The High Throughput X-ray Spectroscopy (HTXS) Mission

An interim report to NASA prepared by

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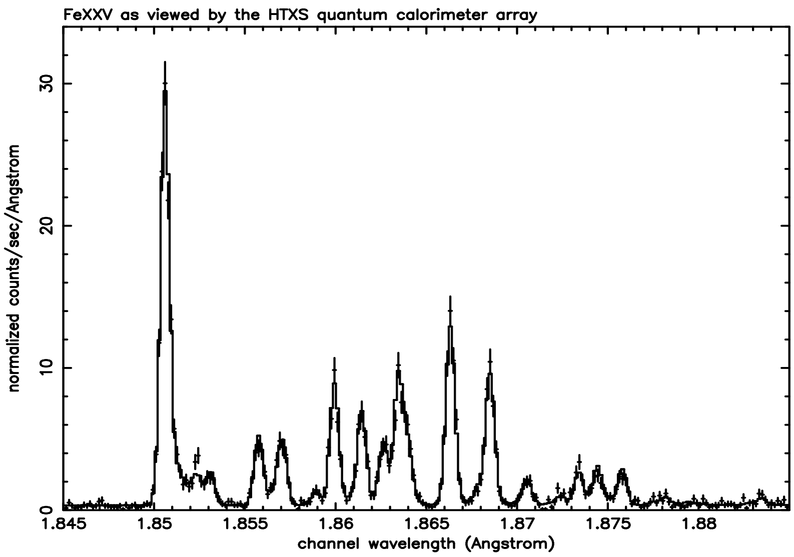

May 30, 1996

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1 Preface

In September 1994, NASA issued NRA 94-OSS-15 soliciting proposals for concept studies of new astrophysics flight missions. The peer review of submitted proposals selected a number of concepts for study, including "The Next Generation X-ray Observatory" (Principal Investigator, Nicholas White of Goddard Space Flight Center) and the "Large Area X-ray Spectroscopy Mission" (Principal Investigator, Harvey Tananbaum of Smithsonian Astrophysical Observatory). Given the similarities of the science objectives emphasizing high throughput, high resolution X-ray spectroscopy, the two teams initiated discussions leading to an agreement in late 1995 to pursue a single study of a common mission, named the High Throughput X-ray Spectroscopy (HTXS) mission.

The HTXS mission represents a major advance, providing as much as a factor of 100 increase in sensitivity over currently planned high resolution X-ray spectroscopy missions. HTXS will mark the start of a new era when high quality X-ray spectra will be obtained for all classes of X-ray sources, over a wide range of luminosity and distance. With its increased capabilities, HTXS will address many fundamental astrophysics questions such as the origin and distribution of the elements from carbon to zinc, the formation and evolution of clusters of galaxies, the validity of general relativity in the strong gravity limit, the evolution of supermassive black holes in active galactic nuclei, the details of supernova explosions and their aftermath, and the mechanisms involved in the heating of stellar coronae and driving of stellar winds.

The study group formed from the original two mission concept teams has been extended (with the concurrence of NASA Headquarters) to include other experimental groups active in X-ray astronomy as well as several observational astronomers and theorists. Most recently, the Principal Investigator (Paul Gorenstein of Smithsonian Astrophysical Observatory) of a third selected mission concept proposal entitled "Hard X-ray Telescope with Simultaneous Multiwavelength Observing from UV to 1 MeV" joined the HTXS team, merging those areas of his study most similar to HTXS in science objectives and technical approach. Following these steps, the expanded team is now a widely-based Science Working Group (SWG) reporting to NASA Headquarters. At present, the SWG includes scientists from 14 different institutions; individuals and institutions involved in the study are listed in Appendix A.

To date (May 1996), the SWG has conducted three working meetings to refine the overall science objectives and to integrate the instrumentation approaches into a single mission concept. This unified concept combines large effective area ($\sim$ 15,000 cm^2 at 1 keV), high spectral resolution (E/ΔE $\sim$ 300–3000), and broad energy bandpass (0.25–40 keV and possibly up to 100 keV) by using replicated optics with reflection gratings, charge-coupled device detectors (CCDs), quantum micro-calorimeters, and cadmium zinc telluride (CZT) detectors. An essential feature of this concept involves minimization of cost ($\sim$ \$350M for development and $\sim$ \$500–600M including launches) and risk by building six identical modest satellites to achieve the large area. The technology required for the HTXS mission is relatively mature and able to support a new start in the 2000–2001 timeframe, with first launch around 2004–2005.

In order to involve the overall scientific community in the planning for this facility and to develop the broadest possible perspective for the mission, we have made presentations to NASA's High Energy Astrophysics Management Operations Working Group, the American

Astronomical Society (poster papers), and the High Energy Astrophysics Division of the AAS (invited talks) and have prepared this status report. An open workshop for the entire community is scheduled for this September. Through these discussions, along with the HTXS web page

http://lheawww.gsfc.nasa.gov/docs/xray/htxs/home.html

the intent is to establish and maintain an open dialogue with the astrophysics community at large to ensure that the HTXS mission focuses on the critical science problems.

2 Historical Perspective

In its early years, dating back to the 1960s, X-ray astronomy was primarily viewed as the science of "extreme conditions" in the cosmos. The first sources detected (the brightest in the sky) mostly involved compact degenerate objects, where the copious X-ray emission results from the presence of high temperature plasmas, high radiation energy density, highly relativistic particles, and high gravitational and magnetic fields. X-ray observations of these and similar sources with improved sensitivity and spectral and temporal resolution continue to provide the most direct means of investigating the basic physical processes operating in such exotic environments. Of particular interest is the recent use of X-ray spectroscopy to probe conditions in the inner regions of accretion disks around black holes in active galactic nuclei, where the predictions of general relativity in the strong field limit can be meaningfully tested.

As the field has matured, however, it has become clear that X-ray emission is a ubiquitous characteristic of virtually all known astronomical systems. In retrospect, this is not surprising, since the virial temperature falls within the X-ray emitting band for a large range of diverse objects (stars, galaxies, clusters of galaxies). In essentially all cases where gravitational forces are important to the dynamics and energetics of the system, the presence of X-ray emitting gas is a natural consequence. As such, X-ray observations can also play a crucial role in addressing many of the more "central" questions in astronomy, i.e. those related to the origin, structure, and evolution of the Universe, and of its principal material constituents: galaxies, stars, planets, and dark matter.

X-ray spectroscopy is especially useful for investigating issues related to the origin and distribution of the elements. The soft and medium energy X-ray bands contain the K-shell lines for all of the abundant metals (carbon through zinc), and the L-shell lines of most. These are bright allowed transitions with large equivalent widths. In general, all charge states are accessible. Hence the ability to measure abundances is not strongly dependent on the physical state of the emitting gas. This contrasts with the infrared, optical, and ultraviolet bands, where only certain molecular and/or ionic species can be measured for each element. The detailed X-ray line spectra are rich in plasma diagnostics which also provide unambiguous constraints on physical conditions in the source.

Below, we summarize a few key astronomical areas where X-ray spectroscopic observations should provide fundamental insight into the most pressing unresolved problems:

- **Clusters of Galaxies**: The hot intracluster medium dominates the baryonic mass content of clusters of galaxies, and is observable only in the X-ray band. Estimates of abundances derived from measurements of both the bremsstrahlung continuum and collisionally excited resonance emission lines trace the origins of stellar nucleosynthesis as we look back in redshift. Mapping the velocity distribution of this hot cluster gas via the Doppler shifts in the emission lines allows us to examine the dynamics within the cluster and specifically to study the effects of mergers between member galaxies and between separate clusters. More detailed constraints on the nature of the merger process are crucial to our understanding of the redistribution of the stellar processed material into the intracluster medium. X-ray spectroscopic observations also provide a direct means of mapping the dark matter content of clusters of galaxies and of understanding its relation to the baryonic tracers.

- **Active Galactic Nuclei**: AGNs are the most distant sources observable in most wavebands and may provide important clues to the formation and early evolution of galaxies. These sources radiate much of their power at high energies, and X-ray observations provide the only direct probe of conditions close to the central engine. The bright X-ray continuum lights up the nearby circumsource medium and generates a forest of discrete X-ray emission and absorption features which provide sensitive constraints on the geometry, dynamics, and elemental abundances of the surrounding environment. Line profile measurements for the fluorescent lines allow us to probe the gravitational field very close to the central engine, and confirm the existence and constrain physical characteristics of the massive black hole that is likely to reside there.

- **Supernova Remnants**: Certainly one of the most important processes contributing to the chemical evolution of the Universe involves the release of stellar processed material into the interstellar medium via supernova explosions. Despite a wealth of theoretical and observational investigations, there are still many aspects of this process that remain mysterious, partly because optical spectroscopy yields very few direct diagnostics of heavy element enrichment. The shock heated plasmas in supernova remnants emit primarily line rich X-ray spectra that directly determine supernova abundances and the blast wave interaction with the surrounding gas. Observations of intermediate age remnants constrain the structure of the interstellar medium and the possible importance of pre-supernova winds. Measurements of the higher energy continuum spectra of young remnants provide crucial information on the possible origin of cosmic ray acceleration.

- **Compact Binaries**: The latter stages of stellar evolution produce compact objects (white dwarfs, neutron stars, and black holes) which can profoundly affect their environments. When these degenerate stars are members of tight binaries, they can accrete sufficiently from their companions to become bright sources of X-ray continuum and line radiation. Radial velocity measurements using the X-ray emission lines determine the mass function of the binary, and can be used to study the mass distribution of the compact objects. In the case of neutron stars, the latter has implications for our understanding of the equation of state at nuclear density, a fundamental issue in nuclear physics, which is difficult to address in the laboratory. The emission line equivalent widths provide information on the geometry and abundances of the accreting flow, which then constrain the nuclear evolution of the companion star.

- **Stellar Coronae:** The outermost layers of the atmospheres of normal stars form hot coronae, confined by magnetic fields. X-ray spectroscopic observations determine the temperatures, densities, and geometries of these plasmas, which then can be correlated with age, rotation, and other stellar parameters to better determine the mechanisms responsible for coronal heating. The detailed line spectra also provide abundance determinations, which, in some cases indicate differences from the abundances derived from optical spectra of the photosphere. Such abundance anomalies are not well understood, but they may be related to the processes by which photospheric material is "lifted" into the corona. X-ray spectroscopy of early type stars directly determines the abundances and ionization of massive stellar winds, which are important in the chemical enrichment of the interstellar medium.

- **Young Stars:** Star formation often occurs deep within molecular clouds, where it is only observable in the infrared and at high energies. The most rapidly rotating young stars are also the most coronally active, and X-ray observations are useful for locating and studying these star forming regions. Spectroscopic observations enable us to derive detailed physical constraints on the interaction of these young stars with their nascent surroundings.

The arguments above demonstrate that advances in X-ray spectroscopy of cosmic sources will be crucial to continued progress on a wide spectrum of outstanding fundamental questions in astronomy. A vigorous effort to enhance our observational capabilities in this area should thus be a key component of NASA's future program in space astrophysics. In the remainder of this report, we demonstrate that the timing is right to begin planning a new mission devoted to high throughput X-ray spectroscopy. We describe a "strawman" concept for such a mission that has emerged from our deliberations, discuss its performance characteristics, and present a few examples of the exciting scientific investigations that it would enable.

3 X-ray Spectroscopy Comes of Age

In spite of its potential as a vital astronomical tool, X-ray spectroscopy has only recently begun to make significant contributions. To a large extent, this can be ascribed to instrumental limitations. Given the rather low photon fluxes from cosmic X-ray sources, experiments have had to be large and have high quantum efficiency in order to acquire spectra of acceptable statistical quality. In the early years, prior to the development of focussing X-ray optics, this argued for the use of proportional counters, which were efficient, relatively easy to operate, and could be scaled effectively to large collecting area. However, the spectral resolution of a proportional counter is compromised by the statistics of the electron avalanche process used to amplify the signal associated with the photon detection. The fundamental limit to the resolving power is $\mathrm{E}/\Delta\mathrm{E} \sim 2.5\ \mathrm{E}^{1/2}$, sufficient for deriving constraints on the shape of the overall continuum, but far too low to reveal significant spectral detail. With the exception of the Fe K transitions between 6 and 7 keV, which are spectrally isolated and therefore easy to resolve, proportional counters could not provide unambiguous detections of discrete X-ray features from even the most line-rich cosmic sources.

The launch of the *Einstein* Observatory in 1978 provided the first true X-ray telescope on a satellite observatory. This led to a dramatic improvement in source detection efficiency, but also enabled the first deployment of higher resolution spectroscopic instrumentation. Specifically, the *Einstein* Observatory carried solid-state (SSS), Bragg crystal (FPCS), and objective transmission grating (OGS) spectrometers. The SSS had comparable quantum efficiency to the earlier proportional counters coupled with a modest improvement in resolving power (a factor of a few) which enabled the detection of strong emission line complexes, especially for optically thin collisional plasmas. The FPCS and OGS had considerably higher spectral resolution, but such limited efficiency that observations could only be performed on a small number of very bright sources.

This field experienced a "quantum jump" in experimental capability, however, with the launch of the Japanese Advanced Satellite for Cosmology and Astrophysics (ASCA) Observatory in 1993. ASCA carried charge-coupled device (CCD) imaging spectrometers mounted at the focus of high throughput grazing incidence telescopes. Although the improvements over earlier instrumentation for various characteristics were only modest (factor four in spectral resolution, factor three in bandpass, factor four in collecting area), these combined together to yield breakthrough results in many areas of astronomy. ASCA has increased the sample of cosmic sources with moderate-to-high quality X-ray spectra by a factor of at least fifty! The new opportunity to acquire spatially and temporally resolved broad-band moderate resolution spectra has had major impact on a wide range of astronomical fields. Highlights include:

- Maps of supernova remnants in prominent X-ray emission lines that show significant variations in both ionization and chemical composition as a function of position, as well as coherent velocity features that directly measure the expansion of the ejecta. The broadband spectro-imaging capabilities of ASCA have made a major impact on all areas of research in this field including the nature of the ejecta of young remnants, the physics of supernova-induced shock waves, and the discovery and study of pulsar-powered synchrotron nebulae.

- Imaging spectrophotometry of clusters of galaxies which has demonstrated that most of the intracluster gas in rich clusters has been processed by Type II supernovae at early epochs. In addition, highly robust determinations of the mass of these systems have been made which require the presence of dark matter on all spatial scales.
- The first direct detection of relativistic line broadening for an X-ray emission line in an active galactic nucleus. The data indicate that the observed iron K line radiation emanates from within tens of Schwarzschild radii of the massive central object.
- Evidence that the center of the Milky Way is filled with ionized hot gas. The mechanism responsible for the ionization remains unknown. Maps of the galactic center also reveal strong localized iron K fluorescent radiation which suggests the presence of a low luminosity active nucleus as recently as a few hundred years ago.
- Measurements of abundances in the coronae of active stars which suggest metal deficiencies when compared to photospheric abundances. The origin of this effect is still controversial.

A second "revolution" in astronomical X-ray spectroscopy will undoubtedly occur near the end of this decade when the three major X-ray observatories currently under development will be launched: NASA's Advanced X-ray Astrophysics Facility (AXAF; 1998), the European Space Agency's X-ray Multi-Mirror Mission (XMM; 1999), and the Japan-US Astro-E mission (2000). AXAF will carry a CCD experiment with comparable resolution and effective area to that of ASCA, but with over one hundred times better spatial resolution. In addition, AXAF will carry two transmission grating spectrometers with resolving powers approaching 1000 in selected bands. XMM will carry a very large area CCD imaging spectrometer as well as a reflection grating spectrometer experiment that will provide high resolving power ($E/\Delta E \sim 100$–600) coupled with high sensitivity, especially at soft X-ray energies. Finally, Astro-E will also carry a large area CCD experiment as well as the first cryogenic X-ray micro-calorimeter spectrometer, which provides even higher effective area coupled with good spectral resolution at higher energies ($E/\Delta E \sim 50$–800). There is a clear complementarity between these various experiments. The Astro-E micro-calorimeter will provide the best combination of sensitivity and resolution at energies of a few keV and above, where the K-shell transitions from the intermediate-Z elements are prominent. The XMM reflection grating spectrometer is optimal in the intermediate band between 300 eV and 2 keV where the prominent oxygen K-shell and iron L-shell features are located. The transmission gratings on AXAF will provide very high resolution and reasonable sensitivity at the softest energies, below 200 eV, as well as high resolution with moderate sensitivity across the entire band. Collectively, these missions will provide a wealth of detailed spectral information on a diverse array of cosmic sources. At that point, astronomers can begin to employ the sophisticated diagnostic techniques which are conventionally in use in solar X-ray spectroscopy or in X-ray spectroscopy of laboratory plasmas.

Nevertheless, as we look toward the future, it is clear that these upcoming missions can only "scratch the surface" of the full exploitation of X-ray spectroscopy to address outstanding astrophysical questions. Despite the impressive observational capabilities they provide, many of the most pressing spectroscopic measurements will remain out of reach. In general, substantial improvements are required in effective area, spectral resolution, and spectral bandpass. Some scientific drivers for performance specifications in these three categories are detailed below.

Effective Area:

Spectra of high statistical quality for large populations of sources, as opposed to just the brightest members of a class of objects, will require significant increases in effective area. To sample representative members of many diverse classes will require getting down to flux levels as low as 10^{-14} ergs cm^{-2} s^{-1} keV^{-1} at energies near 1 keV. For typical observing times less than 10^5 s, this requires an effective area of order 15,000 cm^2 in this band, a factor of 20–100 higher than provided by the spectrometers on AXAF, XMM, and Astro-E.

For many astronomical sources (black hole candidates and AGNs, CVs, ordinary stars, young stars, etc.), short-term variations in the X-ray spectra provide a crucial key to the understanding of the underlying physics. Large effective area is also required to obtain adequate statistics during the physically significant timescales. For stellar flares, these are of order tens of seconds; for active galactic nuclei, several hours. In both cases, effective area in excess of 10,000 cm^2 is required for typical source fluxes.

While the upcoming missions will measure the abundances of the more common elements for a significant sample of bright sources, it will be extremely difficult to obtain even meaningful upper limits for the lower abundance species. However, the latter are equally important for constraining models of stellar nucleosynthesis and the chemical evolution of galaxies. Very high statistical quality spectra are required for these kinds of investigations, which is only possible with large effective area.

Resolution:

High spectral resolution is required first and foremost to enable unique line identifications. In general, a spectral resolving power of at least 300 is required. While that is achieved by each of the upcoming missions, *in some part of the spectrum*, in no case will the resolution be high enough over the entire relevant bandpass. Even higher spectral resolution is required at particular energies to unambiguously derive physical parameters in the emitting plasmas (e.g. temperature, density) from discrete line diagnostics. In the region near the iron K complex, for example, a resolving power exceeding 2000 is necessary to distinguish the lithium-like satellite lines (pumped by dielectronic recombination) from the overlapping helium-like transitions. AXAF and XMM provide no high resolution spectroscopic capability in this band, and the resolving power achieved by Astro-E will be too low by at least a factor three.

Measurement of accurate radial velocities from X-ray emission lines is central for many astrophysical investigations. At low energies, we want to obtain flow velocities in stellar flares; map the coronae of RS CVn and other binary systems; and measure the kinematics of clumps of ejecta in supernova remnants: these all require velocity sensitivity (the ability to centroid a line) better than 100 km/s below 1 keV. At the higher energy of the iron K line, we want to make radial velocity measurements that can determine the mass distribution of black holes, neutron stars, and white dwarfs over a large sample of binary systems. This requires a velocity sensitivity of order 20 km/s.

Bandpass:

Cosmic X-ray sources often exhibit characteristic spectral features over a broad range of energy, and simultaneous coverage of a large bandpass is essential for extracting the key astrophysical information from the observation. Examples include: (1) active galactic nuclei, where Compton reflection off surrounding cold material produces a "tail" to the continuum spectrum at energies > 10 keV, while fluorescence and recombination radiation from the same medium produces a range of discrete emission and absorption features down to low energies; (2) stellar flares, where a hard, nonthermal, impulsive continuum can accompany the line-rich thermal emission produced by heating of coronal plasmas; and (3) supernova remnants, where synchrotron radiation generated by cosmic ray electrons accelerated at the shock front can produce a hard extension to the thermal spectrum from shocked gas. Unambiguous measurement of such effects requires a bandpass which extends from ~ 0.25 keV to at least tens of keV. If the continuum is not adequately constrained at higher energies, it is also difficult to derive unambiguous constraints on discrete iron K emission and absorption features between 6 and 7 keV. None of the upcoming observatories have significant sensitivity at energies beyond 10 keV.

Given the above requirements, it is clear that the era of AXAF, XMM, and ASTRO E will be the "beginning" rather than the "end" of the age of astrophysical X-ray spectroscopy. In some respects, this parallels an earlier phase of X-ray astronomy, when the emphasis was on simple source detection, rather than detailed investigation. While the initial non-focussing satellite observatories were able to detect bright examples of X-ray sources from many different classes of objects, it took the huge increase in sensitivity afforded by the *Einstein* Observatory to really open up this field and bring it into the mainstream of astronomical research. Similarly, while the upcoming missions will provide us with bright examples of high resolution X-ray spectra from most source classes, we require a new mission with the advanced capabilities identified above to fully exploit the power of a broad program of X-ray spectroscopic measurements.

4 Technology Developments

As discussed in the preceding two sections, the fundamental science questions to be addressed by HTXS require very substantial increases in effective area, energy resolution, and energy bandpass. To accomplish these ambitious increases at an affordable mission cost, we must introduce new approaches for the development and operation of the HTXS mission and take advantage of technical advances as well.

A first idea for increasing telescope collecting area above that planned for AXAF, XMM, and Astro-E would be to construct an X-ray telescope with very large aperture and very long focal length. The technical challenges and potential cost associated with such an approach involve a very large mirror and spacecraft appear prohibitive at this time, particularly given the faster than linear scaling of cost with mass and size. An alternative means of achieving the required large collecting area is a design utilizing several mirror modules each with its own spectrometer/detector system. This process can be taken one step further by recognizing that several small spacecraft and modest launch vehicles (e.g. Delta 2's) each carrying one "science unit" can cost substantially less than one very large spacecraft and launcher (e.g. Titan 4) carrying the entire HTXS mission. Therefore, our concept is to build six identical, modest satellites in "assembly-line" style. This approach resonates extraordinarily well with NASA's strategy for the future; the program is very robust in that risks are distributed over several launches and several spacecraft with no single failure leading to loss of mission. By requiring the development time to be relatively short we can further reduce costs, and by launching every 3 to 4 months we can build to full collecting area within 15–20 months, thus enabling us to accomplish the full range of science objectives described in this report. Our conservative estimate for the overall development cost for the six satellites is \$350M. Including the launches, we estimate the cost at \$500-600M, with the range related to the expectation of significantly lower launch costs for moderate-sized satellites within the next few years. We also estimate total mission operations and science data analysis costs of \$100M, covering a 10-year period.

A key technology which supports our mission concept is the extendable optical bench which allows the payload to be folded within a shroud on the scale of a 3-stage Delta 2 for launch to High Earth or Libration Point Orbit, followed by deployment to a focal length of order 8–15m. At least two private companies and one NASA Center have demonstration projects underway to provide such a capability, with several smaller-scale prototypes already working.

The choice of a relatively distant orbit allows simple operational scenarios with all satellites available to point at the selected target with high viewing efficiency (no trapped radiation belts or earth occultations). With such an orbit and a relatively benign environment, the spacecraft can be simpler, lighter, and less costly.

A host of innovative ideas for mirrors, spectrometers, and detectors are already under investigation utilizing SR&T and/or ATD support. Prototype low cost, light-weight replicated mirrors capable of providing the required HTXS large collecting area and modest angular resolution (15-30$''$, compared to AXAF's 0.5$''$) are being developed. Replicated shells using silicon carbide, cyanate ester, and thin-walled rib-reinforced nickel carriers are in-process, with the intent of producing individual assemblies having an X-ray collecting area of $\sim$ 5000 cm^2 at a weight of order 250 kg. Replicated foils already can provide comparable areas with a weight of 200 kg, and modified manufacturing and assembly approaches are under evaluation for improving the angular resolution of these optics to the desired level. With six satellites the projected collecting area at 1 keV is $\sim$ 30,000 cm^2, providing the substantial increase required by the science.

To cover the bandpass up to 40 keV (and possibly up to 100 keV) with appropriate sensitivity requires focussing optics to place a large fraction of the flux collected by a large area telescope onto a relatively small spot in the focal plane. The reduction in particle and sky background in a focussing system represents a significant advance in sensitivity, as well as a major reduction in the weight and cost of the instrumentation. The recent technology development of enhancing the high energy reflectivity using a multilayer coating on a thin mirror optic offers an opportunity to build the first true imaging telescope in the hard X-ray band between 10 and 100 keV. The basic principle uses thin film interference to enhance reflectivity, similar to Bragg reflection. Two materials of different refractive indices are alternately deposited in a quarter wave stack. The number of layers can be up to several hundred and is optimized, along with the deposition thickness, to maximize the reflectivity at the desired wavelength. In the hard X-ray domain, where it is possible to use absorption-free materials, a multilayer coating can be designed with a very broad bandwidth, by using graded layers of different thickness.

In the detector area, SR&T funding is supporting high efficiency quantum micro-calorimeter work at several institutions. The 10 eV energy resolution baselined for flight on Astro-E has already been advanced to a laboratory performance of $\sim$ 7 eV. A thorough understanding of the current limiting factors along with plans for implementing improvements, such as lower heat capacity X-ray absorbers and transition edge thermometers, indicate that a resolution of 2 eV ($E/\Delta E \sim 3000$ at 6 keV), is a reasonable goal which should be attainable over the next 2–3 years. In the same timeframe, these and other improvements in thermometer design and detector fabrication may allow larger arrays, thereby increasing the ability to cover extended fields with good angular and spectral resolution simultaneously. Anticipated advances in cryo-cooler and open cycle dilution refrigerator technologies will enable longer calorimeter lifetimes at lower cost and weight. Ultra-thin foils or mylar substrates could allow us to reduce the weight of the reflection grating arrays by more than a factor of two. Large format, deep-depleted CCDs with rectangular pixels and excellent low energy response for grating readout are already becoming available, and again provide increased capability at reduced power, weight, and cost for HTXS.

The hard X-ray detector must have good efficiency throughout the 10–40 (and possibly up to 100) keV energy range along with fine position resolution, suggesting the use of fine pitch semiconductor strip detectors and/or pixellated detectors. Recent and ongoing developments provide a number of semiconductor materials to choose from, such as the relatively new cadmium zinc telluride (CZT) as well as the more familiar silicon and germanium detectors.

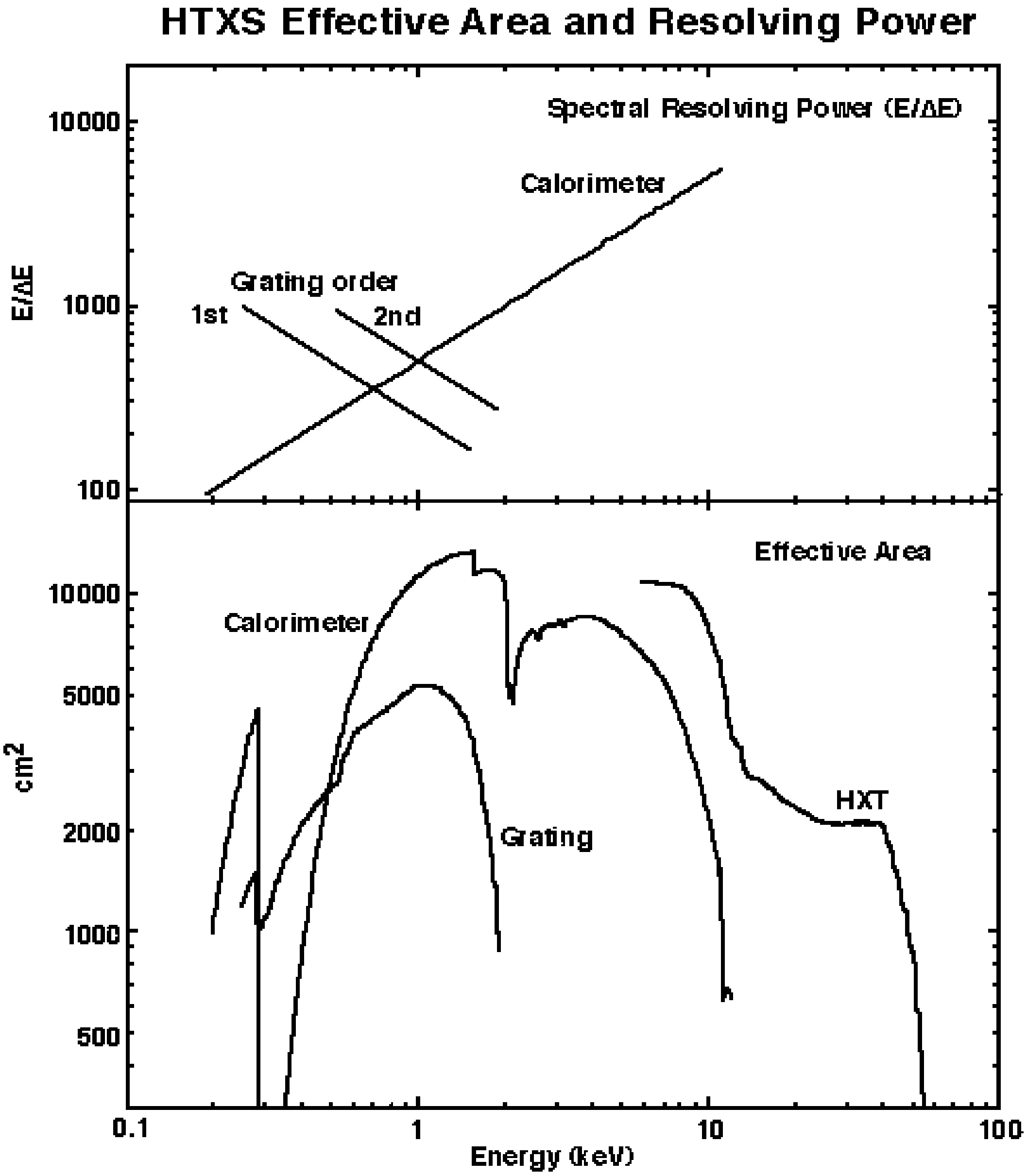

Figure 1: The effective area and resolution of the three HTXS instruments (which are coaligned and operate simultaneously). This is the full area for a six satellite system with the grating, calorimeter and hard X-ray telescope (HXT) shown separately. The gratings are used to both maintain a resolving power > 300 at low energies, and to maintain effective area from 0.3–0.6 keV where carbon in the calorimeter filter causes a drop in sensitivity.

5 HTXS Science Payload

The configuration we present in this report can be thought of as intermediate between a strawman concept and a baseline design for a mission. The specific configuration can be accomplished with a modest extension of present technical capability over the next few years, and it provides a concrete basis for calculating capabilities and projecting science performance. On the conservative side, an extraordinarily powerful HTXS mission could be developed for flight today with technology already in-hand. On the expansive side, breakthroughs beyond those envisioned at present could lead to an even more capable mission than we describe here.

The HTXS science objectives require a factor of 20–100 increase in sensitivity across the 0.25–40 keV band. Our study shows that the required effective area using a grazing incidence X-ray system is at least 15,000 cm^2 at 1 keV, 6,000 cm^2 at 6.4 keV, and 1500 cm^2 at 40 keV. Since it is not practical to cover the entire 0.25-40 keV band with a single telescope/instrument combination, we baseline a matched set of high throughput focussing telescope systems to simultaneously cover the low and high energy bands. The low energy system is a spectroscopy X-ray telescope (SXT) that is optimized to maintain a spectral resolving power of at least 300 across the 0.25-12 keV band pass. Two telescope designs with a diameter of 1.3–1.4 m are under study to achieve both large collecting area and an acceptable angular resolution (15–30$''$ half power diameter, HPD). One design is based on the conical thin foil imaging X-ray mirror, flown successfully on BBXRT and ASCA. The other is a lightweight and more densely packed replicated optics design, derived from that being used for SAX and XMM. A multi-layer, grazing incidence hard X-ray telescope (HXT) system provides the required effective area between 10 and 40 keV (and possibly up to 100 keV). Four telescopes each of 40 cm diameter per satellite are used to build up the hard X-ray effective area. The HXT has a spatial resolution of 1-2$'$ HPD, with a field of view of order 10$'$. The SXT and HXT both have a common focal length of $\sim$ 8m, using an extendable optical bench to allow a Delta class launch. If we are able to extend to a 15 m focal length design, as seems possible from preliminary design studies, then only a single 70 cm diameter HXT system per satellite is required to achieve the required collecting area. The overall effective area of the entire system and the resolving power of the SXT spectrometers as a function of energy are shown in Figure 1.

The SXT uses two complimentary spectrometer systems to achieve the desired energy resolution: an array of high efficiency quantum micro-calorimeters with a resolution of 2eV, and a reflection grating with resolution of $\Delta\lambda$ of 0.05Å in first order and 0.025Å in second order along with a CCD readout. The gratings deflect part of the telescope beam away from the calorimeter array in a design that is similar to XMM, except that the HTXS direct beam falls on a high spectral resolution quantum calorimeter instead of on a CCD. In our concept, gratings are placed behind only the outermost half (or so) of the mirror shells, in order to optimize the fraction of the beam seen by each type of spectrometer. The two spectrometers are complimentary, with the grating optimal for high resolution spectroscopy at low energies and the calorimeter at high energies (Figure 1). This is because the quantum calorimeter has a constant energy resolution of 2 eV, which means that the resolving power increases with energy. In contrast the grating maintains a constant resolution in wavelength, which results in a resolving power that increases with decreasing energy. The gratings also provide coverage in the 0.3–0.5 keV (25–40Å) band, which is essential because the calorimeter light-blocking filters cause a loss of response around the carbon K-edge (Figure 1). This is particularly important for high redshift objects, where line rich regions will be moved down into this energy band.

The power of this combination is illustrated in Figure 2 with a simulated observation of an active stellar coronal source (the RS CVn star AR Lac). For simplicity we have used a two temperature model of 7 and 24 million degrees, based on the ASCA results. The relatively long exposure of 80,000 sec highlights the richness in the spectrum. The upper panel shows the spectrum as a function of wavelength, with a portion centered on the He-like Mg line shown on an expanded scale in the lower panel. Notice how the grating covers the vital low energy part of the spectrum. This spectrum includes the He-like transitions of over 20 elements, and these can be used as a key diagnostic of temperature (in the range 1–100 million degrees) and density (10^8–10^{14} cm^{-3}). Figure 3 further illustrates the plasma diagnostic potential of HTXS by showing the simulated AR LAC data for the important He-like transitions of iron, calcium, silicon, magnesium, oxygen, and nitrogen. The small crosses in Figure 3 (and Figure 5 below) indicate the statistical uncertainties for the observed counts in each individual energy bin for the total 80,000 s simulated exposure.

Maximizing source counts is essential since the primary mission goal is understanding astronomical systems through high resolution spectroscopy. A prudent design decision, in terms of weight and cost, is to accept a reduction in intrinsic spatial resolution in favor of a substantial increase of collecting area. We have baselined 15–30$''$ half power diameter (HPD), which is sufficient to avoid source confusion at the faintest fluxes HTXS will observe, while supporting the requirements for the reflection grating spectrometer. The faintest source that will be observed in a several hundred thousand second exposure by the HTXS mission and still give sufficient counts to obtain a spectrum ($\sim$ 3000 counts) will be at a flux of $\sim 5 \times 10^{-15}$ erg cm^{-2} s^{-1} (0.2–2 keV band). The logN-logS for extragalactic sources shows that over ten million sources are available above this flux level in the ROSAT band ($\sim$ 200 sources degree^{-2}). ROSAT images obtained with 25$''$ spatial resolution demonstrate that even at a deeper 0.1–2 keV flux of $\sim 10^{-15}$ erg cm^{-2} s^{-1} source confusion is not an important issue. Using the ROSAT logN-logS value and a 15 arc second radius gaussian beam gives a confusion level for HTXS of $\sim 5 \times 10^{-15}$ erg cm^{-2} s^{-1} in the 0.2–2 keV band. As the study proceeds, we will also investigate the tradeoffs between a larger field of view for the micro-calorimeter (presently baselined as a 10 $\times$ 10 array of 15 $\times$ 15 elements, covering a 2.5$'$ $\times$ 2.5$'$ FOV) and a secondary wide-field imager such as a CCD outside the micro-calorimeter field of view operating in a parallel-type observing mode. Some of the factors to consider in such an evaluation include micro-calorimeter power, weight, cost, energy resolution, and lifetime; as well as the cost of a separate CCD detector system (possibly minimized by making it identical to the CCDs used to read out the grating); and the gain relative to source confusion which results from improved mirror angular resolution in the context of overall mission weight and cost.

The hard X-ray detector must have good efficiency throughout the 10–40 (possibly up to 100) keV energy range, with spatial resolution of $\sim$ 200 microns. Since there are no narrow atomic lines expected in this region, energy resolution is of less import. The fine position resolution, along with the required efficiency and energy resolution can be met by a cadmium zinc telluride (CZT) detector system, which is what we baseline for our simulations and analysis.

In Figure 4 the effective area curves for HTXS calorimeter and grating spectrometers are

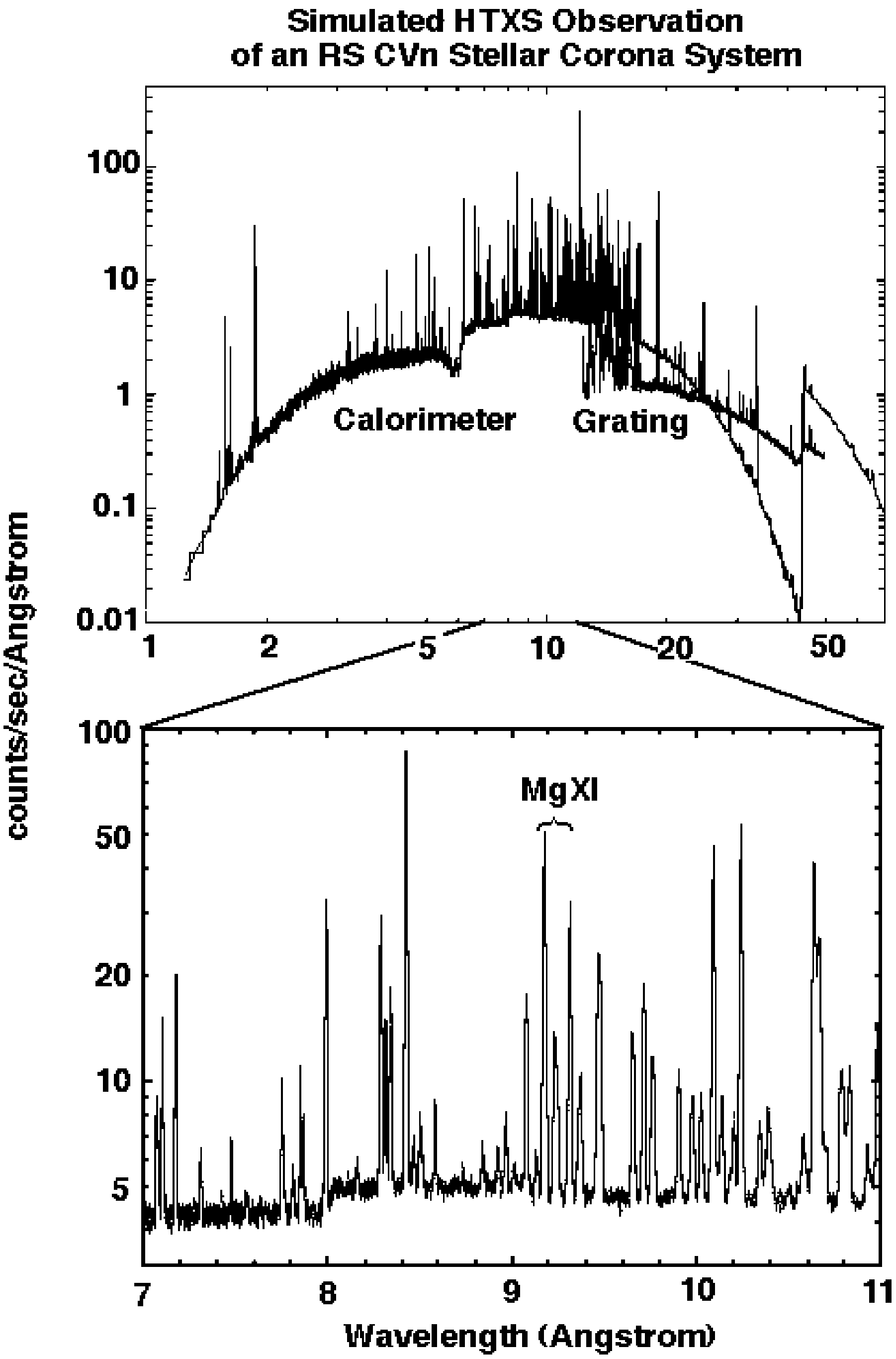

Figure 2: This simulated 80,000s observation of the nearby RS CVn star AR Lac shows the power of the HTXS spectrometers. This is a very active stellar coronae, and for simplicity we have used a bimodal temperature distribution of 6 and 20 million degrees. Both the grating and calorimeter spectra are shown. The upper panel shows the full spectrum and the lower panel an expanded view centered on the He-like Mg line.

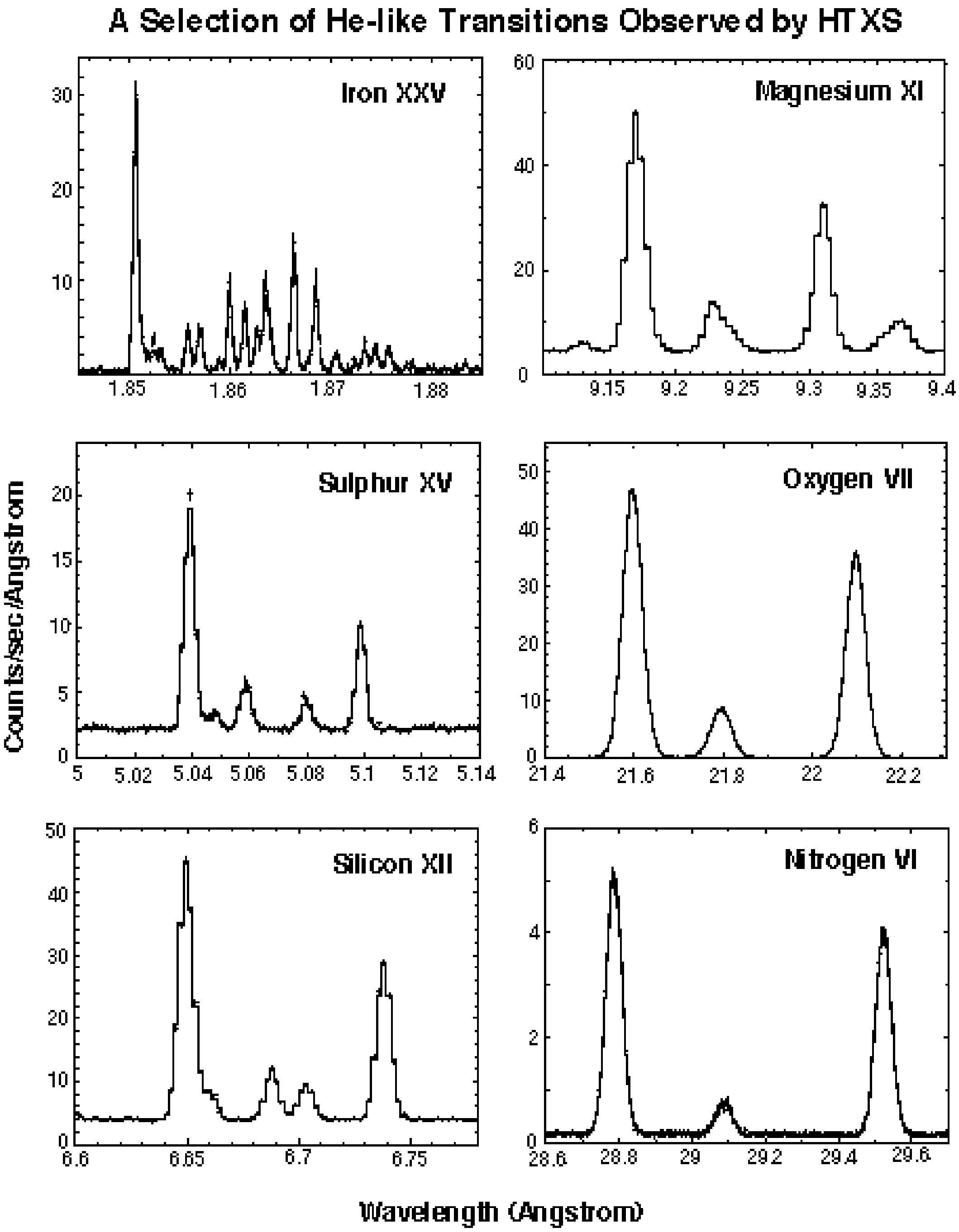

Figure 3: A total of 25 elements have their K shell transitions within the HTXS bandpass. Examples of the plasma diagnostic lines of some of the more abundant elements for the He-like transitions are shown for Fe, Mg, S, Si, O, and N as observed with HTXS. These lines cover temperatures of 1 to 100 million degrees and a variety of plasma densities 10^8 to 10^{14} cm^{-3}. The Fe, Mg, S and Si come from the AR Lac simulation shown in Figure 2. The O and N lines for a 2 million degree plasma, with an emission measure similar to that found from the 7 million degree emission from AR Lac.

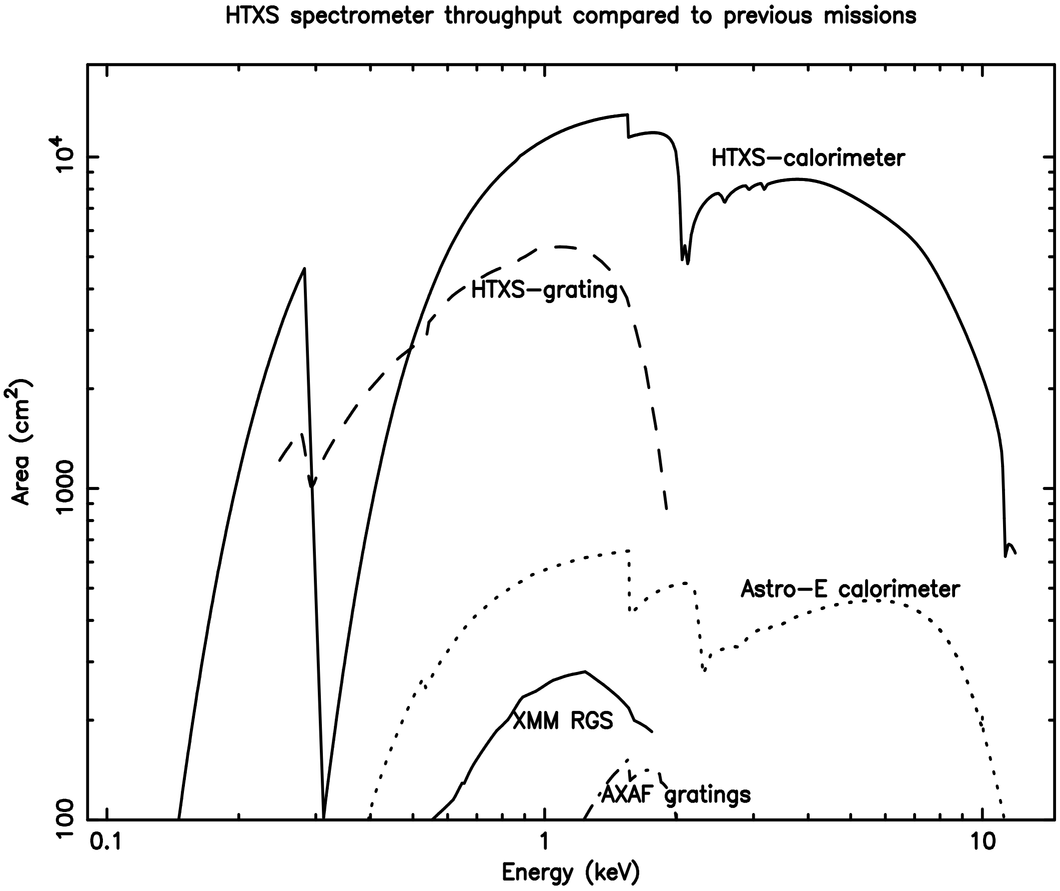

Figure 4: The effective areas of the two HTXS spectrometers compared to those planned for the high resolution instruments on AXAF (transmission gratings), XMM (reflection gratings) and Astro-E (a 10 eV calorimeter). The HTXS area is for a six satellite system with the reflection gratings (HTXS-grating), and calorimeter (HTXS-calorimeter) systems shown separately.

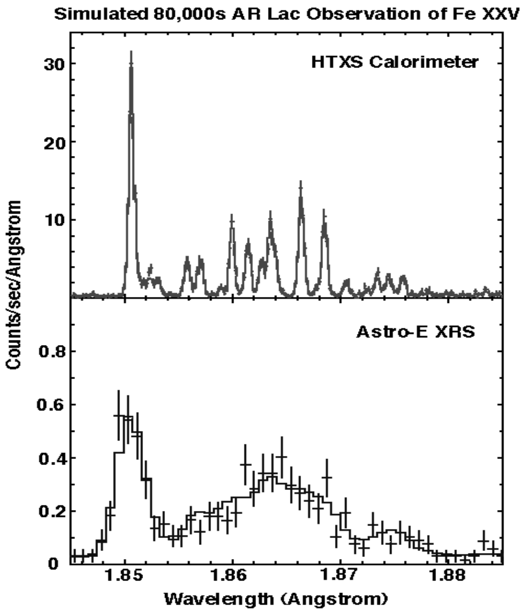

Figure 5: A simulated spectrum based on an 80,000 s observation of AR Lac by the 2eV calorimeter on HTXS (upper) and by the 10 eV calorimeter on Astro-E (lower). A simple two temperature model spectrum with 7 and 24 million degrees, and one third solar abundances (as measured by the ASCA CCD spectrometer). The 10 eV resolution of Astro-E is capable of resolving for the first time in a cosmic X-ray source the resonance from the satellite lines, and clearly is a major advance over current capabilities. But there is still another step to be taken by HTXS in both giving higher throughput and increased resolution to fully resolve the satellite lines. The 2 eV spectral resolution of HTXS fully resolves the iron K satellite and resonance lines and gives a much higher counting rate.

shown along with those of the high resolution spectrometers (R>250) on AXAF, XMM and Astro-E. Both XMM and AXAF use gratings to obtain high resolving power. The gratings on AXAF have effective areas ranging from 3 to 150 cm^2, as a function of energy. The peak effective area of the reflection gratings on XMM is higher, $\sim$ 280 cm^2 (combining two telescopes and the 1st and 2nd orders) but they cover a more limited energy range from 0.3 to 2.0 keV. While the gratings on AXAF and XMM will offer a major increase in performance, they are limited for study of extended sources for which they confuse spatial and spectral features. Long exposures of order 10^5–10^6 s will be required to obtain high quality spectra, even for moderately bright *point* sources. The Astro-E X-ray Spectrometer, XRS, utilizes an array of micro-calorimeters with an energy resolution of 10 eV, to cover the 0.3-8 keV band with an effective area of $\sim$ 400 cm^2. The Astro-E XRS will be able to observe extended sources, but the 10 eV resolution is insufficient at 1 keV to fully resolve many of the key line complexes required for plasma diagnostics. The Astro-E XRS has a limited 2 yr lifetime, because of weight limitations and the need for cyrogenic cooling. It is clear from Figure 4 that HTXS represents a dramatic advance in spectroscopic capability over these missions.

In Figure 5 a simulation compares the capability of the Astro-E XRS with that of HTXS at the He-like iron K line. This figure shows that the Astro-E XRS will, for the first time, resolve the resonance lines from the satellite lines. However the figure also shows that the

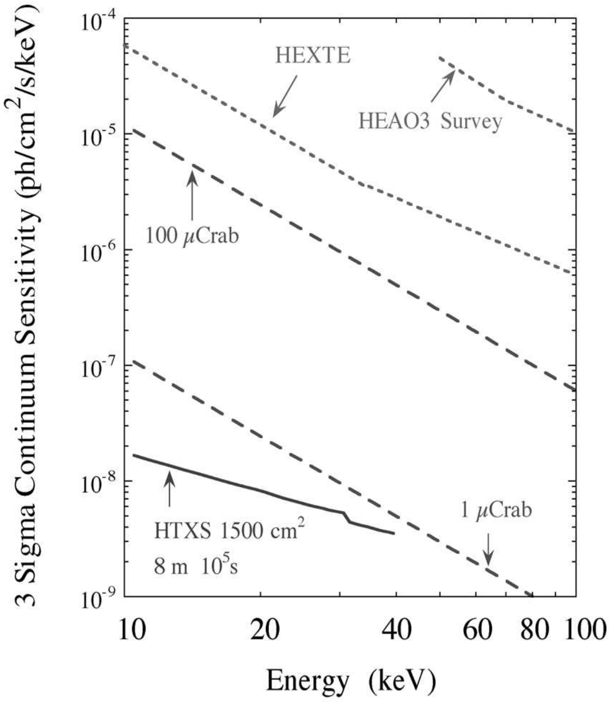

Figure 6: The sensitivity of the HXTS hard X-ray telescope for a 10^5s observation, compared to that of HEXTE and the HEAO 3 survey.

2 eV resolution and increased throughput of HTXS is required to fully unravel the blend of satellite lines into their individual components and extract the wealth of information simply unavailable to Astro-E.

A further limitation in the current generation of imaging grazing incidence X-ray telescopes is the upper energy threshold of 8-10 keV, above which the effective areas drop precipitously. Results from ASCA are showing that sensitive observations of the 10-40 keV band are necessary to constrain the continuum spectra of many classes of X-ray sources. The effective area curve shown in Figure 1 for the HXT shows the effective area available out to 40 keV with a multilayer coating of Pt-C. Figure 6 shows the sensitivity of the full HXT array of telescopes, compared to previous missions. There is a three orders of magnitude increase in sensitivity over that of the XTE HEXTE experiment. This capability is crucial for highly absorbed sources (Figure 7) and for sources where the Compton reflection of X-rays from cold material is present (Figure 8). Extended energy coverage is also necessary to differentiate between thermal and non-thermal continuum emission processes.

With these dramatic increases in capability, high resolution X-ray spectroscopy will become a reality for all classes of objects over a wide range of luminosities. The HTXS mission will bring X-ray astronomy to full maturity as an astrophysics discipline.

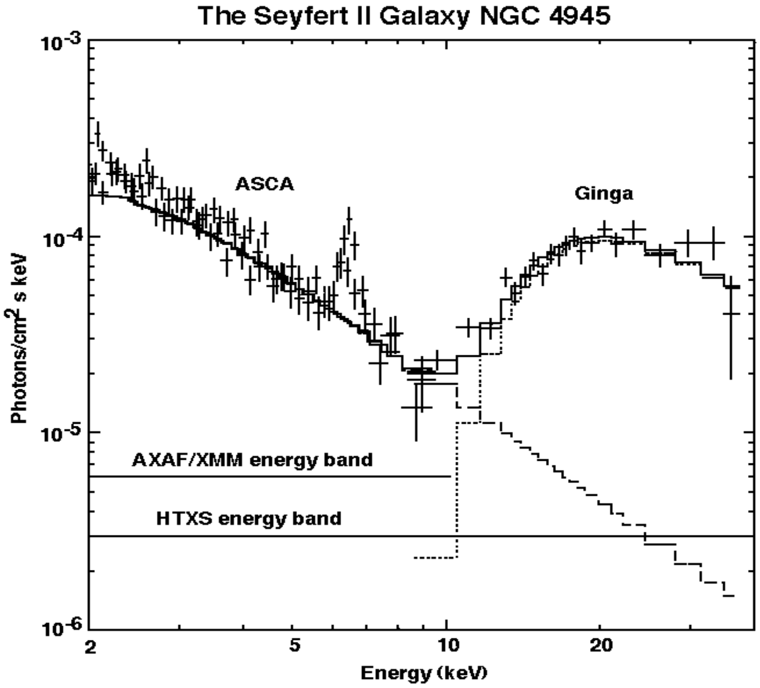

Figure 7: The ASCA and Ginga spectra of the Seyfert II galaxy NGC 4945. The highly absorbed emission from the central source, which is obscured by the molecular torus, is only visible in the >10 keV band. In the ASCA band, where AXAF, XMM and Astro-E will be sensitive, only the emission scattered around the torus is seen.

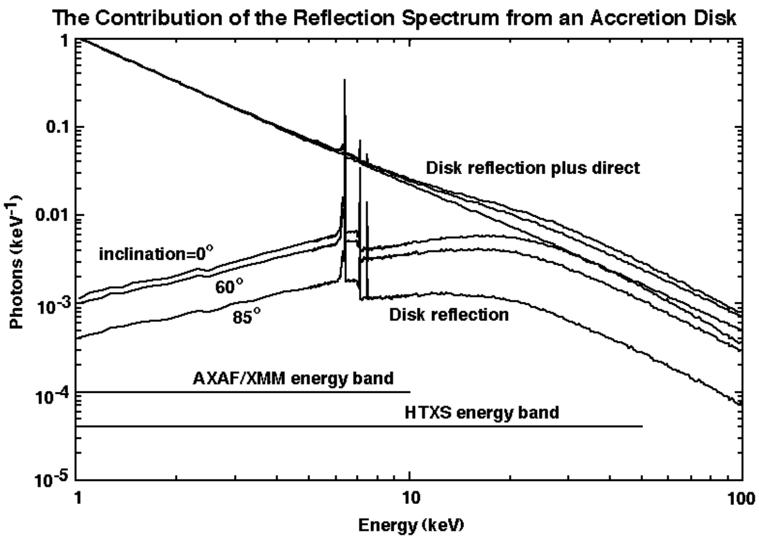

Figure 8: This figure (taken from George and Fabian (1991), MNRAS 249, 352) illustrates the reflected and composite spectra predicted for a flat, optically thick, non-rotating slab illuminated by an isotropic source of primary X-rays above the center. Three different viewing inclinations are shown. Notice the reflection component that peaks around 20–30 keV. The SXT will measure the fine details of the iron K emission line, while the HXT determines the contribution of reflection.

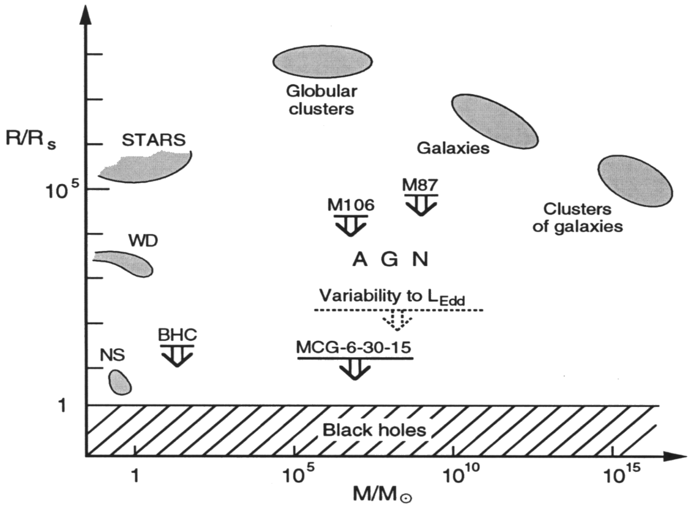

Figure 9: The Schwarzschild radius, R_s of various objects as a function of their mass. The measurements made of the black hole mass by HST of M87 and using maser line emission from M106 are made at relatively large radii of order 10^4 to 10^5 R_s. In contrast the broad iron K lines discovered using ASCA from e.g. MCG-6-30-14 and other black hole candidates (BHC), come from material orbiting very close to the black hole, within a few R_s.

6 Examples of Scientific Investigations with HTXS

As discussed in the previous sections HTXS will an observatory class mission capable of addressing a broad range of astrophysics problems. In the interests of brevity, we will not give an exhaustive list, but rather select a few key investigations to illustrate the overall power of the mission.

6.1 AGN

Since their discovery active galactic nuclei (AGN) have stood out as uniquely luminous objects in the Universe. Today we are quite confident that their ultimate power source results from gravitation, presumably from matter accreting onto a central black hole. However, the mechanism for the production of electromagnetic radiation and jets from the accreting material, and the manner in which the material reaches the black hole, is still unclear. Important questions still abound including, how does material make its way into the surroundings of the black hole and why is the QSO phenomenon more common in the past than it is today? X-ray spectroscopy holds the best prospects for understanding the AGN phenomenon and utilizing it to probe the environment in the vicinity of super-massive black holes. This is well illustrated by Figure 9, which shows the radius at which various signatures of a supermassive black hole have been identified. These show that the exciting radio maser and HST results probe regions many hundreds of Schwarzschild radii from the black hole. Only in the X-ray band does the black hole signature (the broad iron K line from MCG-6-30-15) come from close to the event horizon, where we can hope to test general relativity in the strong gravity limit. Observations of many individual sources with HTXS will allow us to develop a statistical picture of the material surrounding the central black hole. We then can search for changes in this material as a function of look-back time, and thereby extract the details of chemical evolution in AGN. Presumably these changes will in turn unlock the mechanism of evolution which connects QSOs to AGNs and low-luminosity Seyferts.

The HTXS instrument parameters are optimum for simultaneously to probe and understand the AGN central engine and to map the geometry of the surrounding material. The large collecting area of HTXS will provide the first spectra at high resolution for the lower luminosity and/or the high redshift AGN populations at fluxes of $\sim 10^{-14}$ erg cm^{-2} s^{-1} whose mean redshift is ~ 1.5. For the brightest AGN time resolved, high resolution spectroscopy on a timescale of minutes will be possible for the first time. The broad bandpass will simultaneously measure Compton reflection (where the incident central engine spectrum is modified by the effects of reprocessing in surrounding material), and high absorption Seyfert II galaxies (Figures 7 and 8). For QSOs the broadband capability will allow a determination of the high energy cutoff of the continuum in high redshift QSOs (the spectral break predicted in the range 50-200 keV is redshifted into the HTXS band for z $\sim$ 1-2). At lower energies the band pass is optimal to measure the time variability of the soft excess and absorption edges from the inflowing material.

Amongst the most exciting observations to be made by HTXS are detailed examinations of the broad iron K lines recently discovered from ASCA observations of Seyfert galaxies. These show strong Fe line emission which can be resolved into narrow and broad components (Figure 10). The broad components exhibit characteristic signatures of general relativistic effects resulting from the enormously strong gravity within 10 Schwarzschild radii of the black hole. From the distortion of the line profile by these effects it is possible to measure the mass and spin of the central black hole, and to test general relativity close to a supermassive black hole. However, these detailed tests are possible only with the increased collecting area, improved spectral resolution and broad bandpass of HTXS - to eliminate any narrow line components (from material much further out), to separate orbital motion and gravitational redshift effects, to resolve individual "bright spots" contributing to the broad line emission and to fully determine the underlying continuum (which is very important when studying broad line features).

The AGN central engine undergoes rapid brightness changes, presumably due to variations in the rate of accreted material. With the HTXS collecting area, this property offers a unique probe of the spatial distribution of material within the centermost regions of an AGN. As the wavefront caused by the change in central brightness propagates outward, the fluorescent excitation of Fe line emission from cooler material responds causing a reverberation in the line profile that depends on the black hole parameters. An example of the changes expected are shown in upper frames of Figure 11. As time elapses, the fluorescence subsides, and the observed line profile changes. Studies of this kind may lead us to understand the detailed structure and mechanism of the accretion process, based on nearby AGN (Seyfert galaxies) which can be applied to advantage for understanding energy generation in the very distant, much more powerful QSOs. The overall shape of the line is sensitive to the assumed metric and the spin of the underlying black hole.

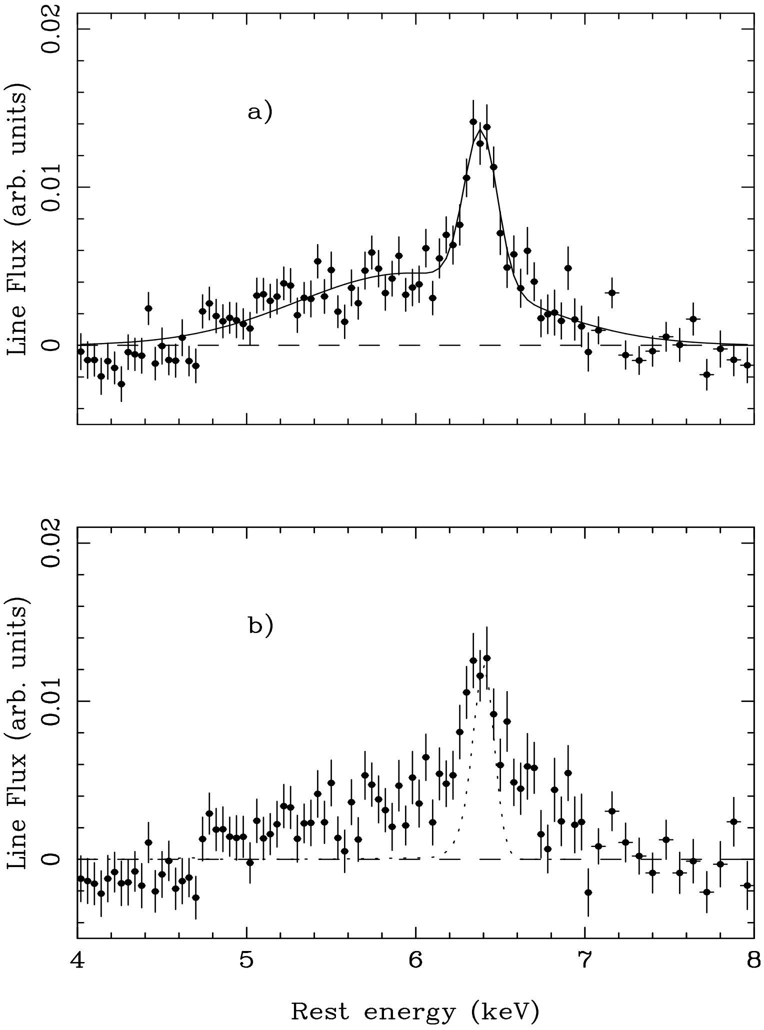

Figure 10: The composite iron K line profile obtained by summing the spectra of 18 Seyfert 1 galaxies observed by ASCA. These were produced by transforming the data/model ratios for each source into the rest-frame of each source, rebinning the resultant residuals, and converting to flux space assuming the mean of the best-fit continua. The upper panel a) shows the results for the whole sample, while b) shows the profile with the lines from the systems MCG-6-30-15 and NGC 4151 (the two with the highest signal to noise) removed. The two plots are remarkably similar. The solid line in a) is a double-gaussian fit to the profile. The narrower component peaks at 6.4 keV with a width of $\sigma \sim 0.1$ keV. The broader component is strongly redshifted, with a centroid energy of 6.1 keV and a width of 0.7 keV. It also carries the bulk ($\sim 75\%$) of the flux. The dotted line in b) is the spectral response of the ASCA SIS detectors at 6.4 keV.

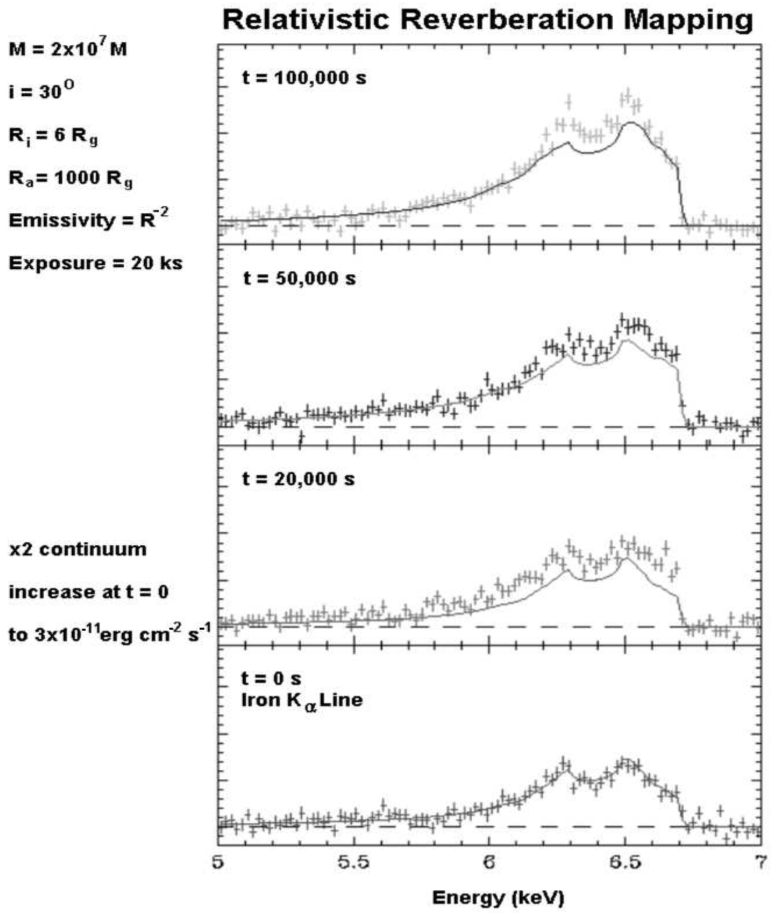

Figure 11: This simulation shows how HTXS can measure line profile variations in a typical Seyfert 1 galaxy. When the central source changes, an echo front propagates through the accretion disk, with the innermost regions responding first. The figure shows the changes we expect when the continuum source increases by a factor of two at time t=0. The time sequence runs from bottom to top, with the crosses representing the simulated data at the time shown and the solid lines the profile from the previous panel. The emission below about 6 keV comes from the inner edge of the accretion disk, where the gravitational forces have displaced the photons from their original energy of 6.4 keV. These relativistic effects are less intense in the outer parts of the disk, where the "double horned" core of the line is produced. There, the line responds more slowly. This can be seen in the top panel: only the core of the line changes significantly between 50,000 and 100,000s. The time it takes for these various components of the line to respond depends on on the black hole mass and the geometry of the system. Realistic estimates of these suggest that the variations will occur on very short time scales, such as those shown here. The combination of high throughput and spectral resolution provided by HTXS will enable these unique experiments to be performed.

6.2 Cluster of Galaxies

Clusters of galaxies are the largest bound systems in the universe. As such detailed studies of their chemical composition, mass, evolution and formation are critical for theories of the formation of structure in the universe. Clusters are the only known systems that are *fair* samples of the large scale structure of the universe, and detailed measurements of their properties can be used to determine the content of the universe as a whole. One of the major surprises in astronomy over the past 30 years has been that the baryonic mass of rich clusters is dominated by the hot X-ray emitting gas. Measurement of the abundances of the elements in this hot gas gives fundamentally different information from that derived from almost any other type of system. In addition, X-ray observations also revealed "cooling flow" galaxies at the centers of clusters, which are the only systems in the low redshift universe that show high rates of star formation unaccompanied by large amounts of dust. As such these systems could be the prototypes of high redshift star forming galaxies. However, the amount of star formation is only 10% of the X-ray indicated cooling rate and the fate of the rest of the cooling material is unknown at present.

HTXS will be able to determine or constrain for the first time the abundance of all of the elements with atomic number between carbon and zinc in clusters; the more abundant species will be visible out to redshifts of at least 1. In particular, HTXS can determine the abundances of carbon and nitrogen for rich luminous clusters at low redshift as well as many of the lower abundance species like Na and Al. Carbon and nitrogen are particularly important since their nucleosynthetic origin is rather different from that of the alpha burning products (O, Si, S etc.) or the type I supernova products (primarily Fe and Ni). Nitrogen is a secondary element and thus its abundance should be related to the square of the original oxygen abundance, while carbon is produced in intermediate mass stars (2–8 $M_\odot$), compared to the $M_\odot > 8$ for oxygen. The ASCA observations of clusters show an abundance pattern of the alpha burning elements and Fe that is consistent with an almost pure Type II supernova origin in rich clusters. This pattern, combined with the lack of evolution of Fe in rich clusters indicates that the metals in these systems were created at high redshift. However in lower mass clusters a wide pattern of abundances seems to exist, which may indicate a much larger variation in the formation time of the heavy elements in these clusters.

Detailed observations of carbon and nitrogen in low z systems as well as measurements of the evolution of the alpha burning elements compared to Fe out to high redshifts will be very important to fully understanding the origin of the elements in clusters. Already, preliminary HST data indicate a different origin for carbon in dwarf galaxies compared to metal poor galactic halo stars and the Lyman alpha clouds. Our simulations show that a relatively short (30,000s) observation with HTXS of a kT $\sim$ 3 kev, bright low z cluster, such as Abell 1060 should result in accurate (better than 10% accuracy) abundances of C, N, O, Ne, Mg, Al, Si, S, Ca, Ar and Fe. Other less abundant elements such as Na will have a 30% uncertainty. Based on scaling laws (since these elements are not in the current plasma codes) other odd-Z elements such as P and K will also have uncertainties of $\sim$ 30%.

Similarly HTXS will for the first time be able to measure the abundances of O, Ne, Si, S and Fe out to z $\sim$ 1 and track the evolution of the alpha burning products relative to those from type I SN (Figure 12). For example a simulated 30 ks HTXS observation of the recently discovered z=1.09 cluster 2016+112 with $L_x \sim 10^{45}$ erg s^{-1} will provide direct information on the Si ,S and Fe abundances in this high redshift cluster. HTXS observations

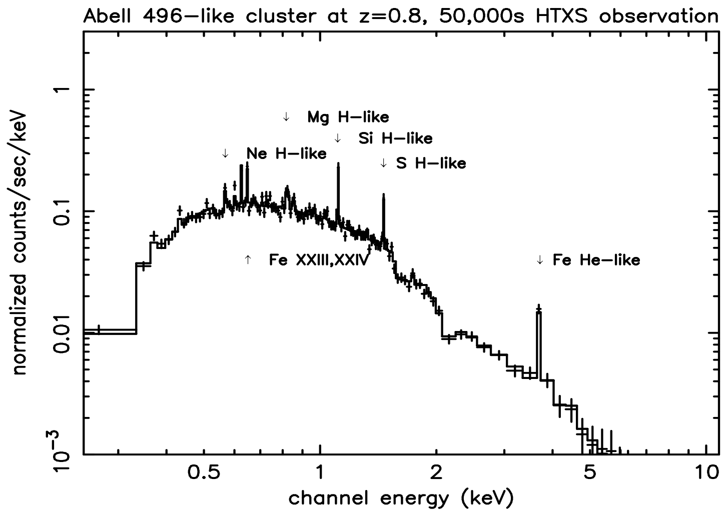

Figure 12: A simulated 50,000s exposure of a clusters at z=0.8 with a characteristic X-ray luminosity of 3.5×10^{44} erg/s. Its X-ray temperature of 4 kev is also a typical value. A type II abundance distribution with oxygen through Si having 0.6 solar and sulfur through Ni 0.3 solar was assumed. The abundances are determined to 10% accuracy for Si, S and Fe and 20% for Ne and Mg. This type of cluster has not yet been found in X-ray surveys since its flux of 4×10^{-14} ergs cm^{-2} s^{-1} is at the ROSAT detection limit.

of other similar high redshift clusters (to be found e.g. by AXAF) will allow the overall abundance patterns and dependence on redshift to be derived. This will allow a direct connection with the abundances of the damped Lyman-alpha systems, which are thought to represent the halos of forming galaxies and that of the Lyman alpha forest. HTXS can determine the metallicity of the cluster gas at a much higher redshift than the metallicity of normal galaxies can be determined from optical and UV spectra. In a related context, HTXS can obtain direct information on the metallicity associated with the filaments and sheets (rather than "normal" galaxies) which may contain much of the matter responsible for the Lyman alpha forest. Much of this matter may be at temperatures of order 10^6 K, with metal abundances about 0.01 solar, implying widespread early metal production. HTXS exposures of 10^5s on quasars with luminosities of order 10^{46} erg s^{-1}, at redshift ~ 1, would yield ~ 1000 counts per 2 eV resolution element. Through absorption line features observed in the quasar spectra due to the intervening Lyman alpha forest metals, we can learn much about the distribution and composition of baryonic matter in the relatively early universe (particularly, if we can use a few more luminous quasars and extend these studies to redshifts of 2 or 3).

Another measurement possible for the first time with HTXS will be the mass motion of gas in the central cooling flow region of a cluster and in the "interaction region" of a merger candidate. This is important because one of the main discoveries in recent years is that most clusters are dynamical entities and far from the static, spherically symmetric objects in hydrostatic equilibrium that they were once thought to be. ROSAT and *Einstein* observations have revealed that >50% of all nearby clusters show strong evidence for interaction.

Numerical simulations indicate that in a merger the velocities can range from 300–2000 km/s and that such motions make determination of the total mass of the system from X-ray temperature profiles impossible without direct measurement of the velocity field. HTXS can easily detect relative velocities of 100 km/s using the shift of the H-like Fe and O lines and turbulence and mass motions of 200 km/s via measurements of the width of these lines. Thus for the first time direct measures of gas motion in clusters will be possible, thereby determining cluster merger parameters and strongly constraining models of cluster evolution. Optical spectroscopy of cooling flow clusters often show gas with a velocity spread of ~ 500 km/s. However this optical emitting gas is confined to the very center (~ 10 kpc) of the cooling flow. HTXS will be able to measure the motion of gas at $\sim 1/4$ this level or down to ~ 100km/s, out to the cooling radius (~ 100 kpc) while at the same time deriving the distribution of emission measure with temperature. These HTXS observations are crucial to fully understand cooling flows, in particular the fate of the inflowing gas.

6.3 Supernova Remnants

Supernovae are widely believed to be responsible for the production of most of the metals in the Universe. Young supernova remnants (SNRs), those with ages less than several thousand years, show line-rich, X-ray spectra which are dominated by emission from shock heated stellar ejecta. CCDs, like those on ASCA and in development for AXAF and XMM, provide sufficient spectral resolution to measure the abundances of the astrophysically common elements O, Ne, Mg, Si, S, Ar, Ca, and Fe. In addition to these, the K-lines from the less common elements: F, Na, Al, P, Cl, K, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, and Zn, lie within the 0.5–10 keV X-ray bandpass. HTXS has the resolution and effective area necessary to measure the abundances of most of these uncommon elemental species.

We consider as an example, the Galactic SNR W49B. The ASCA spectrum of this remnant (with a 2-10 keV flux of $\sim 7 \times 10^{-11}$ erg cm^{-2} s^{-1}) shows bright line complexes from K-shell transitions of He-like and H-like ions of Si, S, Ar, Ca, and Fe. In an observation of merely 1500 s, HTXS will be able to detect (at the 10 sigma level) and resolve the weakest of the He-like lines for these elemental species. In Figure 13, we show the HTXS count rates for the He-like complex as a function of atomic number for all elements from Si to Zn. The five circled points near the top of the plot correspond to the astrophysically abundant elements mentioned above. The next lower set of points are for the elements P, Cl, K, Ti, Cr, Mn, and Ni. Highly significant detections of these lines will be obtained by HTXS in less than 20,000 s. Unless their abundances are significantly enhanced relative to the solar values, the remaining species (Sc, V, Co, Cu, and Zn) will require considerably longer observation times ($> 10^5$s).

Recent ASCA results show the power of X-ray spectroscopy to identify the type of supernova explosion (massive star core-collapse SNe vs. Type Ia SNe) associated with a given remnant through measurements of the relative elemental abundances. The X-ray data provide unique tests and constraints of the detailed nucleosynthesis models, which, in other contexts, are used to model the chemical evolution of systems ranging from our Galaxy to distant clusters of galaxies.

X-ray data on older SNRs, which mainly show emission from swept-up ambient matter in the interstellar medium (ISM), can provide a direct measurement of the metal abundances in the gas phase. As we study the current abundance distribution in these systems we see

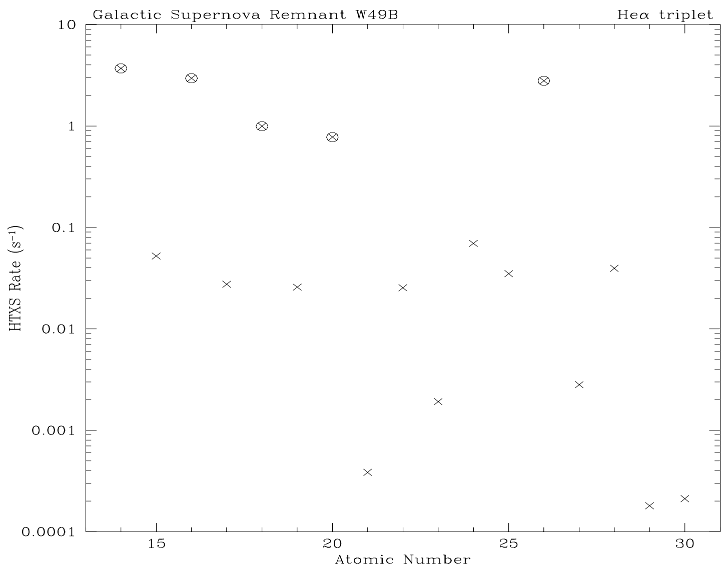

Figure 13: The HTXS count rates for the sum of the He-like triplet lines as a function of atomic number for all elements from Si to Zn in W49B. The five circled points near the top of the plot correspond to the relatively abundant elements Si, S, Ar, Ca and Fe. The next lower set of points are for the elements P, Cl, K, Ti, Cr, Mn, and Ni. Highly significant detections of these lines will be obtained by HTXS in less than 20,000 s. The remaining species (Sc, V, Co, Cu, and Zn) may also be detectable in much longer observation times ($\sim$ 100,000 s), especially if their abundance ratios are enhanced relative to solar values.

the integrated sum of material returned to the ISM by stars of all types and using our models for stellar nucleosynthesis, we can determine the history of star formation in the host galaxies.

ASCA, AXAF, XMM, and Astro-E, allow us to study the sample of SNRs in the Magellanic Clouds down to X-ray luminosities of roughly 10^{36} ergs/s. HTXS will open an entirely new window on such studies by enabling us to observe many of the SNRs in M31 and M33, of which there are over 50 known in each galaxy. These galaxies are ~ 700 kpc away, a factor of 14 more distant than the LMC. The brightest SNRs ($L_x > 5 \times 10^{37}$ ergs/s) will show count rates of roughly 1 ct/s in HTXS and thus excellent spectra of them can be obtained in observations as short as 20 ks. About 1/4 of these remnants should be brighter than $\sim 10^{37}$ ergs/s (simply scaling from the LMC sample) and it will be possible for HTXS to obtain good data on these remnants as well in reasonable observation times. Studies of SNR samples in external galaxies allow us to probe issues related to supernova history and the chemical evolution of galaxies.

The key to using SNRs to determine elemental abundances in ejecta and the ISM lies in our ability to understand and account for the inherent complexity of SNR X-ray spectra. There are uncertainties introduced by the presence of non-solar elemental abundances, nonequilibrium ionization fractions, non-thermal continuum emission components, velocity broadening of lines, and so on. High spectral resolution observations by HTXS will provide a number of important plasma diagnostics to help constrain the interpretation of the spectrum. For example the relative strengths of the He-like lines for the astrophysically abundant elements from O to Fe can diagnose nonequilibrium ionization effects. The rich complex of Fe L-shell lines in the 0.7–1.2 keV energy band provides a number of diagnostics of temperature, ionization and departures from Maxwellian electron distribution. Recombination edges seen in the continuum emission can provide additional constraints on ionization and abundance effects. It may be possible to observe the effects of the abundances on the shape of the bremsstrahlung continuum (though the gaunt factor). As ASCA has shown, increases in spectral resolution and throughput are the most important in improving our ability to understand the complex spectra of SNRs.

By the time HTXS flies, ROSAT and AXAF will have determined the angular expansion rates of the remnants of several historical SNe, including SN1006, Kepler's SNR, Tycho's SNR, and Cassiopeia A. HTXS will be able to determine the radial velocities of knots and filaments seen in projection near the remnant centers. Combining the angular expansion rate with the radial velocity measurements will provide accurate determination of the distances to these remnants. Because the ejecta may be compositionally stratified, it will be necessary to measure the expansion rate and radial velocities using the same set of lines, e.g., the Ly α line of Si.

The ejecta mass and thermal energy content of SNRs depend steeply on the distance $d^{(5/2)}$, which implies that the large uncertainty in current distance estimates severely limits our ability to constrain dynamical models. Note that for the putative remnants of Type Ia SNe (Tycho and SN1006), the X-ray band offers the only way to measure distances in this manner. Although the angular expansion rates have been measured in the radio and optical bands, radial velocity measurements in these bands are not feasible. In the radio, the emission is synchrotron continuum, while in the optical, there are no optical filaments near the centers of these remnants.

It will be necessary to measure the Doppler shifts to approximately 100 km/s of some 10–20 knots (more, if the expansion is spatially inhomogeneous). Note that a radial velocity determination is the measurement of a line centroid. To achieve a radial velocity accuracy of Δv one needs to observe a number of photons, N, from a well isolated single line, given roughly by

$$N \sim 36(\sigma_{2eV})^2(\delta v_{100km/s})^{-2}(E/1keV)^{-2}$$

where σ is the width in eV of the spectral resolution function (assumed constant with energy) and E is the line energy. This study will not be possible with Astro-E given the current estimates of its spectral resolution and smaller effective area.

The recent supernova in the Large Magellanic Cloud, SN 1987A, provides an especially exciting opportunity to study an SNR during its earliest phases of evolution. As pieces of the free-streaming clumpy ejecta from SN1987A crash into the circumstellar shells from the precursor winds, they will light up in the X-ray band. At first we will see the leading edge of the ejecta, which is moving at roughly 10,000 km/s, and which should start hitting the shell from the red supergiant wind about 15 yr after the explosion. Over the next 5 years the X-ray flux from the interaction should rise rapidly to about 10^{37} erg/s or more and will continue to brighten for the next 20 to 30 years as more slowly moving ejecta are shock-heated.

Variability will be the characteristic feature of the X-ray spectrum during the time when the clumpy ejecta encounter the red giant shell. As an individual clump of ejecta enters the shell the X-ray emission will flare with a spectrum that depends on the nature of the clumps. If hydrodynamic instabilities during the SN explosion have randomized the spatial distribution of clumps without homogenizing their composition (as suggested by numerical simulations as well as by observations of other young SNRs), then we should see features of pure elemental composition appearing, e.g., at one time pure Si emission, at another, pure S, and so on. The red- or blue-shifts of the new lines, plus the time lag since the explosion will be critical in determining the three-dimensional structure of the ejecta. Information on the spatial location of the bright X-ray flares obtained from AXAF high resolution images will also be of value, as will detailed models of the structure of the elliptical ring from HST images.

By consistent regular monitoring of SN1987A it will be possible to trace the structure of the red giant shell and determine the mass, clumpiness, spatial stratification, and chemical composition of the ejecta. HTXS has the spectral resolution needed. The Doppler shift of a Si clump at a speed of 3000 km/s is 18 eV. Roughly half of the ejecta, by mass, is moving with speeds greater than this. The high throughput of HTXS is also essential since it will allow us to monitor the source on a frequent basis using short observations. Individual ejecta clumps brighten to X-ray luminosities of order 10^{34} erg/s. Assuming a clump of pure Ne, Si, or Fe composition and using reasonable estimates for the spectral flux distribution, we estimate count rates in HTXS of 300, 50, and 20 per ks for the Ly α line of the respective hydrogenic species. Observation durations of 20 ks will be adequate to characterize the intensity of these lines to at least 5% and determine line centroids to better than 100 km/s. Weekly monitoring observations of SN1987A by HTXS would require roughly 5% of the available mission time.

HTXS will be able to detect the 4 keV K-shell line from the radioactive decay of the newly synthesized Ti_{44} in SN1987A. We estimate that the line flux will reach an intensity of about 10^{-7} photons cm^{-2} s^{-1} by the year 1998 and remain at that level, or increase slightly for the next 15 years or more. A 120 ks observation would yield a highly significant detection of the line ($\sim$ 10 sigma). The intensity of this line is sensitive to the opacity of the SN's atmosphere, which itself depends strongly on the size and clumpiness of the ejecta. Comparison of the flux of the 4 keV X-ray line with the nuclear gamma-ray lines from the decay Ti_{44} (at 68 keV and 78 keV) would provide a unique probe of the structure and nature of the ejecta.

6.4 Stellar Coronae

Stellar coronae exhibit some of the most line-rich X-ray spectra of cosmic sources. X-ray spectroscopy will allow us to derive very sensitive constraints on physical conditions in the coronal plasmas. However, the high resolution spectrometers on AXAF, XMM, and Astro-E will require long exposures to accumulate high-quality spectra of even the brightest stars. Much higher throughput is required to reach the fainter (more distant and/or less luminous) systems, and to obtain high quality time-resolved spectra.

In eclipsing binary stellar systems we can use the morphology of the X-ray light-curve to infer the spatial structure of the coronal plasmas on either or both of the component stars. The duration of an eclipse gives information on the longitudinal extent of the emission associated with the eclipsed star. The problem, however, is that there are too few constraints from the lightcurve alone to give a unique solution. With the spectral resolution and large collecting area available with HTXS, we will for the first time be able to break this degeneracy by using velocity information to map the coronal structures on the underlying stars. This technique, called Doppler imaging, has been utilized in the optical and uv bands to map the location of photospheric features, but only by combining these with X-ray observations can the full three-dimensional structure of the corona be determined. At the Fe XXV resonance line at 6.7 keV, a resolution of 2 eV gives a velocity resolution of 90 km/sec, which will enable us to study close binary systems like AR Lac, which contains a GIII star and a KIV star that are rotationally phase locked to the 2-day orbital period (Figure 14). The maximum radial velocity difference between the two component stars is 230 km/sec. The large effective area of HTXS will enable the first high quality spectra of the Fe K line from this system in an exposure short compared to the orbital period. During an HTXS observation covering a single orbital period, about 50 time-resolved spectra will be obtained, which will enable a study of coronal structures with spatial dimensions much smaller than the stellar radii. HTXS can isolate the Fe XXV resonance line (and other strong resonance lines such as Ca XIX at 3.90 keV) of each star, and determine the coronal abundances. Also through the use of plasma diagnostic line combinations, the densities of the individual active regions can be directly determined and compared with the densities inferred from Doppler imaging and eclipse mapping.

The only star for which time-resolved flare spectra in both the soft ($<$ 10 keV) and the hard ($>$ 10 keV) X-ray bands have been obtained to date is the Sun. Such observations have shown us that there is a fundamental difference between the dominant processes that produce the X-ray emission in these two spectral domains. For a given flare, there is a critical energy E(crit) $\sim$ 3–30 keV such that the hard X-ray spectrum for E $>$ E(crit) is impulsive and well-fit by power-laws, while the soft X-ray spectrum with E $<$ E(crit) changes more gradually and appears thermal in nature. It is believed that the hard X-ray emission is representative of the energy input of the flare, and that it is due to bremsstrahlung from

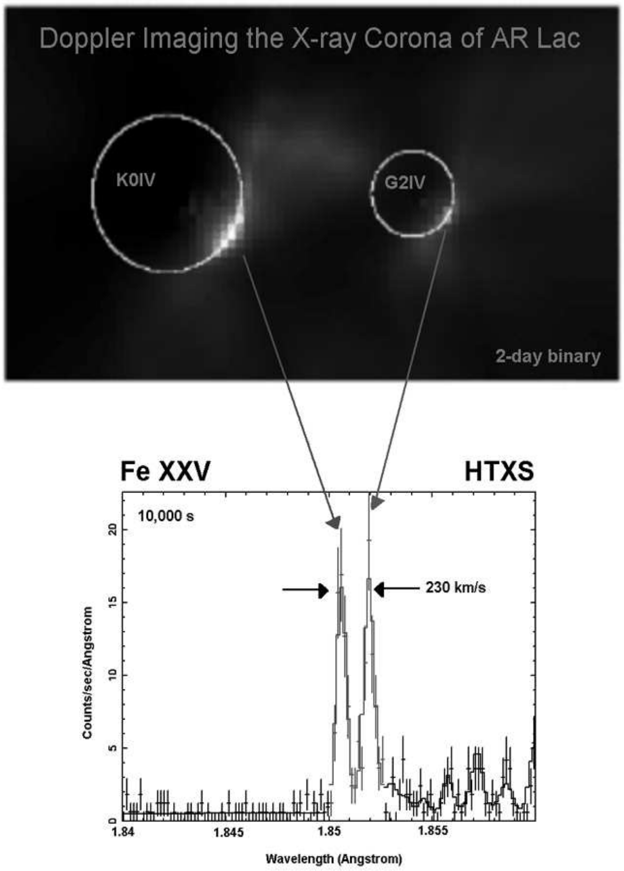

Figure 14: This figure shows in the top panel an eclipse-mapping spatial deconvolution of the coronae of the RS CVn binary AR Lac, as derived from a long EXOSAT exposure. A large fraction of the total X-ray emission from this system at the epoch of this observation came from spatially compact regions, probably associated with bright chromospheric plages, on each star. In the lower panel we show a simulated HTXS Calorimeter spectrum, assuming 2 eV spectral resolution, of what a 10,000 second exposure of AR Lac would look like, assuming that the exposure was centered on orbital quadrature, when the velocity separation of the two stars in this binary system is its maximum value of 230 km/sec. For simplicity, we have assumed that each star contributes equally to the total X-ray emission. The strong Fe XXV resonance line is clearly split into two components due to the differential Doppler shifts of the two stars.

accelerated, nonthermal electrons hitting the denser chromospheric layers, while the soft X-ray emission is representative of the energy output of the flare, in that it is the thermal emission from the material 'evaporated' out of the chromosphere into the corona by the initial input particle bombardment. Thus, in order to constrain flare models, the time history of both the soft and hard X-ray spectra are required. The high effective area and broadband pass of HTXS will carry-out time-resolved X-ray spectroscopy of 'typical' flares on nearby low-mass dwarf stars (e.g., the active K stars AB Dor and LQ Hya, and the dMe stars AD Leo and UV Cet) at much fainter levels and/or higher time resolution ($\sim$ 10–100 seconds) than attained before. The HTXS gratings and calorimeter will be able to make detailed studies of the line profiles of the flare-heated plasma, and of the time evolution of the temperature and emission measure of the thermal plasma. If stellar flares are similar to solar flares, there should be evidence in the early stages of the flare of both an additional blue-shifted component (the signature of the evaporated material), as well as additional line broadening due to turbulence. In addition, the hard X-ray telescope on HTXS will enable a study of the hard X-ray bremsstrahlung component of stellar flares that is emitted by the energetic nonthermal particles in the impulsive phase.

The large collecting area of HTXS will enable detailed spectroscopy of stellar coronae at unprecedented distances and over a large range of coronal luminosities. The high resolution spectrometers on previous missions will not reach stars with coronal luminosities as low as that of our own Sun. HTXS will also obtain high-quality spectra for the first time from the most coronally active stars in the vicinity of the galactic center ($\sim$ 7.5 kpc) and in the LMC and SMC. For example, the giant stars in the Galactic bulge seen through Baade's Window, will be accessible (assuming an interstellar column density of 2.5×10^{21} cm^{-2}). These stars have been studied extensively at optical wavelengths and appear to exhibit a range of abundances, with a mean value that is about twice the solar value (with individual stars having metallicities up to ten times solar). Because of the complexity of modeling the strong line blanketing effects on the optical spectra, these abundance determinations are controversial. At the 50-60 kpc distance of the Magellanic Clouds, HTXS will be able to detect active stars such as RS CVn and Algol binaries that have X-ray luminosities in excess of 10^{31} erg/sec, and to provide spectral information on the most active systems ($L_x > 10^{32}$ erg/sec), in a 100 ksec exposure. There are thousands of such bright coronal stars in the LMC and SMC. Thus, with HTXS we will be able to determine (for the first time for any galaxy) the fraction of the total galactic X-ray luminosity that is due to coronal sources.

7 Further Information

References to the science discussed in this report are available upon request. The HTXS web page at

http://lheawww.gsfc.nasa.gov/docs/xray/htxs/home.html

will be constantly updated to reflect the current status of this mission study. Comments or questions on this report are welcome and should be addressed to the Co-PIs for the HTXS mission study Dr. Nicholas White (white@adhoc.gsfc.nasa.gov) and Dr. Harvey Tananbaum (ht@cfa.harvard.edu).

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