

(Fine-Pixel) Imaging CdZnTe Arrays for Space Applications

Brian D. Ramsey

Abstract— The compound Cadmium-Zinc-Telluride (CdZnTe) offers great promise for astrophysics. As crystal quality improves, the challenge for imaging array development is to derive electrode geometries and readout electronics to satisfy particular applications and to understand how the material will perform in the space environment. An overview of the requirements for CdZnTe imaging detectors at the focus of hard-x-ray grazing-incidence telescopes will be given together with the status of current array developments.

I. INTRODUCTION

Grazing incidence optics, so called because of the shallow angle at which x rays reflect from the mirror's surface, have brought about spectacular advances in soft-x-ray astronomy (< 10 keV.) The ability to collect x rays and focus them to a tiny point provides an enormous increase in signal to noise over non-focusing systems, as the background, against which faint cosmic x-ray sources must be measured, scales with the detection area. By way of an example, the Chandra observatory [1], with sub-arc-sec grazing incidence mirrors having the same effective x-ray collecting area as the large-area proportional counter detectors on the first x-ray astronomy satellite, UHURU [2], has five orders of magnitude more sensitivity due to its superb optics.

This grazing incidence 'revolution' is, however, confined to low energies. Technical challenges have prevented useful mirrors from being developed for higher energies and thus the hard-x-ray region (10-100 keV) remains 'relatively' unexplored at high sensitivities and fine angular scales. This situation is now changing with the development of payloads featuring hard-x-ray focusing optics above fine-resolution imaging detectors, which should bring about similar astrophysical advances at higher energies. Table I lists some of these new payloads.

TABLE I
SOME HARD-X-RAY FOCUSING TELESCOPES UNDER DEVELOPMENT

Payload [ref] / (Institution)	Type	Energy Range (keV)	Mirror Type	Resolution / Focal Length
HERO [3] (MSFC)	Balloon	15-75	Replicated Full shell	15 arcsec 6 m
InFocus [4] (GSFC)	Balloon	15-80	Segmented Foil	1-2 arcmin 8 m
HEFT [5] (Caltech)	Balloon	15-100	Segmented Glass	1 arcmin 6 m
Con-X [6] (Consortium)	Satellite	5-100?	TBD	1 arcmin 8-10 m

II. FOCAL-PLANE-DETECTOR REQUIREMENTS

To complement the new generation of hard-x-ray telescopes under development necessitates focal plane detectors with high performance. These detectors must have :

- High efficiency
 - *All events must be counted and in the photopeak (single photon counting.)*
- Good imaging properties
 - *Detector must oversample the image for maximum mirror angular resolution.*
- Good energy resolution
 - *Needed for continuum studies and for resolving nuclear lines.*
- Low background
 - *Determines the sensitivity of the telescope.*
- Low power
 - *Limited power available and problems with heat dissipation.*
- Low sensitivity to radiation damage
 - *Concern for extended orbital missions especially through radiation belts.*
- Rugged construction
 - *Must survive in space or rigors of balloon-payload landings.*

Brian D. Ramsey is with the NASA / Marshall Space Flight Center, Huntsville, AL 35812 USA (telephone: 256-544-7743, e-mail: Brian.Ramsey@msfc.nasa.gov.)

As will be shown in the following sections, Cadmium-Zinc-Telluride (CdZnTe) detectors currently offer the best

combination of these parameters and as a consequence these detectors are being actively developed for this role.

A. Efficiency

The high effective atomic number of CdZnTe ensures good absorption efficiency with a modest 1-2 mm thickness. Further, at 50 keV the Compton scattering cross section is 2 orders of magnitudes lower than the photoelectric absorption cross section and this ensures that interactions depositing the full incident x-ray energy are predominant. Fig. 1 shows the absorption efficiency of CdZnTe compared with silicon and gallium arsenide.

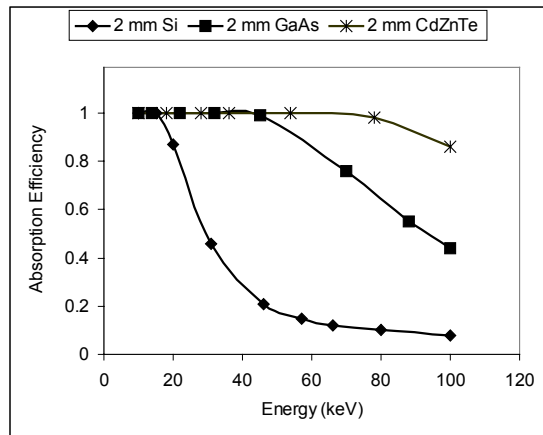


Fig. 1. Comparison of the absorption efficiency of 2 mm of CdZnTe, silicon, and gallium arsenide.

B. Imaging and Energy Resolution

High-angular-resolution hard-x-ray optics necessitate detectors with a large number of very fine pixels, e.g. Hero features 15-arcsec-HPD mirrors, which for a 6-m focal length means a focal spot of diameter 0.43 mm. To ensure that the resolution of the telescope is not compromised by the detector, the detector resolution must be at least a factor of two better than this, or around 200 microns FWHM. Further, to sample the full focal plane the detector must have 128 x 128 pixels, either in one single unit or in a tiled array of detectors. Other telescopes [Table 1] have different requirements due to different angular resolutions, but in all cases a large number of fine pixels must be read out.

Various groups are developing custom detectors plus the necessary readout electronics. The approach is either to use a pixellated array [7,8,9] or a strip-type readout [10]. In the latter, orthogonal grids of readout electrodes are deposited on the two sides of the CdZnTe crystal, with each strip connected to a separate electronic readout channel. This approach reduces the electronic complexity, using 2n channels rather than n^2 for an $n \times n$ effective array. It does, however, result in greater noise as each strip spans the full crystal. In the pixellated configuration, the cathode is contiguous and the anode readout pads are each connected,

via bonding, to a separate readout channel on a custom electronic chip resulting in a 1-to-1 correspondence between the number of readout channels and the number of pixels (Fig. 2). Typically the custom chip, termed an ASIC for Application Specific Integrated Circuit, would contain the preamplifiers and shapers plus a peak level detector and a multiplexing system and would have very low noise --- 40 electrons RMS has been reported [7].

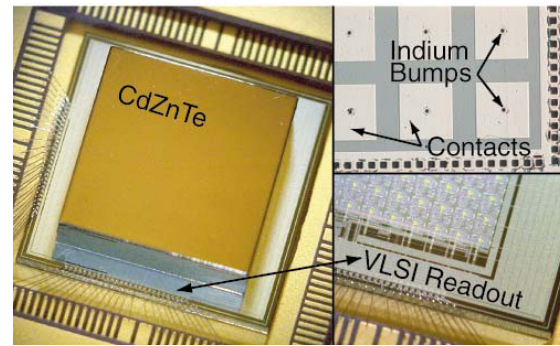


Fig. 2. Implementation of CdZnTe pixellated array with custom electronics [7].

These imaging developments are well underway and CdZnTe arrays with progressively smaller pixels are being tested. At MSFC, for example, devices having 16 x 16 arrays of 300-micron-pitch pixels are currently under evaluation.

The benefit of very-fine-pixel devices is that the total crystal leakage current and capacitance is shared over many channels and so very low noises can be achieved. Further, tailing is significantly reduced through the 'near-field effect' which ensures that most of the signal induction takes place near to the readout electrode. This permits single carrier charge collection, which greatly improves the resolution. Energy resolutions of better than 1% at 60 keV have been reported with 700-micron-pitch pixels [7].

There are, however, some problems associated with fine-pixel detectors which increase as pixel size becomes smaller. One of these is the fact that as pixel sizes are reduced, the ratio of pixel gap to pad becomes larger and so more events materialize in the gap. The field in this gap region is low near the pads and charge loss occurs. To compensate for this, steering electrodes have been introduced. These are shown schematically in Fig. 3, as electrodes interleaved between the readout pads and biased very slightly below the pad potential. Field lines in this region that would normally terminate on the crystal surface are pushed onto the adjacent pixel improving charge collection. In [11] it was reported that with a 100-micron interpixel gap the energy resolution at 60 keV was improved by a factor of two (from 3.5 keV to 1.8 keV) when a steering grid was used.

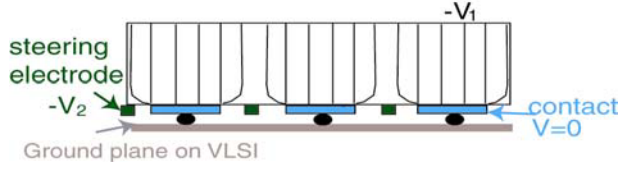


Fig. 3. Inter-pixel steering electrode to reduce charge loss.

A second effect of small pixels is that there are more shared events. Typical charge-cloud diffusions in 2-mm-thick crystals are $\sim 50 - 100$ microns and the range of the K-shell characteristic x-rays are ~ 200 microns, so that as pixel sizes approach this, many events will be shared between adjacent pixels. In [12] it was reported that 24% of events were shared with a 500-micron-pitch detector. Measurements here at MSFC indicate that this increases to 35-40 % for 300-micron-pitch pixels. Adding the signal from adjacent pixels increases the noise level and hence the energy resolution is degraded. However, signal sharing offers the possibility of sub-pixel spatial resolution, which may be a significant benefit as mirror quality improves.

To date, devices with sufficient area and pixel sizes for the hard-x-ray telescopes under development have yet to be demonstrated. However, developments with smaller arrays look encouraging and no *major* problems are foreseen in scaling these up. The question of crystal quality remains but should soon be answered as groups undertake detailed fine-beam scanning of these small-pixel arrays.

C. Background

Although the use of focusing optics dramatically reduces the effective background by concentrating all the source flux into a tiny region, the residual background in the focal spot area eventually dominates the telescope's sensitivity if long enough observations are performed. Table II demonstrates this. Here, the required maximum desired detector background, in units of counts/cm² sec keV, is given for two different telescope systems as a function of observing time. The maximum background is defined as the level below which the source observation will be photon limited, i.e. limited by fluctuation in the number of source photons measured rather than by fluctuations in the number of detector background events present in the image. We can see that as integration times increase, the background level must be progressively smaller to prevent it dominating the source measurement. For reference, the satellite payload used in the calculation was an arc-minute-resolution, 8.5-m-focal-length system with three mirror modules while the HERO system was 15 arcsec-resolution, 6-m-focal-length, with 16 modules.

TABLE II
APPROXIMATE MAXIMUM BACKGROUND TO MAINTAIN
PHOTON-LIMITED OBSERVATIONS IN GIVEN OBSERVING TIME.

Integration Time (s)	Background (Counts / cm ² s keV)	
	Satellite	HERO balloon payload
10 ³	3.10 ⁻³	2.10 ⁻²
10 ⁴	3.10 ⁻⁴	2.10 ⁻³
10 ⁵	3.10 ⁻⁵	2.10 ⁻⁴
10 ⁶	3.10 ⁻⁶	2.10 ⁻⁵

The background in CdZnTe flight detectors consists of an aperture-dependent diffuse component plus direct and indirect effects of charged particles acting with the detector and surrounding structures. Thus the background rate depends among other things on the field of view of the detector, the detector material and thickness, the shield materials and geometry, and, if the shield is an active one, the shield threshold. The key is obviously to maximize background rejection, but minimize valid event losses.

The best way to gauge background levels is to fly test detectors in representative environments and several groups have done this with CdZnTe payloads on high-altitude balloons. A compilation of representative data [13] is given in Fig. 4, plotted in counts per cm² to remove the variation due to the different crystal thicknesses flown. These data show that simple passive shielding does not provide the lowest background and that more sophisticated active shielding, surrounding the whole detector, is necessary. These active shields, which are typically a scintillator such as Bismuth Germanate (BGO) or Sodium or Cesium Iodide (NaI, CsI), provide prompt signals to reject events that trigger both the shield and the detector. Thus any additional secondaries that are produced in the shield and enter the main detector are promptly rejected.

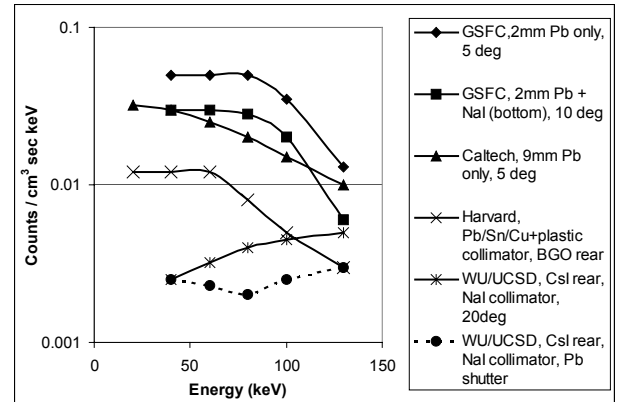


Fig. 4. Compilation of CdZnTe background data taken at balloon altitudes from [13].

Other conclusions of these studies were that the background scales with detector thickness and that there was no evidence of neutron capture effects in the CdZnTe. This latter is of importance as one of the natural isotopes of cadmium has a very high thermal neutron absorption cross section and it was thought that the prompt gamma emission from this reaction could be a large source of background in CdZnTe. No evidence was found for the capture of this prompt gamma ray in the surrounding shields.

Scaling the lower curves plotted in Fig. 4 for a 2-mm-thick detector, the background level at balloon altitudes would be such that we could observe for nearly 10^5 s before the detector background would dominate. Such integration times are typical in x-ray astronomy.

To gauge the background levels expected in orbit, we have taken the satellite experiment configuration above, assumed a 2-mm-thick detector surrounded by a thick BGO active shield, and performed detailed modeling for two different orbits [14]. The first of these was a Low Earth Orbit (LEO), 500 km altitude and 28.5 inclination, and the second was an L2 orbit, at the second Lagrange point, 1.5 million km from earth and desirable for its steady thermal environment and the long uninterrupted viewing of most of the sky which it affords. These two orbits have very different background environments, the former having a much larger cosmic-ray flux due to repeated passages through the South Atlantic Anomaly. This is reflected in the much greater residual detector background rate predicted for the LEO, shown in Fig. 5, which at 75 keV is almost an order of magnitude higher than the L2 orbit detector background shown in Fig. 6. In both cases, the bulk of the background arises from activation of the BGO shield material (simulations with NaI or CsI shields give similar results). Activation of the CdZnTe detector itself is one to two orders of magnitude below this across the energy range of interest. Not evident in this figures is the fact that *without* the BGO the residual rate would be almost an order of magnitude higher, and that the shield definitely reduces the background considerably. Nevertheless, it is probable that the modeled shield in this case is too thick, and that a greater reduction in background can be achieved by making it thinner.

It is evident that in low earth orbit, for the case presented, observations will be background limited in short ($<10^4$ s) observations times. Additional background reduction, beyond thinning the shield, can be obtained by making use of the depth sensing technique in which the ratio of anode to cathode signal is used to determine the depth of interaction in the crystal [10]; any low energy event materializing deep inside the crystal would be rejected as invalid. As Compton scatters of high-energy photons form a significant component of the residual background, this should prove a powerful additional method of background rejection.

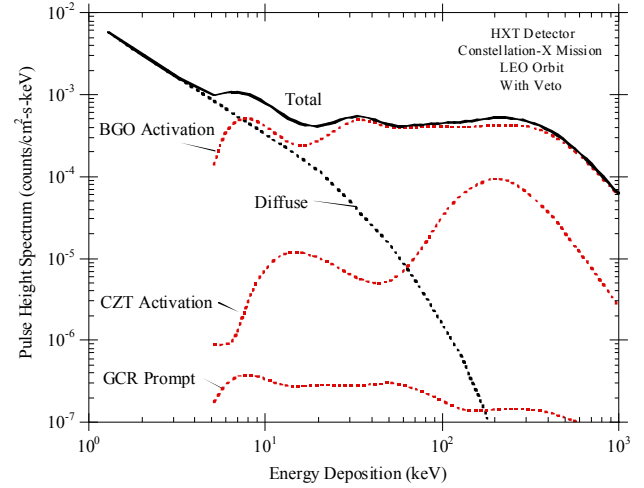


Fig. 5. Modeled CdZnTe background for a satellite in low earth orbit (LEO)

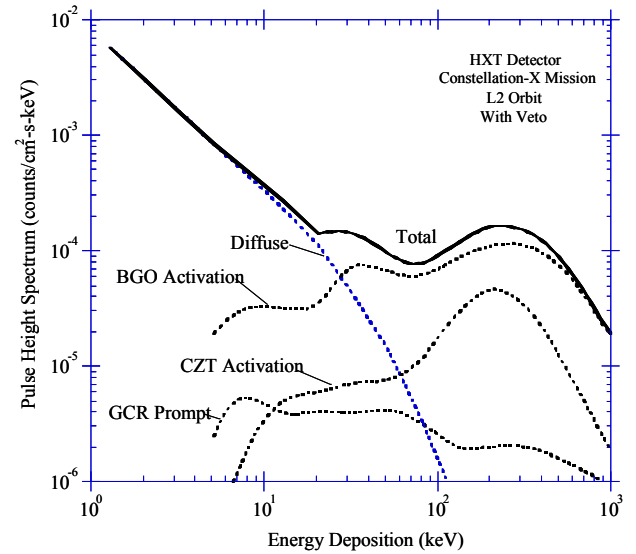


Fig. 6. Modeled CdZnTe background for a satellite in an L2 orbit.

D. Radiation Damage

Semiconductor detectors are known to suffer radiation damage when flown in space. Germanium detectors (p type coaxial), for example, display signs of damage after only a few $\times 10^7$ protons / cm^2 . Typical effects are loss of charge and increased leakage current. For balloon-borne instruments the charged particle fluences are low even for planned 100-200 day flights, but for satellites, the expected charged particle dose depends critically on the orbit. For example, in a 500-km-altitude, 28.5-deg-inclination orbit we could expect around 3.10^8 protons ($E > 1$ MeV) / cm^2 year⁻¹, mostly due to passages through the South Atlantic Anomaly, whereas at the second Lagrange point, this would drop to 6.10^6 / cm^2 year⁻¹.

As CdZnTe detectors rely on the efficient collection of electrons, it is important to know what level of irradiation

will significantly increase electron trapping. To answer this, various groups have carried out irradiation studies; Table III, gives a compilation of recent results [15,16]. These data show that the onset of radiation damage occurs around 10^9 p / cm^2 and thus we can expect to start to see such effects in missions of a few years in low earth, 28.5 degree inclination, orbits. Small changes in gain, of a few percent, can certainly be tolerated provided provisions are made to calibrate these out during flight. For longer missions, the expected gain shifts may be a problem, but there is evidence that damage effects can be annealed out over time, particularly at elevated temperature. In [17], it was reported that almost full recovery was obtained after 12 weeks at room temperature, while in [18] the authors report that after 5.10^9 protons / cm^2 , full pre-irradiation performance could be restored by holding the crystal at 100° C for 12 hours. These measurements indicate that the effects of even prolonged exposures may be mitigated by making provisions for elevated temperature annealing on long-duration satellite missions.

TABLE III
COMPILATION OF CdZnTe RADIATION DAMAGE STUDIES [15,16]

Radiation / Energy	Effects
Proton, 200 MeV	10^9 p/ cm^2 , 2-4% gain shift 5.10^9 p/ cm^2 , 13-15% gain shift, factor of two increase in FWHM.
Proton, 200 MeV	5.10^9 p/ cm^2 , 25% gain shift in strip detector 5.10^9 p/ cm^2 , 50% gain shift in planar detector
Proton, 200 MeV	5.10^9 p/ cm^2 , 10% gain shift in strip detector
Proton, 1.3 MeV	10^{10} p/ cm^2 , interstrip leakage increases 10^{12} p/ cm^2 , bulk leakage increases 2-3 times
Neutrons, thermal and MeV	10^{11} n/ cm^2 , factor of two increase in FWHM and measurable charge loss
Alpha, 5 MeV	$2.5.10^9$ α / cm^2 , start of charge loss effects $1.5.10^{10}$ α / cm^2 , 60% increase in FWHM

III. CONCLUSIONS

Hard-x-ray telescopes place stringent requirements on imaging CdZnTe arrays necessitating a large number of fine pixels with good single photon counting performance. Many groups are now developing such detectors and their associated electronics, and although the full array sizes have yet to be demonstrated no major 'show stoppers' are expected in satisfying current requirements.

When flown on balloon payload with active shielding measured detector backgrounds appear sufficiently low to permit long observations without being background limited. For satellite use, in low-earth orbits, more sophisticated shielding plus depth sensing is needed to keep background rates adequately low.

Finally, although we can expect that charge trapping due to radiation damage will be evident in certain orbits, particularly for extended missions, it should be possible to anneal flight detectors at fairly modest temperatures to restore pre-irradiation performance.

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