Energetic X-ray Imaging Survey Telescope (EXIST)

J. E. Grindlay

Harvard Observatory
Cambridge, MA 02138

T.A. Prince

Caltech
Pasadena, CA 91125

N. Gehrels and J. Tueller

Goddard Space Flight Center
Greenbelt, MD 20771

C.J. Hailey

Columbia University
New York, NY 10027

B.D. Ramsey and M.C. Weisskopf

Marshall Space Flight Center
Huntsville, AL 35812

P. Ubertini

Istituto di Astrofisica Spaziale
I-00044 Frascati, Italy

G.K. Skinner

University of Birmingham
Birmingham B15 2TT, UK

ABSTRACT

We have begun to study a mission to carry out the first high sensitivity imaging survey of the entire sky at hard x-ray energies (5-600 keV). The Energetic X-ray Imaging Survey Telescope (EXIST) would include 2-4 large area coded aperture telescopes with offset fields of view allowing total exposures of $\gtrsim 500$ ksec and flux sensitivities below 1 mCrab over the full sky in a year with time resolution from msec to months for each source as well as high spatial and spectral resolution for sources, transients and gamma-ray bursts. A pointed Observatory phase, with the telescopes co-aligned, would follow and achieve still greater sensitivities and temporal coverage, allowing the detailed study of virtually all classes of accretion sources (cataclysmic variables to quasars) as well as diffuse galactic emission. The baseline concept originally proposed for the detector is a modularized array (4×4) of Cd-Zn-Te crystals (6.25 cm^2 each, or 100 cm^2/module). An array of 5×5 modules, or 2500 cm^2 total detector area with 1.25 mm spatial resolution, would constitute the focal plane readout of each of the 4 telescopes. A brief description of the proposed detector and telescopes and predicted backgrounds and sensitivity is given. An alternative detector concept, employing a hybrid (stacked) gas counter (2 atm Xe/TMA, optical avalanche chamber) and imaging phoswich scintillator (NaI/CsI), is also described and tradeoffs presented.

Keywords: high energy astrophysics; x-ray/gamma-ray detectors; coded aperture imaging; satellite missions

1. INTRODUCTION

In response to the 1994 NASA solicitation for proposals for new Mission Concepts for astrophysics, we proposed to carry out a two year study of a mission to carry out the first imaging survey of the entire sky in the relatively poorly explored hard x-ray band (5-600 keV). The *Energetic X-ray Imaging Survey Telesope (EXIST)* mission was selected for study and is now being investigated so that any flight opportunity with a small-intermediate class (e.g. Medium Explorer, or MIDEX) mission could be achieved on a relatively short timescale. In this paper we first describe briefly the scientific need for a mission such as EXIST, the overall mission concept and Survey and Obseratory modes of the mission, the detector and telescope concept being studied, and the type of spacecraft needed for such a mission.

2. NEED FOR HARD X-RAY IMAGING SURVEY

A critically important region of the astrophysical spectrum is the hard x-ray band, from ~5-600 keV. In this band, an unusually rich range of astrophysical processes occur in both compact and diffuse sources. The band includes the transition from primarily thermal objects – either optically thin, like supernova remnants or galaxy clusters, or optically thick, like the blackbody emission components of high luminosity x-ray binaries (all of which are generally still detectable at 10 keV) – to objects which are primarily non-thermal, or at least display significantly Comptonized spectra. Examples of the very hottest thermal plasmas directly measurable in astronomical objects, the $\sim10^{8-9}$K coronae around or above accretion disks in compact binaries and active galactic nuclei, are best studied in this hard x-ray band. In particular, the rapid pace of discovery of hard x-ray emission from black hole (BH) binaries (the so-called x-ray novae) as well as relatively low luminosity neutron star (NS) binaries (the bursters) have shown that hard x-ray spectra offer particularly direct clues to the study of black holes and accretion flows onto BHs vs. NSs.

Surprisingly, for such a pivotal region of the astronomical spectrum, the hard x-ray universe is still relatively unexplored. Only one survey (HEAO-A4, in 1978-80) has been carried out in this energy range but at relatively low sensitivity and without the benefit of imaging. Yet the scientific impact of survey missions on astronomy is amply demonstrated at X-ray wavelengths by ROSAT and at IR wavelengths by IRAS. In the hard X-ray and low-energy γ-ray bands (5 - 600 keV), a sensitive *imaging* sky survey is yet to be carried out. The HEAO-A2 and A4 instruments carried out the first all-sky observations above 10 keV, achieving a sensitivity of several mCrab at 2-10 keV energies (A2) and 20-100 mCrab at energies 13-180 keV (cf. Figure 1a). The French coded aperture telescope SIGMA on the Russian GRANAT satellite demonstrated the power of wide-field imaging in the ~35 - 300 keV band but it was not extremely sensitive and observed only a small fraction of the sky (primarily the Galactic Center). The OSSE instrument on the Compton Gamma Ray Observatory (CGRO) has significantly better sensitivity than either HEAO-A4 or SIGMA above 100 keV, but does not cover the range below 100 keV well, and its relatively narrow field of view and CGRO pointing constraints has precluded large-area surveys. The upcoming (Fall 1995 launch expected) X-ray Timing Explorer (XTE), with its sensitive broad-band coverage (2-200 keV), also lacks the survey capability as well as 511 keV coverage.

Finally, a survey mission which incorporates very wide field of view detectors and telescopes can also address the general objectives mentioned above for broad temporal coverage: from short bursts to transient sources. The BATSE detectors on CGRO have shown the power of monitoring for both transients and of course the detailed study of gamma ray bursts. A wide-field survey mission can contribute greatly to both of these major topics in gamma-ray astronomy.

3. OVERVIEW OF MISSION CONCEPT

We have begun to study a mission which would conduct the first high sensitivity all-sky imaging survey (5-600 keV) with a wide-field coded aperture telescope. Grazing incidence telescopes, with response limited to $\lesssim 80$ keV and very small fields of view, cannot do this. The Energetic X-ray Imaging Survey Telescope (EXIST) mission characteristics and baseline instrument, as proposed and accepted for study in the recent NASA solicitation for Mission Concepts, are summarized in Table 1.

Table 1. EXIST Mission Characteristics	
Energy Range	5-600 keV
Angular Resolution	10 arc minutes
Field of View	Survey: $80° \times 6°$ ($\leq$40 keV); $80° \times 20°$ ($\geq$80 keV) Pointed: $20° \times 6°$ ($\leq$40 keV); $20° \times 20°$ ($\geq$80 keV)
Orbit	LEO (nominal 30° inclination)
Survey	$\sim$50% sky coverage each orbit Full-sky twice per year 0.5-1×10^6 sec per year effective source exposure Survey Sensitivity: $<$ 1 mCrab (5-200 keV)
Scan Motion	ROSAT-like scan once per orbit
Baseline Instrument Parameters	
Number of Telescopes	4
Detectors	CdZnTe (0.5 cm thick)
Detector Area	4×2500 cm^2
Energy Resolution	1.2 keV FWHM @ 10 keV, 3.6 keV FWHM @ 100 keV
Spatial Resolution	1.25 mm
Shield	BGO (2 cm thick)
Collimator	Copper (0.1 mm) and Tungsten (1 mm) Slats
Mask	Coded-Aperture (5mm Tungsten)
Mask-Detector Spacing	1.2 m

EXIST would be an *all sky* survey mission lasting $\gtrsim 1$ year (for $\gtrsim 2$ passes through the entire sky). The sensitivities for continuum and line detection are given in Figures 1a and 1b and are quite spectacular: EXIST would be $\gtrsim 100\times$ as sensitive as HEAO-A4 over the whole sky and $\sim 10\times$ as sensitive as typical XTE/HEXTE pointings (in 1° fields) which will cover only $\sim$2% of the sky. Below 200 keV, EXIST could achieve line sensitivities comparable to deep pointings with INTEGRAL in its limited sky coverage. The nominal imaging resolution would be $10'$, with $\lesssim 1'$ source locations for bright sources and $\lesssim 10''$positions for bright gamma-ray bursts.

After an extensive Survey, the EXIST mission would continue as a pointed Observatory of unprecedented sensitivity and resolution as well as a powerful survey instrument, with occasional deep pointings. The Observatory sensitivities are typically a factor of 2-3 more sensitive than the Survey sensitivities (Figure 1), depending on exposure time, and of course provide much more complete temporal coverage for the large number of sources in the total field of view for a given pointing. Deep survey studies of the entire galactic bulge population of X-ray binaries in our Galaxy, of active galaxies for their luminosity function and contribution to the cosmic X-ray background, and of GRBs and a definitive test of their possible origin in galaxy haloes by a deep imaging study of our neighbor galaxy M31/Andromeda, are all examples of Key Projects for EXIST in its Observatory phase.

The EXIST mission would include a large array of new-technology Cadmium-Zinc-Telluride (CZT) solid state detectors. These are pixellated to give the high spatial resolution (as well as good energy resolution) needed for a compact coded aperture imaging telescope desisgn. The mission could be launched on the newly defined NASA "Med-Lite" launch vehicle.

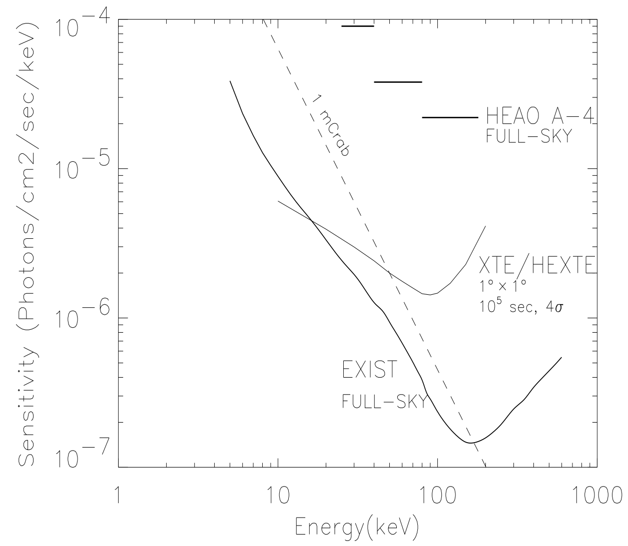

Fig 1a: EXIST Survey continuum sensitivity

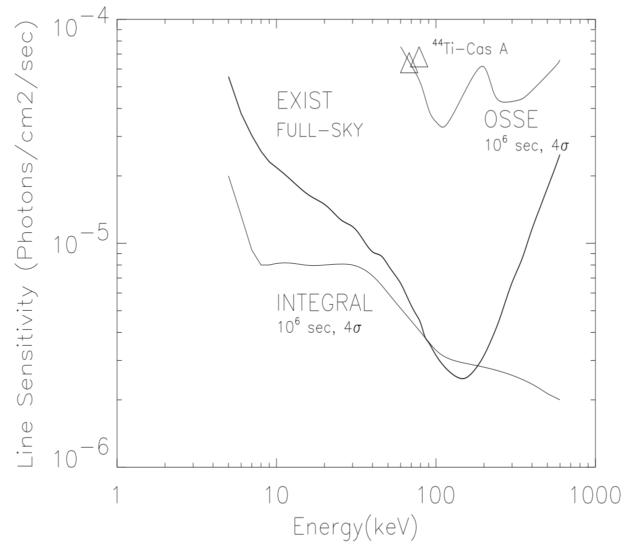

Fig 1b: EXIST Survey line sensitivity

The basic mission consists of a survey mode with a ROSAT-like scanning strategy, i.e. a rotation scan motion perpendicular to the ecliptic with one complete 360° scan every orbit. The baseline instrument originally proposed consists of 4 coded aperture telescope modules, each of approximately 2500 cm^2 detector area. A possible telescope layout on the spacecraft is shown in Figure 4 below. However, other telescope and detector combinations are possible and are being considered as part of the Concept Study. A key feature of the instrument is an energy dependent field-of-view (FOV): 6° $\times$20° at energies below approximately 40 keV, and 20° $\times$20° at energies above approximately 80 keV. The energy-dependent FOV allows optimization of the survey observations in the two background regimes: diffuse-dominated and internal-dominated. In survey mode, it is desirable that the scan swath width be maximally wide to optimize chances for detection of transient behavior. Our design goal is half-sky coverage over one orbit. Use of offset telescopes allows a wide scan-path while maintaining acceptable signal-to-background ratios. The nominal offset (scan mode) total field of view would be 80° $\times$ 20° (FWHM). In the pointed mode, the telescopes could be co-aligned to achieve the optimal on-axis point source sensitivity.

4. DETECTOR AND TELESCOPE CONCEPT

4.1 Baseline Concept

The focal plane detectors for EXIST would incorporate large area (2500cm^2) arrays of CdZnTe (CZT) semiconductor detectors for the baseline instrument. This material has high Z ($\sim$50), has good mechanical properties, and is not hygroscopic. Energy resolution of 5% at 500 keV has been demonstrated with risetime correction, and better values should be possible. The electron and hole mobilities are different, so a risetime measurement allows the depth of the interaction and a correction for hole trapping to be calculated (Parsons et al 1994). The crystals will be 5 mm thick yielding an effective area of $\sim$100 cm^2 (including the blockage of the the detector collimator and coded aperture mask) per telescope module at 500 keV.

The arrays would be divided into detector modules made of multiple crystals with a area of 100 cm^2/module. State-of-art CZT detectors are 1 cm $\times$ 1 cm $\times$ 5 mm or 2.5 cm $\times$ 2.5 cm $\times$ 2 mm, but crystal growth techniques are advancing rapidly. We envision 2.5 cm $\times$ 2.5 cm $\times$ 5 mm detectors to build the modules, but whether the exist.det.3.eps.bb

detectors are larger or smaller in area will primarily effect the complexity of crystal mounting.

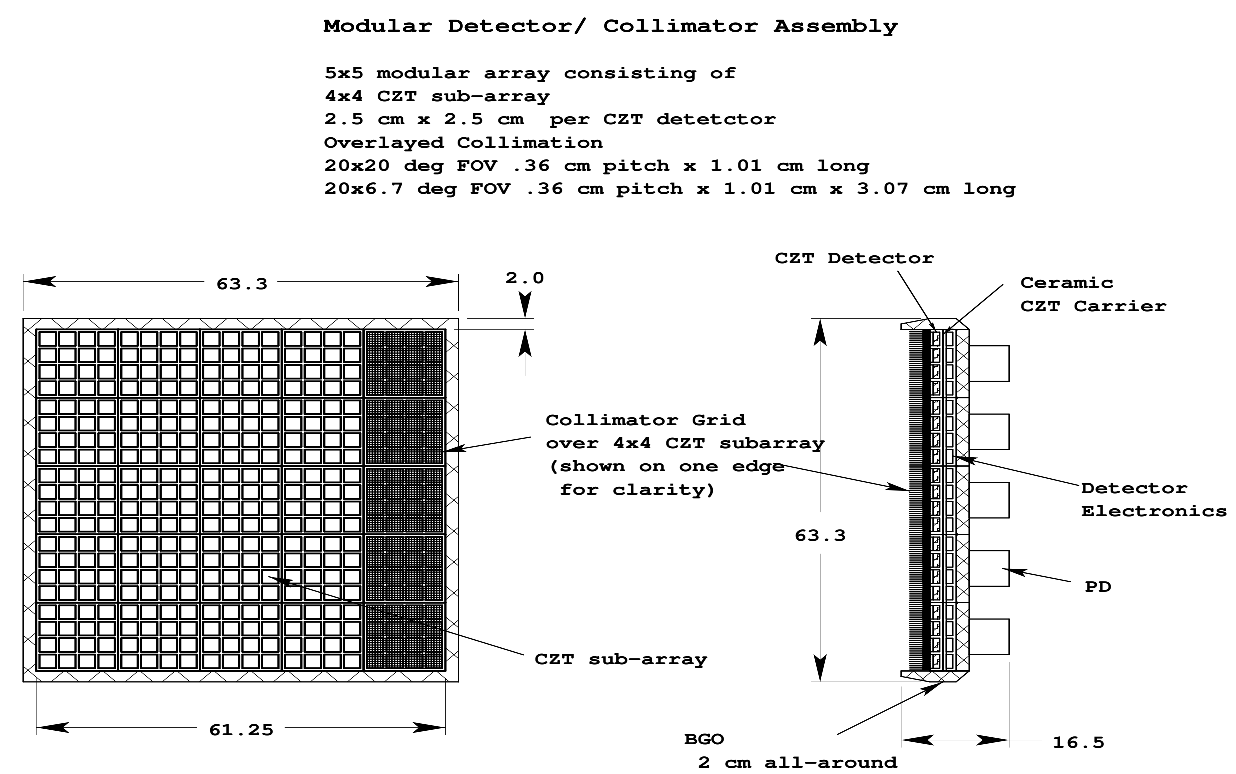

Figure 2: Layout of CZT Baseline detector, collimator and shield

We are investigating various readout schemes for the CZT array. However, to illustrate the readout we have adopted a baseline configuration in which each of the 100 cm^2 module discussed above is composed of a 4×4 array of square double-sided strip detectors. The chosen strip pitch of 1.25 mm provides the necessary position resolution and results in 20 strips on each side of a given detector. Strips on adjacent detectors would be connected to form effectively a single large 100 cm^2 area strip detector having 80 “x” and 80 “y” strips. Each strip, spanning across four detectors, would be instrumented with a separate linear signal chain implemented in custom CMOS VLSI. Each signal chain would provide (1) signal amplification and storage; (2) threshold detection circuitry to enable event timing, shield veto, and sparse readout; and (3) rise- time analysis circuitry to enhance energy resolution at high energies. Stored analog pulse height and rise-time information would be multiplexed to a shared A-D converter. Custom VLSI chips for similar applications (e.g. in particle physics detectors) have been developed which consume as little as 2 to 15 mW per signal chain. In this application the detector segmentation provides each strip with a capacitance and leakage current small enough to allow the electronic noise contribution to the energy resolution to be less than 1 to 2 keV rms for comparatively low amounts of power per chain. Thus although the baseline CZT detector concept would contain 16,000 strips (channels), the total power consumption should be only $\sim$30-100W; the exact figure is one of the design goals of the Study.

The baseline detector concept uses a slat collimator with coarse and fine blades of different material. In order to minimize background from the diffuse background and point source contributions, which dominate at energies $\lesssim$ 40 keV, a nested collimator is planned. The low-energy FOV is $6.7^\circ \times 20^\circ$up to about 40 keV and increases roughly linearly up to the full high-energy FOV of $20^\circ \times 20^\circ$at 80 keV. The high-energy collimator begins to become transparent at about 200 keV. For low-energy collimation 0.1 mm blades of copper are used, while for high energies exist.tele.2.eps.bb

1 mm Tungsten blades are used.

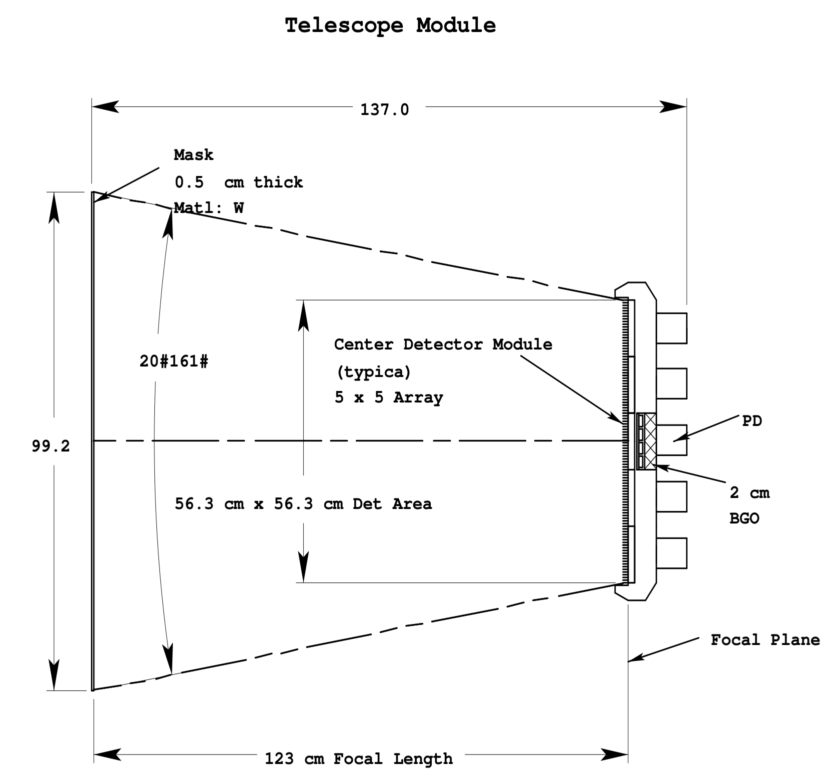

Figure 3: Layout of EXIST Telescope (single module) and shield

A 2 cm Bismuth Germanate (BGO) shield surrounds 5 sides of each of the 4 detector assemblies in order to shield the detectors from atmospheric γ-rays and to aid in Compton suppression. The thickness of the shield was chosen as a compromise between weight and performance. The shield will be read out in standard fashion with photomultiplier tubes (PMTs), or possibly with (low voltage) photodiode detectors.

The 4 coded-aperture masks are 94 cm $\times$ 94 cm, and are located 1.2 m from the detector plane. The mask thickness is 5 mm of Tungsten and the mask cell size is 3.6 mm, yielding an angular resolution of $10'$. The mask would be a fixed, rectangular Uniformly Redundant Array (URA), such as used on a variety of balloon-borne and satellite imagers (e.g. Caroli et al 1987). The exact URA pattern to be used is being considered during the Study. One option is a repeated pattern matching the $6.7^{\circ} \times 20^{\circ}$field of view, such as a 117 $\times$ 35 pattern, for which $10'$ pixels would fill the field. This will give repeats in the pattern at high energies and thus a few cyclic ghosts of high amplitude at well defined and easily predicted positions. They will fill only $\sim$1/2500 of the FOV and ambiguities will be resolved in the scanning mode by the different scan profiles. If instead the URA the cycle is made to match the HE field (i.e. 117 $\times$ 119, say), there will be essentially a random pattern for the LE mask. This will have 'random' sidelobes with a typical amplitude of 1/sqrt(2500) =0.02 of the peak. Some iterative processing would be needed to remove them. Other options are also possible and are being examined in detail in the Study.

In Figure 3 above, we show the overall layout of one of the EXIST telescopes for the baseline design.

4.2 Alternative Design: Hybrid Detector

An alternative detector concept for EXIST we shall study is a hybrid detector composed of a phoswich (NaI/CsI scintillator) and high pressure gas counter. Large-area phoswich detectors are currently being used to provide high sensitivity broad-band coverage with moderate spatial and energy resolution up to 500 keV and beyond. At low energies though, the small number of visible photons emitted by the NaI crystal leads to a serious degradation in performance and sets limits on the imaging capability of solid-scintillator-based telescopes. One way to overcome this limitation is through the use of a hybrid instrument which would couple the phoswich to a second detector providing low energy response. Ideally, such a detector would sit atop the phoswich, utilize the same readout system to provide optimum use of precious spacecraft resources. It would also become transparent at high energies to take full advantage of the crystal's superior high-energy performance.

The hybrid gas detector/phoswich (Grindlay and Manandhar 1989, Ramsey et al 1993) meets these criteria. It consists of an optical avalanche chamber — essentially a proportional counter designed to give large quantities of light photons during charge multiplication — optically coupled to a large area phoswich detector, with both sections being read out by a common set of photomultiplier tubes. Simulations show that this section of the instrument should be designed to provide useful response up to around 100 keV. The uv light from the gas-filled detector is converted to the visible by a wave shifter and will then pass through the optically clear exit/entrance windows and through the phoswich to the underlying PMT array for processing. Above $\sim$100 keV, the gas filling of the avalanche chamber becomes transparent and the incident x-ray photons pass through the chamber and interact in the NaI crystal. For both sections of the hybrid event positions will then be derived using the typical Anger camera center of gravity approach. The simplicity of concept makes the hybrid a logical way to enhance the performance of a standard phoswich detector. The electronics overhead associated with implementing the Hybrid is minimal over the normal Anger camera arrangement. The additional weight is small and no additional area will be taken up. Thus in terms of maximizing scientific return for a given weight, area, power and cost the hybrid is very effective and superior to separate instruments optimized for low-energy and high-energy response.

Such a hybrid instrument is currently under development by HCO/CfA and MSFC for flight in their joint balloon program. Detailed Monte Carlo simulations of its performance have been carried out (Ramsey et al 1993), and tests with an optical avalanche detector module (Pimperl et al 1994) are underway in the lab. The tests show that indeed optical light gain achieved in the avalanche chamber is some 10^3 times that in NaI at energies of 20-100 keV. The spatial resolution possible by centroiding this light (with the PMT readout of the phoswich) is limited not by photon statistics but by physical effects in the counter gas such as diffusion and the finite length of the photoelectron track. These are pressure dependent. Taking, for example a 2 atmosphere gas fill, then better than 1 mm is achievable up to 25 keV, 4 mm at 60 keV and 6-8 mm at 100 keV, which matches (smoothly) the typical spatial resolution achieved in the phoswich. Thus a mask pixel size of $\gtrsim$ 8-10 mm is needed to provide the same imaging resolution ($10'$) and sensitivity as with the Baseline CZT design, and the telescope focal length must then be correspondingly larger ($\sim (10/3.6) \times 1.2 \sim 3.3$m). This makes the Hybrid a much larger mission than the Baseline design with much more demanding constraints for spacecraft and launcher. Thus EXIST as a viable small/intermediate class mission really requires the Baseline compact CZT detector design.

5. SPACECRAFT AND SYSTEM REQUIREMENTS

The spacecraft (S/C) requirements for a scanning mission, such as EXIST, are rather modest: the S/C would be 3-axis stabilized, with pointing stability only needed to about $20'$ but post-facto aspect to about $30''$. A possible layout of the EXIST telescopes on the S/C is shown in Figure 4 below. Total dimensions of the EXIST and its S/C bus are approximately 2.6m $\times$ 2.1m $\times$ 1.9m.

The EXIST Baseline design is a compact, boxlike configuration. The overall shape being cubic rather than cylindrical suggests a truss frame structure as optimal to support the various elements of the instrument. However, we are also considering other designs, including monocoque structures.

The telescope mechanical subassemblies include the mask and support plate,the detector collimator assembly, instrument electronics housing and structural truss assembly. The collimator and mask assemblies are the mechanexist.3D.2.eps.bb

ically weakest elements of the instrument under launch loads. In each case the risk is out of figure distortions due to vibrations. For the collimator this is mitigated by proper selection of the mechanical boundary conditions of the assembly. For the mask a low Z strengthening plate may be required. The telescopes are shown mounted with a 1-D drive mechanism so that they can be driven from their offset (Survey) positions back into co-alignment (as planned for launch) for the post-survey Observatory phase of the mission. This would also allow Targets of Opportunity (e.g. novae and supernovae) to be observed with full sensitivity by temporary interruption of the Survey.

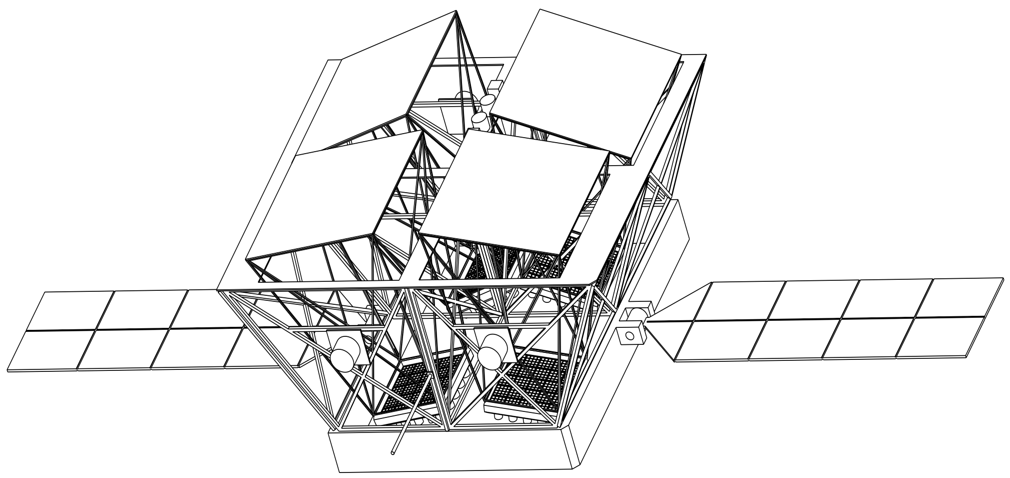

Figure 4: Possible Layout of EXIST Telescopes on Spacecraft

The material of choice for the housing and support structures is a cynate ester/carbon fiber composite. For the mask support plate a composite laminate structure is being studied. Composite laminates have a low density compared to aluminum but a higher elastic modulus, leading to a lighter, yet stiffer structure. They can be tailored to perform in an axisymmetric fashion to provide strength in a preferred direction. The structure is baselined as a truss system. The material of choice is aluminum. Cyanate ester is also a candidate although fastening together of structural members is then more complex.

Preliminary mass estimates have been derived for Baseline concept telescope and instrument mass assemblies (701 kg) and supporting S/C systems (including thermal, attitude control and power for a total of 265 kg) yielding a total mass of approximately 966 kg. This is well within the range of the planned NASA 'Med-Lite' launcher. With a total expected event rate of $\lesssim$ 3000 cts/sec (from diffuse background and bright sources in the large fov), and a telemetry allocation of 35 bits/event (for event postions, energy and time), a telemetry rate of 100-150 kbs is needed. This would be derived with an on-board memory (10 Gb) and several high speed data dumps per day to ground stations.

6. CONCLUSIONS

EXIST would open up a new era in high energy astrophysics by providing both the first all-sky imaging survey at hard x-ray energies as well as nearly continuous coverage and monitoring for a wide variety of variable sources: from X-ray binaries (containing white black holes, neutron stars, or white dwarfs) in the Galaxy to the nuclei of active galaxies and quasars at cosmological distances. It would enable a definitive test of the galactic halo model for gamma-ray bursts by conducting extensive imaging observations of GRBs from our neighboring galaxy M31 (Andromeda). EXIST is possible in a MIDEX-class mission because of the rapidly emerging technology of CZT detectors and arrays. The Concept Study being carried out, together with our program(s) of laboratory and balloon flight tests, will enable these detectors and concepts to be developed in a timely fashion for an upcoming flight opportunity such as the NASA-MIDEX program.

7. ACKNOWLEDGEMENTS

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