosion) at distances comparable to the Virgo cluster (~16 Mpc; closer SNe Ia are very rare). Since time is of critical importance, Constellation-X must be able to observe a target of opportunity SN within 2 days, this is the requirement on response times to Targets of Opportunity.

In addition to observing Type Ia SNe, Constellation-X observations of Type Ia remnants will provide the first sensitive measurements of the odd-z trace elements as well as the trans-iron element zinc in SNRs. These elements provide insight into the star that originated the explosion, as well as the origin of these elements. In particular, variations in the relative proportions of Ni, Cr, Mn, and Fe reflect differences in the temperature and density of the nuclear burning. Badenes, Bravo, & Hughes (2008) showed that the Mn to Cr ratio in remnants of Type Ia supernovae to constrain the initial metallicity of the progenitor. Applying this technique to the recent Suzaku spectrum of the Tycho SNR, Tamagawa et al.[11] and Badenes et al.[12] were able to show, with large errors, that the metallicity of Tycho's progenitor star was supersolar. Constellation-X will for the first time accurately measure the flux in these lines as a function of position in Galactic SN Ia remnants and in the integrated spectra of more distant SNRs. Finally, the detection of Zn in a cosmic X-ray source would be a first step towards determining the origin of these trans-iron elements in a cosmic setting. Again there is no comparable facility that will accomplish these measurements, since any Zn in the SNR will be highly ionized and emitting only the in the X-ray band.

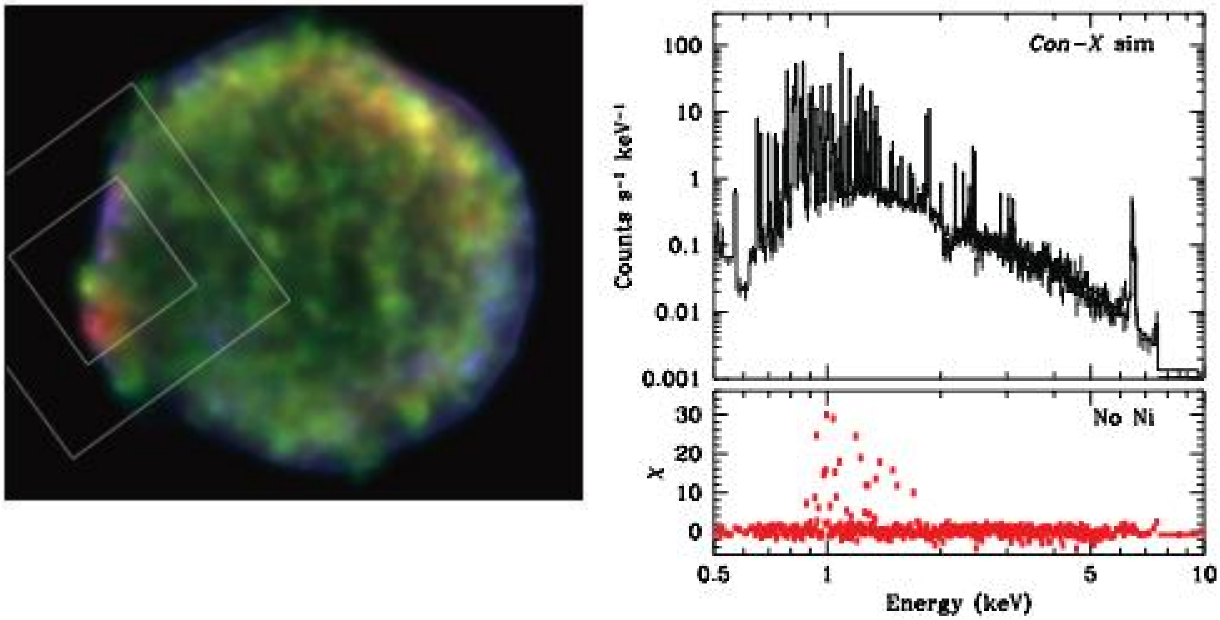

Figure 5 :[Left] Simulated Constellation-X observation of Tycho's SNR with 2.5' and 5' FOV shown. Fe-rich emission is shown in red, Si-rich in green, and non-thermal in blue**. [Right]** Spectrum of Fe-rich knot in Tycho; the lower figure shows residuals in red due to Ni L-shell and K-shell emission lines at 1 keV and 7 keV, respectively. Figure courtesy J. Hughes.

2.6 Cosmic feedback

Current X-ray observations by Chandra and XMM-Newton show that the temperature of the intra-cluster medium in the core of many groups and clusters drops by a factor of two to three from the outer regions, but no lower. The rate at which gas is cooling out of the X-ray emitting hot phase is reduced by factors of 10 to 100 below what would happen without heating. It appears that a finely balanced feedback mechanism exists between the supermassive black holes (SMBH) found at the cores of all massive galaxies and the hot gas in the surrounding cluster. How this takes place is not straightforward or sufficiently well understood, and is a monumental challenge since mechanisms operating on the scale of the Solar System must be tuned to the conditions operating over 10 decades larger in scale and on a relatively short timeframe.

It is known that the feedback from a central black hole on its host galaxy depends on the nature of the gas present. If the gas is ionized and at the virial temperature of the galaxy, it will be little affected by radiation but highly susceptible to jets and winds. This so-called radio or mechanical-mode feedback is common in massive elliptical galaxies, and X-ray observations are the only direct way to detect the gas and its interaction with the SMBH. If the gas is dusty then it is more observable at more wavelengths, although it requires X-ray or far infrared emission to penetrate to the inner regions where the interaction occurs and to view directly the Active Galactic Nucleus (AGN) itself. The feedback is then referred to as in quasar or radiative mode.

Key observational questions arise from both modes of feedback. Two such questions are how energy flows in and around massive elliptical galaxies in groups and clusters of galaxies, and how much energy and mass flows out from AGN. The high spectral resolution of Constellation-X will enable measurements of outflow and turbulent velocities an order of magnitude better than existing satellites, and its large collecting area will allow monitoring of time variability on ever shorter timescales and thus probe infalling and outflowing gas very near to SMBH. Feedback involving all types of interstellar and intergalactic gas, from 10^6K collisionally ionized to 10^4 K photoionized gas can be addressed with

Constellation-X, as it is sensitive to all ionization states from Fe I–Fe XXVI. We see these cooler phases embedded in multiphase AGN outflows with Chandra and XMM, and from neutral gas Ka emission lines. It probes AGN activity over 10 decades in scale, from the inner accretion flow where the outflows are generated to the halos of galaxies and clusters, where the outflows deposit their energy. X-ray observations reveal the total mechanical energy output of AGN, and thus provide the foundation for studying AGN feedback and the nature of extragalactic radio jets over the last several billion years of cosmic history.

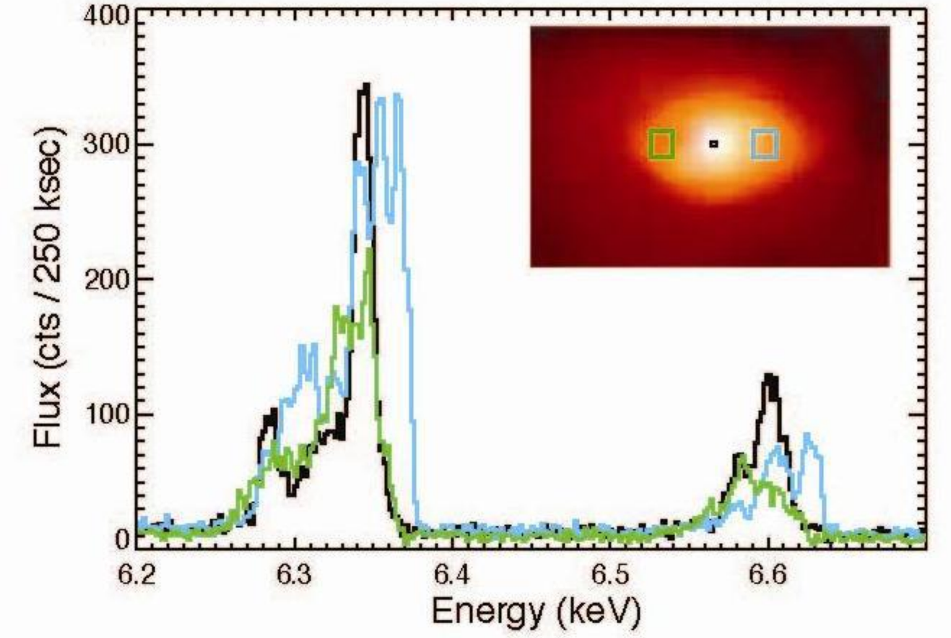

Figure 6: FeK-alpha spectra for three lines of sight through Cyg A, with inset showing the 6.2-6.8 keV Constellation-X image of Cyg A. The black curve (through the center) shows significant turbulent and kinematic broadening in the cluster gas due to AGN activity. The blue and green curves trace lines of sight through two cavities, showing the kinematic signature of the expanding shell. The energy separation between the approaching and receding wall of the cavity gives the actual physical line of sight velocity of the gas of 700 km/s relative to the cluster gas. Figure courtesy of A. Fabian.

Current X-ray satellites have uncovered the importance of cosmic feedback, but only Constellation-X will have the throughput to measure its evolution over cosmic time. The physics of the as-yet poorly-understood feedback process will be unveiled via spatially-resolved high spectral resolution Constellation-X observations within the performance parameters described above.

2.7 Observatory science

Constellation-X is a Guest Observer (GO) facility that will serve the whole astronomical community just as the Chandra X-ray Observatory before it. This science will be done within the performance parameters set by the topics described above, and will include research on:

- **The Sun as a Star**: With 100x the throughput of existing X-ray satellites, Constellation-X will be able to study X-rays from solar-type stars over a range of ages, showing how our solar system must have evolved from the Sun's birth through its death. Although literally hundreds of such systems can be found within a few hundred parsec, they are simply too faint to observe with existing gratings.
- **Starburst Galaxies:** These galaxies, found both in the local and distant Universe, contain a "superwind" which may or may not be responsible for ejecting metals into the intergalactic medium. For local starbursts, Constellation-X will measure the velocity and abundances of these winds and determine when (if ever) they can eject materials out of the host galaxy.

- **Protoplanetary disks:** Recent observations of extrasolar planets have confirmed that the Solar System is not an anomaly, but how planets form remains a puzzle. X-ray flares from young stars may be an important mechanism for ionizing the protoplanetary disk, thus inducing the magnetic turbulence needed to create a viscous disk. These same flares create Fe K fluorescence features that have been observed by Chandra; in 1 Msec of observing a star-forming region such as the Orion Nebula we expect to detect hundreds of such flares.

3. MISSION REQUIREMENTS

The mission and instrument requirements that are driven by the science observations discussed above are summarized in Table 1. While not an explicit requirement from the science topics discussed above, the mission lifetime is derived by estimating the total observing time required to complete the science studies, using expected observation durations and number of objects to be studied. Similarly, the requirement for an L2 orbit is based upon the need for high observing efficiencies, stable thermal environments, and low radiation environments.

Table 1. Constellation-X key performance requirements

PARAMETER	**VALUE**	**DRIVER**
Overall Bandpass	0.3-40 keV	
Effective Area:	15,000 cm^2 @ 1.25 keV 6,000 cm^2 @ 6 keV 150 cm^2 @ 40 keV	Black hole spin evolution with time Large scale structure studies Black hole strong gravity
Spectral Resolving Power (FWHM, E/ΔE)	1250 over 0.3 - 1.0 keV (with 1000 cm^2) 300 over 1.0 keV – 10.0 keV (central 2.5 arcmin only) 2400 at 6 keV (central 2.5 arcmin only) 10 over 10 – 40 keV	Missing baryons Large scale structure studies Black hole strong gravity
Field of View	5 x 5 arcmin (10 x 10 arc min goal)	Large scale structure studies
Angular Resolution (HPD)	15 arcsec over 0.3 – 7 keV (5 arcsec goal) 30 arcsec over 7 keV – 40 keV	Large scale structure studies Missing baryons Black hole strong gravity
Bright source capability	Full capability up to 0.25 Crab flux	Neutron star equation of state
Timing accuracy	100 microseconds relative to UTC	Neutron star equation of state
Mission Lifetime	5 years (consumables sized for 10 years)	
Targets of Opportunity Response	48 hours	SN Ia
Orbit	L2, 700,000km	

Recent changes in the mission and instrument requirements have occurred as the science case has been refined and updated, based both on the most recent work using the current generation of X-ray observatories – Chandra and XMM and on reviews of the science case that took place as part of the Beyond Einstein Program Assessment Committee (BEPAC) review. These changes were reviewed and approved by the Constellation-X Facility Science Team during its

November 2007 meeting. The field of view requirement was increased from 2.5x2.5 arcmin to 5x5 arcmin (a requirement that drives the number of pixels in the microcalorimeter) to allow for cluster studies at larger radii (both surface brightness and temperature profiles) without the need to mosaic multiple observations. Corresponding to this increase in field of view, the spectral resolution is now specified slightly differently; rather than a single resolution requirement across the field of view, the outer portion of the array carries a slightly 10 eV resolution requirement and a lower count rate capability, while the inner 2.5x2.5 part of the array maintains 2 eV. The resolution at low energies was increased from a minimum of 300 to a minimum of 1250 across the bandpass of 0.3 to 1.0 keV, the driving requirement is now the study of the WHIM features as viewed in absorption in front of bright quasars. The hard X-ray telescope has also seen requirements changes, in that the effective area requirement has been reduced from 1000 cm^2 to 150 cm^2, based on simulations of observations needed to define the continuum near 6 keV for the strong gravity science. The spatial resolution requirement is under intense study to determine the impacts of changing the requirement from 15” to 5”, as is the bright source requirement changing from 0.25 crab to 1 crab.

4. BASELINE MISSION CONFIGURATION

Over the last several years, several developments have taken place to drive changes in the Constellation-X mission configuration. The most significant of these has been the need to reduce the overall mission cost as launch vehicle costs have risen significantly faster than anticipated. This launch vehicle cost problem led us to re-examine the mission configuration based on a Delta-IV heavy to one based on the substantially less expensive Atlas V-551. In addition, changes in the overall requirements (outlined above) have also influenced the mission configuration (e.g., the reduction in the number of HXTs required to meet the modified effective area requirement at the higher energies).

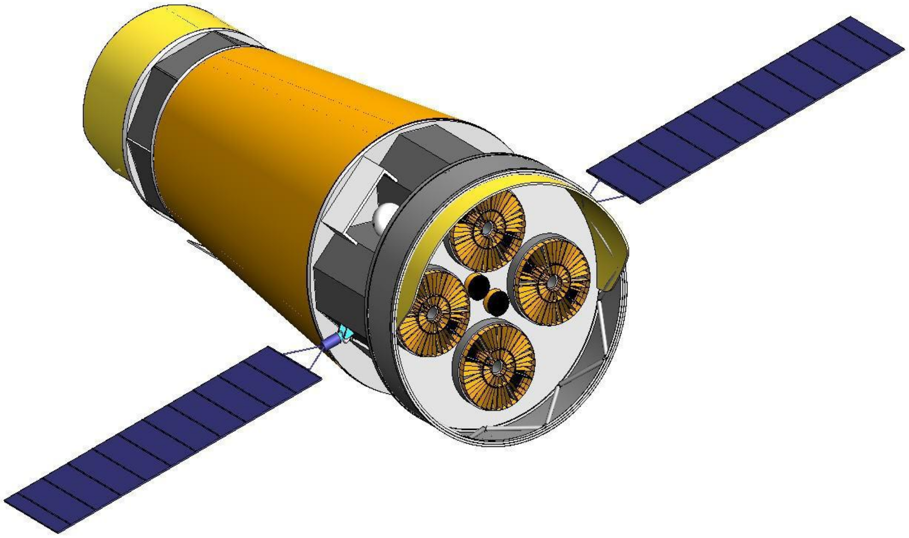

Figure 7: The baseline Constellation-X observatory in its deployed configuration. Viewed from the front, the four Spectroscopy X-ray Telescopes (SXTs) are visible, as are the two Hard X-ray Telescopes (HXTs). This configuration is launched on an Atlas V-551.

The current Constellation-X configuration consists of a single spacecraft launched on an Atlas-V 551 (the previous configuration consisted of 2 spacecraft launched on a single Delta-IV Heavy). The observatory is modular in design, with a mirror system module, a spacecraft module with a non-deployed (fixed) optical bench, and a focal plane module. There is a limited set of deployables on this mission: the solar panels, the mirror covers, and the mirror sunshade.

Constellation-X has two distinct telescope systems: the Spectroscopy X-ray Telescope (SXT), covering the 0.3 - 10.0 keV band, and the Hard X-ray Telescope (HXT), covering the 6 - 40 keV band. Constellation-X has four SXT units, each of which consists of a Flight Mirror Assembly (FMA) and an X-ray Microcalorimeter Spectrometer (XMS). One or two SXT units will have an X-ray Grating Spectrometer (XGS). By providing for the effective area requirement with four telescopes (with modest mirror dimensions) that have common design, manufacturing, assembly and testing, we will minimize the overall mission costs. The HXT will consist of one or two mirrors plus detectors, depending on the selected implementation. Thus, this configuration retains the mission robustness against failure of an individual instrument. Within this configuration, all of the instruments operate simultaneously, a key aspect of studying high energy phenomena that are typically variable on relatively short timescales.

4.1 Orbit

Constellation-X will be launched directly into a 700,000 km radius halo orbit around the Sun-earth L2 point. This orbit was selected to provide a thermally stable environment for the calorimeters, and to provide a low particle background since the spacecraft always remains within the earth's magnetosheath. This L2 orbit also provides the mission with high operational efficiency, and uninterrupted viewing of sources with the field of regard – an important consideration for observations of variable sources. The instantaneous filed of regard is a 360-degree band with a ±20 degree offset from the normal to the sun-spacecraft line. Thus, any location on the sky is observable for at least 5 weeks twice a year. The mission lifetime is 5 years, with sufficient consumables (primarily propellant for L2 orbit corrections, as the microcalorimeter is a cryogen-free system, and requires no consumables) for a 10 year life.

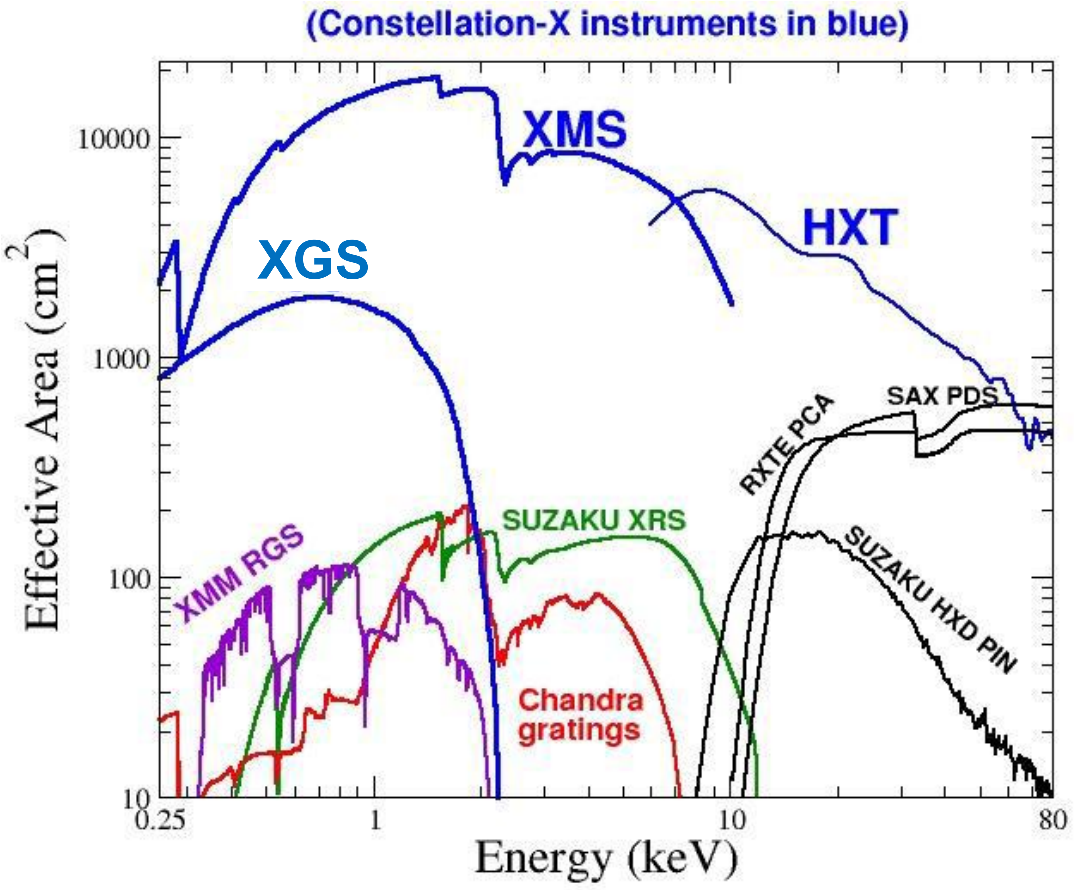

Figure 8: The Constellation-X effective area curves. Note that the effective areas for the XGS and HXT are representative only, as several different implementations of those instruments are under consideration.

4.2 Optics

Each FMA unit is 1.3m in diameter and has a 10m focal length. The FMA consists of 168 tightly nested Wolter-I mirror shells. Each mirror shell consists of identical azimuthal segments, with separate primaries and secondaries. Each individual optic is a piece of 400 micron thick sheet glass with an axial extent of 20cm that has been thermally slumped to the proper optic figure on a precision mandrel, and then coated with iridium. The maximal diameter of 1.3m was chosen to enable full-optic illumination of the FMA at NASA's Marshall Space Flight Center's X-ray Calibration

Facility. The FMA optics and their status are discussed by Zhang et al., Chan et al.. Lehan et al., Reid et al., Freeman et al. and Podgorski et al. in this conference.

In addition to the direct feed that the FMA provides to the calorimeter, a set of gratings will be placed behind one or two of the FMA modules to provide high resolution spectroscopy at low energies. Two different gratings approaches are under study: an “Off-plane Grating (OPG)” being led by the University of Colorado, and a “Critical Angle Transmission” (CAT) being led by MIT. Both approaches are being presented in other papers at this conference and references therein (McEntaffer et al. [13], and Heilman et al.[14], respectively).

The HXT optics consist of grazing incidence nested mirrors (conceptually similar to the SXT) that focus X-rays onto an imaging spectrometer located in the focal plane. There are three main differences between the SXT and HXT mirrors: (1) the radial dimensions of the HXT mirrors are considerably smaller than those of the SXT mirrors, because higher energy photons require smaller graze angles for efficient reflection; (2) the HXT mirrors are coated with depth-graded multilayer coatings to extend the bandpass to 40 keV; (3) the HXT mirrors have a less stringent angular resolution requirement. Two different optics technologies are under study: full-shell nickel optics[15], or segmented glass optics[16].

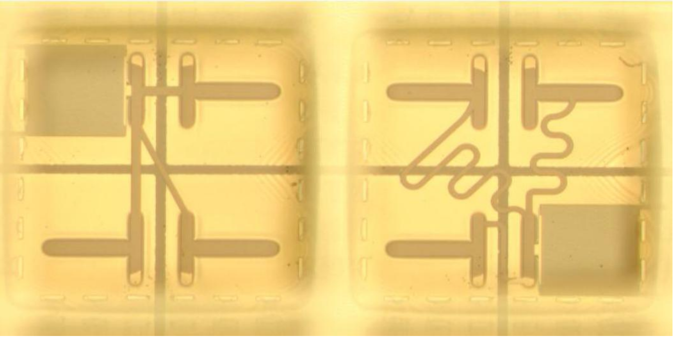

Figure 9: The position-sensitive TES (PoST) approach. A single TES connected by thermal links with different thermal conductances to the TES, so that response signal shapes vary according to the position of the incident x-ray. 5 – 6 eV resolution has been demonstrated, which is significantly better than the required 10 eV for these outer array pixels. Figure courtesy of the GSFC calorimeter group.

4.3 Detectors

Constellation-X hosts three separate types of detector systems: a microcalorimeter (the XMS) resides at the focus of each FMA and provides non-dispersive, high spectral resolution over most of the Constellation-X bandpass. At lower energies, the gratings feed a CCD array (or active pixel sensor array) in the focal plane. On the high energy end, the HXT optics feed a CdZnTe detector. However, over the last year the Constellation-X project efforts have been highly focused on the microcalorimeter array, which has had its field-of-view requirement change, thus necessitating a new detector configuration that consists of an inner array of pixels covering 2.5 arcmin, and an outer array that extends the field of view to 5 arcmin. Devices which use a single thermistor to read out 4 pixels ('hydras') will be utilized for the outer array; these have been manufactured and tested to yield 6 eV energy resolution. This is substantially better than the required 10 eV for the outer array, these devices therefore offer a promising path to extending the FOV to 5' and beyond. Variations in the thermal conductances allow for a determination of which of the pixels was hit by an X-ray (see Figure 9). In addition, we have also achieved 2.3 eV resolution on an array which has the baseline Constellation-X pixel size. The resolution was uniformly good in all in the pixels checked, indicating that flight devices can be made with very uniform (and good) resolution. Progress has been made on the multiplexing front as well: a 2x8 array of pixels with a flight-like decay time constant of 280 usec has been read out with an average energy resolution of 3 eV using common-mode biasing. This effort is reported on by Kilbourne et al[17]. in these proceedings and references therein.

4.4 Mission effective area and resolving power

Given the optics and detectors described above, Figure 8 shows the mission effective area as a function of energy. The effective area curves take into account the following loss factors: geometric obscuration of the mirror support structure, losses due to mis-alignments between the P and H segments, particulate contamination, etc. The Constellation-X effective area curves are compared with previous missions, and demonstrate the improvements of factors 25 – 100, depending on energy, for high resolution spectroscopy over the existing XMM-Newton and Chandra capabilities. The most recent instrument (XMS, XGS and HXT) response matrices are available on the Constellation-X website under the resources tab: (http://constellation.gsfc.nasa.gov/resources/response_matrices/index.html).

Figure 10 shows the Constellation-X resolving power as a function of energy. The XGS option shown in this plot is for the CAT gratings. Note the difference in behavior of the calorimeter resolution (which decreases at lower energies) and the grating (which increases at lower energies), making these two instruments highly complementary.

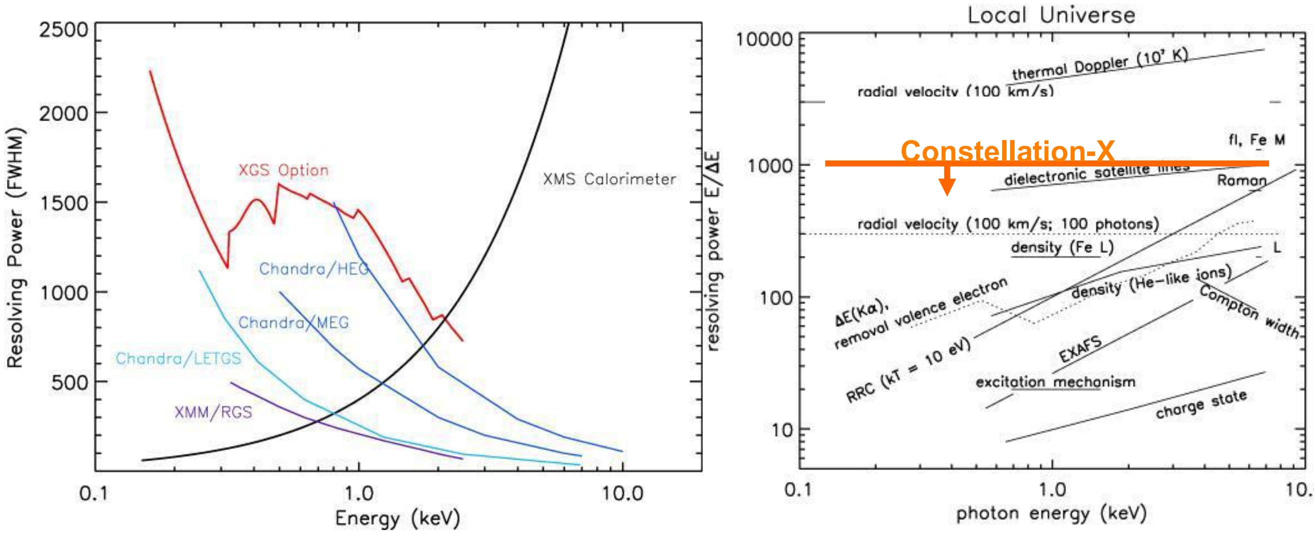

Figure 10 [Left] The spectral resolving power of Constellation-X compared with previous X-ray spectroscopy capabilities. Figure courtesy of R. Heilmann. **[Right]** A sample of the many new kinds of spectral diagnostics that Constellation-X will make available. Note that the horizontal line for the Constellation-X resolution is the minimum it will achieve across the bandpass from 0.3 – 10 keV. Figure courtesy of F. Paerels.

5. SUMMARY

As NASA's next facility class astrophysics mission, Constellation-X will provide a two order of magnitude increase in capability over current missions for high resolution X-ray spectroscopy. These capabilities are based on the requirements needed to achieve the key science objectives of the mission. Ongoing review of the science goals, and the resultant mission requirements are an integral part of the Constellation-X project. The most recent review of the Constellation-0X science case has resulted in modest changes to the mission requirements; these changes have been incorporated into the baseline mission configuration.

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