Concept for an orbiting wide field X-ray imaging spectrometer (WFXIS)

by

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ABSTRACT

We present a concept study for a mission to provide wide field X-ray imaging spectroscopy. Many astrophysical studies in the X-ray regime demand both high energy resolution ($\sim$ 5 eV) as well as high angular resolution ($\sim 10''$). Examples of such studies are: clusters of galaxies, from those with sub-clumps to those at the edge of the universe (minimum radii $\sim 15''$); individual galaxies (nearby ones are easily resolvable on the $10''$ scale); deep sky surveys for clusters and QSO/AGN, which necessitate optimal sky coverage with the avoidance of source confusion for long exposures ($\sim 2 \times 10^5$ sec); supernova remnants (SNRs) in galaxies such as the LMC, SMC and Andromeda; knots in galactic SNRs such as Cas-A; and fine structure in the interstellar medium (ISM). Other studies that require a wide FOV and high energy resolution are studies of the large scale structure of the ISM, nearby clusters of galaxies, and large SNRs, such as the Cygnus loop and the Vela/Puppis region. The instrument concept we propose, the Wide Field X-ray Imaging Spectrometer (WFXIS), will combine the critical characteristics of wide-field, high-resolution X-ray imaging with high energy resolution, and thus provide unique capabilities not available on any single current or planned mission in which NASA is participating. Our preliminary design consists of ROSAT-sized zerodur mirrors with a Ritchey-Chretien figure; $\sim$ 2.5 meter focal length; and a single focal plane detector made up of a 500×500 pixel array of either microcalorimeters or superconducting tunnel junctions. The energy range covered by this system will be $\sim$ 0.1–2.5 keV. The main points of this work are: the science is outstanding; the technology for mirror production and design is in hand; and detector technology has reached the stage that it makes sense to begin planning for the ability to make 500×500 pixel arrays with a factor of 10 improvement in energy resolution over available CCDs.

Key words: *X-ray optics, tunnel junction, microcalorimeter*

1 Introduction

X-ray astronomy has been an extremely rewarding area of astrophysical research since its inception in the early 1960's. Stars, binary stars with compact companions, pulsars, novae, supernovae, supernova remnants, the interstellar medium, galaxies, clusters of galaxies, AGNs, and QSOs all emit detectable quantities of X rays. The observed X-ray spectra and elemental abundances inferred from the spectral line features play a major role in understanding the origin and evolution of nucleosynthesis in the universe. As supernovae are thought to be the primary sources of heavy elements it will be seen that a recurring theme in the science that follows is that we need to understand supernovae/supernova remnants in order to understand elemental abundance evolution. The study of the dynamics of large scale structures in the universe such as galaxies, clusters of galaxies, and superclusters also brings us into direct contact with cosmological questions related to the mass density of the universe and the formation and evolution of the large scale structure of the universe. And, measuring the extent and temperature profiles of the hot coronae of galaxies and of the intra-cluster medium in clusters of galaxies via the X-ray emission, places significant constraints on the mass to light ratios of these systems and the relative location of dark and visible matter in these systems. Measuring line ratios is an extremely sensitive method of temperature determination; hence X-ray spectroscopy and imaging of diffuse sources of X-ray play a crucial role in our study of the universe. Surveys of point sources also require a wide field of view with excellent angular resolution (to avoid confusion problems) and are important for studies of both stars and quasars. We see that X-ray astronomy in general and wide field imaging and spectroscopy in particular, then, are of key importance to contributing to our understanding of the universe.

The concept we describe here addresses a real need in X-ray astronomy to combine high resolution imaging with high resolution spectroscopy and a wide field of view. The X-ray observatory we envision has: a 1-degree field of view, a $10''$ angular resolution over this field, and covers the energy range from ~ 0.1—2.5 keV. The mirrors would be ROSAT-sized, with a comparable collecting area and focal length, as these are the largest that are viable, within current Congressional fiscal constraints. (It is judged that the largest missions that will be considered over the next 10 years are “Delta-class”.) There are several proposed X-ray missions currently supported by NASA: XTE, AXAF, XMM, and ASTRO-E; however, none of these (or the ongoing missions such as ROSAT or ASCA) combine a wide field of view, $\simeq 10''$ angular resolution and $\simeq 5$ eV energy resolution (energy resolutions are quoted at 6 keV unless otherwise stated).

The uniqueness of such a mission compared with existing proposed missions is demonstrated by the following considerations: a) AXAF CCD detectors obtain sub $1''$ imaging but provide only 100 eV energy resolution with only about a $1' \times 5'$ field of view (FOV); b) SRG which has limited imaging ($2'$) capabilities and whose spectral resolution is 200 eV for extended sources (this improves to ~ 10 eV for point sources); c) XMM has $30' \times 30'$ FOV but only moderate energy (100 eV) and moderate imaging ($30''$) resolution; and d) ASTRO-E with excellent (7 eV) energy resolution but only $1'$ angular resolution and a $5' \times 5'$ FOV.

It has been argued that since bright sources are well separated, they can be measured by ASTRO-E, and if a source isn't bright enough, it will not be necessary to have 5 eV energy resolution. Further, AXAF will provide the high spatial accuracy and moderate energy resolution to allow for the study of faint objects at the requisite exposure times. Neither of these arguments stand up under scrutiny, however. First, with deep exposures ($\sim 2 \times 10^5$ s), many objects will produce enough counts so as to require 5 eV energy resolution, but $10''$ angular resolution is required to avoid source confusion problems. Second, there are many cases (cooling flows in cluster centers, galaxies, supernova remnant knots, x-ray sources in external galaxies) where the objects are bright and yet the detailed imaging required will be well beyond the angular resolution of ASTRO-E.

Furthermore, as can be seen in the above summary of properties, ASTRO-E and AXAF will have severely limited fields of view so that even bright nearby sources will require enormous amounts of observing time. For example, a full mosaic of the Perseus cluster (about 1 degree in diameter) has not yet been done with ASTRO-D (ASCA). We also remark that some may complain that the design presented here (with ROSAT-sized mirrors) does not provide enough area, but we must be cognizant of fiscal reality, which does not allow us to consider larger systems at this time. By employing the use of deep pointings, however, truly outstanding science can indeed be done with ROSAT-sized optics with a 1-degree field of view.

For brevity, we will only present detailed discussion of a few areas of X-ray astronomy, but we emphasize that this concept touches upon, and should lead to, great advances in nearly all areas of X-ray astronomy. Beside giving examples of outstanding science that can be done with our proposed satellite, we present a viable mirror design, show that the technology is in hand to fabricate the mirrors, and demonstrate that advances in detector technology should lead to the ability to fabricate large (on the order of 500×500 pixels) arrays in the coming years.

2 Scientific Motivation

2.1 Clusters of Galaxies and Deep Surveys

How clusters of galaxies form and evolve has been one of the key questions of modern astrophysics. The discovery of a diffuse intra-cluster gas (intra-cluster medium; ICM, hereafter) and the fact that this gas contained detectable quantities of heavy elements led to the following set of questions: what is the origin of the ICM? What is the origin of the heating of the ICM? What is the origin of the heavy elements in the ICM? And, what is the mass content (visible, baryonic, non-baryonic, etc.) and distribution that binds clusters? Intial mass estimates of the ICM indicated that galaxies would have to lose about 1/2 or more of their mass to the intra-cluster medium.

The heavy elements in the ICM probably come from supernovae, but did the supernovae eject all the material that makes up the ICM or only the heavy elements? In the former case large quantities of the galactic interstellar medium (ISM) are required via supernova driven galactic winds. However, it may be that the supernova winds only carry away the heavy elements produced in the supernovae. Naively, in either case, as long as the heavy elements were primarily driven from the galaxies by supernovae, then there should be a negligible gradient of the abundances in the ICM, as all galaxies will contaminate the ICM regardless of their location in the cluster. Yet, ASCA results indicate that in at least some clusters, a gradient exists and in the Perseus cluster the distribution may not even be radially symmetric. The radially symmetric case can be explained by assuming ram pressure stripping plays an important role and since the gas and galaxy densities are higher in the center of clusters, the enriched material in the center will get richer (than the lower density outer regions). To measure the range in temperatures in the central, cooler regions, an instrument with high energy resolution, a wide field of view, and moderate angular resolution such as WFXIS will be needed. For a case like the Perseus cluster and probably A2256 as well, the system was formed by a coalescence of two or more smaller clusters and hence the "patchiness" observed in the elemental abundance distribution in the Perseus cluster is a result of a recent merger.

The masses of clusters and the distribution of masses is extremely interesting: there is every indication that the mass to light ratios of clusters is well over 100 and that the dynamical mass is not distributed as the light. This means that the dark matter is tied neither to the galaxies nor to the hot ICM, and hence suggests that it is non-baryonic. A few nearby clusters have been measured and will continue to be measured with the missions that are planned, yet when the clusters approach a redshift of 0.1–0.2, of which there are hundreds detected with the ROSAT all-sky survey (with a $\sim$ 300 seconds integration time), the extents are on the order of 1 arc minute.

Currently there is evidence that suggests there is luminosity evolution of clusters at redshifts as low as 0.2 to 0.5 and that the number of X-ray bright clusters decreases beyond a z of 1. ROSAT in its last year will provide some deep HRI exposures which will detect these objects, but there will be no energy resolution available. Since optical identifications are difficult for distant clusters, this means that the crucial redshift information will be lacking, to say nothing of the lack of measure of elemental abundances and temperatures. Therefore a deep sky survey with WFXIS is needed to provide a complete sample of objects with the crucial spectroscopy information. Based on observations with ROSAT, a deep sky survey with 60 pointings with 2×10^5 seconds per pointing will yield over 50,000 sources, with at least 10,000 yielding high quality spectra, and approximately 1,000 clusters will be detected out to a redshift of nearly 3 (assuming no evolution), and there will be approximately 20 to 100 clusters in this complete sample that will be intense enough to allow for elemental abundance determinations (ASCA measurements have shown that clusters out to a redshift of 0.37 have measurable abundances). By measuring spectra and extents it will be possible to distinguish clusters from AGNs and high redshift QSOs. Hence, this survey will also prove invaluable for the study of these cosmologically interesting point sources. Finally we note that models of the universe must tie together the COBE observations with models of how clusters form and the existence of cold and hot dark matter. Currently theorists seem to favor cold dark matter models but the case is far from closed, and only further observations will properly constrain these current theories.

In conclusion, the study of clusters of galaxies and deep surveys go hand in hand, and WFXIS will allow X-ray astronomy to make important contributions to our understanding of the formation and evolution of the large scale structure of the universe, the existence of dark matter, and the importance of dark matter in the evolution of the universe.

2.2 Studies of Supernova Remnants and the ISM

Beginning with work in the early 1970s, it has been understood that the energy input from supernova explosions is of central importance in shaping the interstellar medium (ISM). Supernova explosions are the primary source of kinetic energy for the interstellar gas, and are responsible for establishing and maintaining the hot phase of the medium. The effect of supernovae on their surroundings almost certainly plays a key role in regulating the process of star formation. Finally, supernovae play a vital role in the chemical evolution of the galaxy.

Supernova remnants (SNRs) provide us with an ideal opportunity for study of these processes. Initially, SNRs serve as direct probes of the structure of the ISM with which supernovae interact. It is possible to look at SNRs at various stages of their evolution, and compare them directly with models of the ISM. Perhaps of greater importance, however, is the fact that SNRs allow us to conduct detailed studies of the physical processes at work in the interstellar medium. For example, SNRs have been of vital importance to observational tests of models of astrophysical shock waves—models that are finding application in a wide variety of astrophysical concepts. Supernova remnants also provide a unique means for the study of such problems as the physics of collisionless shock waves, cosmic ray acceleration, destruction rates of dust in hot gas, and supernova elemental abundances and rates.

The hot interiors of SNRs are copious emitters of X-rays, and X-ray observations have been central to our growing understanding of SNRs and their role in the ISM. SNRs have been studied at X-ray wavelengths with excellent spatial resolution, most recently by ROSAT, and with some spectral resolution by ASCA and the *Einstein* SSS. While a tremendous amount has been learned from this work, it has also been frustrating in many respects. Low spectral resolution images returned by the *Einstein* IPC and the ROSAT PSPC show significant organized structure in X-ray hardness ratios from remnants. Unfortunately, these data, at best, give rough ideas about temperature and column depth, and even these inferences are made uncertain by questions about nonequilibrium effects, sputtering of dust, and other factors which affect the X-ray emissivity of the plasma. As a result, there are a number of fundamental questions which have been raised, but not conclusively answered, by existing data. An example of such a question is the importance of thermal evaporation in the interiors of SNRs. Thermal evaporation plays a fundamental role in a class of ISM models. Observations of bright X-ray emission in the vicinity of radiative shocks have been interpreted as evidence of such evaporation. Whereas others have instead emphasized the role of shock reflection in accounting for the X-ray brightness at the limbs of

SNRs, and called into question most of the assumptions upon which the picture of "evaporation-driven" SNRs is based. This distinction is crucial to further progress in our understanding of the SN/ISM connection, but to date both camps claim success in explaining the X-ray structure at the edges of SNRs. It seems likely that both models will persist until the distribution of ionic species within the hot interiors of SNRs can be answered directly with spatially resolved X-ray spectroscopy.

The WFXIS concept is an instrument that can provide good spatial resolution and excellent spectral resolution. With it, one can imagine making spatially registered images in different individual spectral lines, with sufficient spectral resolution to separate the contribution of a single ionization stage of a single element. An especially valuable tool is a map of a line ratio. For instance, the triplet to singlet or the 3p to 2p intensity ratios of O VII (22.1+21.8 or 18.63 to 21.6 $\AA$) are sensitive to electron temperature. The ratio of O VIII to O VII resonance lines at 654 eV and 574 eV depends on the ionization state of the gas, which in a supernova remnant translates into the product of density times the time since the gas was shocked. The ratio of the Fe XVII line at 825 eV to the O VIII line reflects the abundance ratio of iron and oxygen. Thus a series of line ratio maps of an SNR provides nearly direct maps of crucial physical quantities. Some of these ratios have been measured in the spectra of entire remnants with the *Einstein* FPCS, though not with high statistical accuracy. Because the 500–1200 eV spectral range contains the strong lines of of He- and H-like oxygen and neon, along with a forest of strong lines of Fe XVII–XXIV, it presents a host of opportunities for good diagnostic ratios, but it requires a spectral resolution of order 5 eV to separate the lines. This resolution also provides velocity information for the youngest SNRs. A resolution of 5 eV corresponds to 2300 km/s for O VIII, 1800 km/s for Fe XVII, 1300 km/s for the Fe XXIV 2s-3p line, or 800 km/s for Si XIII. It should be possible to centroid the emission from an individual line to a fraction of this resolution. Thus, for instance in Cas A or Tycho, one might measure the velocity of an individual X-ray knot to place it within the remnant in 3 dimensions and to study the reverse shock and its instability. At lower energies, it should be possible to detect K lines of carbon and nitrogen, along with some of the lower ionization states of Mg, Si, S and Fe. Judging from the DXS spectra, blending may be severe below 1/4 keV, but it should still be possible to choose a few bands dominated by individual lines.

The capabilities of WFXIS would allow us to fully exploit these diagnostic capabilities. It offers angular resolution which is well matched with the observed scales of X-ray structure in galactic SNRs, along with sufficient sensitivity to utilize its spectral sensitivity close to the full spatial resolution of the instrument. One can watch the ionization level rise behind a shock as the cumulative exposure to the hot electrons increases; one can look for lagging elements that are indicative of the rate that, for example, silicon and iron are being sputtered from the dust; one can examine the distributions of different elements in the ejecta of young SNRs; for shocks of various strengths, one can study the spatial separation between the Balmer-dominated fronts and the onset of x-radiation of particular ions, potentially disentangling the effects of shock deceleration and potential non-Coulomb heating of the electrons; one can study the inner edge of the bright x-ray emission interior to the optically bright rims of the Cygnus Loop to see whether the ionic structure confirms the suggestion that there is an inward pointing shock (reflected off the dense regions where the optical emission is bright) at that location. In short, it is difficult to overstate the impact that spectral imagery would have on x-ray studies of supernova remnants. And one of the best features is that the relative intensities of the lines are not the most fundamental feature; which ions are where contains the bulk of the information and makes the value immune to the problems of spectral modelling codes.

As an indication of count rates, a reasonably bright portion of the Cygnus Loop produces about 0.3 cts/s per square arcminute with the ROSAT PSPC. For a similar WFXIS effective area, this means 1000 counts per $10'' \times 10''$ pixel in a 10^5 second integration. Based on typical model calculations, the four brightest lines would each have over 100 counts per pixel. Bright young SNRs such as Cas A or Tycho would give much higher count rates. SNRs in nearby galaxies are also attractive targets, as several could be observed at once within the 1-degree field. N132D in the LMC is an O-rich remnant analogous to Cas A. Its brightness is about 0.01 photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the O VIII 654 eV line. This would be spread over about 100 $10'' \times 10''$ pixels, so a collecting area of a few hundred cm^2 would give a high quality image in only a few thousand seconds. An integration of 30 ksec would provide good images (above 100 counts/pixel) in all the lines down to an order of magnitude fainter, including O VIII Ly β and lines of neon and Fe XVII.

There is also diffuse X-ray emission of galactic and extragalactic origin. The galactic portion arises from stellar coronae, discrete bubbles of hot gas in interstellar space (one of which appears to surround the solar location), hot zones in (or bulging out of the plane into) the lower galactic halo, and possibly from a phase of hot gas pervading much of the medium. This diffuse emission has been studied with excellent spatial resolution, again by ROSAT, but there has been almost no spectral information obtained thus far. DXS, on one flight, obtained one spectrum of a broad swath that contained several contributors from the list above. The resolution was sufficient to show that much of the emission is in lines, confirming the thermal origin, and to show that plasma emission codes need serious attention before being taken too seriously.

Much of what can be said for supernova remnant studies applies as well to studies of the soft X-ray background. The individual bubbles of Orion-Eridanus, Monocerous-Gemini, the North-Polar Spur, etc. can be studied in much the same way. In the case of Orion-Eridanus, however, with the Orion OB association energizing the bubble, it should also offer the unique possibility of studying the wind/SN bubble ionization structure, potentially leading to identification of the wind termination shock location and providing a measure of the degree of thermal evaporation taking place. This would be a major advance over present knowledge of the state of such bubbles, and allow a much better chance of modelling their evolution at great age. The latter is critical to estimating the filling factor of such ancient defunct superbubbles in interstellar space. Numerous other questions await this kind of observational attention as well. It is time we were able to use observed lines arising from specific components to understand the differences between apparently halo hot gas and that of the Local Bubble. X-ray shadowing experiments, using shadows of clouds at measurable distances, will be far more reliable when they can be based on observations of a single emission line rather than emission codes with uncertain line strengths. The potential ability to trace a halo emission feature boundary down into the galactic plane, to attach it to a causative agent in the plane would be stunning. And then there is the Local Bubble itself. We do not know for certain that much of its emission is not non-thermal, though excellent arguments have been presented against all known mechanisms. We do not know that its spectral character does not change drastically from one place to another, though it does not show up in the broad band emission ratios. We do not know what elements dominate the emission, much less their ionization stages. As a result, we do not know whether the dust is surviving nicely in a 10^6 K environment, or was long ago destroyed. One of the great puzzles is the innocuousness of the hot gas interaction with clouds. If the clouds are immersed in hot gas, should there not be some sort of boundary layer that shows up as enhanced EUV or soft X rays? So far, there seems to be no sign of this. Perhaps with ion resolution, a trace element that contributes only modestly to the total emission will make a striking display at such a boundary. If so, we can then begin to model such boundaries with some confidence, rather than the speculations we have been forced to endure thus far. As emphasized at the Elba meeting honoring George Field last summer, our whole understanding of the diffuse ISM is up for grabs at the present, with only future observations of this type to prevent our going on counting angels on pinheads.

3 Technical Description

3.1 Prologue

The goal of this mission is to have as much X-ray collecting area as seems fiscally possible coupled with a relatively large field of view and an energy resolution high enough so as to achieve the outstanding scientific goals that will not be met by currently planned X-ray missions. Our ideal system has many thousands of square centimeters of collecting area covering the energy range up to about 8 keV and provides a non-vignetted field of view of about 1-degree diameter, but this is neither physically nor financially viable at this time. The graze angle at 8 keV for gold is less than $30'$ which limits the effective FOV to about 5 arc minutes at optimal area and angular resolution. Even AXAF has less than 150 cm^2 at 8 eV and new projects as large as AXAF are not currently being considered as fiscally viable projects.

3.2 Mission Concept Description

Therefore, the design for this system is the following: ROSAT dimension and ROSAT-sized mirrors. The mirror figure design for ROSAT will be modified to yield the optimal combination of collecting area, angular resolution, solid angle and vignetting effects. From reference 1 it can be seen that, by placing the detector slightly closer to the mirror system than the optimal on the axis focal point, $20''$ resolution can be achieved out to a $15'$ radius with a standard Wolter I design. Based on ray-tracing studies done by Hughes-Danbury Optical Systems (HDOS) (see below) achieving $10''$ with a planar detector is possible out to $15'$ with a hyperbola/hyperbola design, and further improvements should be possible with a more advanced design. Another way to reduce the off-axis blur is to realize that the focal surface is a gaussian of revolution, and given the segmented nature of the devices we propose to use (see below), it is conceivable that they be specially designed to step-wise follow this surface, which will give another factor of two in collecting area. Other avenues to explore are a shorter mirror, reducing the high energy cutoff/increasing the graze angle, or increasing the diameters and focal length of the system. Given the likelihood that missions of the size of ROSAT seem to be about the limit of the current funding envelope, we do not consider a larger system a viable option at this time.

Keeping to the ROSAT envelope, these mirrors have about 1000 cm^2 collection area on an axis at 0.2 keV and about 400 cm^2 at 1 keV which then falls steeply beyond 2 keV where the effective area is about 100 cm^2. The focal length is about 2.4 meters and the "plate scale" is therefore about 120μm$/10''$. At the focus of this optical system we will place a detector which will cover the designed FOV of 1 degree in diameter. This detector will have a pixel size of about 100μm (to slightly oversample the image) and will be made up of a 500×500 array of either microcalorimeters or superconducting tunnel junctions. A key motivation to put the optics fabrication portion of this project in motion soon is that this would provide continuity with the AXAF optics personnel. This would greatly reduce the costs of the optics as opposed to allowing the expertise lapse and restarting a mirror program about 5 years from now.

Here we provide a condensed version of the results of the HDOS preliminary investigation of the feasibility of producing a 10-arcsecond blur circle grazing incidence telescope, starting with ROSAT-sized blanks: to date we have found that it is feasible to achieve the desired performance over at least a 30-arcminute diameter field of view, but further work can be done to optimize the performance over a larger field of view. Even the less than optimal current design is capable of achieving $20''$ over a 1-degree diameter field. Furthermore, a review of the ROSAT element dimensions and the AXAF equipment indicates that most of the AXAF equipment at HDOS is useable with only minor modifications.

4 STJ Versus MC Tradeoffs

In the past 10 years the development of solid state devices for use as X-ray detectors has blossomed due to advances both in technology and in our understanding of condensed matter physics at low temperatures. Broadly, there have been two types of detectors developed: those that detect a temperature rise in an absorber and those that use the collection of quasi-particles that are produced in a superconductor. The microcalorimeter (MC) approach has produced better energy resolution (about 7 eV at 6 keV) than the STJ approach (about 40 eV at 6 keV). But, based on the underlying physics involved, there are good reasons to believe that ultimately 5 eV at 6 keV resolution will be achieved by STJs. The fabrication techniques for MCs are mature enough that a 6×6 array with pixel sizes of about 0.5 mm is being planned for the ASTRO-E mission, and to our knowledge no STJ system has matured this far. These MC devices generally require colder temperatures (10–100 mK) than STJ systems (50–2000 mK). The photo-lithography techniques that are used to make STJs have been well developed and as

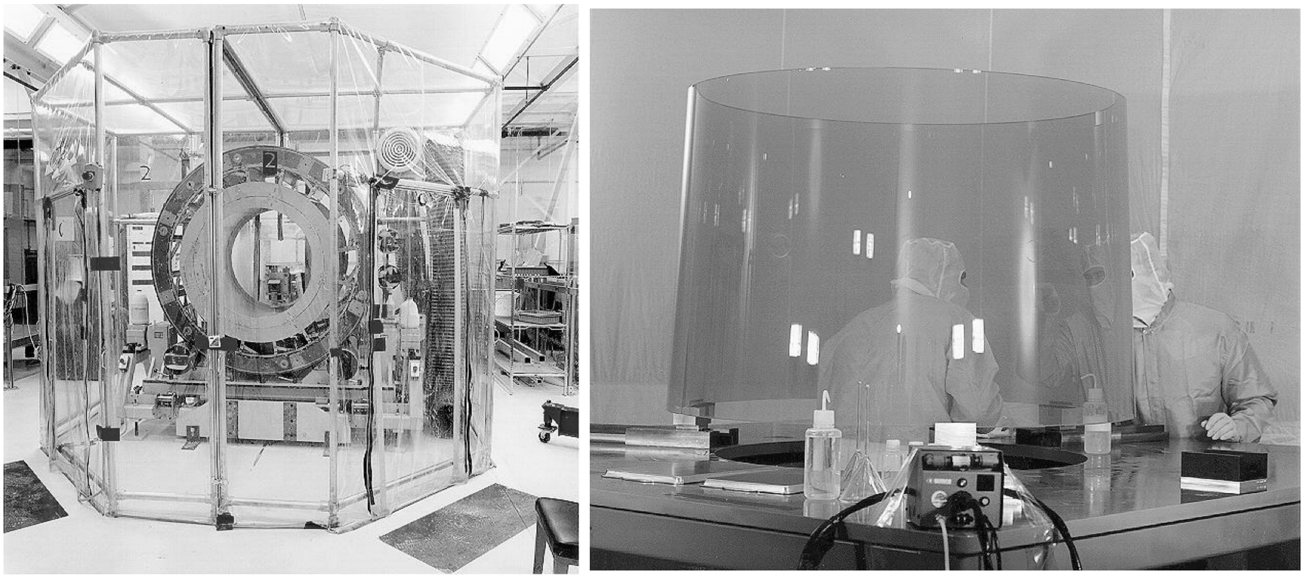

Figure 1: At the HDOS plant: AXAF optic (P3) in its glass support fixture on the Automated Cylindrical Grinder/Polisher (left); the largest AXAF hyperboloid undergoing final inspection.

such lend themselves naturally to being scaled up from a few pixels to a 500×500 pixel device, but the fabrication of large arrays of MCs should also be feasible. The readout electronics required for the MCs seems a more difficult problem than for the STJs, since the charge signal is more readily stored and transported than a thermal signal. The advantage for high T operation only comes into play when there are large arrays such as envisioned here. Then, since it will be necessary to integrate at least some of the electronics for the large arrays onto the detector chip, the power dissipated in the array will no longer be negligible.

To summarize then: the MC detectors currently have the best energy resolution but may be more difficult to fabricate into devices (arrays plus the associated readout electronics) than STJs.

4.1 MC Design Considerations

Here we briefly review the concepts involved in the MC design and then describe the path that is currently the most likely path to be followed to produce a 500 × 500 pixel detector.

As implied by the name, microcalorimeters measure a temperature rise in an absorber. There are three types of underlying physical principles that have so far been used to measure the temperature rise: the change in resistance, the change in capacitance, and the change in the number of hot electrons that can penetrate a properly biased tunnel junction barrier. In some sense this last mentioned device could be considered a hybrid between the STJ concept and the MC concept, but the key point is that a rise in temperature is measured; hence, we classify these hot electron SIN devices as calorimeters. That a temperature rise must be measured definitely places a constraint on the temperature of the absorber, and typically these systems are operated at 50–100 mK. Theoretical arguments suggest that resolution as good as 1 eV may be achievable by these types of devices[2,3,4,5,6].

The resistive microcalorimeter has been pioneered by the GSFC/Wisconsin group and so far has produced the best results (7.3 eV, reference 2). These devices are currently made by fixing an absorber to a semiconductor thermistor which is then read out with a junction field effect transistor (JFET) amplifier. The use of these devices as cosmic X-ray detectors requires that they be fabricated with some kind of thermal isolation to slow the transfer of heat out of the detector to the millisecond time scale. Furthermore, the device must have a window that transmits X rays but prevents the transmission of infrared and optical photons. These steps have been carefully considered and a viable rocket payload has been designed and is nearly built. Arrays of 2×18 have been built and a 6×6 array using this basic concept is being designed for ASTRO-E. Standard photo-lithographic and etching techniques have been used to fabricate these devices and it should be feasible to use this technology to fabricate even 500×500 pixel arrays of the requisite (for the concept study proposed here) 100μ size. However, the readout electronics associated with these devices currently require one channel per pixel, so it is not possible to read out such an array with existing methods. Development of a new readout system is needed that will alleviate this problem. For example, two thermometers could be placed on each pixel and connected in series in rows and columns to reduce the number of readout channels required to one per row and column. But this design gives up a large part of the energy resolution improvement that could otherwise be gained from the small pixels.

A solution to avoiding the use of many JFETS would be to develop a new thermometer technology that is compatible with multiplexed readout on the detector chip, which will allow it to operate at very low temperatures, and not dissipate too much power. One possibility is to use kinetic inductors[6,7] where the temperature is sensed with an inductive pickup. These devices operate under the principle that the inductance formed by two layers of different superconductors diverges as the lower critical temperature is approached from below. A choice discussed by Osterman et al. would operate at about 0.3K. This type of sensor is a good match for a SQUID readout, and SQUIDs can function well at the detector operating temperatures. The power requirement for existing dc SQUID systems is prohibitive for a long space mission with currently available dewar/refrigerator and dewar systems: one NIST SQUID requires about 1 micro-watt, which for 25,000 pixels translates into a requirement of heat dissipation of 0.25 watts at the detector temperature. There are two avenues for further improvement in heat load requirements areas, however: (a) these devices could be made to work at temperatures approaching 500 mK, and (b) it should be possible to reduce the power requirements of the SQUIDs by using flux flow transistors which are basically ac SQUIDs, i.e. the only current that flows is when there is a signal. And it is plausible that the entire 25,000 flux flow transistor array would only use 1μ watt.

Another device to consider is one that uses an entirely different approach from those above: the hot electron/SIN detector system. On the "N" portion of the device, an absorber is placed and this is connected to an "S" layer by an insulator. The current device that has been fabricated might not have been made of the optimal components, but it was one that could be readily fabricated: $Cu/Al_2O_3/Al$. The copper was connected to a lead (Pb) contact that confines the heat but allows for electrical contact. The SIN device is read out relatively easily with a SQUID amplifier and the entire system is run at 10 mK. These devices may not require suspension as the hot electron will not flow into an insulating substrate and even if suspension is necessary the connection to readout electronics will be relatively easy compared to the thermistor-type device. The best achieved resolution has been 20 eV with this device, but it is theoretically possible to approach 1 eV energy resolution. The devices have been currently produced by electron beam lithography and triple angle evaporation, and it should be possible to make two dimensional arrays of these devices with the associated electronics. And, as above, if the dc SQUID readout were replaced with a flux flow transistor readout, the power requirements would be reduced. It remains to be seen, however, whether the operating temperature of 10 mK must be maintained and whether space refrigeration systems can be built to handle even as small a heat load as 1μ watt.

In conclusion, advances continue to be made in the area of microcalorimeters. The best ones to date have excellent energy resolution. Further advances in reducing the power needed for SQUID readouts by replacing them with flux low transistors, developing devices that work at higher temperatures, and improving space refrigerators should lead to the production of a 500×500 array device. At this time the most likely candidates are devices made out of the kinetic inductors or SINs.

4.2 STJ Design Considerations

Here we briefly review the concepts involved in the STJ design and then describe the path that is currently the most likely path to be followed to produce a 500×500 pixel detector. The basic physical principle underlying the superconducting tunnel junction detector is that absorbed X rays produce quasi-particles (electrons) that are then recorded as a charge pulse. Simplistically, the theoretical energy resolution is determined by the number of initial quasi-particles that are produced which leads to theoretical energy resolutions of between 1 and 5 eV at 6 keV. One paper claims that charge amplification in the STJ circuit will lead to degraded resolution[8]; however this has not been proved by experiment yet, and charge multiplication can be suppressed, if necessary, by tuning the tunneling time, detector area, and insulating layer thickness.

There are two basic techniques that have used STJs as soft X-ray (~ 0.25–10 keV) detectors: (a) absorption directly on a single STJ where the quasi-particles produced in the STJ directly lead to a current pulse (assuming a voltage biased circuit); (b) a device in which quasi-particles are produced in a superconducting absorber that is connected to a STJ. The STJ superconductor is made of a material with a lower band gap than the absorber so that the quasi-particles that are produced in the absorber naturally flow into the STJ superconductor. A third scheme has been suggested for detection of X rays above the energy of interest here. This technique uses a crystal to absorb the X rays which are converted to phonons. The phonons break up Cooper pairs in STJs that have been grown onto the crystal. The quasi-particles then produce the requisite current pulse and the amount of current from each STJ allows the localization of the initial X-ray absorption event.

The direct absorption technique has been used to produce energy resolutions at 6 keV as low as 53 eV (reference 9) with the use of single Nb/Al/AlO$_x$/Al/Nb junctions. These junctions have different responses in the upper and lower superconducting layer to X rays as only the lower (the top layer is the direction of the incident X-ray flux) layer is coupled to a Si substrate. These devices typically have superconducting layers that are about 0.15μm thick. This thickness is not enough to efficiently stop ~ 2 keV X rays, as about 1.5μm is necessary. There is a way to improve the absorption. This is by using a multilayered-STJ (MSTJ)[10]. This device is essentially a stacked set of STJs in series and it can be made 2μm or more in thickness which is amply thick enough for efficient ≤ 2 keV detection. The MSTJ scheme also reduces the overall capacitance and inherent noise of the detector. All the STJ devices must be operated at about 0.2T$_c$ which means, for a Nb junction, temperatures near 1–2 keV are possible, and even higher operating temperatures could be achieved with NbN junctions. MSTJs are not commercially produced, as of yet, and the author with co-workers has been developing the technology only over the past 2 and 1/2 years. Also an Italian group[11,12] has shown that viable MSTJs can be produced, and the author's group is in the process of testing these devices as X-ray detectors.

STJs and MSTJs are produced via photo-lithography, etching, and anodizing techniques. Several devices at a time are generally made on a single Si wafer, but the separations are too large to use as an array device. But there is a way that an array could be fabricated: in reference 12 it was shown that it is possible to planarize an entire Nb/Al/AlO$_x$ single flux quantum circuit using Chemical Mechanical Polishing (CMP). After the use of CMP, one is left with a planar dielectric surface with contact pads to the superconducting circuitry below at desired positions. Since the dielectric and the contact pads form a single, smooth surface, another complete layer of superconducting electronics can be fabricated on the surface with the proper electrical contacts made to the lower circuit through the proper geometric alignment with the contact pads. Thus, one could contemplate the fabrication of such a structure with a high density of wiring contacts in the bottom layer and a 500 × 500 array of contact pads upon which an STJ detector array could be deposited. The detector array could then be capped with a thin common ground layer of superconductor. In this way, each pixel could be separately addressed through the buried wiring without "shadowing" the pixels.

In the other major approach, fragile absorber/STJ systems of Al/Al/AlO$_x$/Al STJ attached to Sn have produced about 60 eV energy resolution[13]. A more robust device made up of a Al/AlO$_x$ junction sandwiched between 0.2μm layers of Nb absorber has produced the record resolution at 6 keV of 36 eV (reference 14). These devices currently run at 50 mK, but 100 mK is possible with new materials. The technique allows the positioning of the X-ray event by comparing the signal in several STJs. As a result the STJs need only be spaced at approximately 10 times as far apart as the desired spatial resolution. This means that the 500 × 500 array can be replaced by a 50×50 array of absorber/junctions which would reduce the number of electronic readouts by a factor of 100. This is a decided advantage for large arrays. The readout electronics for these systems could be the same as would be used with the direct absorption devices. Since the operating temperature is 50–100 mK, $\sim 2\mu$W is a tolerable heat dissipation load allowed. Therefore on a 50×50 array, it should be possible to meet this requirement. In summary, the technology exists, in theory, to produce STJ (or MSTJ) devices that would provide us with a 500×500 pixel array (or the equivalent) to cover 1 square degree with better than $10''$ angular resolution. The best resolution achieved to date is 36 eV. Improvements in energy resolution are expected since more work can be done to reduce the noise in the readout system as well as the inherent noise in the detectors.

5 Summary and Conclusions

We have described a wide field X-ray spectroscopy experiment mission. The mission is scientifically well-motivated, and can be sized so as to fit within the confines of current fiscal constraints, which suggest that Delta-class missions are the largest that NASA will consider starting in the coming decade. The mission would provide great advances in nearly all areas of X-ray astronomy from the most distant objects known such as QSOs and clusters of galaxies to the interstellar medium and supernova remnants. We have also shown that the optics requirements lead to a viable telescope design and that fabrication techniques exist that would be greatly reduce costs if employed soon. Finally, we have shown that detector development work has made great advances in recent years so that the fabrication of devices with many pixels is in the offing.We conclude that such a mission as described here should be strongly considered as part of NASA's long range plans.

6 Acknowledgements

We thank the following people who provided input to this project: D. Cox, J. Hester, W.T. Sanders III, D. McCammon, C. L. Sarazin, J. Raymond, and, P. Reid. Most of the ray-tracing used in this investigation was performed by Kristin Lewotsky. The modeling was done by Bill Zmek. The determination of the feasibility of using AXAF handling, metrology, and fabrication equipment was made by Joe Cerino and Dan Dunn.

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