BALLOON-BORNE HARD X-RAY IMAGING AND FUTURE SURVEYS

Jonathan E. Grindlay

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

ABSTRACT

Several payloads for hard X-ray (20-600 keV) imaging with coded aperture telescopes have been developed for balloon flight observations of cosmic x-ray sources. We briefly review the characteristics of these, particularly the EXITE2 system. The recent NASA program to develop an extended long duration (100d) balloon flight capability employing super-pressure balloons would allow a qualitatively new hard x-ray imaging experiment: the Energetic X-ray Imaging Survey Telescope–Long Integration Time Experiment (EXIST-LITE). The longer continuous viewing times (per source) available from an LDB platform than from low earth orbit would enable both surveys and objectives complementary to the EXIST mission proposed for a MIDEX satellite. We summarize the scientific objectives of EXIST-LITE, a possible instrumentation approach incorporating a large area array of Cd-Zn-Te (CZT) detectors, and our program for the development and balloon flight testing of relatively thick (5mm) CZT detector arrays.

INTRODUCTION

Over the past decade several balloon-borne hard x-ray imaging telescopes have been developed and flown. These have enabled the first demonstration of coded aperture imaging of cosmic x-ray sources at hard x-ray energies ($\gtrsim$ 30 keV) with position-sensitive scintillation detectors and coded masks. The first-generation hard x-ray (~20-300 keV) coded aperture imagers, GRIP1 and EXITE1 (cf. Table 1 below) preceeded the first satellite-borne imaging telescope, SIGMA (cf. Paul et al 1991), which established the rich variety of hard x-ray sources available for study from a long-exposure mission.

In this paper we provide a brief overview of the several balloon-borne hard x-ray imagers developed including our EXITE detectors, particularly the current EXITE2 system. These have all been small ($\lesssim 5°$) or moderate (~15°) field of view instruments with emphasis on study of individual sources. With the planning now for possible long-duration balloon (LDB) flights at mid-latitudes, it is now possible to consider future balloon-borne wide-field imagers which could conduct surveys and studies of many sources simultaneously. Such a wide-field, long-exposure survey telescope could be developed and flown on LDB missions as a precursor, or even as an extended follow-on, to a full satellite mission.

The Energetic X-ray Imaging Survey Telescope (EXIST) was proposed in December 1994 as a New Mission Concept for a satellite-borne mission. It would conduct the first imaging survey of the sky at hard x-ray energies (10-600 keV) with a sensitivity some 100× greater than the only previous all-sky survey carried out by HEAO-A4 experiment in 1978-80 (Levine et al 1984). An overall description of the initial EXIST concept is given by Grindlay et al (1995) (and on the Web site *http://hea-www.harvard.edu/EXIST/EXIST.html*). EXIST was accepted for study as a New Mission Concept, and has been developed extensively in the course of preparation and submission of a successful "Step 1" and solicited "Step 2" proposal for the MIDEX program. Although EXIST was not selected (June 1996) for flight, the need for such a satellite mission is just as acute and the Concept Study is continuing (cf. Grindlay et al 1997) for a future MIDEX proposal submission.

Some of the objectives of EXIST could be met by a balloon-borne version *provided that the recently announced NASA program to develop a 100d capability for long duration balloon (LDB) flights is realized.* In this paper we consider the application of such a 100d LDB (hereafter, 100dLDB) program to develop a version of EXIST which would allow for Long Integration Time Experiments on a variety of sources. The EXIST-LITE concept for 100dLDB fights is described here and contrasted with the full satellite-borne EXIST mission. EXIST-LITE could either preceed EXIST (as a development step, and probably as a smaller total detector/telescope combination) or as a follow-on mission to the (proposed) two year EXIST (MIDEX) mission which would enable continuing surveys, monitoring and study of individual sources.

BALLOON-BORNE HARD X-RAY IMAGERS

At energies above ~15 keV, it is increasingly difficult to image x-rays with grazing incidence optics; at energies $\gtrsim$ 100 keV, where even graded multi-layer coatings lose their effectiveness, it is essentially impossible. Thus coded aperture imaging (cf. Caroli et al 1987 for a review), in which the shadow of an aperture mask with ~50% open hole fraction is measured by a position-sensitive detector, has enabled the development of several telescopes for hard x-ray (20-600 keV) and soft γ-ray (~100 keV - 1 MeV) imaging studies of cosmic sources. These imagers have employed uniformly redundant array (URA) coded masks and scintillation detectors (NaI(Tl) or CsI(Na)), or gas-filled proportional counters, for which the required position sensitive readout was achieved by a variety of techniques. Table 1 lists the key characteristics of the balloon-borne hard x-ray imagers in the approximate order of their development or flight. In addition a soft γ-ray (~200 keV - 9 MeV) coded aperture telescope with wide field (~20°) and moderate resolution (~5°) was developed and flown by the UNH group (McConnell et al 1987).

Table 1: Summary of Balloon-borne Hard X-ray Imagers

Instr.	En. range (keV)	Detector and Readout	FOV	Ang. res.	Refs.
GRIP1	35-1500	NaI; Anger camera	15°	2°	1,2
EXITE1	20-300	NaI; image intens.	3.5°	24′	3,4
GRATIS	20-150	CsI; pos.-sens. PMTs	1.5°	2′	5
GRIP2	35-1000	NaI/CsI; Anger cam.	15°	33′	6
EXITE2	20-600	NaI/CsI; Anger cam.	4.5°	22′	7,8
MIXE2	20-100	Microstrip gas counter	1.8°	7′	9

References:

1. Cook, W., Finger, M. and Prince, T. 1985, *IEEE Trans. Nuc. Sci.*, **NS-32**, 129.
2. Cook, W.R. et al 1991, *ApJ*, **372**, L75.
3. Grindlay, J., Garcia, M., Burg, R. and Murray, S. 1986, *IEEE Trams. Nuc. Sci.*, **NS-33**, 750.
4. Covault, C., Grindlay, J. and Manandhar, R. 1992, *ApJ*, **388**, 65.
5. Harrison, F., Hailey, C.J., Kahn, S.M. and Ziock, K.P. 1989, *Proc. SPIE*, **1159**, 36,.
6. Schindler, S. et al 1997, *NIM*, **A384**, 425.
7. Manandhar, R. et al 1993, *Proc. SPIE*, **2006**, 200.
8. Lum, K. et al 1997, *NIM*, in press.
9. Ramsey, B.D. et al 1997, *NIM*, **A383**, 424.

EXITE Telescopes

We developed and flew a first-generation hard x-ray balloon-borne imager, the Energetic X-ray Imaging Telescope Experiment (EXITE) in 1986-90. The EXITE1 detector (cf. Table 1) was a 34cm diameter (round) × 0.6cm thick NaI(Tl) scintillator optically coupled to a large area image intensifier with electron-reducing optics and PIN-diode position-sensitive readout. This provided a relatively simple readout and good position senstivity (FWHM = 14mm/$E_{keV}^{0.5}$. Graded passive shields and cosmic ray anti-coincidence shields reduced measured background levels to F(100 keV) $\sim$ 6 $\times 10^{-4}$ counts/ cm^2-sec-keV (for the geomagnetic latitude of Alice Springs, Australia) yielding a 3σ sensitivity of ~100 mCrab for a 3 hour observation (Covault 1991).

The second-generation EXITE detector and telescope, EXITE2 (cf. Table 1), is a 40cm × 40cm phoswich scintillation detector (1cm-NaI/2cm-CsI) read out by a 7 × 7 array of close-packed (square) PMTs. The detector area 1300 cm^2 (NaI), or 1600 cm^2 (NaI + 2cm surrounding CsI guard ring), is thus $\sim$ 2× the geometric area of the EXITE1 detector. The phoswich discrimination allows a background (at 100 keV) reduction by a factor of 2-3 over the EXITE1 detector, so that allowing for the area and background factors, the sensitivity (per unit time) should be a factor ~2 better. Both the energy and spatial resolution are also each improved by factors of ~1.4, so that improved imaging and spectra are possible. An engineering test flight was conducted in June 1993 (Lum et al 1994) and led to improved cosmic ray rejection electronics and a completed on-board recording and computer processing system as well improved aspect system. Despite campaigns to launch the payload for its first science flight in both May and September-October 1996, winds and the launch queue did not allow even an attempt; the payload is now awaiting a May 1997 launch.

BALLOON-BORNE HARD X-RAY SURVEY: EXIST-LITE

Until now all of the telescopes in the development of balloon-borne (and subsequent spaceflight) hard x-ray imaging have been relatively narrow field of view (FOV $\lesssim$ 5-30° , FWHM; cf. Table 1) for pointed observations of individual fields. A survey telescope at hard x-ray energies can be constructed as a coded aperture telescope with a field of view of up to ~45° without significant projection effects or collimation by the mask aperture, assumed planar. Such a telescope would execute a continuous scan rather than fixed target pointing (although pointings are also possible and would be conducted) to cover a maximum sky fraction in minimum time and would be more sensitive than a scanning grazing incidence (multi-layer) telescope of comparable (or even larger) physical size though smaller effective area and field of view. For example, it can easily be shown that a multi-layer telescope with (currently ambitious) parameters of FOV $\sim 10'$ and effective area $A_{eff} \sim 500\mathrm{cm}^2$ in a scanning (ROSAT-like) satellite mission would be a factor of ~10 *less* sensitive than a wide-field (FOV ~ 20-40°) scanning coded aperture telescope with $A_{eff} \sim 5000$ cm^2 in the 30-100 keV band (the multilayer telescope could achieve comparable sensitivity in the 10-30 keV band due to bright source and diffuse background contributions to the wide-field coded aperture imager). In addition, the wide-field coded aperture imager allows the survey to extend up to the poorly explored 100-600 keV range, totally unaccessible to focussing optics (except for Bragg concentrators, which can work only in a very narrow energy band).

The EXIST-LITE concept would (as with the EXIST for MIDEX) incorporate two wide-field telescopes. However because of the attenuation of the residual overlying atmosphere (assumed to be 4 g/cm^2, averaged over the wide FOV), the survey would have little response below ~25 keV. Thus the background contributions from the cosmic diffuse flux and from bright galactic sources will be less (at ~30 keV) than for MIDEX (though this is partially offset by atmospheric background) and the FOV can be even larger. Thus the separate low-energy (~10-30 keV) 1-D collimators (~3.5°) can be eliminated . Each of the two telescopes for EXIST-LITE would have FOV = 45° × 45° , for a combined FOV = 45° × 90° , and each would (ideally) have total detector area of 2500 cm^2. The schematic layout of the two telescopes is shown in Figure 1.

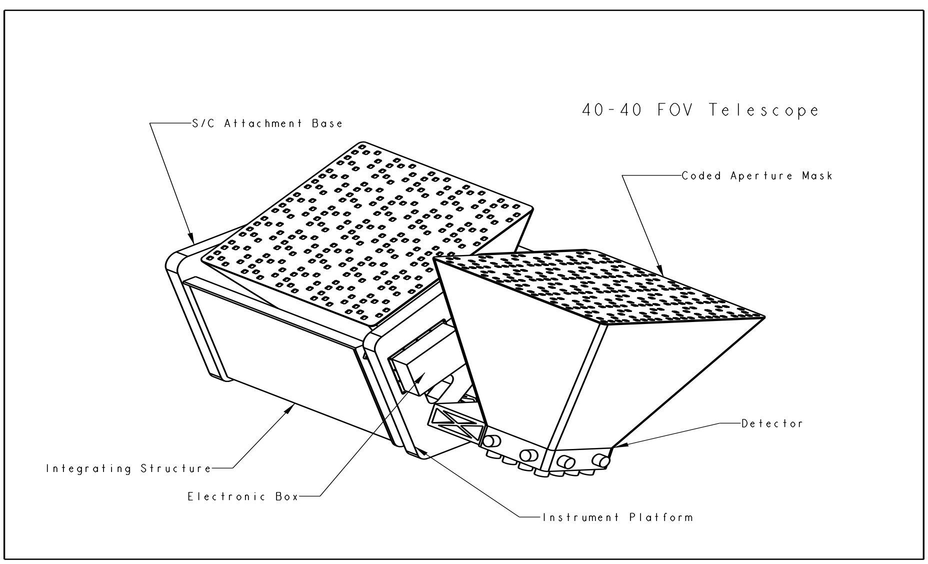
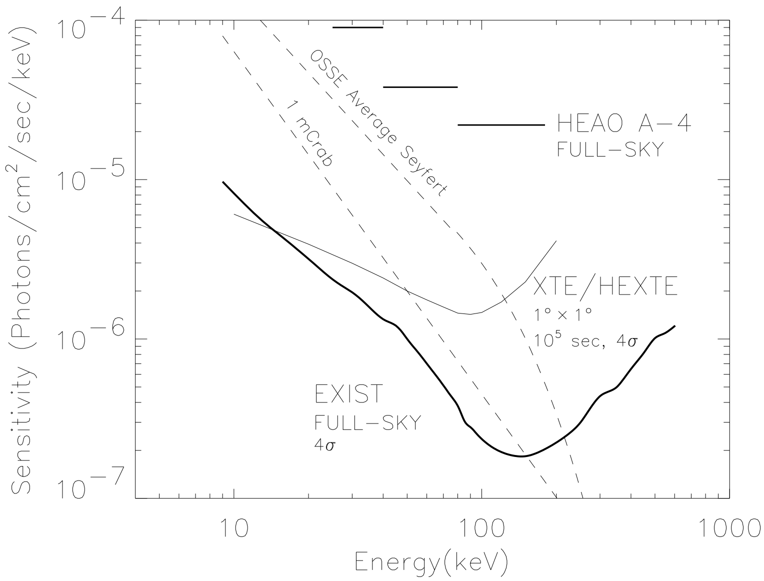


Fig. 1. Schematic layout of coded aperture telescopes for EXIST or EXIST-LITE.

The center of the combined FOV would be fixed-pointed at the local zenith, and the long axis of the combined FOV would be maintained north-south with a gondola pointing system, which would allow inertial pointing as well for a few selected priority targets during the survey (e.g. the M31 galaxy for a GRB survey). The sky then drifts east-west across the narrow (45°) dimension of the FOV, giving a minimum exposure time each day for any given source with declination δ of 3h ($\delta = 0°$) to $\gtrsim$ 12h ($\delta \gtrsim 67.5°$). This is, of course, a continuous exposure rather than the interrupted exposure segments (~15-30 min) achieved in each of (typically) 10 orbits (non-SAA) each day for the MIDEX mission. Thus the key difference for EXIST-LITE is the long(er) continuous integration time experiments possible.

Because of its very large FOV and large area detectors with high intrinsic resolution (both spatial and spectral), EXIST-LITE could approach the unprecedented all-sky sensitivity levels for the full EXIST mission, which are shown in Figure 2. The sensitivity plots are for EXIST for its proposed 9-month all-sky survey (followed by a pointed mission phase), which would allow total integration times of $\sim 10^6$ sec for any source. Comparable or significantly greater total exposures for EXIST-LITE could be achieved for half the sky in a single 100dLDB flight since any source would be observed for $\gtrsim$ 300-1200 hours or $\gtrsim 1.1\text{-}4.4 \times 10^6$ sec. Thus with just two such flights (ideally at latitudes ±45°), the whole sky can be covered with exposure totals from $\sim 1 - 4\times$ that for EXIST. For total exposures on a given source the same as EXIST, the sensitivity for EXIST-LITE would be reduced from Figure 2 by a factor of ~2-3 due to absorption/scattering in the residual overburden atmosphere (~4 g/cm^2 averaged over the large FOV), but this may be compensated in part by the lower and more stable background than encountered in low earth orbit (unless the orbit were equatorial). A detailed study of backgrounds and sensitivities for EXIST-LITE will be carried out.



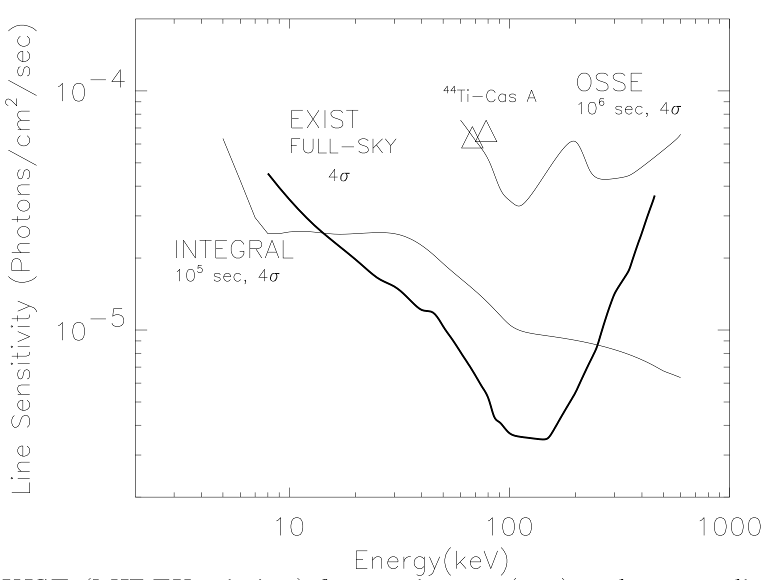


Fig. 2. Sensitivity of EXIST (MIDEX mission) for continuum (top) and narrow lines (bottom).

SCIENTIFIC OBJECTIVES FOR EXIST-LITE

The scientific objectives for the balloon-borne mission, EXIST-LITE, would be essentially the same as for the full MIDEX mision. Here we list these objectives, with a brief discussion of the differences that would apply to the 100dLDB type of mission. In general, the balloon mission can obtain significantly greater exposure times (particularly for high-δ sources) on intermediate timescales (hours-weeks). The entire survey is conducted (for half the sky) in a single $\sim$100day flight (vs. 9 months - 2 years for the MIDEX mission). However on the very shortest timescales ($\lesssim$ 15 min) appropriate to an un-occulted observation in a single satellite orbit, the MIDEX mission is appreciably (factor of $\sim$2-3) more sensitive since it is not affected by absorption and scattering of any overlying atmosphere. Thus the 100dLDB vs. MIDEX versions of EXIST can have complementary capabilities and, accordingly, primary objectives.

Hard x-ray spectra and variability of AGNs

EXIST will have an all-sky sensitivity some 10$\times$ better than that needed to detect the "typical" Seyferts seen with OSSE. More than 1000 AGN should be detected in the all sky survey and at least $\sim$100-300 could be detected in a 100dLDB EXIST-LITE mission. EXIST-LITE has the required sensitivity in the poorly explored 30-100 keV band to detect all known AGN detected with Ginga or with the Einstein slew survey.

Test of halo models and precise positions for Gamma-ray Bursts

EXIST would have a GRB sensitivity approximately 20$\times$ that of BATSE so that a 2 month pointed exposure could both detect and map a halo in the Andromeda galaxy (M31) should one exist. EXIST-LITE could achieve a comparable exposure if M31 pointings were carried out for the $\sim$8 hours of visibility each day although the burst sensitivity would likely be reduced (for comparable backgrounds) by the factor of $\sim$2 mentioned above. For the observed GRB logN-logS relation, EXIST-LITE should detect GRBs at about 1/2 the rate, or $\sim$0.5/day, as EXIST (or BATSE, with its much larger FOV but reduced sensitivity). GRBs will be located to $\lesssim$ 1-5$'$ positions, thereby providing definitive tests of repeaters. Bright burst positions and spectra could be brought down in real time for automated followup searches.

Studies of black hole and neutron star compact binaries and transients

EXIST-LITE surveys 50% of the sky each day (i.e. the full northern hemisphere or sky with $\delta \gtrsim 0°$ for a 100dLDB flight at mid-latitude of 45°) and would achieve continuous integration times of $\gtrsim$ 3-12 hours for each source each day. Thus studies of compact objects on a wide variety of timescales are possible throughout the Galaxy. A deep galactic survey for transients, black hole binaries and pulsars will allow the relative populations of black holes in the Galaxy to be constrained. Relatively short-duration ($\sim$1 day) transients are particularly favorable for discovery and study by EXIST-LITE. A much larger population of fainter sources (e.g. black holes with hard spectra) could also be detected. A galactic plane survey and monitoring for even just a single 100dLDB balloon flight would be highly complementary to the planned galactic plane survey with INTEGRAL, which as a series of discrete pointings requires $\sim$2 weeks to cover the galactic plane. Since EXIST-LITE only observes half the sky in a full flight, it is not able to perform the same all-sky monitor function as the full MIDEX mission and is, again, complementary.

Monitoring and Study of X-ray Pulsars

The measurement and monitoring of spin periods and luminosity/spectra of a large sample of accretion-powered pulsars would greatly extend the studies so successfully carried out with BATSE in the $\sim$20-100 keV band. With the greatly increased sensitivity and resolution (both spectral and spatial), and assuming a logN-logS with slope $\sim$1 for the galactic population of accretion-powered pulsars, EXIST could extend the BATSE sample by a factor of $\sim$10 or, at the very least, to the entire sample of known accretion pulsars. On a 100dLDB mission, EXIST-LITE would provide more densely sampled coverage for some sources. In addition, the high spectral resolution afforded by the CZT detector array for EXIST (or EXIST-LITE) would allow a high sensitivity study of cyclotron features in pulsar spectra.

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

The array of Cd-Zn-Te imaging detectors proposed for EXIST or EXIST-LITE achieves high spectral resolution (e.g. $\sim$5% at 60 keV). Thus emission line surveys can be conducted. The decay of ^{44}Ti (lines at 68 and 78 keV) with long (68 y) halflife allows a search for the long-sought population of obscured supernovae in the galactic plane at sensitivities significantly better than the possible detection of Cas-A (cf. Figure 2). These objects would likely appear as discrete (unresolved) emission line sources. Similarly, 511 keV emission from black hole binaries (or AGN) can be searched for (e.g. in transient outbursts), and the diffuse galactic 511 keV emission imaged with sensitivity comparable to OSSE (cf. Figure 2).

Study of the diffuse hard x-ray background

The spectra of a significant sample of AGN will test the AGN origin of the diffuse background for the poorly explored hard x-ray band. Because the background measured by the EXIST detectors below 100 keV is dominated by the cosmic diffuse spectrum, its isotropy and fluctuation spectrum can be studied with much higher sensitivity than before. This will be more difficult to do with EXIST-LITE because of the additional contribution of atmospheric background, which peaks in the $\sim$60-100 keV band. However this can be modelled and the diffuse background isotropy and spectrum could be studied in a series of 100dLDB flights.

DETECTOR AND TELESCOPE CONCEPT

Detector Concept

EXIST-LITE would incorporate initially one, but ultimately two, large area (c. 2500 cm^2 each) arrays of Cd-Zn-Te (CZT) detectors as proposed for EXIST. Although the detector and telescope design for the full MIDEX version of EXIST may differ, here we describe a detector and telescope concept for EXIST-LITE that is based on our present development of a prototype CZT imaging detector, EXITE3.

The EXIST-LITE detector concept incorporates 2.5mm pixellation on 12 mm (square) CZT detector elements (5-10mm thick), arrayed in a modular configuration. The individual 4 $\times$ 4 pixel detector elements are each read out by a preamp-shaper-multiplexer ASIC readout circuit with very low power dissipation (c. 1mW/channel). The 16-channel ASIC would include a comparator to examine the multiplexed outputs and output the 1, 4, or 16 peak channels (configured on command) so that multi-site detection (e.g. Compton events and internal background rejection) could be accomplished. The ASIC would be packaged with a ceramic/PCB carrier on top (CZT side) with the 4 $\times$ 4 pixel grid of contact pins making contact (with silver epoxy or pogo pins) with the CZT pixel array and conductive traces directly connected to the ASIC inputs. The bottom (output) side of the ASIC would be socketed with a standard multi-pin connector supplying operating voltages, grounds, control lines and output (multiplexed) shaped outputs. The CZT-ASIC package would be mechanically coupled and locked in a thin-walled (0.3 mm) copper square tube (12.5mm $\times$ 12.5mm $\times$ 10mm) epoxied to a closed and insulating (e.g. Kevlar) end cap which provides mechanical rigidity and light insulation. A thin (1mm) conductive rubber washer epoxied to the central 10mm diameter of the end cap is used to supply the negative bias voltage (-500V) to the radiation side of the CZT detector. The washer is connected with a small feed-through pin in the corner of the end cap to an external (top) bias distribution network for the contiguous CZT detectors in the array.

This packaging concept thus provides for complete modularity of individual detector and ASIC for plug in (and easy replacement) on a purely analogue mother board. The individual CZT-ASIC modules are sized for (relatively) easy fabrication and acquisition of CZT (i.e. 12mm x 12mm x 5mm crystals), noise isolation and thermal coupling to the mechanical frame and BGO collimator mounted above.

For the 45° (FWHM) field of view desired for EXIST-LITE, the collimator blade height/spacing ratio is tan (45°) = 1, and for the collimator (assumed to be BGO; see below) to have $\gtrsim$ 50% collimation efficiency at all energies below 600 keV, it must have wall thickness of 3mm (i.e. $\gtrsim$ 5mm in collimation). For the collimator to also provide active shielding for the n-γ background expected in the CZT (see below), it must be $\gtrsim$ 5-10mm thick for the packaging discussed below. Thus the collimator pitch must be (significantly) larger than the CZT-ASIC module size (12mm pitch) or it will block an unacceptably large fraction of the open area. We choose a collimator pitch of 10cm, since this will yield a convenient Basic Detector Module (BDM) size of 8 x 8 CZT-ASIC modules with total area of 100 cm^2. This leads, then, to a choice of the following concept for the detector digitization and overall packaging: the full detector is tiled with 100cm^2 self-contained detector modules (BDM), each with surrounding (4-sided) 7 mm thick BGO collimator (10cm high) providing external shielding, and isolated ADC and interface to the detector data bus. Behind the analogue mother-board (10cm x 10cm) for the BDM would then be a 2cm thick BGO anti-coincidence shield which is optically coupled to the 4-sided BGO collimator shield above. Because of the close packing of the CZT-ASIC and motherboard, it would then be only ~2cm behind the rear of the CZT. All analogue signals from the motherboard would be routed out through a half-hole in one corner of the shield, which would (when the full detector is tiled) require then only one shield feed through for 4 contiguous BDMs. The BGO shield would itself be readout with 2 avalanche photo-diodes (APDs) optically coupled on opposite sides of its bottom (digital) side. Each of the two complete EXIST-LITE detectors would thus consist of an array of 5×5 or 25 such BDMs. These modules would be close-packed and mounted in a common frame. Although the collimator shields will require a net gap of ~1.5 cm between each of the 5 BDMs across the detector array, this does not affect image reconstruction but only makes the detector ~8 cm larger on a side.

By incorporating an active collimator of BGO, the background rejection in each BDM is expected to be optimum: the n-γ activation background induced in the Cd-Zn-Te detector by the interaction of local thermal neutrons in the Cd will be more efficiently rejected since the collimator now actively shields ~90% of the forward hemisphere (vs. having the active BGO shield only shield the rear hemisphere of the CZT detector array as originally considered for EXIST (cf. Grindlay et al 1995). It is likely that this modular construction and active collimation for the high energy FOV would be favorable for the satellite version of EXIST also.

This 10cm $\times$ 10cm packaging concept for the BDM and detector-assembly allows for the incremental development of the detector, as needed for a balloon-flight development program where cost constraints are significant. A key difference from the satellite EXIST 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 LDB flight, this low energy collimation is probably not needed.

The development of a single BDM could occur on a timescale of ~1-2 years and would allow a prototype EXIST-LITE imager, EXITE3, to be demonstrated (complete with coded mask; see below) as a piggy-back on the current EXITE2 telescope and pointing system.

Telescope Concept

The coded aperture telescopes for either a single EXITE3 prototype module or the eventual EXIST-LITE system can be relatively compact design with coded mask at focal length 1.43m and mask pixel size 5mm. This yields an imaging resolution of $12'$, which is appropriate to resolve even the most crowded galactic bulge fields at the high sensitivity expected. In order to cover the full 45° field of view, the EXITE3 prototype would have a URA mask of approximate dimensions 1.3m $\times$ 1.3m and format 257 $\times$ 255 to fully image the 45° FWHM field of view. However, since the BGO collimator on each BDM segment of the detector array would produce partial coding for sources off-axis, the mask must be either smaller format and repeated (e.g. 4 contiguous 127 $\times$ 129 masks, leading to ambiguous source positions) or random. A random mask would be, in any case, as effective as a URA of such large format. The complete EXIST-LITE telescope need only have a mask some 0.5m larger in each dimension or $\sim$ 1.7m. Since the coded mask should not collimate the image significantly, the mask thickness is restricted to be $\lesssim$ 5mm, which (for Ta mask elements) restricts its upper energy limit to be $\lesssim$ 600 keV for partial shadowing. The full dimensions of the mask, and thus its mass (~150 kg for the full mask) can of course be reduced by decreasing the focal length by either degrading the angular resolution or detector oversampling (or both).

CZT DETECTOR AND ARRAY STUDIES

As part of the effort to both conduct the EXIST Mission Concept study and optimize the design for a future MIDEX proposal as well as EXIST-LITE, we are conducting a variety of studies of CZT detectors and array technologies at CfA and in collaboration with both other EXIST Team members and industry.

Balloon Flight Tests of Backgrounds and Shielding Efficiency

A critical area of concern for the use of CZT detectors in space is the possibly high levels of internal background they might experience due to the large neutron cross section(s) for Cd, which result in prompt gamma-ray decays. Balloon flight tests of single isolated CZT detectors by the GSFC and Caltech groups in May and September-October, 1995, suggested disturbingly large in-flight backgrounds compared to those expected for similar scintillation detectors (e.g. Parsons et al 1996). However the GSFC measurement of a marked reduction in background with an external anti-coincidence shield (NaI) suggested this could be effectively reduced by suitable active shielding.

In collaboration with Caltech, we have assembled a flight unit to test the prompt anti-coincidence shielding efficiency of a planar BGO shield immediately behind the CZT detector plane, as proposed for EXIST. The BGO (75mm diameter $\times$ 75mm thick, and supplied by JPL) is centered below a single element CZT detector (10mm $\times$ 10mm $\times$ 2mm, and supplied by eV Products to Caltech). The detector-shield and preamp are mounted in a pressure vessel and shielded with a 1.8mm thick Pb + 0.8mm thick Sn and 1.2mm Cu graded shield to simulate the approximate grammage of the passive collimator in front of an EXIST detector. The raw CZT and BGO (shield) detector preamp outputs are interfaced to shaping amps and digital (discriminator and 12 bit ADC) electronics built at CfA to interface to the flight computer and data system for the EXITE2 balloon-borne telescope. Unfortunately, due to two successive campaigns (May and September-October, 1996) of high surface winds and no launch opportunities, this experiment is still awaiting a Ft. Sumner launch (May 1997).

Balloon Flight Measure of Neutron Backgrounds

In order to fully calibrate the CZT background and shielding experiment so that balloon results may be extrapolated to the full space environment, a simultaneous measure of the neutron flux experienced by the detector is desirable. The atmospheric neutron fluxes as tabulated by Armstrong (1973) are sufficiently uncertain (probably by a factor of $\gtrsim 2$) that we shall attempt to measure the flux by a simple passive experiment: an array (7×6) of gold foils (each $\sim$6cm^2) mounted on top of the gondola in which the n-γ reaction

$$\text{Au-197(n,}\gamma\text{)} \rightarrow \text{Au-198(,e)Hg-198}$$

will be measured after the flight by observing the resulting 412 keV decay γ-ray (2.7d halflife) with a low background Ge spectrometer at JPL (by L. Varnell). This experiment, conducted in collaboration with G. Skinner and L. Varnell, is also awaiting the Ft. Sumner launch.

Spatial Uniformity of CZT

Pixellated CZT detector arrays, as proposed for the full EXIST mission or EXIST-LITE, will require relatively uniform response across both the projected surface area and depth of the detector elements. Non-uniformities of detector response can be calibrated out (by flat fielding) but will be simplified to the extent the detectors are uniform (and will be less of a problem with the relatively large pixel detectors for EXIST than with small pixel CZT imagers for focussing optics). We have conducted a program of mapping the spectral response of single detectors and comparing the observed variations with IR micrographs (obtained at eV Products) of the detector to correlate spectral response with grain boundaries and inclusions in the detector. Spectra (Am-241) obtained in a 3×3 raster scan of a 0.5mm beam across a 4mm $\times$ 4mm $\times$ 3mm CZT detector show variation in spectral response which correlates with the grain boundaries as well as inclusions and precipitates. Results were reported by us at the NASA-SEU Technology Workshop (December, 1996).

Development of PIN Readouts for CZT Detectors

CZT detectors are conventionally fabricated with metal (gold) contacts deposited directly on the CZT crystal. These metal-semiconductor-metal (M-S-M) detectors are of course the subject of intense development and are baselined for EXIST. However, they suffer from limitations of charge collection efficiency (although these are at least partially overcome with "small pixel" electrodes; cf. Barrett et al 1995) and poor ohmic contacts. Several groups, most recently SBRC (Hamilton et al 1996) have investigated alternative readouts incorporating P-I-N junctions. The Spire Corp. (Bedford, MA) has developed a new method for fabrication of P-I-N electrodes on CZT by using CdS(p-type) and ZnTe(n-type) layers deposited by thermal evaporation on both high pressure Bridgman (HPB) CZT crystals (from eV Products) as well as lower cost vertical Bridgman (VB) crystals (from Cleveland Crystals), and the results appear very encouraging. At CfA we are testing these P-I-N readout CZT detectors which offer advantages of improved charge collection and ease of fabrication for their use as thick detectors. We are working with Spire to fabricate a 4×4 array P-I-N detector (on a 10mm $\times$ 10mm $\times$ 5mm CZT substrate) for balloon flight tests of background and uniformity of response.

Development of Thick CZT Detector Array Readouts

Thick detectors (5mm or greater) as desired for EXIST pose special challenges for the optimum design of the detector and readout. In particular, the electric field configuration needed for the small pixel effect (Barrett et al 1995) must be carefully considered, and the effects of charge diffusion and spreading become more important. We are exploring these effects in collaboration with the RMD Corporation (Watertown, MA), who have developed evaporative mask techniques for array fabrication and have built a prototype array (3 x 3; 1mm pixels) using 4mm thick CdTe grown by RMD. Results for Co-57 show high photopeak efficiency and uniformity. In collaboration with RMD, we have now extended this to CZT: RMD has just completed fabrication of a prototype 4×4 array M-S-M detector (on a 10mm $\times$ 10mm $\times$ 5mm CZT substrate) and initial results appear very promising and will be reported in Shah et al (1997). At CfA, we shall test fully this array for its small-pixel effect properties. We are also integrating the array with an ASIC readout, using a prototype 16-channel preamp/shaper ASIC developed by IDE Corp. The same ASIC readout system will allow comparative tests of the MSM array detectors from RMD and Spire, and the PIN array being developed by Spire. Initial results will be presented in a forthcoming paper by Bloser et al (1997).

ACKNOWLEDGEMENTS

The EXIST Concept was developed by the author in close collaboration with T. Prince, F. Harrison, C. Hailey, N. Gehrels, B. Ramsey, M. Weisskopf, G. Skinner and P. Ubertini, all of whom are gratefully acknowledged. The EXITE3 and CZT development is being done with P. Bloser, Y. Chou, G. Monnelly, T. Narita and S. Romaine, all of whom are also thanked. This work was supported in part by NASA grants NAGW-624 and NAG5-5103.

REFERENCES

Armstrong, T.W., Chandler, K.C. and Barish, J., Calculations of Neutron Flux Spectra Induced in the Earth's Atmosphere by Galactic Cosmic Rays, *JGR*, **78** (16), 2715 (1973).

Barrett, H., Eskin, J. and Barber, H, Charge Transport in Arrays of Semiconductor Gamma-Ray Detectors, *Phys. Rev. Letters*, **75**, 156 (1995).

Bloser, P., Grindlay, J., Narita, T. *et al*, in preparation (1997).

Covault, C., *Ph.D. Thesis, Harvard University* (1991).

Caroli, E., Stephen, J., DiCocco, G., Natalucci, L. and Spizzichino, A., Coded Aperture Imaging in X- and Gamma-Ray Astronomy *Space Sci. Rev.*, **45**, 349 (1987).

Grindlay, J., Prince, T., Gehrels, N.., Tueller, J., Hailey, C. *et al*, Energetic X-ray Imaging Survey Telescope (EXIST), *Proc. SPIE*, **2518**, 202 (1995).

Grindlay, J. Prince, T., Gehrels, N., Hailey, C. Harrison, F.*et al.*, Proposed (to) EXIST: Hard X-ray Imaging All Sky Monitor, *All Sky X-ray Observations in the Next Decade*, Proc. Workshop in Riken, Waco, Japan, March 1997, (M. Matsuoka and N. Kawai, eds.), in press.

Hamilton, W., Rhiger, D., Sen, S., Kalisher, M., Chapman, G. and Millis, R., HgCdTe/CdZnTe P-I-N High Energy Photon Detectors, *Jour. Elec. Mat.*, **25**, 1286 (1996).

Levine, A., Lang, F., Lewin, W., Primini, F., Dobson, C. *et al.*, The HEAO-1 A-4 Catalog of High Energy X-ray Sources, *ApJ Suppl.*, **54**, 581 (1984).

Lum, K., Manandhar, R., Eikenberry, S., Krockenberger, M. and Grindlay, J., Initial Performance of the EXITE2 Imaging Phoswich Detector/Telescope for Hard X-ray Astronomy, *IEEE Trans. Nucl. Sci.*, **NS-41**, 1354 (1994).

McConnell, M., Dunphy, P., Forrest, D., Chupp, E. and Owens, A., Gamma-ray Observations of the Crab Region Using a Coded Aperture Telescope, *Ap.J.*, **321**, 543 (1987).

Parsons, A., Barthelmy, S., Bartlett, L., Birsa, F., Gehrels, N. *et al.*, CdZnTe Background Measurements at Balloon Altitudes, *Proc. SPIE*, vol. 2806, 432 (1996).

Paul, J., Mandrou, P. and Ballet, J., SIGMA: The Hard X-ray and Soft Gamma-Ray Telescope on board the GRANAT Space Observatory, *Adv. Sp. Res.*, **11** (8), 289 (1991).

Shah, K., Cirignano, L., Klugerman, M., Dmitreyev, Y., Grindlay, J. *et al.*, Multi-Element CdZnTe Detectors for Gamma-Ray Detection and Imaging, *IEEE Trans. Nucl. Sci.*, submitted (1997).

(and see additional references given in Table 1).