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Report of the X-Ray and Gamma-Ray Sensors Panel

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INTRODUCTION

As one of the youngest wavelength ranges to be opened up for astronomical observations, the X- and gamma-ray regions have grown from an infancy of proportional counters and emulsion stacks to instruments as sophisticated as can be developed by collaborative efforts of the individual observers' groups. While these individuals have carried detector design to an advanced state, detector development has most often been pursued as a side effort of an observing program tied to a sounding rocket or balloon proposal. While proportional counters could be developed with "garage-sized" efforts using apparatus that can be found in any good physics lab, many of the new detector ideas with the greatest promise require expertise and equipment far outside the range an individual astronomy organization can be reasonably expected to possess. Thus further development will require explicit support and an appropriate level of funding. The next generation of instruments promises order-of-magnitude improvements in sensitivity and resolution, and will greatly expand the available discovery spaces. New high-energy sensors will provide unique capabilities for exploring objects as exotic as black holes and neutron stars, as well as directly addressing fundamental questions about the origin of the elements and the composition of the universe. Figure 1 provides an example of the unique information that can be obtained through high-energy measurements.

The charge to this panel was to examine the needs of the Astrotech 21 mission set in regards to X- and gamma-ray detectors and to propose a commensurate plan for the development of the technologies required to meet these needs. The capabilities required for future X- and gamma-ray missions, and the promising technologies for achieving those capabilities have been examined in a series of previous works. Prior to the workshop, the panel chair reviewed the results of these efforts, including the reports of the program working groups, the proceedings of the Taos Workshop (*High-Energy Astrophysics in the 21st Century*, AIP Conference Proceedings # 211, P. C. Joss, ed., AIP, 1990), the proceedings of the Annapolis Workshop (*Astrophysics from the Moon*, AIP Conference Proceedings #207, M. J. Mumma and H. J. Smith, eds., AIP, 1990), and the list of topics that had been submitted during recent proposal calls of the High-Energy Astrophysics Branch of the Astrophysics Division at NASA headquarters. From these, the promising sensor concepts relevant to astrophysics missions were extracted, as a starting point for the panel discussions at the workshop itself.

Discussion of the panel lead to a further narrowing of the field to focus on technologies relevant to the proposed set of missions and instruments which form the Astrotech 21 mission set. The particular technology areas and development schedules were also chosen to guarantee that detectors would be developed on an appropriate schedule to meet the technology freeze dates of the mission set. Thus there may be promising technologies which are absent if they did not appear to be demanded by the candidate missions, or if development of such technologies before the relevant freeze date was not deemed feasible. This may seem somewhat arbitrary, since the mission set is very much a moving target, as various basing options go in and out of vogue. Nevertheless, many aspects of the sensors required for these mission concepts remain stationary even if locations, sizes, and schedules of the selected missions were to change. The panel grouped the selected technologies and found them to fall naturally into five areas. A summary list of these areas is provided in Table I. The items are ordered by a

SECTION II. PANEL REPORTS

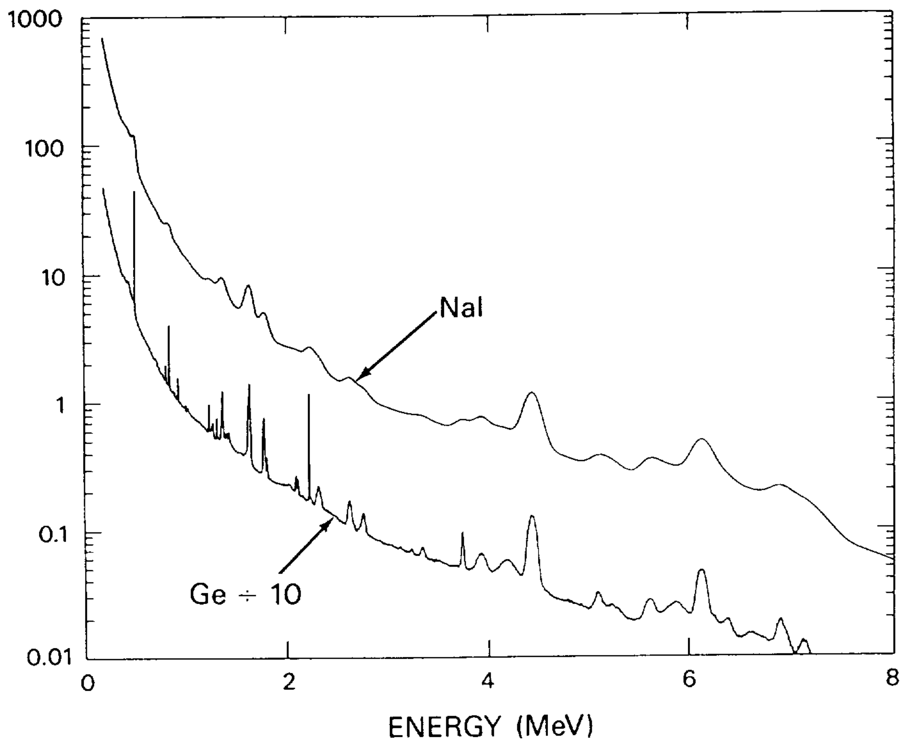

Figure 1. Detector response to model solar flare illustrates the increase in information available as gamma-ray spectrometers evolve from conventional sodium iodide detectors to cooled, high purity germanium detectors.

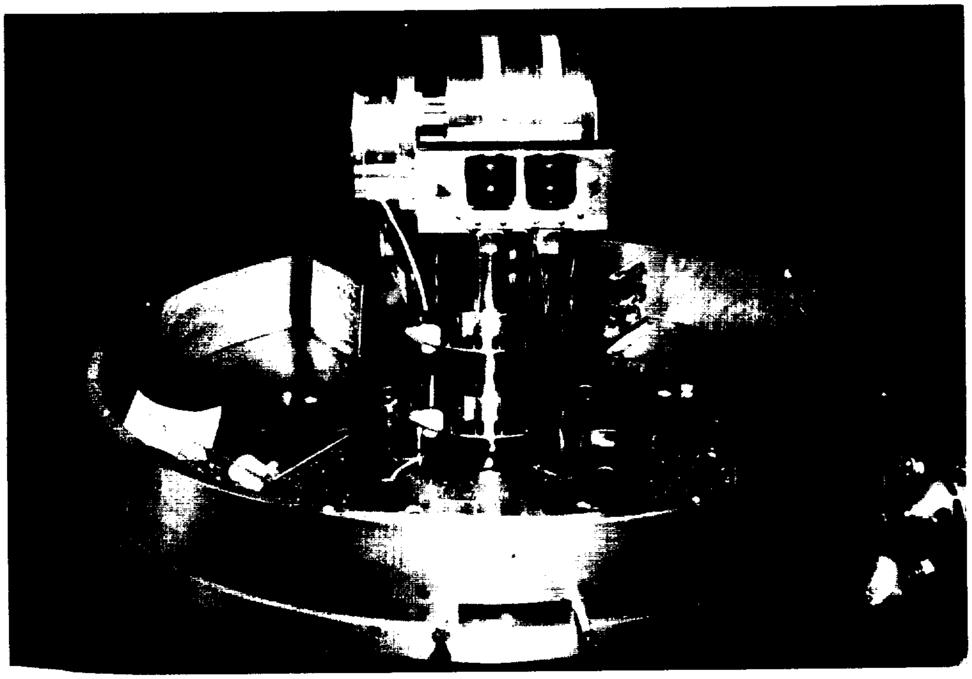

Figure 2. Photo of a position-sensitive germanium detector. Visible are the crystal, electrical contacts, FETs, feed throughs, and pre-amps. (Crystal vacuum housing is not shown.)

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priority determined by consideration of technology need dates and promise; however, all five areas are deserving of support now.

In order to view the development history and prognosis of these detector technologies in the context of space implementation, Tables II A and B provide a comparison of performance specifications for past, current and future NASA gamma-ray and X-ray missions. In the gamma-ray region (Table II A), the Energetic Gamma-Ray Experiment Telescope of the Gamma Ray Observatory (GRO/EGRET) and the balloon instrument, the Advanced Compton Telescope (ACT), have been selected to serve as examples of detector technologies that have already flown, and that have already been developed for an upcoming mission, respectively. NAE and GRSO are used as a representative examples of near- and far-term Astrotech 21 missions, for which additional technology development will be required. A similar chart for X-ray detectors is provided in Table II B, where the existing capabilities are exemplified by the Einstein Observatory Imaging Proportional Counter (HEAO II / IPC) and AXAF CCD instruments, and future requirements by instruments for HXIF, VHTF, and replacement instruments for AXAF.

These tables clearly demonstrate the relative immaturity of detector capabilities in these spectral ranges, as well as the large gaps that exist between existing technology and the performance desired for missions in the Astrotech 21 set. In addition, because the need for sensitive, high-energy detectors is unique to NASA, the agency must expect to bear the full funding responsibility to bring about the desired development. In the remainder of this report, each of the five areas recommended by the panel for special attention will be discussed in order of priority. Within each area, the suggested technology development entries are also listed in order of priority. If the entire program cannot be supported initially, the panel recommends that the items at the top of the lists under each area be funded first.

HIGH RESOLUTION GAMMA-RAY SPECTROSCOPIC DETECTORS

A. Technology Assessment

Missions such as NAE and GRSO require 10 keV - 10 MeV detectors with greatly improved sensitivity (more than a factor of 100 better) and orders of magnitude improved imaging capabilities (to a few arc seconds), which will require position sensitivity to < 1 mm. Adding spatial resolution to Ge spectrometers will allow observers to simultaneously realize their existing capabilities for high resolution spectroscopy with the position finding capabilities of coded-aperture or Compton

Table I. Technology Areas Recommended for Development

Technology Area	Requirements	Missions	Freeze Date
High-resolution gamma-ray spectroscopy for 10 keV to 10 MeV	Large volume, high sensitivity Spatial resolution < 1 mm Energy resolution $E/\Delta E > 1000$	NAE GRSO	'94 '04
Cryogenic detectors for range of few eV to few hundred keV	Large format, $(10)^2$ to $(2000)^2$ Energy res.: ≤ 0.5 eV at 100 eV ≤ 5 eV at 8 keV ≤ 100 eV at 100 keV	HXIF, AXAF II * XST AXAF III VHTF GRSO	'95 '96 '00 '03 '04
Advanced X-ray CCDs for 100 eV to 10 keV with smart readouts	QE > 90% Energy res. = 60 eV Spatial res. = 15 - 50 μm Detector size = 1 - 4 cm Radiation hard	AXAF II XST AXAF III VHTF	'95 '96 '00 '03
Position sensitive detectors for 5 - 500 keV (gas & liquid volume interaction chambers)	Pos. res. = 200 μm - 0.5 mm Energy res. $E/\Delta E \sim 10 - 100$	HXIF VHTF GRSO	'00 '03 '04
Large position sensitive detectors for 200 keV - 2 MeV (solid volume interaction chambers)	Area > few m^2 High stopping power 2D resolution to 1-2 mm	HXIF GRSO	'00 '04

* Terminologies II & III refer to 2nd and 3rd generation instruments.

Table IIA. Gamma-Ray Capabilities for NASA Missions

Development Status	Flown in Space	Developed for Space	Under Development	Desired for Future Mission
Sample Mission	GRO/EGRET	Balloon/ACT	NAE	GRSO
Quantum efficiency & energy range (MeV)	30% 20-3000	40% 100-1000	70% 0.1-10	70% 0.1-10
Energy resolution ($E/\Delta E$)	10	10	1000	> 1,000
Spatial resolution	~ mm	~ mm	7 cm	< 1 mm
Readout technology	Digital spark chamber	Photomultiplier tube	FET	Power < 5 nW/pixel Time constant < 5 µs

Table IIB. X-Ray Capabilities for NASA Missions

Development Status	Flown in Space	Developed for Space	Under Development	Desired for Future Mission
Sample Mission	HEAO II / IPC	AXAF / CCD	AXAF II	VHTF
Array format / area	$(100)^2$	$(500)^2$	$(700)^2$	$(1000)^2$
Pixel size (µm)	1000	60	40	20
Quantum efficiency & range (keV)	~ 60% 0.4-4	~ 75% 0.3 - 8	> 90% 0.1 - 10	> 90% 0.1 - 20
Energy resolution (FWHM, eV)	600	90	60	60
Readout technology	Wire grids	Conventional CCD	Re-sampling	"Smart"

telescope schemes. At the present, Ge spectrometers are available in a moderate size (7 cm diameter) and are occasionally partitioned into two segments for background rejection. To meet the requirements of future missions will require larger crystals, with lower backgrounds, and position sensitive readout techniques. (Fig 2.)

B. Development Plan

The recommended areas of technology development are summarized in Table III. The position-sensitive Ge detector array development should be a moderate-sized program, designed to proceed from the initial success with segmentation of Ge detectors for background rejection, to the position sensing needed to create future imaging spectrometers. The development of large, single crystal Ge spectrometers is an optional large-scale program. Much benefit has been gained from the previous advances in detector size, which has allowed more collecting area to be flown (with something like the number of detectors being held constant). While larger spectrometers have larger photopeak efficiencies, a study should first be done to see if astronomers think that larger crystals, which are unlikely to be produced for any need other than astronomy, are actually worth the investment this would require, or if the resources would be better spent assuring a larger supply of detectors in the sizes available now. For high-resolution Ge spectrometers, the Junction field-effect transistor (JFET) must be carefully integrated with the Ge crystal in the detector housing and so is considered part of the detector assembly rather than part of the separate readout electronics. Advanced JFETs, optimized for gamma-ray spectroscopy use, would require a small development program. This effort would fund the creation of JFETs specifically designed and mounted for compatibility (capacitance, operating temperature range, etc.) with Ge spectrometers. Finally, it would

Table III. High Resolution Gamma-Ray Spectroscopic Detectors

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Development of position-sensitive Ge detector arrays	Discrete detectors	1D demo 2D demo	91 - 94 93 - 96	Moderate
Large, high-quality Ge detectors	7 cm (diameter)	10 cm	91 - 94	Large
Advanced JFET development	Off-the-shelf JFETs with large 1/f noise	Low-power, < 5 nW Time constant < 5 μs 85 - 90 K operation Lower 1/f noise	93 - 97	Small
Solid-state drift chamber	Concept only	Feasibility Demo for GRSO	93 - 95 95 - 98	Small Small

be useful to carry out a small program to test which may offer a better combination of spectral/spatial resolution than existing techniques.

CRYOGENIC X-RAY AND GAMMA-RAY DETECTORS

A. Technology Assessment

Large-format detectors for the energy range of a few eV to a few hundred keV with much improved energy resolution are desired for a variety of X- and gamma-ray missions including AXAF refurbishments, HXIF, VHTF and GRSO. Formats of $(10)^2$ to $(2000)^2$ are desired in order to make it practical to determine spatial structures and investigate large numbers of different sources. A one to two order-of-magnitude improvement in energy resolution will enable spectroscopic determinations of compositions and physical conditions of the sources. The term "cryogenic detectors" is used here to cover several innovative technologies which offer great potential benefits, but which require cooling to liquid helium temperature or lower. The first of these techniques is "quantum calorimetry", where the temperature rise from the absorption of individual photons is measured to determine the energy of that photon. While the principle was suggested three decades ago, it has languished until the GSFC/University of Wisconsin collaboration revived the technique, by demonstrating spectrometers capable of performing in the next generation of observatories. The idea that performance increases could be large enough to justify the overhead of cryogenic cooling, sparked inquiries into other type of detectors. Most of these other investigations are focused in two areas: new thermometry techniques (capacitive readout, kinetic inductors, etc.) and in direct detection by absorbing photons in superconducting films attached to tunnel junctions. A third technique involves sensing the changes in a magnetic field applied to an array of supeconducting granules. When initially cooled down, the field is excluded from the interiors of the granules by the Meissner effect. When a photon is absorbed by a granule, that granule is heated above its transition temperature, enters the normal metallic state, and the field rushes into the formerly excluded volume. The detection of the flipping of individual granules has been demonstrated.

B. Development Plan

The areas of technology development recommended are summarized in Table IV. The development of calorimeter technologies represents a continuation from the detectors developed for the AXAF spectrometer to extend the range of sensitivity to higher energy resolution, and to add spatial resolution. It should begin with a moderate program in devices using semiconductor thermometry, with additional small programs to evaluate alternative thermometry technologies such as kinetic inductors, dielectrics and tunnel junctions. After down selection to the most promising option, the development should continue at a moderate level until the desired energy resolution has been achieved, with a mission deadline of 2003 - 2004 to impact VHTF and GRSO.

Amplifier and readout technologies need to be developed in close concert with the detectors, which operate near 4 K and 0.1 K. Both readout items listed address the difficulties of using Si JFETs, which must be operated near 100 K to avoid carrier freeze-out. The 4 K development would be amplifier elements such as Ge JFETs, which could be run at temperatures where it would not be necessary to shield the detectors from the FETs' thermal radiation. Without the need to intercept radiation from hot FETs, many more pixels could be accommodated. The superconducting electronics element is a placeholder for emerging technologies which may permit replacement for FETs.

Table IV. Cryogenic Detectors

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Semiconductor calorimeter arrays	Format: 1x12 arrays E res: 7 eV at 6 keV	Format: $(10)^2$ to $(2000)^2$ E res: ≤ 0.5 eV at 100 eV ≤ 5 eV at 10 keV ≤ 100 eV at 100 keV	Now - 95	Moderate
Alternate thermometries	Concept	Selection of best Development of best	93 - 98 98 - 03	Several small Moderate
Amplifier & readout technologies				
Semiconducting electronics	~100 K	4 K operation	93 - 95	Moderate
Superconducting electronics	Concept	0.1 K operation	94 - 00	Moderate
Superconducting granules	Concept	Feasibility	93 - 98	Small
Development of high energy res		Demonstration	98 - 04	Moderate
Development of readout		Demonstration	98 - 04	Moderate
Tunnel junction fabrication	Concept			
Evaluate different materials		Selection of best	93 - 96	Few small
Tunnel junction readouts		Selection of best	96 - 00	Moderate
Discrete devices		Position sensing	95 - 00	Moderate
Development of arrays		Demonstration	99 - 03	Moderate

The program for investigation of superconducting granule detectors starts small with some additional demonstrations of the feasibility of the technique. If arrays of granules can be fabricated with the required uniformity of properties, the program size is increased to bring the technology further along, perhaps adding a spectral ability by measuring the interval between the time the grain goes normal and when in re-enters the superconducting state.

The final item, development of tunnel junction arrays and readout, offers great promise for imaging X-ray spectrometers, and offers some promise for an advanced Compton telescope for the GRSO era, if manufacturing techniques for producing the required stopping power and area can be developed. There are several different properties which must simultaneously be realized in materials of a tunnel junction used as a detector. The films must have an adequate stopping power for the photons to be detected, but this stopping power cannot be achieved by increasing film thicknesses if a sizable fraction of the quasi-particles created by the absorption are lost while propagating across the film. The combinations of materials used in these junctions must be compatible with each other and the environment, so that the detector is sufficiently robust to survive fabrication and testing, which has not been the case with the detectors demonstrated so far.

ADVANCED X-RAY CCDs

A. Technology Assessment

AXAF II and III, XST and VHTF require radiation-hard, large-format arrays with improved sensitivity, especially in the high-energy range. Although CCDs do not have the energy resolution possible with the cryogenic detectors just discussed, they can be made in a much larger format taking advantage of the industrial base, and they do not require liquid helium temperatures. For XST and the AXAF refurbishments, advanced X-ray CCD arrays would provide: (i) extended on-orbit operating life with improved energy resolution through the elimination of radiation-induced degradation of the charge-transfer efficiency (CTE); (ii) more than an order-of-magnitude improvement in the response in the important 0.1 - 0.5 keV bands; (iii) increased quantum efficiency at 10 keV by a factor of 2-3; (iv) order-of-magnitude extension of the dynamic range for bright-source observation. Since VHTF requires a large number (~ 20) 100-cm^2 focal planes, the reduced-dark current and passive cooling capability offered by CCD technology will be essential. Existing technologies also fall short in the area of readout techniques for large arrays. Currently, the readout of a large CCD requires a large dead-time while the pixels are shifted out. For most fields, the X-ray images will be sparse, and the linear readout of the entire chip represents much wasted time. Improved "smart" readout techniques would allow the sampling bandwidth to be dedicated to the parts of the chip where signals are located.

B. Development Plan

The suggested areas for technology development are shown in Table V. Although significant charge-coupled device (CCD) development will be performed for commercial industrial uses, and some will be recommended by the other wavelength panels, the X-ray requirements for CCDs are unique and will not be met except by a focused development effort. The focal planes of some of the optical systems envisioned for future missions are larger than the size that we can reasonably expect to fabricate reliably, so we require formats that allow abutting individual chips. Among the other unique requirements are increased depletion depths, to extend to higher X-ray energies, and smaller "dead" layers, either from gate structure or regions with low mobilities, to extend to lower energies. Some of the early work could actually be carried out in parallel, new devices could be fabricated to attempt to improve both radiation resistance and bandpass. Improved high energy response will require the use of high resistivity substrates which would allow the creation of deeper depletion regions. Technologies worthy of consideration for lowering the dark current include guard-ring or edge-diode structures, ultra low impurity wafer materials, and intermediate gate structures.

A large program is recommended for the development of readout electronics. There are several advanced readout techniques to be investigated; in addition to improvements to on-chip amplifiers for lowering read noise levels, advances such as array segmentation techniques, 3-D focal plane approaches and parallel register structures. There is also the possibility of circuitry to take advantage of the sparse nature of most X-ray fields, either by selective readout of sections of the CCD where signals are present, or by constructing "smart pixels", which do not require any output bandwidth until an X-ray photon is collected.

POSITION-SENSITIVE DETECTORS

A. Technology Assessment

The development of high-pressure gas and/or liquid chamber technologies for the detection of 5 - 500 keV photons is recommended. Current gas counters do not provide adequate position resolution to meet the requirements of missions such as HXIF, VHTF and GRSO, for which sufficient position identification is desired in order to individually identify the sources of hard X-ray and gamma-ray sources. Improved volume interaction chambers, either liquid or high-pressure gas, will be required.

B. Development Plan

The recommended development program can be split into six parts, as summarized in Table VI. In this area it is less clear which of several contenders will emerge as the optimal choices for the fairly different requirements for the three candidate missions. High stopping power is of great importance for HXIF and GRSO, energy resolution for GRSO, very fine position resolution over a small detector for VHTF, and moderate position resolution over a large detector for HXIF. The panel recommends a small-scale

Table V. Advanced X-Ray CCDs

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Radiation hardening	Radiation-induced CTE degradation	Invulnerable to protons, neutrons and electrons	93 - 96	Moderate
Improved low-energy response	QE < 5%	QE > 90% 0.1 - 0.5 keV	93 - 96	Moderate
Improved high-energy response	QE < 40%	QE > 90% at 10 keV	93 - 97	Small
Lower readout noise	2 e^- rms	0.2 e^- rms	07 - 00	Moderate
Advanced readout techniques	Concepts	Smart readouts for large arrays	93 - 96	Large

Table VI. Position-Sensitive Detectors (Gas & Liquid Chambers)

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Improved multistep & fluorescence gating	Laboratory demo	Flight worthy	93 - 99	Small
High-pressure gas counters with readouts	Concept	Demonstration E/ΔE = 10-100 Spatial res ~ 200 μm	95 - 99	Small
Liquid Xe detector	Concept	Demonstration E/ΔE = 10-100 Spatial res ~ 200 μm	95 - 99	Small
Development to meet requirements for VHTF	None	Prototype(s)	00 - 03	Moderate
Development to meet requirements of GRSO	None	Prototype(s)	00 - 04	Moderate

effort, with an early start, to develop improved multistep or fluorescence-gating techniques. Additional small programs are recommended for methods to increase the detector pressure in gas-chamber detectors, and to develop fiber-optic readouts. A small program is also suggested to develop liquid Xe detectors. Additional work at a moderate level of effort will be required following the development of these capabilities to meet the stopping power and energy resolution required for GRSO, and the very fine position resolution for VHTF.

LARGE POSITION-SENSITIVE DETECTORS

A. Technology Assessment

For higher energy photons in the 0.02 to 2 MeV range, it is necessary to achieve the greater stopping power offered by solid scintillators. HXIF and GRSO require large area (> a few square meters), and two-dimensional position sensing accurate to 1 - 2 mm. This must simultaneously be realized in a system with backgrounds low enough to permit sensitivity at the 10^{-6}-10^{-7} photons/cm^2-sec level. These detector capabilities will enable high-sensitivity surveys with a ~ 1 arc-min resolution, leading to the anticipated identification of > 10,000 high-energy sources. This will permit class studies of active galactic nuclei (AGN), the variability of these AGN, and detailed studies of compact objects such as neutron stars and black holes.

B. Development Plan

A set of five technology development programs is recommended, as detailed in Table VII. First, a moderate program is recommended to develop and optimize solid scintillator materials, to meet the sensitivity requirements. Realistic implementation of solid-state scintillators also requires the development of low-profile, position-sensitive optical readout, and passive and active coded mask development, recommended for moderate- and small-scale programs, respectively. As an alternate to optical readout, the development of low-profile photomultiplier tubes (PMTs) or of photodetectors of Si or other materials, including the "solid state PMT" technologies, could be considered. Coded mask development may also involve small optical sensors for readout of scintillators in active mask elements. Finally, following the demonstration of the basic capabilities, the final focused development must be undertaken to meet the position resolution and stopping power for the high-energy ranges of HXIF and GRSO.

SUMMARY

Overall five major areas of technology are recommended for development in order to meet the science requirements of the Astrotech 21 mission set. These are detectors for high-resolution gamma-ray spectroscopy, cryogenic detectors for improved X-ray spectral and spatial resolution, advanced X-ray CCDs for higher energy resolution, larger format, and extension to higher energies, and liquid and solid position-sensitive detectors for improved stopping power in the energy ranges 5 - 500 keV and 0.2 - 2 MeV, respectively. Development plans designed to

Table VII. Large Position-Sensitive Detectors (Solid Scintillators)

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Scintillator material development & optimization	Concepts	Demonstration	93 - 97	Moderate
Low-profile, position-sensitive optical readout	Concepts	Demonstrations	93 - 96	Moderate
Passive & active coded mask technologies	Concepts	Demonstrations	93 - 96	Small
Advanced development focused on HXIF requirements	None	Prototype(s)	97 - 00	Moderate
Advanced development focused on GRSO requirements	None	Prototype(s)	00 - 04	Moderate

achieve the desired capabilities on the time scales required by the technology freeze dates have been recommended in each of these areas. For high-resolution gamma-ray spectroscopy, the focus is on the development of large-area arrays and associated advanced readout technologies. New cryogenic technologies are desired to increase the energy resolution beyond that available with existing semiconductor calorimeter arrays. Imaging in the X-ray regime would greatly benefit from the development of radiation-hard CCDs with improved low- and high-energy sensitivities, and smart readout techniques. Finally, the development of improved gas, liquid and solid volume interaction chambers could greatly increase the sensitivity of detectors in the highest energy ranges where the stopping power currently limits the response. Each of the development programs shows an artificial end at the technology freeze date of the last relevant mission of the Astrotech 21 set, namely 2000 - 2004. In fact, new missions will be coming over the planning horizon during this time, and we expect that new technologies will be identified for development in order to have instruments which can meet the challenges of the subsequent generation of observatories.