Evolution of EXIST: Original Concept to ISS

The Energetic X-ray Imaging Survey Telescope (EXIST) has evolved considerably since its original study as a New Mission Concept (NMC), following its selection for the NMC solicitation in 1994. The scientific objectives have also evolved and become even more compelling. The hard x-ray survey science, and evolution of the EXIST concept, are summarized here.

1 Introduction and Overview

The hard x-ray band (~10-600 keV) is nearly the final portion of the astronomical spectrum still without a sensitive imaging all-sky survey. This is despite the enormous potential of this band to address a wide range of fundamental and timely objectives – from the origin and physical mechanisms of cosmological gamma-ray bursts (GRBs) to the processes on strongly magnetic neutron stars that produce soft gamma-repeaters and bursting pulsars; from the study of active galactic nuclei (AGN) and quasars to the origin and evolution of the hard x-ray diffuse background; from the nature and number of black holes and neutron stars and the accretion processes onto them to the extreme non-thermal flares of normal stars; and from searches for expected diffuse (but relatively compact) nuclear line (^{44}Ti) emission in uncatalogued supernova remnants to diffuse non-thermal inverse Compton emission from galaxy clusters. A high sensitivity all-sky survey mission in the hard x-ray band, with imaging to both address source confusion and time-variable background radiations, is very much needed.

We have carried out a study for a New Mission Concept for an Energetic X-ray Imaging Survey Telescope (EXIST) mission, as summarized initially in Grindlay et al (1995) and as developed in more detail in Grindlay et al (1997) and Grindlay (1998a). The need for a hard x-ray imaging survey mission has been recommended (1997 and 1999) as one of the highest priorities for gamma-ray astronomy in the coming decade by the NASA Gamma-Ray Program Working Group (GRAPWG). Because the hard x-ray survey science is so closely connected to compact objects and time variable pocesses, the surveys needed are imaging in both space and time, and maximizing both spatial and temporal coverage is then important (Grindlay 1998a). Thus both very wide field and long duration missions are needed. This combination can be effectively and efficiently obtained for a hard x-ray imaging mission flown as a future free flyer or possible space station payload, and an initial version would be an ideal candidate for an ultra-long duration balloon (ULDB) flight, as suggested by Grindlay (1998b).

The ultimate sensitivity for a deep hard x-ray (HX) survey could be obtained with a very large area (~8m^2) array of coded aperture telescopes that would be particularly well suited for an attached payload on the International Space Station (ISS). EXIST-ISS could achieve sensitivities (~5-100 keV) of ~0.05mCrab (and ~0.5mCrab, 100-600 keV) and thus match or exceed the sensitivity of the first 2-10 keV all sky imaging survey, ABRIXAS2 (likely to be launched by Germany by c. 2002). A very deep HX survey such as EXIST-ISS would conduct fundamental science on black holes, obscured AGN, gamma-ray bursts, and compact objects as well as obscured supernova remnants in the Galaxy. It would provide the needed all-sky view for future HX focusing missions, such as HXT on Con-X, or follow-on more sensitive narrow-field focusing missions.

2 Scientific Objectives

An all-sky imaging HX survey will enable a number of key studies: from AGNs (nature; evolution; hard x-ray background) and galaxy clusters (IC components and embedded AGNs) to compact objects and binaries (BHs vs. NSs; disk accretion; BH formation and binary evolution) and active stellar coronae (stellar flares and magnetic reconnection). Gamma-ray bursts (as well as SGR events and even some Type II x-ray bursts) can be well detected and imaged for $\lesssim 1'$ locations in near real time with sensitive spectra so that constraints on emission models and afterglows may be derived. And finally the nuclear line (^{44}Ti lines at 68 and 78 keV) afterglows from galactic supernova remnants may be found for any obscured but nearby young SNR. Each of these is described briefly in the following sub-sections. For consistencey, EXIST mission parameters are taken to be those for EXIST-ISS unless otherwise noted.

2.1 Extragalactic Surveys

AGN Luminosity Function: Survey for Obscured AGNs

Perhaps the most compelling HX survey science is the first high-statistics survey of AGNs in the hard x-ray ($\gtrsim$ 20 keV) band. Einstein MSS and ROSAT results have established the logN-logS for AGN in the soft x-ray band (0.2-4 keV), but until recently only the relatively low sensitivity HEAO-A2 results of Piccinotti et al (1982) are available for the medium (2-10 keV) band. These have been extended by Ginga, ASCA and now BeppoSAX (cf. Giommi et al 1998, Gilli et al 1999 and references therein) with the surprising result that in the 5-10 keV band a factor of ~4 excess in AGN counts is apparently being seen. The implication is, of course, that a significant population of AGNs exist that are heavily absorbed and not seen at low energies: an EXIST mission with ~0.1mCrab sensitivity should discover $\gtrsim$ 3000 self-absorbed AGN which would then be available for detailed followup study. Due to their expected large low energy absorption, many of these self-absorbed AGN may not have been detected with the ABRIXAS all-sky survey, which will reach a 2-10 keV flux limit of ~0.1mCrab ~1 $\times 10^{-12}$ergs cm^{-2} s^{-1} (Trumper et al 1998). However, they could be readily detected with Chandra and precise locations for optical/IR identifications derived.

AGN Spectra

The broad-band spectra (~2-100 keV) of AGNs are still only poorly known for all but the brightest ~30 systems surveyed by OSSE ($\gtrsim$ 50 keV) and Ginga ($\lesssim$ 50 keV). BeppoSAX and RXTE both have HX ($\gtrsim$ 20 keV) detectors of comparable sensitivity (~1 mCrab) and will extend this sample to perhaps 50 AGN. The EXIST survey can achieve comparable sensitivity as RXTE long pointings but for the whole sky and so increase the sample by at least a factor of 10. However, most important is that the HX survey spectra will be for a significant HX-selected sample, rather than the optically selected samples studied thus far. This allows an unbiased study of the broad-band x-ray/HX spectra of AGN to be carried out and compared to models for the central engine (as well as to the HX diffuse background; see below). EXIST spectra when combined with ABRIXAS (2-10 keV) will enable disk components (Fe line and Compton reflection humps) to be isolated effectively from the underlying continuum. Thus disk vs. coronal geometries, and the role of advection dominated accretion flows (ADAFs; cf. Narayan 1997 for recent review) can be measured for a broad range of objects and luminosities for the first time.

AGN Variability

The likely wide field (40° x 160°) for EXIST allows significant new AGN variability measurements. An important product of the EXIST survey will therefore be a HX-selected AGN variability catalogue. This would contain at least the AGN bright enough for significant variability measures (i.e. increases in flux above a ~0.5mCrab threshold for ~1 day integrations) and thus allow the first large scale systematic study of variability properties. Until now, the only comparable AGN x-ray variability data sets are on a few bright objects (e.g. NGC 5506 or 4151) and even then typically only span 1-2 months and contain significant gaps. Thus apart from these few exceptions the power spectral behaviour of AGN vs. AGN type (e.g. Seyfert 2 vs. Blazar) is generally unknown.

Blazar HX Spectra: Constraints on the Diffuse IR Background

The recent detection of TeV emission from Mkn 421 and Mkn 501 is best explained by inverse Compton or synchrotron self-Compton (SSC) models in which synchtrotron x-ray or HX photons are Compton scattered to TeV photons by the high energy synchrotron electrons in the jet. Thus the shape of the x-ray and HX spectra, and in particular the spectral break in the HX regime, constrains the instrinsic spectral shape in the GeV-TeV gamma regime. The observed break at these gamma-ray energies, in turn, then allows direct measure of the diffuse IR cosmic background. Thus simultaneous HX spectra and GeV-TeV gamma spectra (from GLAST and VERITAS) are needed. In particular the wide-field and thus all-sky capability of EXIST is key: it both can provide Blazar alerts and also would ideally complement the similarly wide-field coverage of GLAST for a complete sample of Blazar spectra.

Origin of the Hard X-ray/Soft γ-ray Background

The spectra of a significant sample of AGN will test the AGN origin of the cosmic x-ray background (CXB) for the poorly explored hard x-ray band. With a total sample of $\gtrsim$ 3000 AGN, at least half of which will have been measured at 2-10 keV with ABRIXAS, the spectral distributions of a pure HX-selected sample will be derived. Since the EXIST or ABRIXAS positions will usually enable optical or IR identifications and thus redshifts, the redshift distribution can be measured. These are the prime requirements to not only determine the AGN luminosity function in the HX band but also to directly constrain models of the HX background. In particular, the spectral slope above the (typical) break energy of ~50-300 keV (in Seyferts) must be measured in a significant sample of objects for comparison with the CXB spectrum with energy index 1.38 above its (redshifted ?) break energy of ~30 keV. By establishing the distribution of spectral break energies in a large sample of Seyferts, the required redshift distribution can be derived and compared with other constraints on AGN evolution. By further comparisons with the mean spectral shapes for differing classes of AGN (Seyferts vs. Blazars, etc.), the dominant contributors to the CXB above its spectral break can be derived and constraints imposed on overall AGN evolution.

Magnetic Fields, Cosmic Rays and Relaxation in Galaxy Clusters

Galaxy clusters are usually considered to be dominated at x-ray energies by the thermal emission from their hot gas. However it has long been recognized that inverse Compton (IC) scattering of cosmic ray electrons in diffuse radio sources in clusters on the 3K microwave background will produce diffuse hard non-thermal emission as a hard tail extending beyond the thermal cutoff and would directly constrain the intergalactic magnetic field in the cluster. Although not detected with OSSE (e.g. Rephaeli et al 1994), probably because of too high an energy threshold ($\gtrsim$ 50 keV), recent searches with BeppoSAX (cf. Piro et al 1998) have provided tantalizing evidence (e.g. Coma) for detection.

Recently, Sarazin and Lieu (1997) have proposed that the apparently ubiquitous EUV emission from galaxy clusters also arises from IC scattering of CR electrons, but with Lorentz factors Γ ~100 due to synchrotron cooling over a Hubble time. However if the clusters have had more recent episodes of shock acceleration, such as from a merger event, this Γ will be larger and non-thermal x-ray (rather than UV) emission is expected. Thus detection of non-thermal medium to hard x-ray emission can also be expected in clusters that have undergone recent mergers.

2.2 Precise Positions and Spectra for Gamma-ray Bursts and SGRs

Given its larger total effective area, lower background, and imaging capability, EXIST would have a GRB sensitivity $\gtrsim$ 20 x that of BATSE. Thus allowing for the factor of ~3 smaller instantaneous field of view, and the observed GRB logN-logS relation with limiting slope ~1, EXIST could detect GRBs at ~6 times the rate as BATSE, or ~1/4h. With the increasing evidence that GRBs are related to massive stars (e.g.

hypernovae or collapsar models), it is likely that a very high sensitivity mission, such as EXIST, to study GRBs could provide the most direct probe of the earliest generations of massive stars (Pop III) at z $\sim$ 10-30. Since the luminosity function for "short"-duration bursts appears to be even broader than the (increasingly broad) values derived for "long"-duration bursts, as located by BeppoSAX, a much larger population of fainter bursts appears likely.

GRBs will be located to $\lesssim 1'$ positions, thereby providing definitive tests of repeaters. Bright burst positions and spectra would be brought down in real time for automated followup searches. The high spectral resolution imaging detectors (pixellated Cd-Zn-Te) proposed for EXIST would provide high resolution (E/dE $\sim$50-100) spectra of GRBs and thereby provide new spectral constraints on source emission models. Since EXIST would time-tag each photon to 1μsec, a search for rapid spectral evolution in discrete spikes in GRBs would be possible for the first time.

The wide-field $\sim$arcmin imaging capability at high sensitivity will also allow a sensitive survey for more soft gamma-ray repeaters (SGR) in the galactic plane. At present only 4 such sources are known (essentially the same population for the past 15 years) and much more sensitive imaging surveys are needed. It is likely that BATSE has missed these sources due to its degraded sensitivity and resolution for occultation imaging for sources in the crowded galactic bulge, where most SGRs are expected to reside. Given their now almost certain identification with magnetars, a larger population is important to determine the evolutionary links of magnetars to the pulsar population.

2.3 Galactic Surveys

Black Hole Binary Population in the Galaxy

With a 40° x 160° field of view, EXIST-ISS observes the full sky each 90min orbit and is therefore a sensitive hard x-ray all-sky monitor for the study of spectra and variability of transients. Thus a prime objective for the EXIST survey is to conduct a deep galactic survey for "soft" x-ray transients, which are now understood to be dominated by black hole binaries (cf. Van Paradijs 1996), since at low to moderate accretion rates their accretion efficiencies are lower than NSs and their disks are therefore not x-ray heated and are more likely to undergo the thermal limit-cycle instability found for dwarf novae.

The total population of BH transients in the Galaxy has been estimated (from outburst rates of bright transients) to be $\gtrsim 1000$ (e.g. Tanaka and Shibazaki 1996). Searches for this large underlying population have been conducted with only limited success with BATSE (e.g. Grindlay et al 1997b) given its limited sensitivity ($\sim$50-100 mCrab for sources in the galactic plane). The EXIST survey will be sensitive to transients with $\gtrsim$ 1-10 day durations and integrated fluxes of only $\sim$0.5 mCrab, or some 100×more sensitive than BATSE. A similar increase in position resolution results from the EXIST images: sources ($\gtrsim 5\sigma$) are positioned to $\lesssim 1'$. This powerful combination will allow the relative populations of black holes in the Galaxy to be constrained.

Relatively short-duration ($\sim$1 day) transients are also favorable for discovery and study by EXIST. A recent bright example of such a source, CI Cam, was discovered with the ASM on RXTE and detected with BATSE (for $\lesssim$ 1-2 day). This system appears to be a symbiotic star but the nature of the compact object is unknown. Detection of a class of such (fast) transients may allow the nature of these systems, which may contain BHs, to be determined.

BH vs. NS Accretion and Structure of Compact Objects

Studies of x-ray and hard x-ray spectra and variability probe the accretion onto black holes and neutron stars and provide the most direct measures of their structure and space-time in the strong-gravity limit. The hard x-ray spectra and variability are particularly direct measures of the innermost regions of the accretion flow, where Comptonizing temperatures are greatest or non-thermal effects most extreme. Hard x-ray studies probe the disk vs. corona structures within the central ~10-100 gravitational radii. The current paradigm of advection dominated accretion flows (ADAFs), developed by Narayan and colleagues for BH accretion in galactic BH systems and AGN, may best be tested by hard x-ray spectra since breaks are typically predicted in the 50-100 keV range. The extension of this highly promising model to NS systems has not yet been done but may be motivated by the already tantalizing differences and similarities in the hard x-ray spectra of NS vs. BH LMXBs in their low-medium accretion states (e.g. Barret, McClintock and Grindlay 1996).

The very large detector area proposed for EXIST will allow sensitive spectra on a large number of galactic BH and NS sources to be measured throughout the mission. Most of the time, portions of the field of view will include the galactic plane, and nearly half the plane will be visible each day. Thus a large area survey of spectral variability of BH and NS accretion sources will be conducted over the mission. This will allow tests of current models of state changes in BH systems that are thought to either originate in changes in ADAF structures in the accretion flow (Esin et al 1997) as a function of $\dot{m}$ or have instead recently been attributed to magnetic field structure changes and instabilities in the disk corona (diMatteo et al 1998).

X-ray Pulsars and Be Binary Population in the Galaxy

The measurement and monitoring of spin periods, luminosities and spectra of a large sample of accretion-powered pulsars would extend the studies successfully carried out with BATSE in the ~20-100 keV band (cf. Bildsten et al 1997). With the greatly increased sensitivity and resolution (both spectral and spatial), and assuming a logN-logS with slope ~1 for the galactic population of accretion-powered pulsars, the EXIST survey could extend the BATSE sample by a factor of $\gtrsim 100$. The survey would not only detect, and allow P and P-dot measurements of, the entire sample of known accretion pulsars, but would also detect most of the much larger reservoir of uncatalogued Be systems (Be primary + NS secondary) thought to dominate the accretion powered pulsar populaton of the Galaxy. At least 1-2 $\times 10^3$ of these systems are believed to be present with 2-10 keV accretion luminosities $L_x \sim 1 - 10 \times 10^{33}$ ergs/s at any given time. Their spectra are typically hard power laws with cutoffs in the 20-30 keV band and are thus well suited for measurements of spectra and $\lesssim 1'$ positions with EXIST.

Stellar Flares and New HX Sources in the Galaxy

As with any sensitive survey in a new band, the unexpected sources are particularly interesting. The recent discovery with the BeppoSAX hard x-ray detector (PDS) that HX flares were detected at $\gtrsim 50$ mCrab from Algol and several other RS CVn systems (Fiore 1998, private communication) was totally unanticipated. The EXIST survey could detect these at ~10×the distance and thus study non-thermal vs. high temperature processes for a wide range of flaring stellar sources (RS CVn, dMe, etc.).

Other classes of HX sources may be expected to show up in this sensitive survey: cataclysmic variables (CVs) are expected to have significant HX components since the free-fall temperature onto a WD is ~100 keV. This allows a measure of GM/R, and thus WD mass.

Emission line surveys: hidden supernovae via ^{44}Ti emission and 511 keV sources

The array of Cd-Zn-Te imaging detectors proposed for EXIST achieves high spectral resolution (e.g. $\lesssim 4\%$ at 60 keV). Thus emission line surveys can be conducted. The decay of ^{44}Ti (lines at 68 and 78 keV) with long (~90 y) halflife allows a search for the long-sought population of obscured supernovae in the galactic plane at sensitivities significantly better than the possible CGRO detection of Cas-A. These objects would likely appear as discrete (unresolved) emission line sources, and since their location is (by definition) unknown, a wide-field galactic plane imaging survey (rather than a series of pointings with a very narrow field focusing telescope) is essential to find them.

Similarly, 511 keV emission from black hole binaries (or AGN) can be searched for (e.g. in transient outbursts, as was detected by SIGMA for Nova Musca 91). Since the point source line sensitivity for 511

Table 1: EXIST-NMC Characteristics

Energy Range	5-600 keV
Angular Resolution	10 arcminutes
Field of View	Survey: 80° × 6° ($\lesssim$ 40 keV); 80° × 20° ($\gtrsim$ 80 keV) Pointed: 20° × 6° ($\lesssim$ 40 keV); 20° × 20° ($\gtrsim$ 80 keV)
Orbit	LEO (nominal 30° inclination)
Survey	~50% sky coverage each orbit Full-sky twice per year 0.5-1×10^6 sec per year effective source expos ure 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

keV emission (cf. Figure 7) is significantly better than OSSE and in fact is only a factor of ~2 below that expected for INTEGRAL, the EXIST sky survey could yield unanticipated 511 keV sources (which have thus far been only claimed by SIGMA) that could be followed up with pointed INTEGRAL observations. This enhanced annihilation line sensitivity and ability to do an all-sky 511 keV survey is a key driver for choosing relatively thick (5mm) Cd-Zn-Te detectors for the EXIST mission.

3 EXIST Mission Concepts

Two different versions of the EXIST mission were studied for the New Mission Concept study: the first was the original concept proposed for the NMC; the second was the 1995 MIDEX proposal, which itself evolved from Step 1 to Step 2. These are both summarized in the Tables 1 and 2.

Spurred in part by this NMC study, we have also initiated a separate concept study (under the ULDB concept study program) for a balloon-borne version of EXIST (EXIST-LITE), as summarized in Table 3.

The evolving science needs for a Deep HX survey have spurred the Ultimate version of EXIST: an 8 telescope version which would be a natural mission for the International Space Station (ISS). The EXIST-ISS Concept is summarized in Table 4.

3.1 EXIST-NMC

The original NMC proposal for EXIST presented the broad scientific case for a sensitive HX survey mission with imaging. The detector and telescope concept originally conceived are described by Grindlay et al (1995) and are summarized in Table 1.

The overall telescope layout is illustrated in Figure 1, and expected continuum and line sensitivities for a 1 year survey (2 passes, all sky) are shown in Figures 2a and 2b, respectively.

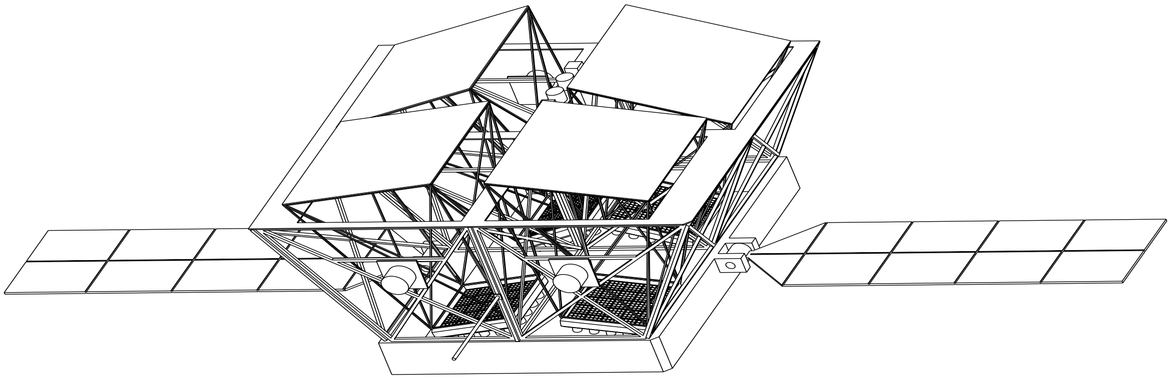

Figure 1. Layout for original EXIST concept (NMC proposal).

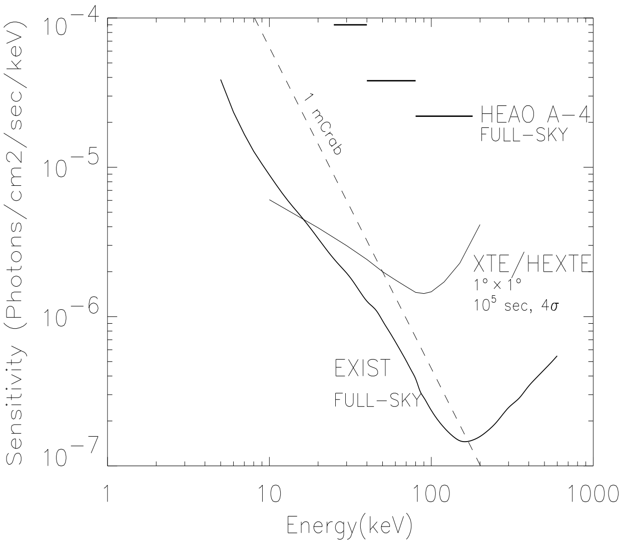

Fig 2a: EXIST-NMC Survey continuum sensitivity

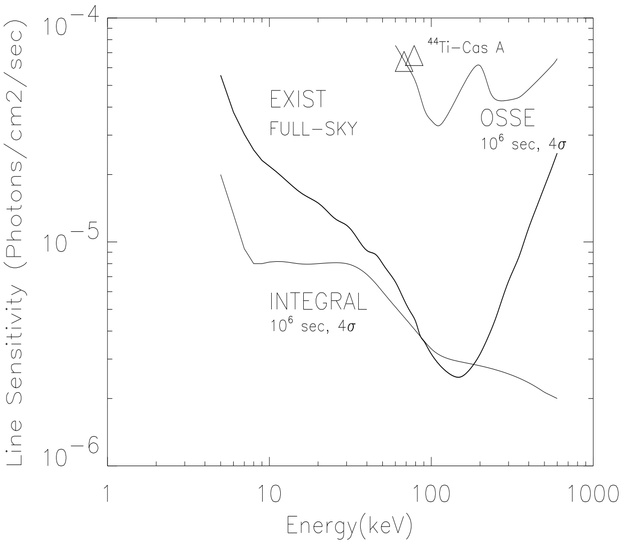

Fig 2b: EXIST-NMC Survey line sensitivity

The telescope concept employed 4 detector arrays (2500cm^2 each) each collimated by a low energy ($\lesssim$ 40 keV) thin collimator to a 20° ×6° (FWHM) field of view (FOV). Above ~80 keV, a thicker high energy collimator provided a 20° (FWHM) square FOV. This narrower FOV at low energies was oriented perpendicular to the zenith-pointing satellite scan direction and minimized the contribution from diffuse and bright point sources at low (x-ray) energies. The detector-telescopes were offset pointed in two pairs at angles ±20° and ±40° to yield a combined FOV of 80° ×6° ($\lesssim$ 40 keV) merging to 80° ×20° at higher energies. An additional feature contemplated was allowing the two pairs of telescopes to offset point in elevation (only) to become co-aligned for a single 20° ×6° or 20° ×20° FOV for higher sensitivity pointed observations after the survey phase (1 year) of the mission.

3.2 EXIST-MIDEX Concept

A full MIDEX proposal was prepared in response to AO-95-OSS-02. This proposal represented the major part of this EXIST concept study, with considerable further development of the original mission concept. The overall parameters of the proposed EXIST-MIDEX are given in Table 2.

Table 2: EXIST-MIDEX Characteristics

Energy Range	10-600 keV
Angular Resolution	14 arcminutes
Field-of-View	80° × 3.5° ($\lesssim$ 40 keV); 80° × 20° ($\gtrsim$ 80 keV)
Orbit	Low Earth Orbit (nominal 30° inclination)
Survey	~60% sky coverage each orbit Full-sky each two months Survey sensitivity: $<$ 1 mCrab (10-200 keV)
Survey Scan Motion	Optimized; pointing axis always $\lesssim$ 15° from zenith
Baseline Telescope Configuration	
Number of Telescopes	2 – pointing axes offset by 40°
Detectors	CdZnTe (3 mm thick)
Detector Area	2 × 2300 cm^2
Energy Resolution	3.9 keV FWHM @ 10 keV, 6.3 keV FWHM @ 100 keV
Detector Array	160 × 160 pixels each telescope, 3 mm in size
Shield	Bismuth Germanate (2 cm thick)
Collimator	Titanium and Tantalum/Tin Slats
Mask	Uniformly Redundant Array Coded-Aperture (Tantalum/Tin/Copper)
Mask Size	1.59 m × 1.03 m
Mask-Detector Spacing	1.5 m

The sensitivity for both continuum and line emission for the survey are very similar to the estimates shown in Figure 2 although the detector/telescope number and area have been reduced in half. The major factor yielding this improvement is simply to have opened up the narrow direction of the FOV from 20° to 40° at high energies ($\gtrsim$ 80 keV) while decreasing it to 3.5° at low energies ($\lesssim$ 40 keV). This more than doubles the effective exposure time on a given source (and increases the full sky survey coverage from 2× per year to 7× per year), whereas the diffuse aperture flux (and contribution of bright point sources) at lower energies remains approximately the same. An added benefit is the increased (2×) total FOV and thus coverage for both source variability and GRBs. This increased total exposure and instantaneous field of view is an important addition to the overall Quality factor, Q, defined and derived by Grindlay (1998b) for survey missions. Indeed, EXIST-MIDEX would conduct a sky survey with this combined measure of imaging resolution and total instantaneous coverage that is orders of magnitude better than any other planned (or previously conducted) hard x-ray or γ-ray survey and would be comparable to the effective Q for the imaging 2-10 keV survey of the upcoming ABRIXAS mission.

CZT detector arrays were again proposed but now with a pixellated 2D format. Each 2.5cm square ×5mm thick detector crystal was envisioned as flip-chip bonded to its own individual 64 channel (8 ×8 pixel) readout ASIC, providing a lower noise and higher spectral resolution readout than the strip detector approach but with the need for higher channel count (N^2 vs. 2N for the same N ×N pixels). However, the pixel size was increased from 1.25mm to 3mm, so the readout channel count is in fact increased by $\lesssim$ 2×. Furthermore, with the rapid progress in ASIC development this larger channel count is no longer demanding (and, as proposed, is only ~10% of the channel count now being envisioned for GLAST). The backup hybrid detector (hybrid, or common readout NaI/proportional counter) was rejected for the

EXIST-MIDEX (or subsequent concepts; see below) since it would require considerably more detector and shielding volume and thus mass and would yield degraded position and energy resolution.

The EXIST-MIDEX proposal included just two detector arrays (2300 cm^2 each) and overlying coded aperture masks rather than the 4 originally envisioned for the NMC version. This reduction in mass and power allowed the same survey sensitivity to be achieved in a more compact configuration appropriate for a MIDEX budget and Delta-2 launch option.

EXIST was selected to proceed to the Step 2 proposal phase in the 1995 MIDEX competition. Development of the mission proceeded considerably during this Step 2 phase, with attention to spacecraft design (through a Team arrangement with Orbital Sciences Corp.), power and thermal design. The mission was proposed with a detailed data handling and processing as well as distribution plan built around an EXIST Science Operations Center (EXSOC) to be located at the CfA during the operations phase of the mission.

3.3 EXIST-LITE Concept

Although developed after the NMC study, we briefly describe the related and ongoing ULDB study for a ultra long duration balloon (ULDB) version of EXIST. Given the $\gtrsim$ 3h continuous exposures possible from a balloon platform (vs. ~20 min each ~100 min orbit from a LEO platform), this version of EXIST would be a **L**ong **I**ntegration **T**ime **E**xperiment, and hence EXIST-LITE. EXIST-LITE (Grindlay 1998) would incorporate four large area (c. 1600 cm^2 each) arrays of Cd-Zn-Te (CZT) detectors. Indeed the overall telescope layout in the gondola (cf. Fig. 3) bears a superficial resemblence to the original EXIST/NMC layout but with many improvements based on the EXIST-MIDEX proposal study. Each of the 4 telescopes would have 40° ×40° field of view (FOV), with telescope pairs aligned ±20° from the vertical to yield a combined 40° × 80° FOV. The ULDB gondola would contain a pointing system to align the long axis of the FOV north-south in a fixed-pointing mode. Thus the sky drift scans (E-W) across the narrow (40°) dimension of the FOV, yielding source exposure times of $\sim 3\text{h}/\cos(\delta - \lambda)$, where δ, θ are the source dec and balloon latitude, respectively. The overall parameters of the proposed EXIST-LITE concept are given in Table 3.

Table 3: EXIST-LITE Characteristics

Energy Range	20-600 keV
Energy Resolution	2.5 keV FWHM @60 keV
Field of View	40° × 80°
Angular Resolution	$12'$
Time Resolution	0.6 millisecond
Survey Sensitivity	~1mCrab (30-200 keV)
Number of Telescopes	4
Mask	URA (~256^2) 5mm thick Ta
Focal Length	1.43 m
Detectors	CdZnTe (5 mm thick)
Detector Area	4 × 1600 cm^2
Collimator/Shield	1 cm/2 cm CsI
Payload mass	875 kg
Power	350 W
Event Rate	$\sim 2000 - 4000$ sec^{-1}
Data Rate	65-130 kbs (full); ~30 kbs (binned)
Command Uplink	100 bps (~3×/day)

Each of the 4 EXIST-LITE detectors is formed by contiguous-tiled 100cm^2 self-contained detector modules (BDM), each with surrounding (4-sided) 5 mm thick Pb-Sn-Cu/plastic scintillator or CSI(Tl) collimator (12cm high) optically coupled to a 2cm thick CSI(Tl) rear anti-coincidence shield providing external shielding and interface to the digital processing plane below and full detector data bus. Thus the total dimension of the completed single telescope module is ∼50cm ×50 cm.

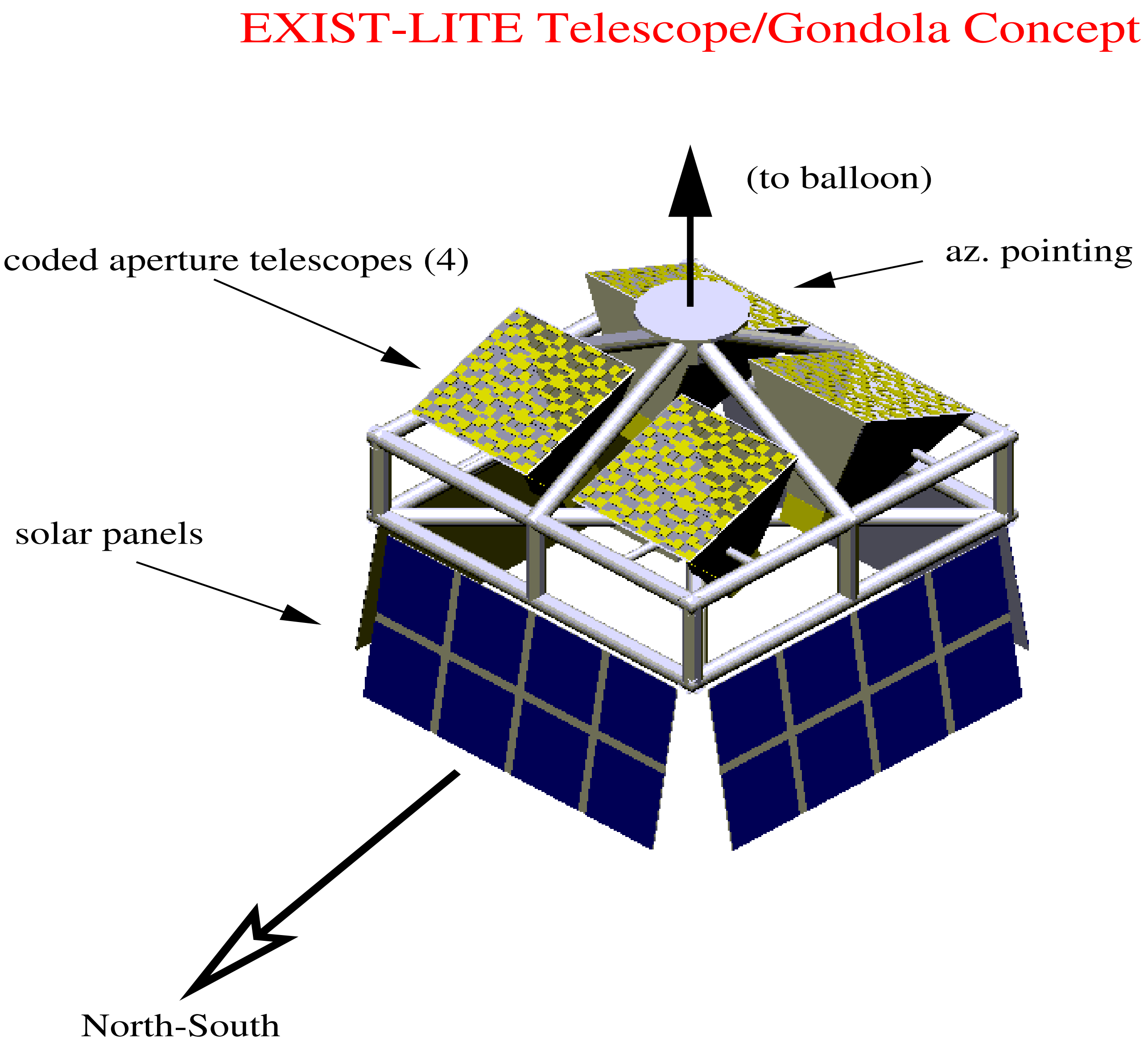

Fig. 3 EXIST-LITE concept for gondola and telescope layout.

A key difference, and simplification, from the proposed EXIST-MIDEX mission is that the low energy collimator could be eliminated since it was primarily intended to reduce the cosmic diffuse and point source background below 30 keV by restricting the low energy FOV (below ~30-40 keV) to approximately 10% of the solid angle of the high energy FOV. Since EXIST-LITE would have a low energy cutoff of 25-30 keV imposed by the overlying residual atmosphere (effectively ~4 g/cm^2) at its expected altitude appropriate for a ULDB flight, this additional low energy collimation is not needed.

Survey Exposure and Survey Modes

The EXIST-LITE survey follow naturally from the baseline plan of continuous pointings of the telescope array with its long axis North-South. This requires geo-centric pointing (i.e. non-inertial), and would yield the maximum total effective exposure times and source coverage. The total survey area × time product for a 100d flight from Alice Springs is shown in Fig. 4.

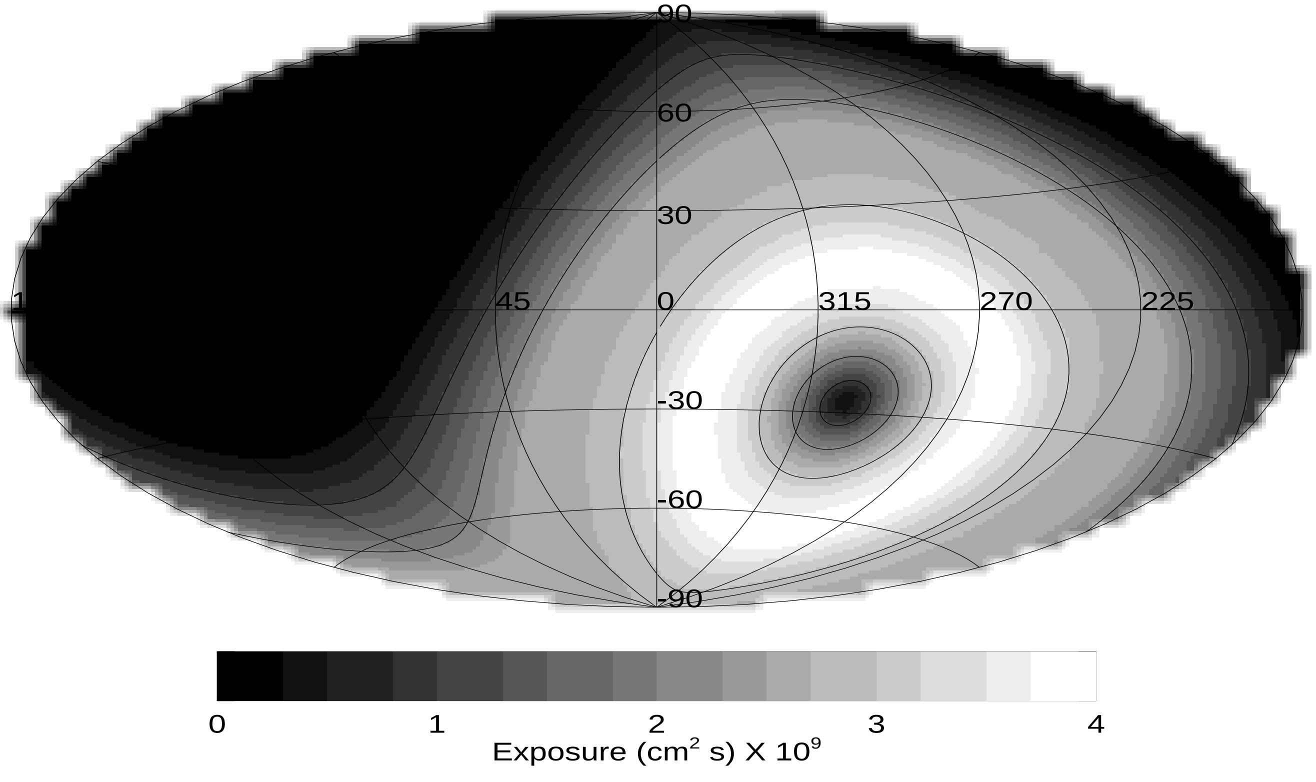

Fig. 4. Exposure time for 100d flight of EXIST-LITE.

However the azimuth control system will also allow fixed azimuth pointing at any position, or inertial azimuth tracking, as on our present (EXITE) balloon gondola. Thus inertial tracking *and* survey mode can be exercised for selected programs or for followup observations on newly discovered transients or GRBs.

Expected Backgrounds and Sensitivities

The measured flight CZT background (Bloser et al 1998a) is used to predict a total background spectrum for all four telescope detector arrays. The predicted total background count rate of B ~1930 cts/s over the full 20-600 keV energy band (and used to size the telemetry requirements in Table 3). This estimated background for EXIST-LITE would enable the sensitivity estimates shown in Fig. 5 given the exposure area ×time product for a single 100d flight shown in Fig. 4.

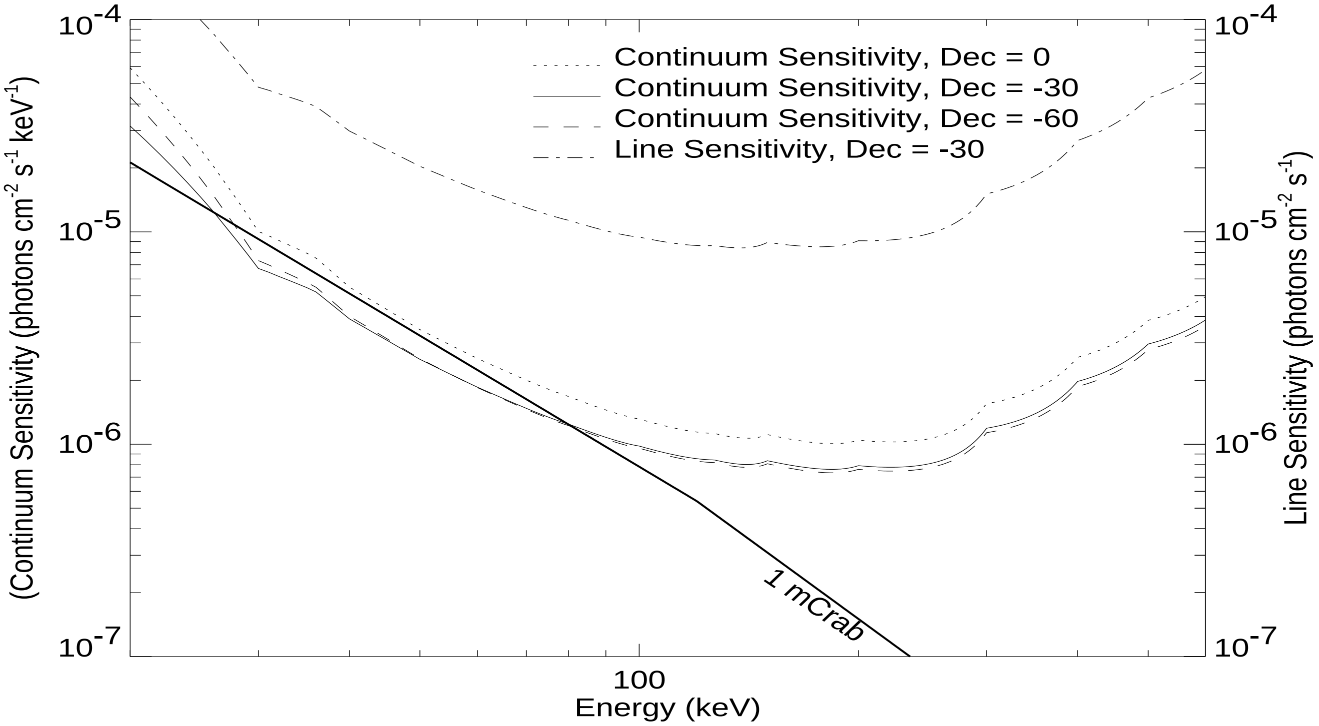

Figure 5. Estimated sensitivity for EXIST-LITE (100d flight)

The overall sensitivity of EXIST-LITE is impressive: a 5σ minimum detectable flux in the conventionally used broad-bands of width $\Delta E = E$ is ~1mCrab at ~100 keV for the full 100d survey for sources with maximum exposure. The minimum detectable flux ranges over a factor of ~1.5 depending on the declination of the source (due to the differing atmospheric attenuation of sources viewed at lower elevations), but this is effect is offset by the increased exposure time for sources at larger declination. Three sensitivity curves are therefore plotted in Fig. 5: for sources at declinations δ = -60° , -30° , and 0° .

Spectra of sources require, of course, detections in narrower energy bands. For our many science objectives requiring *continuum spectra*, we estimate minimum fluxes only a factor of ~2 higher than for detection: a spectral break for a BH binary or AGN, for example, could be measured at ~100 keV to within ~20 keV for a source with total flux ~3 mCrab and an assumed Crab-type spectrum. For *line spectra*, as required for our final galactic survey objective of searching for ^{44}Ti sources (68,78 keV) or 511 keV sources, the sensitivity is computed from the predicted background and for bandwidths $\Delta E = 2E_{res}$, where E_{res} is the energy resolution (FWHM) expected for the CZT detectors at a given energy E and is given by our measured results (Narita et al 1998, Bloser et al 1998b) for prototype CZT imagers as $E_{res} = 2.4(60/E)^{0.5}$ keV. The line sensitivity plotted in Fig. 5 is for a single source declination (-30°), but would scale in the manner shown for the continuum sensitivities for sources at other declinations.

3.4 EXIST-ISS Concept

A full scale version of EXIST is well suited for the International Space Station (ISS). The need to reach all-sky survey sensitivities (100 keV) of $\lesssim$ 0.1mCrab (to fully match expected ABRIXAS2 sensitivities) means that a very large total detector and telescope area is needed. A practical limit is an 8-telescope version of EXIST, employing $1\mathrm{m}^2$ detector (CZT) arrays at the focus of each coded aperture telescope. Each telescope would (again) have a FOV of 40° × 40° , and be offset by 20° from its adjacent telescope for a combined FOV of 40° × 160° (FWHM). The large FOV would be aligned perpendicular to the ISS orbital vector, so that with its fixed zenith-pointing on ISS the coverage is all-sky each 90 min orbit. A view of the EXIST-ISS concept is shown in Figure 6.

The overall parameters of the proposed EXIST-ISS are given in Table 4.

Table 4: EXIST-ISS Characteristics

Energy Range	5-600 keV
Angular Resolution	$5'$
Field-of-View	160° × 4° ($\lesssim$ 30 keV); 160° × 40° ($\gtrsim$ 30 keV)
Orbit	Low Earth Orbit (nominal 52° ISS inclination)
Survey	~100% sky coverage, ~2mCrab sens. (10-100 keV) each orbit Exposure uniform to within ~25%
Sensitivity (~10^7s, 5σ)	~ 0.05 mCrab (10-100 keV); 0.5mCrab (100-500 keV)
Baseline Telescope Configuration	
Number of Telescopes	8 – pointing axes offset by 20°
Detectors	CdZnTe (5 mm thick)
Detector Area	$8 \times 10,000$ cm^2
Energy Resolution	2.8 keV FWHM @ 10 keV, 4 keV FWHM @ 100 keV
Detector Array	400 × 400 pixels (2.4mm) each telescope; centroid to 1.2mm
Shield	Bismuth Germanate (2 cm thick)
Collimator	Tantalum/Tin Slats
Mask	Uniformly Redundant Array Coded-Aperture (0.5cm Ta/Sn/Cu)
Mask Size	1.3 m × 1.3 m; 2.4mm basic pixel size
Mask-Detector Spacing	1.3 m
Mission Parameters	
Total telescope mass	2800 kg
Power	1.5kW
Telemetry	Full: 1.4Mbs; Compressed: 32 kbs

The estimated sensitivity and exposure coverage are shown in Figure 7 and are derived for the ISS orbit (including precession) and for detector background spectra due to internal background in the CZT (scaled from the balloon flight results of Parsons et al (1996) and Bloser et al (1998a)) and the expected (dominant) cosmic diffuse flux in the large field of view. The large diffuse (aperture) flux and the relatively low altitude renders the relatively high inclination ISS orbit suitable for EXIST. The large telescope mounting area (though modest total mass), and desired fixed pointing (local zenith) are also well-suited to ISS.

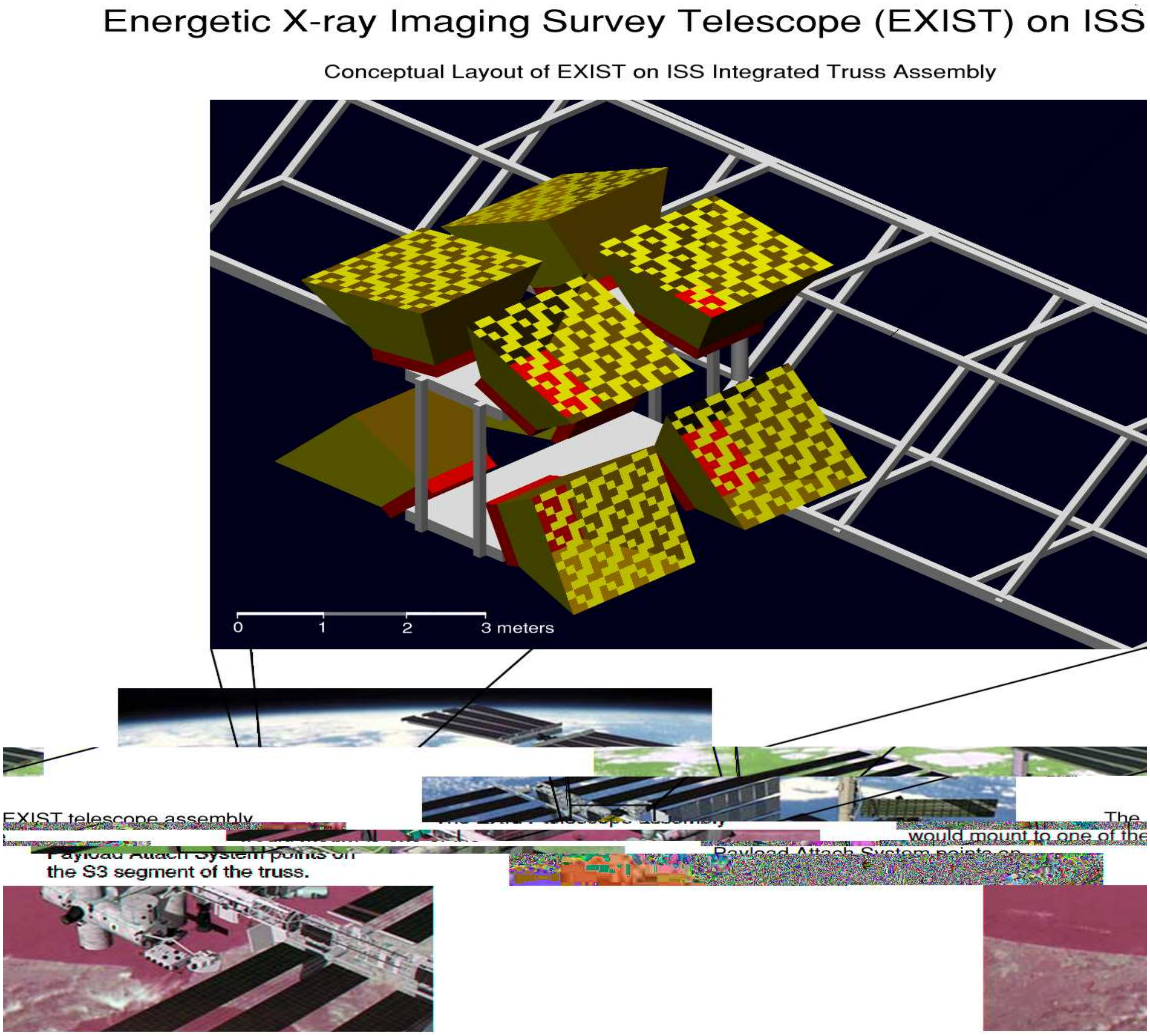

Figure 6. EXIST-ISS concept: 8 coded aperture telescopes, with combined FOV of 160° × 40° and full-sky coverage each orbit.

The exposure coverage and sensitivity for both continuum and line emission for the survey are shown in Figure 7.

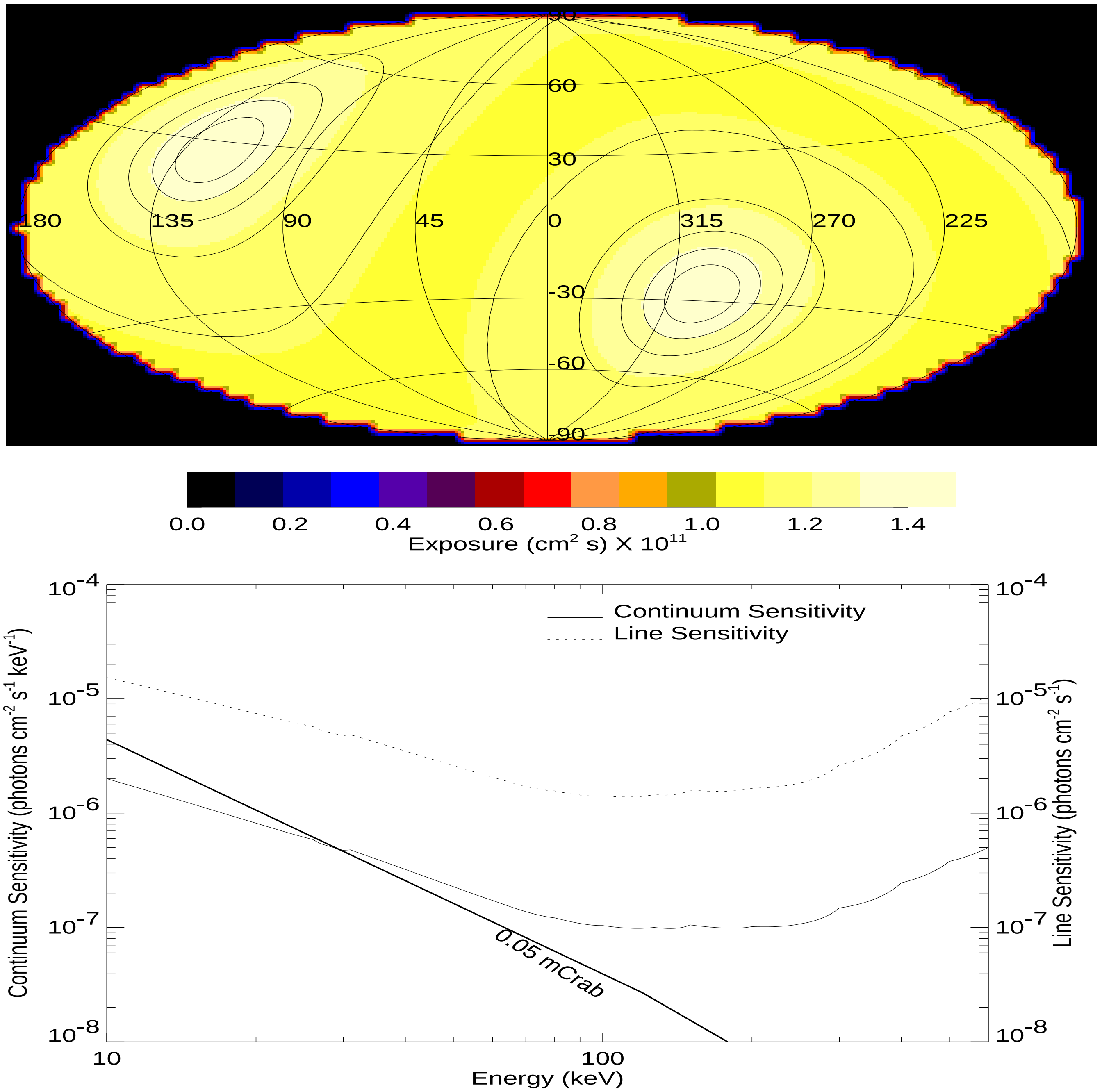

Figure 7. Exposure and sensitivity for EXIST-ISS concept.

The sensitivities in Figure 7 were derived for the expected background spectrum and all detector and imaging efficiencies. For the continuum sensitivity, the sensitivities are “monochromatic” for a bandwidth dE = E. The line sensitivity is for an assumed (measured, CZT) energy resolution of dE = $2.4(E/60)^{0.5}$ keV (FWHM) and is plotted as photons/cm^2-s on the right hand scale. A more useful continuum spectrum sensitivity plot would be for an assumed source spectrum and realistic energy bands. Figure 8 shows such a plot for a Crab spectrum and energy bands with approximately equal logarithmic energy width.

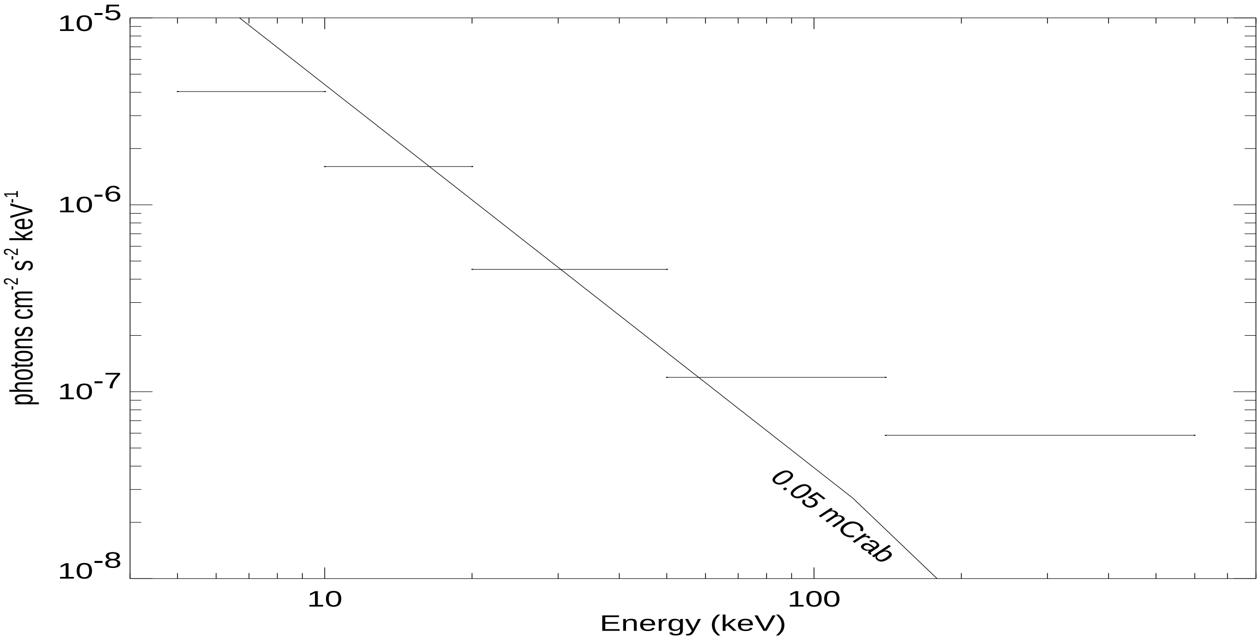

Figure 8. Continuum sensitivity (10^7s survey effective exposure time) for Crab-like spectrum for EXIST-ISS concept.

4 EXIST Data Distribution

We have considered how the products of an EXIST survey could be rapidly analyzed and disseminated to the community. Following are representative results and catalogues:

- *Cumulative Source Catalogue:* As the mission proceeds, detected sources are continuously (daily) added in to a cumulative source catalogue (CSC). The EXIST source detections are derived from a bootstrap method beginning with a seed catalogue of known bright (e.g. $\gtrsim$ 10 mCrab) sources, which are themselves checked. As exposure builds on a given sky element to allow detection of fainter sources (e.g. ~0.5 mCrab for 1 day exposures), the catalogue is updated. Thus at any given time in the mission a complete initial catalogue is available.
- *Daily Transient Summary:* The daily flux averages for each source in the cumulative catalogue allow the continual compilation of a list of current transients and strongly variable sources. This daily transient summary (DTS) generates automatic alerts for possible fixed (inertial) pointing obsevations, subject to other mission constraints and GRB followups in progress.
- *Source Light Curves:* All source detections are entered into running light curves, which include upper limits for any intervals of non-detection.

- *Final HX Survey Catalogues:* After initial and post-processing, final source catalogues and light curves are produced. These include results of automated spectral fitting and constraints (combined spectral fits; positions) from soft-medium surveys (ROSAT/ABRIXAS) or followup pointings.

All HX survey results and data products would be made available on the Web for public access as soon as they have been derived from mission data. Particularly, the DTS and CSC results will provide quasi-realtime results for not only EXIST mission planning but other (e.g. INTEGRAL, Constellation-X and GLAST) missions as well. As with most missions, post-processing will improve the overall data products. Final Survey Catalogues and all-sky maps will be produced in a successive (two part) post-mission processing.

5 Relation to Other HX Surveys and Future Missions

No other mission (current or approved – through August, 1999) has the capability of EXIST to conduct wide-field HX surveys. The OSSE instrument on CGRO has both very coarse angular resolution (as noted above) and no sensitivity below 50 keV (and only limited sensitivity below 100 keV). The PDS on BeppoSAX is a sensitive hard x-ray detector system but, like the HEXTE on RXTE, is a narrow-field (1°) instrument not suited for surveys. The broad-band imaging HX capability of the ESA mission INTEGRAL (2001 launch) will enable partial sky surveys, but the IBIS imager has a much narrower field of view (∼15°) and can thus cannot attain the all-sky coverage of EXIST. As part of its Core Program, INTEGRAL will conduct a galactic plane survey as a series of discrete pointings which require ∼1 week to cover the inner 160° of longitude of the galactic plane (Ubertini et al 1997). The EXIST survey would achieve greater depth and temporal coverage for galactic plane survey sources: ∼0.5 mCrab for 1 day sensitivities vs. ∼15 mCrab for IBIS for a given point in the 160° region of the galactic plane surveyed (only) once each week. Finally, the Swift mission (Gehrels 1999), currently in Phase A study for a possible MIDEX mission (c. 2003 launch), would conduct a HX survey with $22'$ resolution and ∼1mCrab sensitivity in the ∼10-150 keV band. Swift would conduct long (typically 1d) stable pointings on GRB positions determined initially by its wide-field (2sr) BAT imager and thus would not have the rapid all sky survey coverage or the extended bandwidth of EXIST. The survey sensitivity would be some $\sim 10 - 20\times$ less than EXIST for a full 2 year mission.

Perhaps the prime utility of a high sensitivity HX survey will be to guide the upcoming generation of focusing HX telescopes for their most efficient and effective pointing strategies. The HXT on Constellation-X will have ∼5-80 keV sensitivity $\gtrsim 30\times$better than EXIST due to the focusing advantage of much lower backgrounds. However its very small field of view ($\sim 10'$) precludes large area surveys, and its targets will thus all be otherwise selected from known objects or soft (ROSAT) or medium (ABRIXAS) surveys. A wide-field, all sky HX survey is needed to identify the key objects for detailed study in the HX band, just as has been the case for the soft and medium bands previously.

6 Community Participation in EXIST Concept Study

As part of the NMC study, we have endeavored to solicit community discussion of the science goals and needs that would be met by a hard x-ray imaging sky survey. Broad-based discussion of the mission concept was also carried out. The primary forum was a special Topical Session we organized at the June, 1997, AAS meeting in Winston-Salem, NC. The scientific program for this session consisted of the following series of invited talks:

All-Sky Imaging Surveys of AGN and Black Hole Candidates - I:

- Hard x-ray imaging survey science objectives
  T.A. Prince, Caltech

- Comparison of the galactic distributions of LMXBs with black holes and with neutron stars
  J. van Paradijs, U. Amsterdam/U. Huntsville

- Temporal signatures of black holes in x-ray novae
  J.C. Wheeler, U. Texas

- Spectral signatures of black holes in x-ray binaries
  E. Liang, Rice U.

- OSSE results on AGN spectra and variability
  N. Johnson, NRL

- Annihilation lines and cutoffs in XRBs and AGN
  A.A. Zdziarski, Copernicus Center, Warsaw

- Heavily obscured AGN and the x-ray background
  A.S. Wilson, U. Maryland

All-Sky Imaging Surveys of AGN and Black Hole Candidates - II

- Investigations of black hole binaries and AGN with the RXTE all sky monitor
  R.A. Remillard and A. Levine, MIT

- BeppoSAX Wide Field Camera hard x-ray survey: some first results
  J. Heise and J. in tZand, SRON/Utrecht

- ABRIXAS, an imaging telescope for an x-ray all sky survey in the 0.5-10 keV band
  R. Staubert, U. Tuebingen

- INTEGRAL galactic plane survey
  P. Ubertini, IAS-CNR, Frascati, Italy

- Optimization of choices for survey mission parameters and possible implementation
  N. Gehrels, NASA/GSFC

- Hard x-ray imaging survey: EXIST concept
  J.E. Grindlay, Harvard

An EXIST Science Working Group (EXSWG) is currently being formed (with encouragement from NASA) to further define the mission concept and possible ISS implementation. Initial members of the EXSWG are:

L. Bildsten (ITP/UCSB)

D. Chakrabarty (MIT)

A. Fabian (IOA, Cambridge)

F. Fiore (Rome Observatory and BeppoSAX Center)

M. Elvis (CfA)

N. Gehrels (GSFC)

J. Grindlay (CfA)

F. Harrison (Caltech)

D. Hartmann (Clemson Univ.)

T. Prince (Caltech)

R. Rothschild (UCSD)

S. Woosley (UC Santa Cruz)

7 References

Barret, D., McClintock, J. and Grindlay, J. 1996, ApJ, 463, 963.
Bildsten, L. et al 1997, ApJS, 113, 367.
Bloser, P. et al 1998a, Proc. SPIE., 3445, 186.
Bloser, P. et al 1998b, Proc. MRS Symp., vol. 487, 153.
Cagnoni, I. et al 1998, ApJ, 493, 54.
Chou, Yi et al 1999, in preparation.
diMatteo, T. et al 1998, preprint (astro-ph 9805345)
Esin, A., McClintock, J. and Narayan, R. 1997, ApJ, 489, 865.
Giommi, P. et al 1998, preprint.
Gilli, R., Risaliti, G. and Salvati, M. 1999, Astron. Ap., in press (astro-ph/9904422)
Gehrels, N. 1999, BAAS, AAS Mtg. 194, 97.03.
Grindlay, J. 1998a, Astron. Nach., 319, 133.
Grindlay, J. 1998, Adv. Sp. Res, 21 (No. 7), 999.
Grindlay, J., Prince, T. et al 1995, Proc. SPIE, 2518, 202.
Grindlay, J. et al 1997a, Proc. Workshop on X-ray Surveys and All Sky Monitors in Next Decade, Riken (eds. M. Matsuoka and N. Kawai), p. 247.
Grindlay, J. et al 1997b, in Proc. 2nd INTEGRAL Workshop, ESA-SP382, 551.
Levine, A.M. et al 1984, ApJS, 54, 581.
Narayan, R. 1997, in IAU Symp. 188, 41.
Narita, T. et al 1998, Proc. SPIE, 3446, 218.
Parsons, A. et al 1996, Proc. SPIE, 2806, 432.
Piccinotti, G. et al 1982, ApJ, 253, 485.
Rephaeli, Y. et al 1994, ApJ, 429, 554.
Sarazin, C. and Lieu, R. 1997, preprint (astro-ph 9712049).
Tanaka, Y. and Shibazaki, N. 1996, AR&A, 34, 607.
Trumper, J., Hasinger, G. and Staubert, R. 1998, Astron. Nach., 319, 113.
Ubertini, P. et al 1997, Proc. Workshop on X-ray Surveys and All Sky Monitors in Next Decade, Riken (eds. M. Matsuoka and N. Kawai), p. 253.
van Paradijs, J. 1996, ApJ, 464, L139