NASA/CR-97- 207580

Final Report of Grant NAGW-624:
Development of an Energetic X-ray Imaging Telescope Experiment (EXITE) and Associated Balloon Gondola System
(April 1, 1984 - December 31, 1997)

IN-89-CR
077658

1 Introduction

This is the Final Report for grant NAGW-624, which was our original grant to develop the Energetic X-ray Imaging Telescope Experiment (EXITE) and Associated Balloon Gondola. The EXITE grant was changed over to a new grant (from GSFC), NAG5-5103, beginning in FY97 and is currently very much continuing under that grant. The Final Report presented here then covers the EXITE development under the original grant, which in fact continued (with a 1 year no-cost extension) through December 31, 1997.

1.1 Overview of EXITE Program

The EXITE program has been carried out at Harvard and the Harvard-Smithsonian Center for Astrophysics (CfA) in order to develop a balloon-borne hard x-ray (20-600 keV) imaging telescope for the study of black holes and other compact objects. The telescope has employed the coded aperture technique, whereby a shadow mask is used to cast the image of a source or sources on a position-sensitive hard x-ray detector and images are then constructed (uniquely) by correlating the detector and mask arrays. EXITE has progressed through two generations of detector-telescope combinations thus far (and a third generation system is now under development under the continuation EXITE grant): EXITE1 (1984-90) was the original program for which the detector was a position-sensitive single NaI scintillator read out by a large-area (34.5cm diameter) image intensifier tube; and EXITE2 (1990-97) was the followup program in which the detector was replaced by a larger area (40cm square) and lower-background phoswich type (NaI/CsI) scintillator read out by a 7×7 array of close-packed square (2-in) PMTs in an Anger Camera configuration. For both EXITE1 and EXITE2 a gondola and pointing system was designed and built which allowed telescope pointing and aspect reconstruction at the $\sim 1'$ level.

The EXITE1 program was carried out to develop the single EXITE1 detector and telescope inside the gondola but with provision in the detector and gondola electronics for a possible second detector and telescope. Three balloon flights were carried out with EXITE1 in 1988-89, culminating in the successful 1989 flight from Alice Springs, Australia, as part of the SN87A campaign. Although emission from SN87A was no longer then still detectable, several other discoveries were made, including the first hard x-ray image of the black hole candidate GX339-4 (Covault et al 1992) and the discovery of a new hard x-ray transient and possible back-scattered 511 keV source near the galactic center (Grindlay et al 1992). This final EXITE1 flight landed on the edge of a hurricane in Australia and the gondola and detector frame suffered mechanical damage after impact. Consequently the payload was not flown again, but development begun instead on a higher sensitivity and lower background EXITE2 system.

EXITE2 was designed (Manandhar et al 1993) as the first imaging phoswich detector system. The original concept also envisioned upgrade of a single EXITE2 detector/telescope to a dual (side-by-side) systeml, with a further upgrade path for one (and eventually both) detectors to have a hybrid configuration: the EXITE2 detector would read out both the phoswich and an overlying high pressure proportional counter in which x-ray up to $\sim$100 keV would be detected and positioned with higher resolution (than in the phoswich) by detection of the uv-optical radiation produced in an optical avalanche. This hybrid detector concept was the initial concept for the third generation EXITE3 system (cf. Grindlay and Manandhar 1993), but has now been replaced by a different concept currently under development (under the follow-on EXITE grant NAG5-5103) in which EXITE3 will instead be a still higher sensitivity and resolution Cd-Zn-Te (CZT) system. However, the initial EXITE3 concept for the hybrid detector (EXITE2+gas counter) led to the close collaboration between the EXITE program at Harvard and the MIXE (Marshall Imaging X-ray Experiment) at the NASA/Marshall Space Flight Center (B. Ramsey, PI). A collaboration with the MIXE team had in fact begun in 1989 with a piggy-back flight of the MIXE1 detector on the EXITE1 balloon flight from Australia. The MIXE detector could naturally be extended to the optical readout needed for a hybrid, and during detector development the MIXE2 detector (a high pressure Xe proportional counter employing microstrip readout) could be flown in the second-EXITE2 detector/telescope position in the EXITE gondola. Considerable work was done on the initial development of the hybrid detector (Ramsey et al 1993, Pimperl et al 1994).

Provision for the EXITE2 and MIXE2 dual telescopes (as precursor to the dual EXITE2 system) entailed considerable gondola and detector electronics re-design as well as the development of the first imaging phoswich detector. An engineering flight for EXITE2 was conducted from Palestine, TX, in June 1993 in which a pointing system problem prevented acquisition of science data but for which valuable detector background and in flight performance data were acquired. The detector and gondola systems were developed significantly further for the first science flight which was originally scheduled for May 1996 but was finally accomplished in May 1997 after two (May and September-October, 1996) frustrating weather-delayed campaigns in Ft. Sumner, NM. This flight not only achieved our first science results with images and spectra of Cyg X-1 and observations of other sources but also included the first flight test of a prototype CZT detector and BGO anti-coincidence veto shield (Bloser et al 1998a).

1.2 Plan for Report

We present this Report in inverse-chronological order, beginning with the most recent work first and working backwards to the beginning of the grant with increasingly large time steps. After this summary of the major work done under the grant, we conclude with brief sections describing the future work enabled by this grant and now continuing under our current investigation and with a summary of the students and outreach supported by this grant.

2 Summary of EXITE Program in FY97

Much has been achieved over this past year. In the following sections we provide a brief summary of major milestones and results, as well as work in progress.

2.1 EXITE2 Flight and Analysis

After two prior and lengthy field campaigns in Ft. Sumner (May and September-October, 1996) during which no launch opportunities were possible for the new EXITE2 payload, we finally flew on May 7-8, 1997. We had a successful flight, with some 12 hours at float altitude, and observed a variety of targets: Crab, 4U0614+09, NGC 4151, 3C273 and Cyg X-1.

Payload Development

The payload development continued over the two prior launch attempts (May-September, 1996), as outlined in our FY1996 Report, and then in the subsequent interval (October, 1996 - April, 1997). The following major tasks were accomplished:

- additional development of flight software and flight computer and data recording system.
- development of detector/telescope vs. star camera boresite fixture and analysis system.
- additional development and sensitivity calibrations of off-axis CCD camera for below-the-balloon aspect determination.
- development of both off-axis and on-axis CCD camera aspect software system.
- further development of flight CZT/BGO detector and final optimization of the detector interface to flight computer system.
- further development of EXITE2 calibration and analysis system.

In addition, a major part of our effort during this period in Cambridge was the development of thick CZT detectors (see below).

Balloon Flight: May, 1997

After some 7 launch attempts beginning April 20, the EXITE2 (and MIXE2, from our MSFC collaborators) payload was successfully launched on May 7, 1997, at 16:30UT. Performance of the 39m.cu.ft. balloon was excellent, and the payload reached a float altitude of 126,000 ft. at c. 20:00UT May 7. Although several sounding ballons before launch had indicated turnaround conditions, the high altitude winds carried the balloon NE at a mean speed of 20 knots so that the limit of telemetry range (and allowed impact area) was reached at c. 10:00UT May 8, at which time the ballon was terminated just West of Oklahoma City. The 20 ft. high EXITE2 gondola landed at night on the banks of a 15 ft. wide creek (swollen from recent rains) and toppled in, so that the two exposed electronics racks for the EXITE2 detector-gondola interface and gondola pointing control were effectively ruined (as was the MSFC MIXE2 detector and electronics). Fortunately, the EXITE2 detector itself, and flight computer systems, were in separate pressure vessels and survived with no apparent damage.

The first several hours of the flight were devoted to detector and gondola testing as several problems were encountered: the gondola azimuth pointing stability was initially poor, due to (it was later determined) overheating on an electronics board component for the azimuth gyro; and the flight computer (SBC) had intermittant crashes and had to be re-booted several times in flight. Consequently the first target observed, the Crab, suffered from only moderate pointing stability, although a successful Crab observation and image was made. The flight computer later achieved stable operation, possibly as the internal temperature in the computer pressure vessel achieved more moderate levels of 10° C (most of the early crashes were at temperatures below 0° C, resulting from lack of heater power during the cold launch ascent through the troposphere). Also, as the aximuth gyro heating problem was understood, it was controlled by occasional shutdowns (during the solar-heated daytime portion of the flight) and stable pointing was achieved. The nighttime portion of the flight achieved relatively stable pointing, with drifts typically less than 5 arcmin per minute.

After the Crab observations, the flight achieved some 8 hours of moderately good pointing on 4 science targets: the LMXB 4U0614+09, the QSO 3C273, the Seyfert NGC 4151, and finally the black hole candidate Cyg X-1. A high priority science target, GRS1915+105, was scheduled to be observed immediately after Cyg X1 but the higher than expected float winds did not allow this observation, or several others planned.

Analysis and Preliminary Results

Due to the problems encountered early in the flight with the flight computer, relatively little data was recorded on board for the Crab. Furthermore, because the detector was initially configured with the upper level discriminator (ULD) set higher (at nearly 1 MeV) than later in the flight, the detector trigger rate was higher and the possible telemetry to the ground (and quick-look data recording) was thus lower. Also, since the gondola pointing was unstable for the early portion of the flight due to a gyro electronics overheating problem during the daytime portion of the flight (as mentioned above), only short segments of data had pointing within $\sim 1°$ of the Crab.

The Crab data have been reduced with aspect corrections for each second (given the large pointing excursions) derived from the EXITE sunsensor. We also flew a GPS system for the first time and achieved excellent agreement in its azimuth readouts from those derived from the sunsensor. The GPS antennas and receiver (supplied by MSFC) were mounted on top of the gondola with plastic pipe booms separating the 4 antennas on baselines of ~3.5m. This antenna separation enabled GPS azimuth determination each second with an rms uncertainty of about $4'$, or somewhat better than the sunsensor (with $6'$ positional resolution each 2 sec readout).

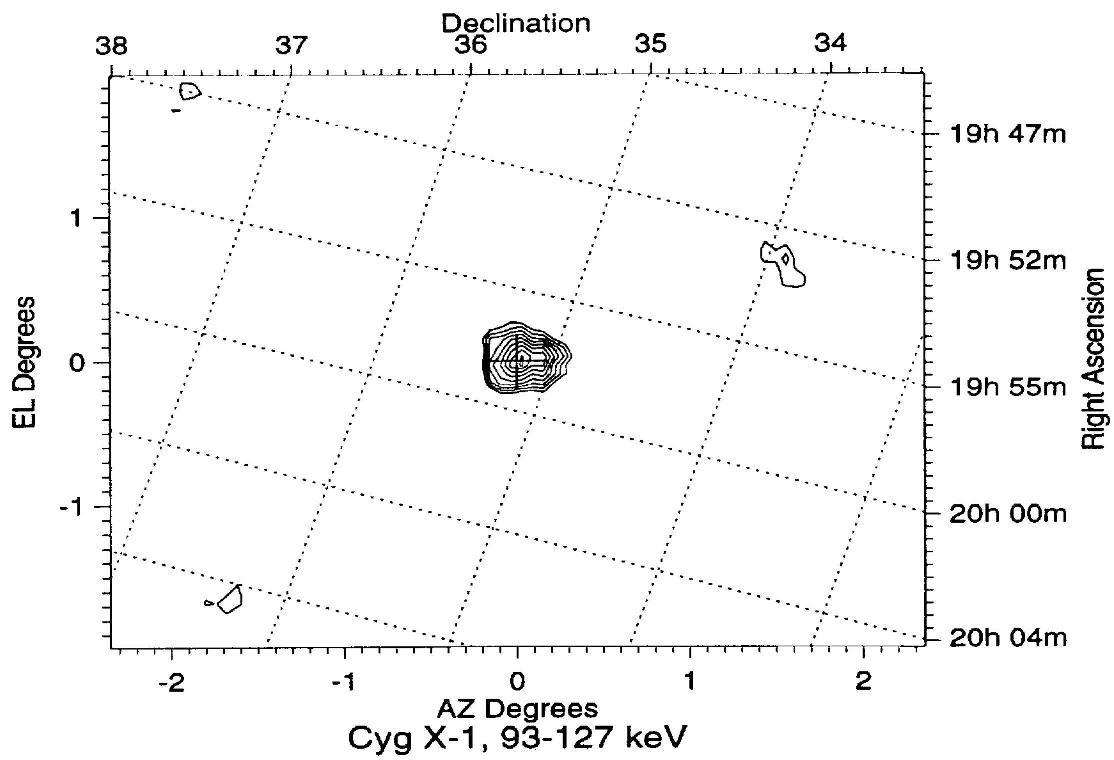

Fig. 1. Image of Cyg X-1 (93-127 keV) for an effective ~3 min exposure.

As analysis software and reduction of flight engineering data has only just been (largely) completed, we have only begun to analyze the science targets. Below we show a (preliminary) image of Cyg X-1, which was the final target observed before the (early) cutdown necessitated by high winds. The image is shown for just one of the 12 EXITE2 energy bands, covering the 93-127 keV band, and is for a total effective exposure of (only) about 3 min. The short exposure time is the result of the 25 min observation time being recorded on the ground with only 12% data throughput for this dataset (for which data compression was not used) and the fact that the flight computer DAT tape drive did not record this dataset (although other sources were successfully recorded on board with typically 70-80% data recovery).

Although for the Cyg X-1 observation the telescope pointing was good (with typical deviations smoothly varying over ~5-15′ over the half hour pointing period), these images have been reduced with aspect corrections for each second derived from the EXITE2 on-axis star camera. Similar aspect corections were derived from the GPS system. We also successfully tested in flight the off-axis star camera (an integrating CCD camera) for which we also conducted day-time star sighting tests. We found that even with a light-tight baffle system and red-pass filter, sky backgrounds even at 126,000 ft. were still too bright to image even the bright star Sirius in full daylight. However, we were able to record Sirius images under pre-dusk conditions, and this (brightest star) case was an overly stringent test: Sirius was only some 50° from the Sun.

Problems Identified for EXITE2 Hardware/Software

In the course of analysis of both Cyg X-1 and Crab data, we have developed a nearly complete understanding of the performance of the EXITE2 detector and gondola systems in flight. We have identified significant improvements in both software and hardware that will be made for the next flight:

- Event times (tagged to 30μsec accuracy) were contaminated by pickup noise in the higher background flight environment and will be buffered/shielded. Event times have now been corrected in software only to within ~0.5 sec for preliminary aspect analysis.

- PSD rejection efficiency was generally good above about 30-40 keV except for the early portion of the flight (including Crab), when a commanding error resulted in a higher than desired ULD (as mentioned above) and hence increased background rate of large events. These were not (therefore) rejected by the newly implemented dynode discriminator, since it (as the ULD) was set too high, and resulted in an increased low energy background with a false PSD signature that could not be rejected on board in hardware. These events may be possible to reject (in subseequent analysis) by having very different PMT relative pulse height spectra.

  However, even under normal ULD conditions (as for Cyg X-1), the PSD efficiency in the prime science band of 30-300 keV was degraded from ~99% (typical ground-test values) to only about 90% during flight. This resulted in only somewhat higher background than otherwise expected but did produce residual variations in background image shape (e.g. stripes). This is now understood as being due systematic difference in light distribution for these non-rejected background events, which had interacted in the CsI rear shield of the detector, and so could not be properly positioned by our maximum liklihood method (MLM) image analysis, which was only calibrated for events in the NaI prime detector. Fortunately these systematic background shape effects may be removed by careful flat fielding, now in progress. We may also be able to model the light distribution in the CsI directly (using onboard LED calibration data) and thus extend the MLM analysis to CsI events (for which it had not been originally deemed necessary).

- The first few hours of flight computer crashes were likely due to low temperatures in the computer pressure vessel during ascent and the fact that internal heaters had not been commanded on early enough. The intermittant flight data recording onto the DAT tape will be fixed with both improvements to the flight software and DAT driver as well as (especially) the addition of significantly more computer (and DAT) status displays. Due to limited status bits available, the flight computer and DAT could not be monitored as effectively as needed during the flight.

3 Summary of EXITE Program in FY93-FY96

The second-generation Energetic X-ray Imaging Telescope Experiment (EXITE2) detector and telescope system are described in Manandhar et al (1993), Lum et al (1994), and Manandhar (1994). Here we provide an overview of the development of EXITE2 over this 3 year grant cycle. We first give a brief summary of the (many) new features added to the EXITE2 detector and gondola system since our test flight of the detector in June 1993. We then present some typical performance results of the detector (energy spectra, PSD spectra, and images) and expected performance (sensitivity and resolution) for the upcoming science flight (May 1996) from Ft. Sumner. Finally, we describe the progress already achieved for implementation of the originally proposed EXITE3 (hybrid) flight detector.

3.1 Milestones in Development of EXITE2

The EXITE2 detector system is a phoswich (NaI/CsI) scintillator read out as an Anger camera with a 7 × 7 array of 2-inch PMTs. The prime NaI detector is 36cm × 36cm × 1cm (1300 cm^2) and is surrounded on the rear and all 4 sides with a 2cm thick CsI veto shield for a total detector geometric area of 1600 cm^2. This detector was the first (to our knowledge) imaging phoswich (Manandhar et al 1993) and thus achieved a background a factor of ~3 lower (per unit area) than our original EXITE detector (EXITE1; cf. Covault 1991 and Grindlay et al 1990). EXITE2 was designed in 1990 after the last (1989) flight of EXITE1, built in 1991-92, and flown on a short (6 hour) engineering test flight from Palestine on June 13, 1993. Although a short science program was planned (Crab calibrations followed by a planned deep exposure on the Coma cluster and the newly discovered x-ray transient (and now super-luminal source) GRS1915+10), a first-ever problem with the azimuth pointing system (failure of the main azimuth bearings due to contamination) precluded science observations. However the detector background was measured in flight and found (Lum et al 1994) to be low as expected for the phoswich: $F_B(100keV) \sim 2.7 \times 10^{-4}$ counts/cm^2-sec-keV. As might be expected on the first flight of an all-new instrument, a number of anomalies were found, and some systems (e.g. flight data recording and data compression for telemetry to ground with an on board PC system) were not yet implemented. Over the past 2.5 years, these have all been completed and numerous design enhancements made to the EXITE2 detector and gondola system, as summarized below:

Improved CR Rejection and System Dead Time: The electronics have been sped up by a factor of 2 in all 49 channels (to approximate time constant $\tau \sim 3\mu$sec) and a pole-zero compensation network added to eliminate a long-tailed negative undershoot on the preamp outputs after large saturation events. The test flight revealed that (despite pre-flight tests with muons) the cosmic ray (CR) immunity was not adequate; preamp saturation and undershoots following CR (protons and α's caused distortion of the baseline and thus decreased energy (and spatial) resolution. A blanking "super-discriminator" which inhibits triggers for 100μsec following a large amplitude pulse was also implemented, and provided with commandable thresholds and rate counters in housekeeping data.

Implementation of Dynode Channels: The super-discriminator was designed to be triggered by a low gain channel that would not saturate for CR events. This is provided by the (last) dynode on each PMT, which is now brought out to the preamps (in addition to the anode signal) so that the number of channels now populated on the boards is doubled to 98. The low gain dynode channels will also be the primary channel for the very large light output expected for the detection of x-rays in the gas counter half of the possible EXITE3 hybrid detector and can be dynamically switched into the ADCs (in place of the anode channels) in response to an external trigger (which would be provided by separate trigger from the gas counter for EXITE3). Thus the dynodes are the low gain imaging channels needed for EXITE3 and are now complete. Images of muons in the detector have been made in the lab.

Enhanced PSD and Digital Control: The test flight included a prototype pulse shape discriminator (PSD) board, the double-differentiation circuit which distinguishes the NaI (200 nsec) from CsI (600 nsec) pulse shapes for phoswich discrimination. A flight board, with numerous enhancements (e.g. an added LLD, to set PSD threshold above a baseline noise value associated with false triggers and seen in the test flight) has now been thoroughly tested.

Reduced System Noise: Considerable testing and effort has gone into reducing system electronic noise, with a resulting improved baseline performance. Spurious switching noise from the HV supplies in the detector electronics section was eliminated by modification of test pulse inputs. This low level switching noise was the probable cause in the test flight of a mysterious low energy peak (cf. Lum et al 1994) which indeed had appeared as very low value PSD events (which could now be eliminated by the added LLD) suggesting very fast rise times.

Implementation of Flight Computer and Data Recording: A major effort over the past year has gone into the completion of the EXITE2 (and EXITE3) flight computer and data recording system. An original system which incorporated two separate 386/SX single board computers (SBCs) and was only partially implemented for the test flight (only star camera video data were processed by a frame grabber board), was found to be unreliable. A simpler system using a single (SBC) 486/DX-66 for the flight computer and a DSP computer (SBC) TI-xxxx for the data capture and interface (in place of balky FIFOs used with the original 386/SX system) has now been successfully implemented for both the flight and a new ground station data capture and recording system. The flight computer runs a single program (under DOS) which continuously executes three major tasks under command control from the ground: i) immediate on-board recording of the full detector data stream (49 channel PMT data, with time stamps, but no housekeeping data) onto an on-board DAT tape recorder; ii) compression of the full detector data stream using one of 16 modes (e.g. selection of peak PMT and nearest neighbors only) so that full data can be telemetered to ground for quick look and full analysis within the 267kbs telemetry; and iii) on-board recording to DAT of star camera video frames captured (and compressed) and interleaved (e.g. every 10 sec) with detector data. The flight DAT recorder is mounted in a compact DAT stacker, which holds 8 DAT cassettes, so that data recording can be accomplished for a full 10 day LDB flight.

Gondola System Enhancements: The original EXITE1 gondola was extensively modified to accomodate the new EXITE2 detector, and in fact accomodate two such detectors side-by-side or (as for the June 1993 test flight as well as the upcoming May 1996 science flight), to accomodate EXITE2 and the microstrip imaging proportional counter MIXE2 of our MSFC collaborators. This two-detector configuration was designed for easy upgrade to one or even two EXITE3 detectors, as proposed below. Numerous other enhancements have now been made since the test flight. The gondola (constructed of 4-inch Al tubes) has been re-built (after being damaged on the test flight) with corner and inter-tube joints which are bolt-clamped rather than bead-welded for easy replacement and gondola dis-assembly. This is an important step towards preparation for LDB flights, where recovery may demand gondola disassembly. Part of the azimuth control system (the "dither" sub-system, to break bearing stiction) was re-built after the bearing failure on the test flight; the pointing stability should now be significantly better than the $\sim 5'$ achieved with EXITE1 and will be tested on the upcoming EXITE2/MIXE2 flight. An off-axis TV star camera (an integrating CCD) has been added, with a near-IR filter, so that star fields are not occulted by the balloon at telescope elevations above $\sim 65°$ (the camera is offset 15° low in elevation) and to further design a daytime star camera to be developed in this proposed investigation. Finally, a GPS aspect system, which uses differential phase analysis from orthogonal antennas separated by ~ 3 m booms on the top of the gondola, has been provided by MSFC and incorporated into the EXITE2 flight preparations.

Data Analysis and Processing System: The full EXITE2 data processing system has been designed and largely installed (although additional enhancements will surely be made). Nearly real time plotting of immediate or past histories of housekeeping data is now possible; real time overlay displays of predicted star fields on both on-axis and off-axis star camera data displays allow joy-sticking of pointing offsets during flight and ready reconstruction of aspect immediately following; and both quick look and final production of images using a new wavelet smoothing technique to flat field spatial variations in background on the detector (cf. Grindlay et al 1996). Post-processing analysis can now be done using standard tools for spectra (XSPEC) and temporal analysis (XRONOS) rather than the more limited EXITE1 processing.

3.2 EXITE2 Performance and Expected Sensitivities

With the improvements made, EXITE2 now achieves spectral and spatial resolution as well as background rejection at state of the art levels which surpass those demonstrated (or published) for any other comparably broad energy range scintillation detector, let alone imaging phoswich. Here we provide a few representative results which update those given in Lum et al (1994).

Energy Resolution: EXITE2 has been tested with calibration sources (e.g. ^{133}Ba) to derive energy resolution for the seveal lines from 30 - 356 keV. The measured energy resolution of $(\Delta E/E)_{FWHM} = 14\%(E_{keV}/60)^{-0.5}$ is better than non-imaging phoswich detectors like HEXTE because of the essentially continuous coverage of the exit window by the continguous and square PMT array which provides optimal light collection.

Spatial Resolution and Distortions: The measured spatial resolution for EXITE2 is $(\Delta s)_{FWHM} = 9.7\text{mm}(E_{keV}/60)^{-0.5}$ and is remarkably constant across the full detector, as demonstrated by the measured profiles of scan points with a ^{241}Am source collimated to a ~3mm beam size on the detector and stepped with our computerized scanning table at 2.1cm intervals across the detector. The same raster scan used to illustrate spatial resolution were used to demonstrate the relative lack of spatial distortions in the detector.

Imaging and PSD Performance: A boresight image (~500 sec) of a bright ^{241}Am source positioned some 9.5m in front of the EXITE2 coded aperture mask was reduced with MLM processing and PSD background rejection applied in software in a broad band appropriate to the 60 keV line energy of the image. Tests with various calibration sources have also demonstrated the current performance of the PSD system, which is able to discriminate NaI events from background CsI events (i.e. in the rear shield) down to the lowest effective energies, 20 keV, observable with EXITE2.

Estimated Sensitivity: Using the measured (test flight) background (for Palestine) and improved (particularly at low energies) PSD rejection efficiency, we derive the background spectrum shown in Lum et al 1997 where we also present the results of a full Monte Carlo simulation of the background and expected detector response. This background study also derived the separate contributions expected for the background due to the detector shields (4 sides and rear) and telescope mask. The expected sensitivity was derived for this background with a complete detector simulation which includes the measured spatial and spectral resolutions and full detector response. Event files were generated which are then analyzed with the actual EXITE2 analysis system to produce correlation images in given bands. The simulation was done for the Crab flux and a 3200 sec exposure and yields detection S/N ratios of typically 20 in each band. Thus in a 3 hour exposure, we expect that spectra for ~150 mCrab sources can be studied even in relatively short balloon observations.

4 Summary of EXITE Program in FY90-FY93

In order to significantly increase sensitivity in the original *EXITE1* band (20-300 keV) as well as to increase the high energy response beyond the 511 keV line where pair annihilation signatures of BHs and AGNs may be studied, we initiated the development of a new detector and telescope system, EXITE2. The reasons for this also include the facts that the basic technology employed for EXITE1, an image intensifier readout system, was not practical to extend to very large detector areas (or modular arrays) and was no longer commercially available. Thus, despite the simplicity and success of the EXITE1 detector system, we embarked on a program to develop an imaging phoswich detector and telescope of modular design for extension to both very large areas and a future hybrid detector system EXITE3. The total NaI detector geometric area is 1300cm^2, or more than 50% larger than EXITE1, and the phoswich detector was designed to lower backgrounds by a factor of $\sim$3. Thus the overall sensitivity was expected to be $\gtrsim 3\times$ that of EXITE1, and the detector/telescope could be the basis for a still more sensitive larger area array.

4.1 EXITE2 Description

The key element of the EXITE2 telescope consists of a position sensitive NaI(Tl)-CsI(Na) phoswich detector with total geometric area 1600 cm^2 (including the CsI guard shield). The phoswich is constructed with a 36cm x 36cm x 1cm NaI(Tl) primary detector (1300 cm^2) backed by a 40cm x 40cm x 2cm CsI(Na) rear shield and surrounded by four 38cm x 2cm x 1cm "sidebars". Thus the entire NaI detector is surrounded (rear and 4 side edges) by 2cm of CsI. The detector was fabricated by Bicron and only delivered to CfA in June 1992 (after a 1.5 year order time !) due to difficulties they encountered in manufacturing the CsI crystals to our specification: $\gtrsim$ 85% of the light output of NaI(Tl) and primary decay time constant $\lesssim$ 700 nsec. (The raw CsI crystals were ultimately procurred from a source in Russia or the Ukraine and then machined and polished at Bicron). The CsI rear shield plate is tiled (optically coupled) from four 20cm x 20cm plates, while the sidebars are each made from two pieces butted at the same mid-point joint as the rear plate. The phoswich is read out by an array of 7 x 7 PMTs, each a 2-inch square Hamamatsu R1534-01. Phoswich discrimination is achieved on the summed PMT signal using a double-differentiation circuit similar to that employed for OSSE.

The EXITE2 detector design thus has several distinguishing features:
basic geometry: modularity. The phoswich is square and thus relatively compact and capable of being mounted in a minimum mass frame such that a modular array can be built for extension to very large area with minimum supporting mass (and thus minimum induced background) and occupied space. For operation in a balloon payload, with limited resources, the detector frame also serves as a pressure vessel so that the 49 PMT readout system need not be potted. This could easily be eliminated for a spaceflight environment.
light collection: resolution and low background. The square PMT array provides maximum photocathode coverage of the exit window, resulting in excellent light collection and thus optimum energy and spatial resolution (cf. test results). The decision to size the total detector area to 1600 cm^2 was also based on minimizing the dead-time due to after-glow from cosmic ray (CR) events which deposit enormous energy (and thus light) in the scintillator. Scaling from our EXITE1 results (Covault 1991), as well as carrying out Monte Carlo simulations for interactions of the known CR spectrum at float altitude allows us to predict that Poisson fluctuations on the low-level but long time-constant component of the CsI light output will contribute a background at energies $\lesssim$ 6 keV, well below our operating LLD threshold ($\sim$10 keV) and of course well below the atmospheric cutoff ($\sim$20 keV). A much larger detector module size would raise this effective low energy threshold, thus compromising

low energy performance.
distortions and background: imaging performance. The 2cm wide CsI sidebars are designed to provide efficient light collection for the outermost PMT rows/columns for events near the edge of the NaI primary detector. Extensive Monte Carlo simulations of the imaging performance of the detector (Manandhar 1994) show that distortions of image scale factor start to become most significant within about 2 cm of the edge of the detector. Our extensive simulations of the background spectrum *and image* expected at float altitude showed that the EXITE2 detector should have an enhanced background "ring" in the outer 1-2 cm of the detector (as did EXITE1), or just where the CsI guard shield is. Thus the sidebars are "active light-pipes" and should improve both imaging and background rejection.

The EXITE2 telescope uses an extended (~4 x 4) array of a 13 x 11 element basic coded-aperture (URA) mask (i.e. the same pattern as used for EXITE1) at a focal length of 2.4m. The URA mask fills an area 72cm x 72cm (allowing imaging out to the FWZI response of the collimator) and is constructed with 1.6 cm x 1.6 cm cells (of 12 mm thick Pb + 1mm Sn + 1mm Cu). The mask is matched to both the collimator pitch and the detector position resolution to achieve an angular resolution of 23 arcmin over a 4.6° field of view defined by a 2-D graded collimator constructed by us of 0.9mm Pb slats bonded between 0.2mm brass sheets. The URA mask construction is an improvement from the EXITE1 mask: the mask pixels are located at precisely-machined positions by locating pins, and the entire (larger) mask frame (which again sandwiches the mask between 1mm thick Lexan sheets) now includes 3 supporting cross-bars running across the full mask under closed-pixel columns. The detector and collimator are surrounded by graded passive shields and overlying plastic scintillator active (charged particle) shields (as on EXITE1, which demonstrated a factor of nearly 3 reduction in ~20-300 keV background possible with external plastic anti-coincidence shields–cf. Covault 1991).

The EXITE2 detector electronics include 49-channels of fast preamps and 12-bit ADCs and a flexible data-handling system, which interfaces to the "old" EXITE1 detector electronics and gondola/telemetry electronics systems. The full 49-channel data stream can be brought down within a 250 kbs telemetry rate for events with the phoswich-rejection and external shield rejection flags set. In addition, we developed a much more powerful on-board data-compression and data recording system for EXITE2: a separate (small) pressure vessel containing two '386/SX PCs (single-board computers), a digital audio tape (DAT) drive and an 8-cassette DAT stacker. One PC will be devoted to data compression, with typically only the peak PMT and surrounding array of 3 x 3 being selected for real-time telemetry mode for all events (i.e. not imposing phoswich rejection in the air), whilel the other PC will be tasked to continously record all 49 channels of all data to DAT tape. (NOTE: these two single-board 386/PCs were later replaced by a single-board 486/PC and DSP interface computer as described above). With the 8-cassette stacker, we have data storage for the full data stream for a 40 hour flight without compression and for a LDB flight with data compression.

4.2 EXITE2 Status

By FY93, nearly all subsystems and flight electronics had been built and are being integrated for the flight payload. The precision Pb blocks for the mask and the overlying Sn and Cu wafers have all been received and are being assembled into the mask. The collimator is completed, as are the external passive shields, active shields and PMT light guides/couplers, external (potted) shield PMTs (4) and HV supplies (2), and full detector mounting frame and electronics pressure vessel.

The sub-systems have been extensively calibrated. For example, each of the 49 flight PMTs has been raster scanned with our newly acquired computer-controlled scanning platform with a collimated (1mm) LED for measurement ofthe gain variations in a 25 x 25 grid (i.e. 2 mm separation between grid points) across the full 50mm photocathode. These gain maps will be used later for the complete image analysis processing system for the EXITE2 (and proposed EXITE3 detector. Absolute (total) PMT gains were also measured, so that PMTs could be divided into 4 separate groups, each with its own HV supply, to nearly equalize the gain across the detector. An "initial gain map" (IGM) of the flight detector has also been performed with a single (reference) PMT moved to each of the 49 locations in the PMT strongback (cf. Figure B.2) and a spectrum recorded of a finely collimated, exactly centered, ^{241}Am source (60 keV). The relative gain of each of these spectra provides an accurate measure of the true gain and light collection efficiency of the detector at each PMT location; the measured variations in relative gain (typically $\lesssim$ 10%) are then combined with the measured PMT gains to derive a final adjustment of the gain of each of the 49 preamps in order to "flatten" the net detector gain to within $\lesssim$ 5%.

The detector calibration system has been fabricated and is being integrated: four low-level (50 nci) ^{241}Am sources will be embedded within 4 cells of the collimator (1.6 cm square) and collimated to produce a $\sim$12 ct/sec rate of 60 keV x-rays in a $\sim$3 mm diameter spot on the detector at the junction of 4 PMTs. Each source is actually a doped "red"-plastic scintillator (BC-430), only 3mm in diameter (and 3mm high), and is read out on its "top" (away from the detector entrance window) by a red-sensitive Hamamatsu photodiode, which detects the coincident light flash in the plastic scintillator from the 5 MeV alpha which accompanies each event. This simple tagged calibration source may have wider application on other payloads. This primary calibration is accompanied by a secondary calibration *which also continously calibrates the phoswich rejection efficiency*: a pulsed LED system, with alternating 200ns and 600ns pulses (of fixed height) which are applied sequentially through 12 fiber optic cables (1mm diameter) through the PMT strongback on to the rear window of the detector. This LED gain and offset calibration, as well as phoswich calibration, system is (we believe) another EXITE2 innovation.

The *EXITE* gondola has been extensively rebuilt following the hard landing on our last flight (Alice Springs, May 1989), when due to an NSBF command failure our retracted (for launch) roll-over shocks (cf. Figure A.1) on the top of the gondola did not deploy and the gondola was thus stressed upon roll-over. The fact that cutdown of the (highly) successful EXITE1 flight occurred in a hurricane in northern Queensland, and the payload was then dragged through trees since the parachute could not be separated on the ground, did not help the gondola either ! The re-designed EXITE2 gondola now has longer space between the elevation axis and top of gondola frame, allowing a 2.4m focal length (vs. 2.0m before), and the detector/telescope mounting flange on the elevation axis is re-designed to accomodate two detectors/telescopes viewing either common or separate masks supported by a new rectangular strut mask tower. Both the azimuth and elevation systems have also been improved during the current EXITE2 development: the azimuth drive has been re-built with an improved "dither" system and is also nearly 50 lbs lighter than the EXITE1 system, and the elevation encoder has been upgraded from 12 to 14-bits for arcmin elevation readout accuracy. The gondola has been checked out and operated and will be fully integrated with the EXITE2 detector and telescope upon their complete assembly, testing and calibration.

4.3 Doubly-Encoded Coded-Aperture Masks

As part of the planned development for the initial concept for *EXITE3*, with its significantly higher spatial resolution at energies 20-80 keV due to the PRIORPIC detector, we explored the design and construction of a doubly-encoded mask. Such masks, with a finer pitch mask (URA) pattern encoded within the coarser pixels of an overlying mask, have been proposed and discussed by Skinner and

Grindlay (1992) with application to just such a stacked detector as the primary motivation. It appears possible to design and construct a mask with fine resolution of, say, $6'$ embedded in a $24'$ high energy mask. This would give the EXITE3 telescope distinct new capabilities over any other previously flown hard x-ray imaging telescope

5 Summary of EXITE Program in FY84-FY89

The development of the initial detector, telescope and gondola for EXITE1 was carried out over the first 5 years of the grant. The major objectives of the EXITE1 program were to demonstrate the feasibility of hard x-ray imaging in the 20-300 keV band at higher angular resolution than previously achieved using a simplified position-sensitive scintillation detector readout employing a moderate area (900 cm^2) NaI crystal and image intensifier. The 34 cm diameter image intensifier, obtained from the French electronics firm Thomson CSF which had developed it for medical x-ray imaging, de-magnifies the optical image of the scintillation flash and detects its centroid with a second-stage intensifier and PIN diode readout (Garcia et al 1986). The imaging detector is mounted in a telescope configuration with an extended array of 13x11 URA masks for the coded aperture at 2 m distance, yielding an angular resolution of 22 arcmin in a 3.4^o (FWHM) field of view defined by two orthogonal 1-D collimators made of graded materials. The telescope was mounted in its gondola, which provides gyro-stabilized pointing with $\sim$1 arcmin accuracy, as well as power and telemetry systems. The gondola was developed with some sub-systems (e.g. magnetometers) inherited from the previous CfA gondola developed by G. Fazio for far-IR imaging.

The EXITE1 telescope had three flights within the year May 1988- May 1989. The first flight, from Alice Springs in May 1988 as part of the SN1987A campaign, was an engineering test flight in that a fluke problem prevented pointing the telescope in elevation on scientific targets: due to a manufacturer's defect in a lot of "balloon tape" used to secure ethafoam insulation on the telescope pressure vessel, the tape failed under daytime solar heating, causing the foam insulation to slip and the elevation motion of the telescope to jam. Valuable detector background data, in flight calibrations (with a fixed ^{109}Cd source), and gondola performance data were obtained which verified the basic systems and predicted backgrounds. A second flight (19 hrs.) was carried out from Ft. Sumner, NM, in October 1988 and a third flight (30 hrs) was achieved in May 1989 during the final supernova campaign. Both flights were technical and scientific successes.

5.1 Scientific Results

Although all of the data from both science flights of EXITE1 were not completely analyzed due to the followon work on EXITE2, a rich variety of results were obtained and reported:

- The first hard x-ray image (20-100 keV) of the BH candidate GX339-4 was obtained and confirmed the soft x-ray (and optical) identification of this source as well as provided a measure of its spectrum in a high state (Covault, Grindlay and Manandhar 1992).

- The hard x-ray image of the galactic center region showed not only the '1E' source still bright (thus establishing its long-term variability timescale vs. the low flux measure made 1 week later by the non-imaging detector of Ubertini et al 1991), but also that a second hard source with possible 100 keV line emission and a soft excess was also detected only $40'$ offset (cf. Grindlay, Covault and Manandhar 1992).

- The first upper limits for hard x-ray emission from the eclipsing millisecond pulsar (MSP) PSR1957+20 and the $\gtrsim$ 12 MSPs in the globular cluster 47 Tuc were reported (Grindlay, Covault and Manandhar 1990).
- The first upper limits for residual persistent hard x-ray emission from a BH transient, A0620-00, such as predicted by the Hameury, King and Lasota model for SXRTs, was obtained (Covault 1991).
- Good hard x-ray images and spectra of both the Crab and Cyg X-1 verified both the constancy of the Crab spectrum and the spectral state of Cyg X-1 as well as the telescope performance and calibration (Covault 1991).

5.2 Technical Results

Some of the principal technical results from the EXITE1 program were:

- The *EXITE* concept of using a large area NaI scintillator and position-sensitive image intensifier readout was shown to be both viable and relatively simple as an astrophysical imaging system for hard x-rays (Covault et al 1988a).
- Both the energy and spatial resolution achieved were appreciably better than in previous or concurrent hard x-ray experiments (Braga et al 1989).
- The gyro-stabilized pointing system was shown to be stable to ~1 arcmin accuracy and capable of scans and slews (Covault et al 1988b).
- The novel shock protection system of hydraulic shocks (for the detector support) and pneumatic shocks (for gondola impact and roll-over) were demonstrated to protect the delicate image intensifier and gondola systems and allow (in principle) rapid turnaround between flights (Braga et al 1989).
- A new sun sensor design was demonstrated to give $\lesssim$ 3 arcmin daytime aspect on the last flight, and a daytime star camera (an integrating CCD/TV with deep red filter) was flown (Grindlay et al 1991).

6 Current and Projected EXITE Program Enabled By NAGW-624

As mentioned in the Introduction to this Report, the EXITE program is now supported under the replacement grant NAG5-5103 for 3 years (subject to renewal). The major emphasis is now to re-fly the EXITE2 detector and telescope for a longer science flight in May 1999 after having re-built the gondola and detector-gondola interface electronics which were destroyed in the water-landing on the May 1997 flight. This re-build effort was of course not anticipated but yet was in effect originally proposed in order to upgrade the gondola and electronics systems for the capability to fly EXITE on a long duration balloon (LDB) flight with eventual duration of up to 100d. This would enable hard x-ray observations fully competitive with satellite missions for at least some objectives.

In addition to the gondola upgrade, the major emphasis of the experimental program for EXITE is now the development of imaging Cd-Zn-Te (CZT) detectors for the next-generation EXITE3 detector/telescope system. Over the past year of the new grant we have in fact achieved the highest spectral resolution (4% FWHM at 60 keV; vs. ~14% with EXITE2) in a prototype 4 × 4 pixel CZT array (cf. Bloser et al 1998b). In collaboration with local industry, we have developed and tested the first CZT imager showing the small pixel effect (Bloser et al 1998b, Narita et al 1998) and are pursuing development of PIN contacts on the arrays which hold promise for both lower leakage current, and thus noise, as well as lower cost fabrication of much larger arrays. In collaboration with the IDEAS co. in Norway, we are developing an ASIC readout for CZT imagers and will be exploring ASIC-CZT bonding schemes.

Motivation for this balloon-borne testing of a CZT imaging array, EXITE3, is based in part on our desire to conduct a MIDEX mission for a very high sensitivity all-sky hard x-ray imaging survey such as our New Mission Concept (NMC) study for the Energetic X-ray Imaging Survey Telescope (EXIST) mission. In several recent papers (Grindlay et al 1995, 1997; Grindlay 1998a,b) we have developed the scientific case and possible implementation of a mission like EXIST. Our balloon-flight tests of the first CZT single detector and BGO shield (cf. Bloser et al 1998a), carried out as a successful piggy-back experiment on our recent EXITE2 flight, is an important first step in demonstrating these detectors and understanding their background characteristics in a space environment. We plan to fly the first imaging array and shield in our May 1999 flight.

7 Students and Outreach Supported By NAGW-624

Over the 14 year duration of the grant, the EXITE program has had a significant impact on education of students at Harvard and elsewhere as well as education of the public.

7.1 Involvement of Harvard Students and Postdocs

A considerable number of students and two postdocs have made significant contributions to the EXITE program.

Postdocs:
Dr. Kenneth Lum, who had completed a first postdoc at MIT, joined the EXITE project as its first postdoc in January 1991 and continued with the project through December 1996 (as a Research Associate for the final 2 years). He carried out much of the testing and software development for the EXITE2 detector and its first engineering flight as well as preparations for the first science flight. He joined a Boston area company in January 1997.

Dr. Tomohiko Narita, who had completed his Ph.D. at Wisconsin, joined the EXITE project in July 1997. He is carrying out both development and testing of CZT detectors and imaging arrays for the proposed EXITE3 system as well as supervising the re-build of detector and gondola electronics rack for the next flight(s) of EXITE2.

Graduate Students:
Four graduate students have completed their Ph.D. research at Harvard with theses based on EXITE:

Michael Garcia (1987, Harvard Astronomy) carried out much of the early development of EXITE1 with emphasis on development of the image intensifier detector readout system. He is now a staff astrophysicist at SAO.

Corbin Covault (1991, Harvard Physics) completed the overall development of EXITE1 and was the central designer of the entire payload and initial software system. He participated in the 3 flights of EXITE1 and conducted the scientific analyis. He is now an Associate Professor of Physics at the

University of Chicago.

Joao Braga (1991, University of Sao Paolo, Brazil) carried out his thesis research on EXITE1 with extensive system testing and the initial design and testing of the anti-coincidence shield system. He participated in the first flight and is now a starff scientist at the INPE (Brazilian Space Agency) in Brazil.

Raj Manandhar (1994, Harvard Physics) participated in the analysis of EXITE1 data and calibrations and then carried out the detector design and initial construction of the EXITE2 detector and telescope system. He participated in the engineering flight for EXITE2 and the analysis of results. He is now working for aerospace industry.

In addition, three other graduate students carried out significant work on the early phases of the EXITE1 program (Richard Burg, MIT Physics graduate student) and EXITE2 programs (Stephen Eikenberry and Martin Krockenberger, both Harvard Astronomy students). In particular, Eikenberry and Krockenberger made significant contributions to the early development of EXITE2 and participated in the engineering flight.

Two Harvard graduate students are now nearing the completion of their Ph.D. thesis work on EXITE2:

Peter Bloser (Harvard Astronomy) is completing the development of the aspect, in flight calibration system, and spectral analysis system for EXITE2 as well as carrying out much of the development of the imaging CZT detector systems for EXITE3. He participated in the first science flight for EXITE2.

Yi Chou (Harvard Physics) has played a key role in the EXITE2 detector development and ground calibrations. He has also led the development of the PSD, MLM and imaging analysis systems. He participated in the first science flight for EXITE2.

Undergraduates:
At least 25 Harvard undergraduates have worked on the project, many for several years. Two Harvard and one MIT senior theses have been written with work based on *EXITE* data. The project has drawn in a significant number of undergraduates from other allied disciplines or majors: a number of computer science students, for example, have played key roles in the development of flight computer software systems. Some of the key software for both flight and ground computers have been written in large part by undergraduates. As current examples (1996-98), J. Grenzke and B. Robbason have written much of the flight software code, while M. Christopher wrote much of the aspect reduction system.

7.2 High School Students, Interns and Public Talks

Over the past decade the EXITE project has hosted a number of high school students for term-time jobs or projects as well as summer jobs. These include 4 students from a Cambridge private school, 4 from local area high schools, and two from distant schools (MI and CA) who visited for the summer. Most of these have gone on to become physics majors in college and then graduate school in physics or astrophysics, and one is already back at SAO as a staff scientist.

A number of public/popular talks have been given to describe the EXITE program and balloon-borne astronomy. The lab at CfA and the gondola and experiment integration lab at the Harvard

High Energy Physics Lab (high bay area needed for gondola testing) have been frequent stops on tours for visitors.

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