Constellation-X Science Requirements Document
Version of 09/18/2007PM

TABLE OF CONTENTS

Scope:

Other Applicable Reference, Derivative, and Contractual Documents:

1) The primary source for this document is the ‘Science with Constellation-X’ booklet of May 2005, NASA/TP-2005-212784.
2) Additional information has been taken from the publicly available presentations from the Con-X team to the NRC BEPAC (Beyond Einstein Program Assessment Committee) during 2007; and
3) a series of white papers written by the Con-X Facility Science Team during 2004 and 2005 and,
4) a Con-X white paper on Dark Energy submitted to the NSF/NASA Dark Energy Task Force (June 2005) and,
5) the Con-X TRIP report (Feb 2003) and,
6) the Con-X Top Level Requirements Document (TLRD) of December 2005 (the “TRIP 2003” version of the TLRD) and,
7) the 2000 NRC Decadal Review ‘Astronomy and Astrophysics in the New Millennium’.
8) ‘Connecting Quarks to the Cosmos’, NRC report
9) an interim report to NASA (May 1996) ‘The High Throughput X-ray Spectroscopy (HTXS) Mission’
10) the proposals in response to NASA NRA 94-OSS-15, from GSFC (‘The Next Generation X-ray Observatory’ PI N. White) and SAO (‘Large Area X-ray Spectroscopy Mission’, PI H. Tananbaum) and,

Definition of Terms:

Performance levels are given in this document for the key parameters of the Con-X mission. The following terms and definitions apply:

- Requirement: Design level. Failure to meet triggers a Project Change Control Review.
- Minimum: Level below which, if violated, significantly compromises the scientific return of the mission. Failure to meet triggers a Program Review.
- Goal: Level which, if met, produces significantly enhanced scientific return.

SRD Summary Table [short version]

A more detailed version of this SRD summary table is located in an appendix to this document.

Parameter	Value
Overall Bandpass	0.3-40 keV
Effective Area	1,000 cm^2 over 0.3 – 10 keV
	150 cm^2 over 10 – 40 keV
	15,000 cm^2 at 1.25 keV
	6,000 cm^2 at 6 keV
Spectral Resolving Power (FWHM, E/ΔE)	1250 over 0.3 - 1.0 keV
	300 over 1.0 keV – 10.0 keV in central 2.5 arcmin only
	2400 at 6 keV in central 2.5 arcmin only
	10 over 10 – 40 keV
Angular Resolution (HPD)	15 arcsec over 0.3 – 7 keV 5 arcsec goal over 0.3 – 7 keV
	30 arcsec over 7 keV – 40 keV
Field of View (FOV)	5 arcmin on a side
Bright source capability	Full capability up to 0.25 Crab flux
Temporal accuracy	100 microseconds relative to UTC
Temporal resolution	10 microseconds
Celestial coordinate accuracy	5 arcsec (3 sigma)
Mission lifetime	5 years, consumables for 10 years

Executive Summary of Science Topics

1) **BLACK HOLES**: A 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. In addition Constellation-X will utilize the observed properties of accreting black holes to constrain the growth of black holes by measuring the fundamental parameter of black hole spin.

This requires 6000cm^2 of effective area at 6.0keV, 150cm^2 at 40keV, a bandpass of 1.0 – 40.0 keV, and angular resolution of 30 arcsec HPD above 7 keV.

2) **DARK ENERGY**: The two separate highly complementary Con-X DE experiments will each, individually, in combination with Planck data, obtain uncertainties on the time-averaged dark energy equation of state w to ±0.05. In combination with other, contemporary constraints (such as those from Planck) Con-X will provide an order of magnitude improvement in our knowledge of the key dark energy parameters. This requires 15000cm2 at 1.25keV, spectral resolution of 2400 FWHM at 6 keV over a 2.5 arcmin FOV and >300 over the 1.0 – 10.0 keV band in the central 2.5 arcmin, a FOV of 5.0 arcmin, and an angular resolution of 15 arcsec HPD. Note that this effectively requires an imaging spectrometer.

3) **MISSING BARYONS**: Constellation-X will measure these WHIM filaments in absorption along the line-of-sight to 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. This requires high spectral resolution (R) at low energies, specifically R>1250 FWHM over the 0.3-1.0 keV band assuming 1000cm2 area over this band.

4) **NEUTRON STAR EQUATION OF STATE**: 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. This requires the observatory to operate at full capacity up to rates equivalent to 0.25 Crab flux units.

5) **SMBH EVOLUTION AND COSMIC FEEDBACK**: Current satellites are able to detect these SMBH, but Con-X will measure their evolution, physical conditions and geometry. Recent discoveries have shown that the growth of SMBH and their host galaxies are intimately connected via a process called ‘cosmic feedback’. The physics of the feedback process can be understood via spatially resolved high spectral resolution Con-x observations. Both of these studies can be carried out within the performance parameters set by the four driving topics above

6) **OBSERVATORY SCIENCE**: Con-X is a Guest Observer facility that will serve the whole astronomical community just as the *Chandra* X-ray Observatory before it. Important science will be done spanning the entire range of astronomy from solar system studies to cosmology and dark matter studies. This science will be done within the performance parameters set by topics 1 through 4.

1.0 STRONG GRAVITY AND BLACK HOLES

On macroscopic scales, General Relativity (GR) remains our best theory of gravity. For weak gravitational fields, GR has passed precision tests but strong-field tests of GR are more difficult. The lack of a single parameterization/theory for alternatives to GR highlights the need to probe strong-field gravity in as many independent and unbiased ways as possible. Of the known inventory of astrophysical objects, only neutron stars and black holes are strong-gravity entities. Black holes are observationally much simpler objects, having only two parameters: mass and spin. Constraint of black hole spin is a difficult measurement that has been achieved in very few cases.

1.1 Using Black Holes to Test GR

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 orbit, is also where the disk is hottest.

The most powerful technique for inner accretion disk studies to date is the study of the broad iron fluorescence line seen in the X-ray spectrum of many accreting black holes. 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.

1.1.1 Measurement of Matter and Photon Orbits using FeK

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 cm2 collecting area at 6 keV is required to ensure 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 that are usable 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. Note that 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 data for 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, and the inclination at which the accretion disk is being viewed. 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 (break down of GR). If the latter were the case, these measurements would provide a framework to examine alternate gravity theories, or extensions to GR.

1.1.1.1 Bandpass

The 1.0-7.0 keV bandpass will be critical in studying inner accretion disks in AGN. Although the primary feature has a rest-frame energy of 6.4-6.7 keV (Fe K), it will be gravitationally redshifted , meaning that soft response down to 1 keV – 2 keV will be required to characterize the line, and the orbits of knots at the inner edge of the accretion disk. Variations in the hard component above 10 keV, and in the softer component below 1.0 keV will not be important for these studies of individual orbiting knots and for reverberation mapping.

1.1.1.2 Sensitivity/Effective area

Studies of strong gravity in AGN require that a sufficient number of Fe-Kα X-ray photons be detected within the relevant physical timescales. Thus although sensitivity limits are quoted, in this particular science area, instantaneous effective area is of critical importance. These timescales include the light-crossing timescale for reverberation mapping and the orbital timescale for tracking the motion of knots of material in the accretion disk. For a 10^7 solar mass black hole, fairly typical of nearby bright Seyfert galaxies, these timescales are roughly 200 seconds and 2500 seconds (for the last stable orbit), respectively.

In order to measure the global properties GR in the strong gravity regime (i.e, over different black hole mass, black hole spin, and fluxes), we require a minimum of ~10 nearby bright AGN with modestly strong Fe-Kα lines suitable for reverberation studies and measuring the orbits of individual knots at the inner edge of the disks., The relevant figure of merit (FOM) for these AGN is a product of the orbital timescale at the inner edge of the disk and the X-ray flux. With 6000 cm^2 area at 6.0 keV the required FOM>50, where the units of the FOM are 10^{-11} ks-ergs/cm^2/s. This FOM calculation is based on an estimate of the equivalent width of the Fe Kα lines from the inner disk as being 200 eV and also being the sum of ~10 individual knots of equal strength. Should the required 6000 cm^2 not be met, the critical FOM would increase by the same percentage as the area decreases. Stated another way, the product of the FOM and the area at 6.0 keV must be greater than 3×10^5 for a minimum of ~10 sources. Current (2007) studies with ASCA and XMM-Newton indicate that there are more than a dozen AGN above the critical FOM=50 limit, and continuing studies may reveal substantially more such AGN. '

As these sources are bright, any detector and/or sky background will be insignificant.

1.1.1.3 Spectral resolution

In order to accurately track the orbital velocity of these hot spots, we require a resolving power of >1500 at Fe Kα. Computer simulations of the gas flow in the inner edge of the accretion disks indicate that they will follow the paths of free-falling test particles to ~1%. The resolution of 1500 is ~0.1% and thus is sufficient to measure the departure from these free-falling paths.

1.1.1.4 Angular resolution

Angular resolution is not a significant consideration for this science, arcmin resolution would be sufficient. The 15 arcsec requirement (as derived for example in Section 2) will be more than sufficient to resolve the bright nuclei in these sources from their surrounding host galaxies.

1.1.1.5 Instanteous FOV

FOV should be a minimum of 5 times the PSF to allow for background subtraction. Section 2 sets a much more stringent requirement.

1.1.1.6 Other

We require time resolution of a few seconds in order to track the orbital motions.

1.2 BH Properties (Spin, Mass)

Iron line studies by Constellation-X of the brightest AGN (1.1.1) will allow us to determine the spin of these black holes from data taken at sub-orbital time scales. By averaging that data over long times, we can build up a series of time-averaged line profiles for measuring black hole spin. With the calibrated profiles in hand, further Constellation-X observations can then be used to measure the spin of any accreting black hole displaying this spectral feature, down to very faint flux levels. Our best indications are that >70% of all black holes display this feature. The result of these studies will be an explosion of knowledge about the distribution and demographics of black hole spin, which is crucial if we are to understand the origin and evolution of black holes of all masses.

1.2.1 BH Properties from AGN

Theory predicts that accretion of matter onto a black hole, or the merger of multiple black holes, causes them to spin up (up to a maximum angular momentum), spinning space-time along with it. 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 (for example, is black hole spin related to z, to the Hubble type of the host galaxy, or to the presence of jets; and why are the spins of galactic disks 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 Con-X 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 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 to their time averaged Fe line profiles, and determine the run of BH properties with cosmological time. The redshift of AGN at $F_X \sim 10^{-14}$ (2-8keV) spans the range $0<z<4$ and has a mean z~1.0 (Barger etal 2005 AJ 129 578). Measuring the shape of the Fe line in these sources is enabled by an effective area of 15,000 cm2 at 1.25 keV. This will allow the collection of 100,000 counts in reasonable (but long) deep survey exposure times of a few Ms. 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, thus resolving powers of 1500 - 3000 may be required 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 cm2, combined with an angular resolution of 30 arcsec to limit background, ensures that sensitivity from 10 keV - 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.

From a General Relativity perspective, black holes have only two 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 measure 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.

1.2.1.1 Bandpass

A bandpass of 1.0-40 keV will be critical in studying inner accretion disks in AGN. Although the primary feature has a rest-frame energy of 6.4-6.7 keV (Fe Kα), it will be gravitationally and/or cosmologically redshifted ($0 < z < 4$) in many cases, meaning that soft response down to 1-2 keV will be required to characterize the line. We also note that Con-X will need a high energy capability in order to determine the shape of the high energy continuum which undlies the Fe Kα line, the magnitude of the Compton reflection bump (peaks at ~30 keV) due to cold matter in the disk, and the high energy cutoff of the continuum (the spectral break predicted in the range 50-200 keV is redshifted into the 10-40 keV Con-X band for z~1-2). This high energy cutoff probes the physics of the flow in the accretion disk corona, yielding maximum electron temperatures and the degree of coupling between electrons and protons in 2-temperature flows.

1.2.1.2 Sensitivity/Effective Area

Investigation of the evolution of BH parameters (ie, spin) with cosmic time around the peak of the AGN age (ie, z~1.5) will require 6000cm^2 at ~6keV (Fx~10^{-13} – 10^{-14}, 2-8keV, Barger etal Fig 9b) and also 15,000 cm^2 at 1.25 keV for the higher z objects ($1<z<3$, Fx~10^{-14} – 2x10^{-15}, 2-8keV, Barger etal Fig 9c). Long, few Ms exposures in targeted areas (the Lockman Hole, the CDF, etc) will collect 100,000 counts [10^{-14} 2-10 keV, $\alpha=1.7, N_H=10^{18}$, same at $Nh=10^{20}$], which is sufficient to accurately measure the shape of the Fe Kα line and determine the spin to 5% precision. Measurement of the underlying continuum at 10 – 40 keV energies is necessary in order to determine the shape of the Fe Kα line. This requires 150 cm^2 over the 10 – 40 keV band for AGN with 100,000 counts in the 2 – 10 keV band.

1.2.1.3 Spectral Resolution

A crucial diagnostic in the study of inner accretion disks will be the temperature of the material and the nature of the ionizing radiation. Such information can be acquired from determining the ionization state of the iron line. Note that while the separation between $K\alpha 1$ lines is aproximately 13 eV for the first 15 ionization states of iron (FeI $K\alpha 1$ is 6391 eV whereas FeXV $K\alpha 1$ is 6602 eV; Mewe and Kaastra 1993), the $K\alpha 2$ lines (which are half as bright as the $K\alpha 1$ lines) differ from the next ionization state's $K\alpha 1$ line by only 3 eV. For instance, FeI $K\alpha 2$ has energy 6405 eV whereas FeII $K\alpha 1$ has energy 6408 eV. Given the different strengths of the lines, spectral resolution of 4 eV is the minimum value which will allow these lines to be deblended.

Additionally, *Chandra* and XMM-Newton studies of relativistic Fe K lines have shown complex absorption in the relativistically broadened Fe K line in roughly one third of these systems. This absorption complicates the characterization of the Fe K line, and can only be separated from the relativistic broadening with high spectral resolution. R=2400 at 6 keV will resolve these features and allow identification of the different ionization states.

For the higher z objects, we require R>500 at ~2keV. This is because Fe K will be redshifted and the spacing between the lines similarly compressed. At z=2.5, FeK~ 2keV, and the average spacing is ~4eV.

1.2.1.4 Angular Resolution

Angular resolution is not a significant consideration for this science. Over the 1.00 – 10 keV band, an ~arcmin beam would be sufficient to avoid the confusion limit in the faintest of these bright AGN (~10^{-14} erg/cm^2/s(2-10), 1/18 AGN per sq arcmin, Hasinger 2001, or ~2 AGN in our baseline 5'x 5' FOV). However background subtraction would be difficult with a beam this large and the baseline 5 arcmin FOV. Over the 10 – 40 keV band, we require a PSF of 30 arcsec HPD in order to limit the background and therefore achieve the required sensitivity with 150 cm^2 of effective area.

1.2.1.5 Instanteous FOV

The FOV must be sufficient to allow accurate subtraction of the background from the source using the same image, which should not be a large driver for the mission. From general statistical considerations, this requires a FOV at least 3 (TBR) times larger than the 90% (TBR) encircled energy function (ECF). Over 1.00 – 10 keV, the baseline FOV of 5' should be sufficient for the baseline PSF of 15'' HDP, unless the PSF has unusually strong wings. The goal FOV of 10'x10' would allow collection of excellent spectra (100,000 counts) from ~10 AGN at the flux level of 10^{-14} erg/s/cm^2. Over 10 – 40 keV, the FOV of 5 arcmin should be sufficient.

1.2.1.6 Other

There are no other performance requirements for this topic.

2.0 Dark Energy

Determining the nature of the "Dark Energy" that appears to dominate the energy budget of the Universe and is driving the acceleration of its expansion remains a major goal of both fundamental physics and astrophysics. To constrain Dark Energy we require multiple, independent means of testing its nature so that we may rule out some of the many competing theories. There are important tools available in the X-ray bandpass that provide extremely important tests of dark energy. This is thanks to the nature of the largest gravitationally bound structures in the Universe - galaxy clusters.

X-ray observations of galaxy clusters are crucial since ~85% of the baryons within them are in the hot X-ray emitting gas. Detailed measurements of the temperature and density profiles of this hot gas permit two types of tests of Dark Energy using galaxy clusters, one based upon the observationally-verified baryon mass fraction "standard candle" (a geometric measurement) and the other based on the evolution of the cluster mass function (a 'growth of structure' measurement). Conveniently, the key measurements for both tests can be made using the same set of large, relaxed clusters of galaxies. Constellation-X will observe large samples of clusters of galaxies (> 500 objects) over a wide redshift range (0<z<2; median redshift z~1) with high precision to constrain Dark Energy parameters.

Note that the Con-X DE cluster program is a "Class IV" project (the highest level) according to the classification of the Dark Energy Task Force (DETF). Moreover, the DETF emphasizes how both geometrical measures and those concerning growth of structure should be employed. Con-X will constrain the time evolution of dark energy with a DETF figure of merit [σ(wa) * σ (wp)]-1 ~ 30. These data will constrain dark energy with comparable accuracy and in a beautifully complementary manner to the best other techniques available circa 2017.

To provide precise and accurate measurements suitable for DE studies, Con-X must be able to measure the properties of the X-ray emitting gas on large scales in clusters where gravity dominates (approximately half the virial radius) and the physics is well understood. Given the typical angular size of relaxed clusters, this requires a field of view (FOV) of 5 arcmin on a side. The largest, nearby clusters will overfill this field, and this drives our FOV goal of 10 arcmin. Neither *Chandra* nor XMM have sufficient collecting area to study sufficient numbers (~500) of distant (z~1) clusters in reasonable exposure times - this large sample of objects can be done if the collecting area is sized to allow fairly fast spectral measurements. Constellation-X must be able to derive accurate temperature profiles (requiring spatially-resolved X-ray spectroscopy) for massive clusters out to z~1 in a reasonable exposure (~25 ks). This exposure time drives our effective area requirement at 1.25 keV to be 15,000 cm2, and at 6 keV to be 6,000 cm2. The need to derive accurate temperature profiles over the entire surface of the cluster drives our spectral energy resolution requirement over the full field of view. This is sufficient to resolve the strong transition lines used for temperature diagnostics. These requirements are carried in Table 4-2 line 3. Con-X must also have sufficient spatial resolution and resolving power to recognize merging clusters and separate out the complex physics in the centers of clusters. This will allow us to measure gas motions in the center of clusters (via the Fe Kα lines) and therefore quantify any non-equilibrium pressure support it may introduce. An angular resolution of 15 arcsec will allow us to remove the complex central regions from our fgas and G(z) analysis when it is necessary (Table 4-2, line 4). A resolving power of 2400 is required only in the center of the

FOV, as it is in the center of some clusters where effects of turbulent heating may be detected (velocities are expected to be ~ 100 - 300 km/s so resolving powers of 1000 – 3000 are needed). The fgas measurements can benefit from slightly higher angular resolution, and this drives our 5 arcsec goal for this item.

Experience from *Chandra* shows that imaging the low surface brightness of the outer regions of clusters requires that the particle induced detector background be at or below a level of 10-2 c/cm2/s/keV. When combined with the effective area and plate scale effects, the limiting surface brightness for Con-X is predicted to be several times below that of *Chandra*. However, during times of high solar activity (coronal mass ejections) the *Chandra* background rates are high enough to render the data unusable for low surface brightness studies.

2.1 Dark Energy via geometric distance with f_{gas}

It is now clear that relaxed, simple clusters of galaxies can be used as "standard candles" for relative distances using the observationally-verified prediction that the fraction of the cluster mass, in rich clusters, that is in baryons is independent of redshift. The transformation from the observed X-ray temperature and surface brightness to gas mass depends on the absolute distance of the cluster, so the constant baryonic mass fraction over redshift gives strong constraints on the amount and evolution of dark energy.

The current collecting area projected for Constellation-X can derive accurate temperature profiles for massive clusters out to z~1 in a reasonable exposure (~25 ks). Simulations show that Constellation-X data alone can obtain uncertainties on w to ±0.05 and, in combination with the microwave background data, constraints on w and its evolution that are substantially smaller.

2.2 Dark Energy via G(z), Growth of structure using clusters

Clusters of galaxies are sensitive probes of cosmic structure growth. The perturbation growth factor, G(z), is the second [together with d(z)], crucial dark energy observable. Dark energy constraints from G(z) are highly complementary to those from distance measurements (Linder & Jenkins 2003). Indeed, the combination of these two approaches is uniquely useful to test whether cosmic acceleration is due to the presence of Dark Energy or a modification of the gravitational field equations (Linder 2005). Future large X-ray and SZ surveys will provide catalogs of ~100,000 clusters spanning the redshift range 0<z<2.

X-ray data provide very high-quality Mtot proxies, such as the product of ICM mass (derived from X-ray imaging) and average temperature (derived from X-ray spectroscopy) (Kravtsov et al. 2006). The Mtot vs. proxy relation can be calibrated using relaxed clusters (the same objects used for the fgas work) for which mass uncertainties at the few percent level from X-ray analyses are already achieved. To achieve the desired percent-level accuracy in Mtot determinations across the full redshift range of future surveys will require that second-order effects in the ICM (e.g., turbulence, bulk motions) be under control, utilizing the high spectral resolving power of Con-X. Combining these constraints with the larger, self-calibrated survey data, accuracies in w of ±0.04 or better should be achievable from the growth of structure test (Haiman et al. 2006; Albrecht etal. 2006).

The instrument requirements for the G(z) and fgas work are the same, so we list the requirements only for G(z) below and understand they apply to fgas as well.

2.2.1 Bandpass

The large, relaxed clusters of galaxies used in f_{gas} studies will have temperatures ranging from ~2 keV – 10 keV, so the most important bandpass will be 0.3 keV – 10 keV.

2.2.2 Sensitivity/Effective Area

Collecting area and sensitivity is a major driver for this science topic. Routine, short observations (~5ks) of clusters of galaxies with 0.5-10 keV flux of 10^{-13} erg/cm^2/s must yield high signal/noise spatially resolved images which are needed to determine if clusters are relaxed. Moderate-length observations (~40 ks) should allow measurement of the ICM emission at surface brightness values of ~3x10^{-16} ergs/cm^2/s/arcmin^2 over 1-3 keV, TBR).

The relevant target sample is the 1000 most luminous, relaxed clusters in the Universe. These clusters will have "bolometric" X-ray luminosity \$>10^{45} erg/s (0.5-10 keV, TBR). This sample may have a median redshift of z=1(TBR) , and the science is enabled if these 1000 clusters can be observed in ~5 ks to determine if they are relaxed or not. We should be able to collect ~1000 counts (TBR) for a 10^{-13} (0.5-10 keV) source in 5 ks. Assuming kT=5 keV, 0.3 solar abundances, and z=1with a MEKAL model, a collecting area of 15,000 cm^2 at 1.25 keV and 6,000 cm^2 at 6 keV (TBD) is required.

Since clusters will be extended over large areas, however, it is the surface brightness sensitivity that is actually important. The surface brightness profile must be measured out to a significant fraction of the cluster virial radius. *Chandra* and XMM-Newton are unable to detect cluster X-ray emission to the virial radius because their particle backgrounds are too high. Once the cluster surface brightness falls below the particle background, the exposure time required to detect the cluster emission rises very rapidly (quadratically). Putting a precise limit on the Constellation-X particle background is difficult, as the equivalent surface brightness of the particle background depends on the telescope focal length and effective area.

Both *Chandra* and XMM-Newton have specific particle backgrounds of approximately 10^{-2} counts/s/keV/cm^{-2} at 1 keV. With the baseline Constellation-X effective area one needs to reach values of 4 x 10^{-3} counts/s/keV/cm^{-2} at 1 keV (corresponding the 3 x 10^{-16} ergs/cm^2/s/arcmin^2 over 1-3 keV) to do surface photometry to the virial radius for luminous clusters at moderate redshifts (z~0.3).

2.2.3 Spectral Resolution

In order to do this work on clusters it is essential to have non-dispersive imaging spectrometers such as the calorimeters planned for Con-X. A spectral resolution in the central 2.5 arcmin square of 2400 (corresponding to ΔE=2.5eV) is required in order to measure the influence of turbulence and bulk motions. These measurements are required in order to reach the desired level of accuracy. Obtaining this calibration of the cluster mass scale will be a large part of the contribution Con-X will make to cosmological studies with clusters. This spectral resolution requirement can be relaxed by ~4X in the larger 5 arcmin FOV.

2.2.4 Angular Resolution

Con-X must also have sufficient spatial resolution (≤ 15 arcsec HPD at 1.25 (TBR) keV) to recognize merging clusters and separate out the complex physics in the centers of clusters. The fgas measurements can benefit from slightly higher angular resolution, and this drives our 5 arcsec HPD at 1.25 keV goal for this item.

2.2.5 Instantaneous FOV

To provide precise and accurate measurements suitable for DE studies, Con-X must be able to measure the properties of the X-ray emitting gas on large scales in clusters where gravity dominates (approximately half the virial radius) and the physics is well understood. This requires a FOV of 5 arcmin on a side. Nearby clusters will overfill this FOV, and this motivates our goal of a 10 arcmin on a side FOV.

2.2.6 Other

Diffuse source sensitivity as a function of detector background and telescope focal length is described in a presentation to the Dec 2006 FST by Kilborne and Bautz, and by a memo by Bautz presented to the Oct 2004 Con-X Cosmology workshop.

3.0 THE 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. This began an extensive search for the missing baryons, 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. Cosmological mulations are in broad agreement that the majority of the baryons exist in the temperature range 105 – 107.5 K, with most of the material lying in the lower overdensity filaments that connect clusters and groups.

The high temperature of the Warm-Hot phase of the Intergalactic Medium (WHIM) may only be probed with X-ray spectroscopy due to the ionization states involved. 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 etierh in the Galactic halo or the Local Group (Bregman and Llyod-Davies 2007). Accounting for the remainder of the WHIM remains a major goal of observational astrophysics.

Constellation-X will measure these filaments in absorption along the line-of-sight to 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.

3.1 Finding The Missing Baryons Via Absorption Feathers In The WHIM

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, and determination of the turbulent width of the line measures 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 FX > 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 hydrogenic and helium-like oxygen, with the possibility of deeper observations that can detect other transitions such as Ne IX and Ne X. The OVII ion is sensitive to gas at 0.5 – 3 × 106 K and is measured through the 1s-2p transition at 21.60Å (574 eV), while the OVIII ion is common in the 1 – 7 × 106 K range through its Lyα line at 18.97 Å (654 eV). The ratio of these two lines is a temperature indicator. The other lines will permit more detailed characterization of the ionization state of the gas and will extend the temperature sensitivity to 107 K. If high spectral resolving powers are available, the lines will be resolved and effects of turbulent heating or ongoing collapse in the WHIM might 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 certainly possible) 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.

3.1.1 Bandpass

The band pass required for this topic is 0.3 keV to 1.0 keV. The lines we aim to detect from the WHIM are all within this bandpass, and include those from O VII/VIII (0.57keV, 0.65keV), NVI/VII (0.43keV, 0.5keV), Ne IX (0.93keV), and CVI(0.37keV). The band from 0.5 to 1.0 keV is particularly critical, as it allows us to probe at the low Z range ($z<0.5$) where we expect to find most of the WHIM. The band from 0.3 keV--0.5 keV will allow us to probe from $2<z<0.5$) where significant fractions of the WHIM may be hiding, but theory predicts that the hot phase we are searching for may be weaker at this epoch.

3.1.2 Sensitivity/Effective Area

An effective area of 1,000 cm^2 (TBR) over the 0.3 – 1.0 keV band pass is required for this science. Detectability is a function of both the spectral resolving power and the effective area of the telescope. Note that a given absorption line equivalent width sensitivity may be achieved by various combinations of effective area and spectral resolving power. To detect absorption lines with equivalent widths of 1Må (the required sensitivity to detect 100 filaments) a combination of 1000 cm2 and 1250 spectral resolving power is required. Note that meeting the spectral resolving requirement of 1250 at 0.6 keV (the two strongest features are OVII and OVIII at 574 eV and 654 eV), with a grating spectrometer implies higher resolving power at lower energies, which will ensure that we meet the resolution requirement for higher redshift filaments. Alternatively, because the detectability (minimum equivalent width) of WHIM lines scales like the $(\Delta\lambda/\mathrm{Area})^{1/2} = (\mathrm{RA})_{-}^{1/2}$, other combinations (within a factor of ~2, but always requiring R>1250) of area and resolution are allowable as long as they follow this scaling law.

3.1.3 Spectral Resolution

A spectral resolution of 1250 (FWHM) over the 0.3 – 1.0 keV band is required for this science. Lines of interest over this band include OVII/VIII at 0.6 keV, NeIX at 0.9 keV, and CVI at 0.36 keV The best line to work with is the OVII/VIII line (product of oscillator strength and abundance is highest), next best is CVI which is perhaps one half the strength (therefore requiring brighter sources), and the NeIX line is anywhere from half (Drake and Testa 2005) to 1/7 the strength of OVII.

At lower resolutions it is unlikely that individual absorbing slabs can be resolved in velocity space and counted, so any measure of the amount of missing matter will be directly tied to a model of the WHIM distribution. A resolution of 2500 will allow easy resolution of individual absorbers, and also allow their thermal widths to be measured.

3.1.4 Angular Resolution

Angular resolution is not a significant consideration for this science. An ~arcmin beam would be sufficient. However, background subtraction would be difficult with a beam this large and the baseline 5 arcmin FOV. Moreover, given the interplay between a grating spectrometer spectral resolution and the mirror angular resolution, an angular HPD of 15 arcsec is required assuming a grating spectrometer.

3.1.5 Instantaneous FOV

The FOV must be sufficient to allow accurate subtraction of the background from the source using the same image, which should not be a hard driver for the mission. From statistical considerations, this requires a FOV at least 3 (TBR) times larger than the 90% (TBR) encircled energy function (ECF). The baseline FOV of 5’ should be sufficient for the baseline PSF of 15’’ HDP, unless the PSF has unusually strong wings.

3.1.6 Other

There are no other requirements for this section.

4.0 NEUTRON STAR EQUATION OF STATE

Neutron stars contain the highest density matter known in the Universe and their structure depends on the physics of the interactions between fundamental particles: protons, neutrons and their constituent quarks. The theory of such interactions, Quantum Chromodynamics (QCD), is not yet sufficiently constrained to accurately predict the state of matter at such extremes. The only way to constrain the low temperature - high-density regime of QCD is with precise measurements of both the masses and radii of neutron stars. Accurate masses for some neutron stars have been obtained from observations of young neutron star pulsars in binary systems, but essentially nothing is known about the radii.

Accreting neutron stars in binary systems provide several unique opportunities to probe the structure of neutron stars: 1) A continuous supply of fresh metals allows higher atmospheric abundances of the line producing elements (such as Fe) to be present than in isolated (non-accreting) neutron stars, increasing the likelihood for the formation of a detectable absorption line spectrum. 2) Accretion also leads to thermonuclear X-ray bursts; brief but bright flashes of thermal X-ray radiation shining through the neutron star atmosphere, during which the spin rate of the neutron star can be observed directly (so called ‘burst oscillations"). These old neutron stars have also gained enough mass to probe the mass/radius relation in a different regime than the young 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.

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.

4.1 Measuring Absorption Lines in ThermonucThermonuclear X-ray Bursts

In order to escape a neutron star's powerful gravitational field, photons will be redshifted and if this can be measured, it will provide a direct measure of the stellar mass to radius ratio, GM/c^2R, also called the compactness. Cottam, Paerels & Mendez (2002) 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-NewtonRGS. 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 (Villarreal & Strohmayer 2004), but present data do not have the statistical precision to tightly constrain the radius (Chang et al. 2006).

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 many 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 a unique determination of both M and R.

4.1.1 Bandpass

The low energy end of the Con-X bandpass is more important than the high end for this science. The lines of interest are typically between 0.3 and ~2.0 keV, but may also include Fe-Kα at 7.0 keV. The the 0.3 keV – 10.0 keV bandpass will be needed.

4.1.2 Sensitivity/Effective Area

An effective area of 1,000 cm^2 at 0.3 keV, 15,000 cm^2 at 1.25 keV, and 6,000 cm^2 at 6 keV, is required in order to collect sufficient counts to do the spectral and timing studies needed for this science.

4.1.3 Spectral Resolution

The scientific goals outlined above all require a spectral resolving power of 1,250 or more across the 0.3 keV – 1.0 keV band, and 2400 or more at 6 keV. The presence of target absorption lines at energies slightly above 1.0 keV provides motivation for the goal of obtaining resolution of >1,250 up to 1.25 keV.

4.1.4 Angular Resolution

Angular resolution is not a driver for this science, as the targets are bright and relatively isolated. The PSF should be sufficient to allow accurate background subtraction.

4.1.5 Instantaneous FOV

The FOV is not a driver for this science, but should be sufficient to allow accurate background subtraction.

4.1.6 Other

An additional requirement for this science is the ability to count at high rates and maintain both spectral and timing resolution as well as high throughput while doing so.

Sources with fluxes up to ¼ Crab (equivalent to 9×10^{-9} $ergs/cm^2/s$ over 2 keV – 11 keV) must be observable without degradation of spectral or timing resolution precision relative to fainter sources. At higher fluxes some degradation of the spectral resolution is acceptable, but it should occur gradually.

To perform phase-resolved spectroscopy of emission from bursting neutron stars (spin frequencies up to ~700 Hz have been seen) requires the capability to time-resolve photon arrival times well below a millisecond (eight phase bins in a 1/700 sec period results in a timing accuracy requirement of 1/5600 sec, or 0.16 msec). During an X-ray burst, the X-ray flux increases dramatically, and the observatory must be able to handle high count rates without loss of spectroscopic or timing resolution. (Note that this does not require that no information be lost on any photon; counting slower at full resolution is of course acceptable, because to first order that just increases the observation time.)

4.2 Using Burst Oscillations to Probe Neutron Star Structure

Constellation-X will also be able to probe neutron star structure using the spin modulation of a non-uniform brightness pattern 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 (Nath, Strohmayer & Swank 2001; Muno, Ozel & Chakrabarty 2002; Bhattacharyya et al. 2005).

4.2.1 Bandpass

Burst oscillations effect the continuum flux from the neutron star, so the full 0.3 keV – 10.0 keV bandpass will be needed for this science.

4.2.2 Sensitivity/Effective Area

An effective area of 1,000 cm^2 at 0.3 keV, 15,000 cm^2 at 1.25 keV, and 6,000 cm^2 at 6 keV, is required in order to collect sufficient counts to do the timing studies needed for this science.

4.2.3 Spectral Resolution

Spectral resolution is not critical for this science. A resolution typical of a x-ray CCD would be sufficient.

4.2.4 Angular Resolution

Angular resolution is not a driver for this science, as the targets are bright and relatively isolated. The PSF should be sufficient to allow accurate background subtraction.

4.2.5 Instantaneous FOV

The FOV is not a driver for this science, but should be sufficient to allow accurate background subtraction.

4.2.6 Other

An additional requirement for this science is the ability to count at high rates and maintain both spectral and timing resolution as well as high throughput while doing so.

Sources with fluxes up to ¼ Crab (equivalent to 9×10^{-9} $ergs/cm^2/s$ over 2 keV – 11 keV) must be observable without degradation of spectral or timing resolution precision relative to fainter sources. At higher fluxes some degradation of the spectral resolution is acceptable, but it should occur gradually.

To perform timing studies of bursting neutron stars (spin frequencies up to ~700 Hz have been seen) requires the capability to time-resolve photon arrival times well below a millisecond (eight phase bins in a 1/700 sec period results in a timing accuracy requirement of 1/5600 sec, or 0.16 msec). During an X-ray burst, the X-ray flux increases dramatically, and the observatory must be able to handle high count rates without loss of timing resolution.

5.0 NON-DRIVING SCIENCE OBJECTIVES

There are many important astrophysical studies that Constellation-X will carry out as a Guest Observer facility, but it is not feasible to have all of these science topics carried as driving objectives for the mission. The mission performance parameters are driven by the four science objectives described above. However, there are two very important science topics that we highlight here.

5.1 Constaining the Evolution of Supermassive Black Holes

Our understanding of the growth and evolution of massive black holes has undergone a revolution over the last few years as thanks to the *Chandra* Observatory we have finally resolved the Cosmic X-ray Background between 0.3 to 10 keV into individual sources. These X-ray observations have uncovered an order of magnitude higher AGN source density than found at other wavelengths (e.g., $\approx$ 7200 deg^{-2}). These X-ray sources are accreting supermassive black holes (AGN) that together are the integrated fossil signature of massive black hole accretion over the history of the universe. The majority of this AGN population is heavily obscured and while our understanding of the X-ray emission from high-redshift AGNs has advanced rapidly since the launches of *Chandra* and XMM-Newton (see Brandt et al. 2005 for a review), our current *Chandra* and XMM-Newton detections of high-redshift AGNs are just that – detections. Current photon statistics are simply insufficient for detailed investigations of high-redshift AGN continuum and emission-line properties/components. There are a number of important reasons why a better understanding of accreting supermassive black holes is needed, as it now seems likely that the development of supermassive black holes and galaxies are intimately connected (see the next section on Cosmic Feedback). Deep X-ray surveys have indicated that the growth of massive black holes undergoes a curious evolutionary trend whereby the most massive objects are grown first, a process often referred to as cosmic downsizing (e.g., Cowie et al. 2003; Marconi et al. 2004).

Constellation-X will provide direct astrophysical insight into the evolution of the environment around accreting massive black holes by exploring changes in the X- ray spectral shape and components of luminous AGN out to and beyond z ~ 6. The high-quality data that will be produced by Con-X will reveal a wealth of spectral diagnostic detail, permitting constraints on the continuum shape, absorption, recombination emission, fluorescent iron K line emission, Compton reflection, physical conditions/geometry of emitting plasmas, and the variability of accreting black holes. The energetics and demographics of z>1 obscured/Compton-thick AGNs will be quantified and spectroscopic redshifts of optically invisible obscured AGN will be directly possible from the detection of the iron K emission line. The large-scale AGN outflows (in absorption and emission) that likely regulate star formation in massive galaxies can be studied in the crucial z~1-3 era where black-hole growth and star-formation activity was at its peak, providing estimates of mass and energy outflow rates and chemical enrichment/heating of the IGM.

This science requires that Con-X be able to efficiently characterize sources as faint as ~10-15 erg cm-2 s-1 (0.5 - 2 keV), the level at which 80% of the Cosmic X-ray Background is resolved. The median redshift of these sources is z~0.8 (Barger et al. 2005) so soft energy bandpass is also important. With Constellation-X we anticipate gathering ~1000 (0.5-2 keV) counts in 100 ks for a 2 ×10-15 erg cm-2 s-1 (0.5-2 keV) source. A large enough field of view to observe multiple CXRB sources at once would enable efficient use of these observations which will be among the longest Con-X will make. Coincidently, the angular resolution, low background and FOV requirements for Dark Energy measurements with clusters are as stringent as the requirements for CXRB science. Hence, we keep this as a major topic enabled by Con-X but allow DE science to be the driver. Note that the 10-40 keV sensitivity required for the BH spin measurements also enables some hard CXRB studies.

5.1.1 Bandpass

The low energy end of the Con-X bandpass is important for the more highly redshifted sources, and the high end of the bandpass is important for the highly obscured background sources. A great deal can be learned about the central engine of SMBH by studing their hard x-ray emission up to 200keV, and sources at high redshift will have this emission shifted down to 40keV. Thus the full 0.3 keV – 40 keV bandpass will be utilized.

5.1.2 Sensitivity/Effective Area

An effective area of 15,000 cm^2 at 1.25 keV, 6,000 cm^2 at 6 keV, and at least 150 cm^2 from 10 keV – 40 keV will allow Con-X to collect sufficient counts to do the spectral studies needed for this science.

5.1.3 Spectral Resolution

These studies of the CXRB will typically detect 1000s of counts from individual sources. Given the inherent statistics, spectral resolution of 10 to 100 is optimum. Resolutions approaching 1000 would oversample the available data.

5.1.4 Angular Resolution

Angular resolution of 15 arcsec over 0.3 keV – 10.0 keV will allow Con-X to reach the sensitivities needed for this science and to avoid confusion with the CXRB. Angular resolution of 30 arcsec is needed for the same reasons at higher energies, from 10 keV – 40 keV.

5.1.5 Instantaneous FOV

The FOV of 5 arcmin will allow sufficient numbers of CXRB AGN to be detected in single, deep exposures.

5.1.6 Other

There are no other specifications for this section.

5.2 Cosmic Feedback – Measuring The Effects Of AGN On The Formation Of The Universe

Numerical simulations of the formation of large scale structure and galaxy formation over-produce the most massive galaxies in the Universe. A source of energy that arrests star formation is needed. At present the best explanation for these effects is the 'feedback' between the central black hole and its host galaxy such that they co-evolve (Hopkins et al. 2006). Starburst winds are believed to create similar effects on lower mass galaxies. Many theoretical simulations now use

AGN feedback as a knob that is turned to produce the correct number of massive galaxies, but the physics of the mechanism is poorly constrained. Various possibilities include mechanical winds from the central AGN, radiation (Ostriker and Ciotti 2006) and relativistic particles (jets). These same processes may also solve the riddle of cooling flows in galaxies, clusters and groups, and determine why cluster scaling relations differ from those predicted by dark matter only models.

In order to measure what is actually occurring one needs to directly measure the energy injection and this requires X-ray observations that only Constellation-X can provide. With spatially-resolved high spectral resolving power detectors, Con-X will determine the effects of the AGN on surrounding gas (e.g., groups and clusters), as a function of redshift determine the energy input from star formation (e.g., superwinds), and observe the IGM and determine its metallicity as a function of redshift. Only Con-X of all the missions being presently considered can obtain the needed measurements and provide us with a proper understanding of how structure in the universe forms and evolves.

The instrumental specifications needed in order to understand cosmic feedback are very similar to those for the dark energy experiments described in section 2. We itemize and expand on these specifications below.

5.2.1 Bandpass

Feedback appears to take place on all scales – from the the large, relaxed clusters of galaxies used in the DE studies (with temperatures ranging from ~2 – 10 keV), to somewhat cooler groups of galaxies, and down to individual galaxies. The AGN themselves have spectra extending up to high energies. Therefore the full 0.3 keV – 40 keV bandpass will be important for these studies.

5.2.2 Sensitivity/Effective Area

The collecting area and sensitivity specified for the dark energy observations will be sufficient for these cosmic feedback studies. The same clusters will not be observed, as the relaxed clusters needed for the dark energy studies are not experiencing active feedback. However, the surface brightness will cover an overlapping range.

5.2.3 Spectral Resolution

Active galactic nuclei and quasars have been shown to harbor extremely powerful winds, with material ejected from their central engines at typical speeds 100-1000 km/s, and reported speeds as high as 50,000 km/s. The ejected matter is hot and has been either partially or fully ionized by the intense radiation from the central supermassive black hole and accretion disk.
Velocity measurements will be important for establishing a connection between the mechanical heating phenomena and the AGN. With the microcalorimeter's spectral resolution (<4 eV), we can probe the ICM's velocity field to 200 km/s or less. We can also map the bubbles' velocity field and determine whether they are rising or expanding. AGN-induced turbulence in the ICM can be detected and spatially mapped. In addition, spectroscopy will offer measurements of abundance gradients, which can show the extent of entrainment by the rising bubbles, and information about the ionization mechanisms in the cluster gas that may reveal the role of, for example, cosmic rays in the ICM.

As for the dark energy work, here it is essential to have non-dispersive imaging spectrometers such as the calorimeters planned for Con-X. A spectral resolution in the central 2.5 arcmin square of 2400 (corresponding to ΔE=2.5eV) will allow one to measure the influence of turbulence and bulk motions. This spectral resolution requirement can be relaxed by ~4X in the larger 5 arcmin FOV.

5.2.4 Angular Resolution

As for the dark energy studies, a spatial resolution (≤ 15 arcsec HPD at 1.25 (TBR) keV) will be sufficient to map out the spatial structure due to the feedback in the centers of clusters. The improved angular resolution defined by the goal of 5 arcsec HPD at 1.25 keV will allow efficient removal of the bright point sources (AGN, bright binaries) associated with feedback and also allow more accurate measurement of the associated abundance gradients.

5.2.5 Instantaneous FOV

The FOV as required by the dark energy studies, of 5 arcmin on a side with a goal of 10 arcmin on a side, is sufficient to study cosmic feedback.

5.2.6 Other

Diffuse source sensitivity as a function of detector background and telescope focal length is described in a presentation to the Dec 2006 FST by Kilborne and Bautz, and by a memo by Bautz presented to the Oct 2004 Con-X Cosmology workshop.

6.0 OBSERVATORY SCIENCE

Constellation-X is a Guest Observer facility that will serve the whole astronomical community just as the *Chandra* X-ray Observatory before it. Although the four science objectives we have listed are of critical importance and define the basic measurement requirements, the following is a summary of some of the important science that this capability will enable.

6.1 The Nature of Dark Matter

X-ray observations of the hot plasma trapped in the gravitational field of the Dark Matter in clusters of galaxies remain one of the most powerful techniques to map the location of the Dark Matter and constrain its interaction with normal matter. Constellation-X will for the first time bring the spectral resolution and collecting area required to map the velocity field of the plasma on scales of a hundred of km/s, the relevant velocity scale for these systems. By deriving precise mass profiles and directly comparing the baryonic component of clusters Constellation-X will provide a direct measurement of the amount and distribution of dark matter to a unprecedented level or precision and allow accurate comparisons with weak and strong lensing measurements and determinations of the gas content via the Sunyaev-Zeldovich effect. There are no comparable X-ray facilities planned with similar capabilities. Note that the measurement of the content of Dark Matter comes ‘for free’ from the normalization of the f_{gas} experiment (Section 2.1).

Warm Dark Matter has become a viable “alternate” to the standard cosmological structure formation scenario, as it may resolve many problems in structure formation. Sterile neutrino dark matter, in the standard production scenarios, is detectable or potentially excludable with Constellation-X and by no other means. These particles are expected to decay, but with rather long time scales into two photons. The present best limits on these particles, if they are to represent the bulk of the dark matter, is between 1-20 keV. Constellation-X will be able to improve on the present limits by a factor of over 30, definitely either detecting or ruling out sterile neutrinos as the dark matter.

An additional interesting measurement that will come from these Cluster measurements will be constraints on the mass of the neutrino. The neutrino mass density originates primarily from the fact that the cluster of galaxies X-ray Luminosity Function provides a robust constraint on sigma-8 for a given value of Omega matter, while the CMB data predict sigma-8 as a function of the neutrino mass. So combining the two provides constraints on the neutrino mass (Allen 2003 astro-ph/0306386). Constellation-X data combined with Planck can be expected to place more accurate constraints on the neutrino mass.

The requirements for the dark matter measurements are the same as those for the dark energy Fgas and G(z) experiments. As with the F_{GAS} measurements, these measurements would benefit from higher angular resolution and provide additional motivation for the goal of 5 arcsec HPD. This would allow better removal of point-source emission and one to derive the morphology of high-redshift clusters so that mergers can be recognized. A field of view of 5 arcmin on a side is desirable to obtain cluster mass profiles out to a significant fraction of the virial radius, as at z~0.3 the virial radius of a massive cluster is approximately 5 arcmin. A larger field of view is desirable to allow sufficient solid angle to determine local background. As with the Dark Energy studies, we require that the particle induced detector background be low.

6.1.1 Bandpass

The large, relaxed clusters of galaxies used in Fgas studies will have temperatures ranging from ~2 keV – 10 keV, so the most important bandpass will be 0.3 keV – 10 keV.

6.1.2 Sensitivity/Effective Area

As with the Dark Energy studies, collecting area and sensitivity is a major driver for this science topic. Since clusters will be extended over large areas, however, it is the surface brightness sensitivity that is actually important. The surface brightness profile must be measured out to a significant fraction of the cluster virial radius.

Both *Chandra* and XMM-Newton have specific particle backgrounds of approximately 10^{-2} counts/s/keV/cm^{-2} at 1 keV. With the baseline Constellation-X effective area one needs to reach values of 4×10^{-3} counts/s/keV/cm^{-2} at 1 keV (corresponding the 3×10^{-16} ergs/cm^2/s/arcmin^2 over 1-3 keV) to do surface photometry to the virial radius for luminous clusters at moderate redshifts (z~0.3). The Suzaku (Astro-E2) calorimeter has a specifice particle background rate of approximagely 3×10^{-3} counts/s/keV/cm^{-2} over the 0.1 keV - 12 keV band (R. Kelly, PC Dec 2005, and in SPIE paper).

6.1.3 Spectral Resolution

In order to do this work on clusters it is essential to have non-dispersive imaging spectrometers such as the calorimeters planned for Con-X. Spectral resolution requirements are identical to those for the Dark Energy measurements.

6.1.4 Angular Resolution

The angular resolution requirements for the Dark Energy experiments, in particular those for the fgas measurements, are sufficient for these Dark Matter studies.

6.1.5 Instantaneous FOV

A field of view of 5 arcmin on a side is desirable to obtain cluster mass profiles out to a significant fraction of the virial radius, as at z~0.3 the virial radius of a massive cluster is approximately 5 arcmin. Nearby clusters will overfill this FOV, and larger field of view is desirable to allow sufficient solid angle to determine local background. These facts motivate our goal of a FOV 10 arcmin on a side.

6.1.6 Other

Diffuse source sensitivity as a function of detector background and telescope focal length is described in a presentation to the Dec 2006 FST by Kilborne and Bautz, and by a memo by Bautz presented to the Oct 2004 Con-X Cosmology workshop.

6.2 Constraints On Binary Black Holes: Precursors To BH Mergers

The formation of SMBH binaries following galaxy merging has been suggested as a natural consequence of galaxy formation for quite some time (Begelman, Blandford & Rees 1980). Among the possible observational indications that coalescence of binary SMBHs has occurred are the peculiar properties of some jets/lobes in radio galaxies (Merritt & Ekers 2002; Liu, Wu & Cao 2003). In a recent review of supermassive black hole (SMBH) studies, Ferrarese & Ford (2005) presented crucial areas of future research. Among these was the determination of the prevalence of SMBH binary systems. X-ray observations of SMBH binaries have already shown great success with in the nearby galaxy NGC 6240 two SMBHs about 1 kpc apart are detected (Komossa et al. 2003).

Constellation-X will search for the dual Fe-K lines which may betray the presence of the binary SMBH (see Figure 1-8). The detection of such features will effectively mimic the resolving power of *Chandra* with high-resolution X-ray spectroscopy by spectrally resolving the narrow part of the iron line into two components in “closer” SMBH binaries. Interestingly, candidate binary black holes are currently being identified with optical spectroscopy in e.g., the DEEP2 survey (Gerke et al. 2007). By 2017, with ground-based observatories such as LSST operating,

and a multitude of wider-field optical spectroscopic and X-ray surveys (e.g., XBOOTES; Murray et al. 2006), there should be more candidates for Con-X to follow-up.
For the case of NGC 6240, for instance, the velocity difference between the two cores is approx 20 km/s as the nuclei are separated by ~1 kpc and still very early in the merger process. However, for black holes farther along in their evolution towards merger (300 km/s will be easily detected), Con-X could well detect the two peaks in the (narrow) iron line.

6.2.1 Bandpass

The primary bandpass for this work will be 1.0 keV – 10 keV, so the required energy band pass of 0.3 keV - 40 keV is sufficient for these studies.

6.2.2 Sensitivity/Effective Area

The required effective area of at least 1000 cm^2 over 0.3 keV – 10 keV, 15000 cm^2 at 1.25 keV, and 6000 cm^2 at 6 keV is sufficient for this science.

6.2.3 Spectral Resolution

The required spectral resolutions of 1250 over 0.3 keV – 1.0 keV and 2400 at 6 keV are sufficient for this science. This will give a velocity resolution of 125 km/sec at Fe K at z=0, and somewhat less at higher redshifts.

6.2.4 Angular Resolution

The required angular resolution of 15 arcsec HPD over 0.3 keV – 7.0 keV is sufficient for these studies.

6.2.5 Instantaneous FOV

The required FOV of 5 arcmin on a side is sufficient for these studies.

6.2.6 Other

There are no other considerations for this science.

6.3 Intermediate Mass Black Holes

There is a class of luminous, variable, point-like X-ray sources found in many nearby galaxies that may have inferred isotropic luminosities hundreds of times larger than the expected maximum luminosity of a stellar mass black hole. This has led to speculation that some of these ultra-luminous X-ray sources (ULX) may form a new class of black holes with masses in the range from about 100–2000 solar masses, so called intermediate-mass black holes (IMBH). Currently there are 20-30 of these sources known which can be resolved from nearby emission with a 15 arcsec angular resolution. (Miller 2004, talk at Oct 2005 Con-X FST meeting).

Constellation-X will spectroscopically confirm the presence of cool accretion disks in IMBH candidates. Currently there are ~6 ULX sources with significant detections of a soft thermal spectral component consistent with an accretion disk with an average inner edge temperature of ~0.15 keV (Miller, Fabian and Miller 2004 astro-ph/0406656). Perhaps more importantly, Con-X will detect relativistic iron K-shell emission lines if they are present. Detection of these lines would confirm the disk origin of the soft X-ray emission, and would strongly rule out beaming arguments for the high inferred luminosities. If Constellation-X confirms the existence of IMBHs, then X-ray probes of General Relativity will be possible across an enormous range of black hole masses.

X-ray timing measurements can identify the characteristic timescales on which the objects are variable. By comparing studies of supermassive black holes with those of stellar mass black holes in our Galaxy, it has been shown that the characteristic variability times scale with black hole mass.

6.3.1 Bandpass

The nominal energy band pass relevant to IMBH studies is 0.3 keV - 40 keV. The FeK line at 6 keV will be important for determining the nature of the inner accretion disk in these sources and measuring their spin. The continuum at lower energies (0.3 keV - 7.0 keV) will be important for determining the overall shape of the disk spectrum and measuring the temperature at the inner edge of the disk, which can lead to a measurement of the radius of the last stable orbit. The continuum at higher energies (10 keV - 40 keV) will allow measurement of the likely Compton reflection bump and will constrain the continuum, which is necessary to accurate measurement of the Fe Kα line.

We carry a goal to extend the lower energy limit to 0.10 keV, and this extended limit will be very helpful to IMBH studies. Achieving this goal would allow the observed 0.15 keV accretion disk inner edge temperature to be more accurately and efficiently measured.

6.3.2 Sensitivity/Effective Area

X-ray spectroscopy of sources brighter than 10^{-13} ergs/cm^2 must be achieved in reasonable length (<100ks) exposures. More than 1000 (TBR) counts must be obtained at FeK (roughly from 5 to 7 keV) in these exposures. With 0.6m^2 of area at 6keV, the 2005 reference Con-X will collect 1000 counts from 5 to 7 keV for a typical ULX (α=3, Fe Kα equivalent width of 200eV, flux of 6 x 10^{-13} ergs/cm^2/s 0.3-10.0keV) in 100ks. Thus we see that the nominal area as specified above is sufficient.

However, IMBH studies would also benefit from additional effective area, particularly for the timing studies. Studies of Galactic black holes has revealed quasi-periodic oscillations (QPOs) with a 3:2 frequency ratio that scales with the black hole mass. Detection of this 3:2 QPO frequency ratio in a few of the more massive IMBH would be expected in the 1-10 Hz band and would require 1.0 m^2 at 6 keV, and 2.0 m^2 at 1.25 keV.

6.3.3 Spectral Resolution

Spectral resolution requirements and motivations here are the same as those for the studies of GR with bright AGN (section 1.1.1.3).

6.3.4 Angular Resolution

An angular resolution (HPD) of 15 arcsec is required in order to separate IMBH from nearby bright point sources and diffuse emission in nearby (z<0.1) interacting galaxies.

We note that the goal of 5 arcsec angular resolution would allow ULX/IMBH studies to be extended to higher z, and allow more accurate separation of IMBH from surrounding diffuse emission in nearby galaxies.

6.3.5 Instantaneous FOV

The required FOV of 5 arcmin on a side is sufficient for these studies. We note that the Goal of 10 arcmin FOV would increase the likelihood of observing multiple ULXs in nearby galaxies simultaneously, therefore increasing the observing efficiency and ULX sample. The number of currently identified ULX groups that cover 5 arcmin is 23, and that cover 10 arcmin is 31.

6.3.6 Other

In order to measure the 2:3 QPOs discussed above, we require a time resolution of 400 microseconds. This is easily satisfied by the requirements set by the NS studies (Section 4).

6.4 Supernova Remnants

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 high angular and spectral resolution of Constellation-X will enable determination of the composition, ionization state and velocity of the material throughout the SNR to build a complete model for the structure of the shocked ejecta and the ambient medium.

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.

Constellation-X will also provide the first sensitive measurements of the odd-z trace elements as well as the trans-iron element zinc in supernova remnants. These elements provide insight into the star that originated the explosion, as well as the origin of these elements. The most abundant species from Ne to S all contain an integral number of alpha particles in their nuclei and are believed to come from carbon and oxygen burning in stellar interiors. The less abundant species (Na, Al, P) come from H-burning beyond the CNO cycle (NeNa, MgAl cycles). The Cr, Mn, and Ni species, in particular, are very important for discriminating among Type Ia SN models. The detection of Zn in a cosmic X-ray source would be a first step towards determining the origin of these elements in a cosmic setting. Again there is no comparable facility that will accomplish these measurements.

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. Another issue for SN follow-up studies is the area of sky available for rapid slew. If Constellation-X's slew capability is limited to some fraction of the sky, then the number of targets it could potentially observe drops by that same fraction. With 20% sky coverage over the course of the 5-year mission, then Constellation-X would have a good chance of targeting one bright SN Ia over its lifetime.

6.4.1 Bandpass

The nominal energy band pass relevant to SNR studies is 0.3 keV - 40 keV.

6.4.2 Sensitivity/Effective Area

The nominal effective area will be sufficient. In order to make significant headway in the study of SNeIa projenitors, Con-X must reach flux limits of 10^{-16} ergs/cm^2/sec in ~20ks, which can be done with the nominal effective area of 1.5m^2 at 1.25keV. The non-X-ray background <10 keV needs to be kept at or below the level of the unresolved cosmic X-ray background, as for the Dark Energy studies.

6.4.3 Spectral Resolution

The nominal spectral resolutions of 1250 over 0.3 keV – 1.0 keV and 2400 at 6 keV are sufficient for this science.

6.4.4 Angular Resolution

The most important instrumental performance characteristic for this subject area considered in its entirety is the point-spread function (PSF) of the telescope. Some studies of larger SNRs (e.g., Tycho and SN1006) would yield valuable results with the nominal PSF 15 arcsec HPD, but a better PSF would result in better science. Achieving the goal PSF of 5 arcsec would allow important studies that of the ejecta knots in Cas A, SNRs in the Magellanic Clouds and beyond.

6.4.5 Instantaneous FOV

The required FOV of 5 arcmin on a side is sufficient for these studies.

6.4.6 Other

Due to the rare and transient nature of SNeIa, their study requires the ability to carry out a ToO within 2 days and the ability to observe at least 20% of the sky at any time. The high count rate and event timing accuracy as required by the NS Studies (section 4) are sufficient for these SNR studies. The counting requirement for SNRs is 3,000 cts s^{-1}, which corresponds to a 2.5' square region of a bright portion of Cas A. Event timing accuracy of 100μs for all instruments should be adequate for pulsar timing studies.

6.5 Stellar Coronae

Time series analyses of EUV and X-ray observations of active stars have provided evidence that plasma at temperatures ≥ 4 × 10^6 K arises purely from flares, analogous to the idea of "nanoflare" theories of solar coronal heating. Constellation-X will provide a sensitive test of flare heating through both Doppler shifts and photon arrival times. A Constellation-X XMS effective area of 6,000 cm^2 at 6 keV and resolving power of $E/\Delta E > 1{,}000$ brings within reach Doppler diagnostics in H-like and He-like S (λ4.73, 5.04), Ar (λ 3.95, 3.73) and Fe (λ1.85).

Another major Constellation-X breakthrough in the study of stellar flares will be the enormous improvement in photometric precision of flare light curves and spectra, allowing direct measurement of coronal loop resonant frequencies themselves. Loop "wobble" velocities on the Sun have reached up to 200 km s^{-1}. Constellation-X detections of loop oscillations, both spectroscopically and photometrically, could provide unique measurements of these quantities in a wide range of stars, from accreting T Tauri stars to evolved giants. Resolving powers of 1000 are needed to make firm detections of line-of-sight velocity components of 100 km s^{-1}.

Detection of hard X-rays in stellar flares would define a major breakthrough for stellar physics. This emission is unequivocally related to impulsively accelerated electrons and ions that do not suffer from magnetic trapping (as radio-emitting electrons do). In the case of the Sun, hard X-rays and gamma rays have been the prime source for the study of energy release physics, particle acceleration in magnetic fields, and coronal heating. The different, and probably more extreme, magnetic configurations in magnetically active stars could lead to quite different acceleration histories and heating efficiencies in large flare events. Detection of hard X-ray components would thus open an entirely new avenue in the study of the energetics of hot, magnetized coronal plasma. For the Constellation-X HXT area of 150 cm^2, bright flares on nearby stars can be detected in only 100s.

6.5.1 Bandpass

The required energy band pass of 0.3 keV - 40 keV is sufficient for these studies.

6.5.2 Sensitivity/Effective Area

The required effective area of 6000 cm^2 at 6 keV and 150 cm^2 at 40 keV will be sufficient for these studies.Measurements of the plasma parameters in stellar flares require 6000 cm^2 at 6 keV and detection of hard X-rays in nearby stellar flares requires an area of 150 cm^2 at 40 keV.

6.5.3 Spectral Resolution

The required spectral resolutions of 1250 over 0.3 keV – 1.0 keV and 2400 at 6 keV are sufficient for this science. The large number of H and He-like lines between 0.3 keV and 6 keV provides motivation for spectral resolution >1000 throughout the 0.3 keV to 6 keV bandpass.

6.5.4 Angular Resolution

The required angular resolution of 15 arcsec HPD over 0.3 keV – 7.0 keV and 30 arcsec over 7.0 keV – 40 keV is sufficient for these studies.

6.5.5 Instantaneous FOV

The required FOV of 5 arcmin on a side is sufficient for these studies.

6.5.6 Other

There are no other considerations for this science.

6.6 Solar System – Jovian Planets

X-ray studies of Jupiter's auroral zones near the north and south poles, where the X-ray emission is most intense, offer a probe of Jupiter's magnetosphere (see the review by Bhardwaj and Gladstone 2000). *Chandra* and XMM-Newton data show that this auroral emission is due to the precipitation of highly ionized oxygen and either sulfur (favored by *Chandra*) or carbon (favored by XMM-Newton) into the polar regions (Horanyi et al. 1988; Cravens et al. 1995, 2003); the ionization states and the line characteristics provide information on the electric fields, thus probing the polar magnetosphere dynamics. Oscillations in the northern auroral flux observed in December 2000 (Gladstone et al. 2002) are likely associated with the energetic particle flux in the outer disk magnetosphere and with quasiperiodic radio bursts from Jupiter (McKibben, Simpson & Zhang 1993; MacDowall et al. 1993; Karanikola et al. 2004). More detailed observations of these oscillations and the conditions under which they appear would further constrain the dynamics of Jupiter's polar magnetosphere.

Chandra observations of Saturn found variations in the averaged X-ray flux of a factor of ~4 over one week (Bhardwaj et al. 2005b) that appeared closely tied to the incident solar X-ray flux. In addition, on timescales of ~0.5 hour, an X-ray "flare" from Saturn was closely linked to the eruption of a solar X-ray flare. The same observations showed emission from the south polar cap and an emission line probably due to oxygen Kα fluorescence from the rings. These new objects are faint X-ray sources, and detailed investigation of their X-ray properties require the high-throughput and high-energy resolution provided by Constellation-X.

6.6.1 Bandpass

The primary bandpass for this work will be 0.3 keV – 10 keV, so the required energy band pass of 0.3 keV - 40 keV is sufficient for these studies.

6.6.2 Sensitivity/Effective Area

The required effective area of at least 1000 cm^2 over 0.3 keV – 10 keV, 15000 cm^2 at 1.25 keV, and 6000 cm^2 at 6 keV is sufficient for this science.

6.6.3 Spectral Resolution

The required spectral resolutions of 1250 over 0.3 keV – 1.0 keV and 2400 at 6 keV are sufficient for this science. The large number of H and He-like lines between 0.3 keV and 6 keV provides motivation for spectral resolution >1000 throughout the 0.3 keV to 10 keV bandpass.

6.6.4 Angular Resolution

The required angular resolution of 15 arcsec HPD over 0.3 keV – 7.0 keV and 30 arcsec over 7.0 keV – 40 keV is sufficient for these studies.

6.6.5 Instantaneous FOV

The required FOV of 5 arcmin on a side is sufficient for these studies.

6.5.6 Other

There are no other considerations for this science.

6.7 Solar System – Comets

Constellation-X will provide important, unique, and highly diagnostic observations of X-ray emission in comets giving unique insight into cometary origins, spatial and temporal morphology, and simultaneously provide remote observations of the spatial and temporal composition of the solar wind.

X-ray emission from comets was first discovered using the ROSAT X-ray observatory in 1996 (Lisse et al. 1996). This discovery was entirely unexpected as cometary atmospheres are known to be cold with a characteristic temperature between 10 and 1,000 K, much too cold for thermal X-ray production. Observations with *Chandra*, XMM, Swift, and Suzaku have shown that the X-ray emission is dominated by line emission that is strongly consistent with charge exchange interaction between the highly charged solar wind and neutrals in the cometary halo. The low resolution X-ray spectra obtained by the current generation of X-ray satellites is consistent with both experimental measurements of charge exchange in the laboratory (Beiersdorfer et al. 2003) and with numerical models (Cravens 2002; Lisse et al. 2001; Krasnopolsky & Mumma 2001).

Unfortunately, current X-ray observatories are limited to a resolving power of ≤15 for diffuse sources in the 0.1-1 keV band where the strongest cometary X-ray emission occurs. With this resolving power, and the limited collecting areas of current satellites, the diagnostic utility of these observations are limited. Currently, we can determine the species and charge state of the most abundant elements in the solar wind and roughly determine the morphology of the X-ray producing region behind the cometary bow shock. However, Beirsdorfer et al. (2003) have shown that the ratio of the higher Rydberg transitions in charge exchange emission are uniquely sensitive to the composition of the neutral material in the cometary coma. This is critically important since this implies that with sufficient collecting area and spectral resolution we can remotely determine the composition, density and ionization state of the cometary coma.

The high spectral resolution and large collecting area of Constellation-X make it possible to uniquely determine the species, charge state, and velocity of the solar wind as well as the spatial and temporal composition, charge state, and density of the cometary coma. Even for fairly dim comets (for example, using the observed flux and surface brightness of 73P/Schwassmann-Wachmann 3C, at perihelion on June 8, 2006 where it was 0.2 AU from the Earth) we could detect the entire Rydberg series of He-like and H-like C, N, and O transitions in the spectrum. Constellation-X will enable routine spatial and temporal observations of the solar wind using short comet observations as well as unparalleled remote diagnostics of the cometary coma.

6.7.1 Bandpass

The primary bandpass for this work will be 0.3 keV – 10 keV, so the required energy band pass of 0.3 keV - 40 keV is sufficient for these studies.

6.7.2 Sensitivity/Effective Area

The required effective area of at least 1000 cm^2 over 0.3 keV – 10 keV, 15000 cm^2 at 1.25 keV, and 6000 cm^2 at 6 keV is sufficient for this science.

6.7.3 Spectral Resolution

The required spectral resolutions of 1250 over 0.3 keV – 1.0 keV and 2400 at 6 keV are sufficient for this science. The large number of charge exchange lines between 0.3 keV and 1.0 keV provide motivation for spectral resolutions of at least 1250 over this band.

6.7.4 Angular Resolution

The required angular resolution of 15 arcsec HPD over 0.3 keV – 7.0 keV and 30 arcsec over 7.0 keV – 40 keV is sufficient for these studies.

6.7.5 Instantaneous FOV

The required FOV of 5 arcmin on a side is sufficient for these studies. Nearby comets will fill this FOV, providing motivation for the goal FOV of 10 arcmin.

6.7.6 Other

There are no other considerations for this science.

6.8 Formation Of Stars And Planets, Young Stars

Recent research points to protostellar and pre-main sequence X-ray and energetic particle activity as crucial aspects of star and planet formation. These produce the ionization necessary for accretion to proceed in stellar systems throughout protostar evolution, and mediate both terrestrial and Jovian planet formation. X-rays from large flares reprocessed into cold iron K lines by circumstellar disks have been detected in several protostars. The time-dependence of the Fe K flux can be used for “reverberation mapping” of the structure of gas and dust in inner protoplanetary disks revealing gaps at the locations of inner planets in the process of formation.

The Sun can be imaged in X-rays in fine detail, yet we currently know very little about how other stars can generate huge flares and sustain coronae up to 10,000 times brighter than that of the Sun, and how these coronae are structured. While some spatial inference is possible from line shifts and broadening seen in *Chandra* spectra of nearby active stars full Doppler imaging requires both very high throughput and spectral resolution. A minimum resolving power that would allow study of the most rapidly rotating nearby systems is $\lambda / \Delta\lambda = 2000$ (FWHM). Stars such as AB Dor will provide up to 10^6 counts in a day long observation, allowing for quite detailed coronal images. A few hundred counts in the He-like λ 1.85 resonance line of Fe XXV, and substantially more in H-like and He-like lines of S (λ 4.73, 5.04), Si (λ 6.18, 6.65) and Mg (λ 8.42, 9.17) can be acquired in only a few ks, enable imaging of the very high temperature (10^7 K) plasma separately to that at lower temperatures (several 10^6 K). Doppler imaging of classical T-Tauri stars will allow the location of the X-ray emitting region to be determined, which initial indications suggest are in loops up to 10 stellar radii in size and may have footprints connecting the stellar surface to the accretion disk.

6.8.1 Bandpass

The primary bandpass for this work will be 0.3 keV – 10 keV, so the required energy band pass of 0.3 keV - 40 keV is sufficient for these studies.

6.8.2 Sensitivity/Effective Area

The required effective area of at least 1000 cm^2 over 0.3 keV – 10 keV, 15000 cm^2 at 1.25 keV, and 6000 cm^2 at 6 keV is sufficient for this science.

6.8.3 Spectral Resolution

The required spectral resolutions of 1250 over 0.3 keV – 1.0 keV and 2400 at 6 keV are sufficient for this science. Doppler imaging of nearby stars would be enhanced by resolving powers reaching 2000 FWHM over the 0.3 keV - 1.0 keV bandpass.

6.8.4 Angular Resolution

The required angular resolution of 15 arcsec HPD over 0.3 keV – 7.0 keV and 30 arcsec over 7.0 keV – 40 keV is sufficient for these studies.

6.8.5 Instantaneous FOV

The required FOV of 5 arcmin on a side is sufficient for these studies.

6.8.6 Other

There are no other considerations for this science.

APPENDIX

SRD SUMMARY TABLE, LONG FORM:

- The left side of the table describes the planned science objectives, investigations, and observations in sufficient detail to allow the performance requirements on the right hand side of the table to be derived.
- Performance parameters in red boldface set the baseline observatory performance requirements. Performance parameters in green italics are more challenging than the baseline observatory requirements and are goals.
- A description of each of the columns in the summary table follows.

OBSERVATION DESCRIPTION:

- Science Objective: Top level science topics or categories for the mission.
- Science Investigation: Somewhat more specific ways in which the top level science objectives can be investigated.
- Target Category: Types of objects which will be observed in order to carry out specific science investigations.
- Type of Observation: Primary way in which the science investigation will be carried out, for example, by measuring spectra, detecting and counting sources, measuring time variability, detecting the structure of the sources (=imaging), etc…
- Number of Targets: Approximate number of targets which will need to be observed in order to carry out the science investigation.
- Number of Observations per Target: For variable targets, multiple observations of a single target may be required in order to carry out the science investigation. For extended targets, multiple pointings (rasters) may be required to image the entire target.
- Source Extent: Either point like or extended, if extended, an approximate angular size.
- Flux (min, max) 0.25-10.0 keV: Minimum and maximum fluxes for targets to be observed under this science investigation. Unless otherwise stated, fluxes are for point sources in ergs/cm^2/s integrated over the 0.25-10.0 keV bandpass
- S/N (Signal to Noise): Signal to noise required in order to carry out this science investigation. If stated as an absolute number of counts in a specific observation time, then the background for the observation is required to be small compared to this number.
- Typical Exposure Time per Observation: Typical on-target dwell time for each observation

DERIVED PERFORMANCE PARAMETERS:

- Bandpass: Energy range over which data will be needed in order to carry out the science investigation.
- Area (m^2) / Sensitivity: Effective area of the telescope/detector system needed in order to carry out the science investigation, in m^2 Specified at particular energy points within the bandpass. Alternatively a flux sensitivity may be specified.
- Spectral Resolution FWHM: Energy resolution of the primary detector, in dE/E, full width at half maximum (FWHM). Specified at particular energy points within the bandpass.
- Angular Resolution HPD: Spatial angular resolution of the primary detector, expressed as a half power diameter.
- Instantaneous FOV: Field of view of the primary detector. An area of the sky of at least this size will be maintained within the active area of the detector during the entire science observation.
- Other: Comments, or additional performance requirements set by the science investigation which are not covered in the previous columns.