SCIENTIFIC INVESTIGATIONS WITH THE DATA BASE

HEAO-1 SCANNING MODULATOR COLLIMATOR

NASA Grant NAG8-496

Final Report

For the Period 1 October 1984 through 30 September 1991

Principal Investigator
Daniel A. Schwartz

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Prepared for:

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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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The NASA Technical Officer for this grant is Ms. Donna Havrisik, Code EM25, NASA,
1 Introduction

NASA Grant NAG8-496, Scientific Investigations with the Data Base of the HEAO-1 Scanning Modulation Collimator, is a follow-on to our work under Contract NAS8-30453, the Scanning Modulation Collimator experiment provided for the first High Energy Astronomy Observatory (HEAO-1). This final report encompasses the scope of the total project, as our final report to NASS-30453 stated would be done. For brevity, most information is provided via reference to our previous reports and proposals already submitted to MSFC. A summary of our hardware and data processing is reproduced here as Appendix A.

The hardware specification for the Scanning Modulation Collimator (MC) experiment on HEAO-1 was to measure positions of bright (> 10^{-11} ergs/cm^2s), hard (1 to 15 keV) x-ray sources to 5–10 arcsec, and to measure their size and structure in three energy bands down to 10 arcsec resolution. The scientific purpose of this specification was to enable the identification of these x-ray sources with optical and radio objects in order to elucidate the x-ray emission mechanism and the nature of the candidate astronomical system.

SAO has served as Principal Investigator for this experiment (under Dr. Herbert Gursky until June 1978, and Dr. Daniel Schwartz thereafter). In this role we were responsible for the concepts and requirements; supervision of the design, manufacture, and test by our hardware contractor American Science and Engineering (AS&E); and for mission operations, data reduction, scientific analysis, and publication of scientific results. In all these tasks we functioned as a single team with our Co-Principal Investigator Dr. Hale Bradt, and assisted by his entire staff at MIT.

The experiment was an outstanding success. Hardware systems functioned perfectly, although loss of one (out of eight) proportional counter degraded our sensitivity by about 10%. Our aspect solution of 7 arcsec precision, allowed us to achieve statistics-limited location precision for all but the strongest sources. We vigorously pursued a strategy of determining the scientific importance of each identification, and of publishing each scientific result as it came along.

2 Progress of the NAG8-496 Efforts

Efforts for the interval 1 October 1984 through 31 March 1987 are summarized in our progress reports Nov. 1 through 5, submitted under single cover in March 1987. Progress from 1 April 1987 through end of grant on 30 September 1990 is summarized chronologically as follows:

November 1987

Another 7-night observing run at Kitt Peak on the 36" Schmidt yielded 27 new prism plates of A-3/NRL unidentified x-ray source areas. An observing run at McGraw-Hill obtained observations on two nights, giving identifications with 2 RS CVn stars, a cataclysmic variable, a candidate BL Lac object and an unclassified H-alpha emitter associated with an Einstein source under an IPC rib.

Work is underway on a poster session on clusters of galaxies, for the AAS meeting in January. Photo work has also been started for an AAT observing run in February. Archiving
of A-3 finding chart maps continues.

A data disk crash has left some data temporarily inaccessible. A new disk will be built, and the heads cleaned and aligned on the affected drive. The DG dual-access tape drive still awaits repair.

December 1987, January and February 1988

The Trident T-200 data disk which experienced a head crash last month, was rebuilt and duplicated data files were loaded from back-up tapes. Versatec print-head problems occurred several times, but were overcome by resetting and adjusting the angle of the print-head.

Photographic fields were reproduced for 22 southern hemisphere A-1/A-3 x-ray sources, to be worked up as finding charts for a February AAT observing run.

A-3 results were analyzed and mapped for Abell clusters for a poster session at the AAS meeting in January. Work continues on the archiving of A-3 unidentified results.

April and May 1988

All Trident and Century disks were cleaned and inspected. One Trident data disk failed inspection and has subsequently been replaced and rebuilt.

A total of thirteen new finding charts were produced from recently analyzed A-3 data for observing runs. Thirty-four new Schmidt 2-degree prism plates were obtained during a nine-night run at CTIO, and were scanned during the 2 cloudy nights. Several interesting emission-line objects were found to be well associated with the A-1 LOP.

June 1988

A draft paper on the new BL Lac identification H1720+117, was prepared (by Brissenden) and reviewed internally. R. Remillard is nearing completion of the nine “mini-catalogs” which summarize the entire identification content of the HEAO-1 NRL source catalog.

September 1988

The nine mini-catalogs have been prepared, summarizing the status of all HEAO-1 identifications in categories as follows: AGN, BL Lac Objects, Cataclysmic Variables, Binaries, Be Stars, Clusters of Galaxies, RS CVn-like stars, Supernova Remnants, and Miscellaneous. NASA headquarters has deemed that the PI program will continue for two final years, FY89 and 90. In response to their direction for preserving the HEAO-1 data we have made a plan to publish the NRL catalog as a single table, in right ascension order, giving the identification status of every object. (The catalog will contain the 842 entries of the NRL survey, plus about 40 sources which appear later in the HEAO mission.) This will be followed by the 9 tables of mini-catalogs, each of which give supplementary information relevant to the particular class of object (e.g., redshifts for extragalactic objects).
October 1988

As a follow up to earlier VLA work, fifty-eight interesting radio sources relating to 12 LASS x-ray sources were measured and photographed to search for optical counterparts. Spectroscopy will be performed on all hopefuls. Fourteen new finding charts are being constructed for unidentified A-3/LASS sources visible in the southern sky during a December observing run.

A major head crash during September resulted in the loss of five T-200 Trident disks. Upon inspection one 40mb disk also had hard errors, and an additional one was found to have ‘too many top platters’ and removed from service. Nineteen heads had to be replaced, and heads were cleaned and aligned on all four drives. Two I/O boards were found to have blown and were replaced. The drives were brought up on the system, and four of the lost disks were rebuilt. Intermittent problems with the low density DG tape drive still persist causing vacuum loss when loading tapes.

December 1988

Seven unmasked IPC sources with A-3 results were worked up for further optical studies. Fourteen new A-3/NRL finding charts were made for a December observing run at CTIO. Nine figures were prepared for an RS CVn paper, and a contour map figure was prepared for an unmasked IPC source.

The CTIO observing run appears to have been highly successful with possibly ten to fifteen new identifications of southern x-ray sources.

Tape drive problems still persist. The power supply now appears to be unreliable. One 200mb data disk was rebuilt, and most of the data files were replaced.

February 1989

Ten newly discovered IPC unmasked source possibilities were mapped with A-3 error boxes. Finding charts were made, and eight were found to be interesting enough to warrant further investigation as IPC/A-3/A-1 x-ray sources. During three recent observing runs 28 new identifications of x-ray sources have been made, including many QSO, several BL Lac, RS CVn’s and CV’s. Precise positions of many of the new objects are being measured. Of particular interest are a quasar with m=13.7, $z=0.09$ identified with H1033-142, and an optically shrouded luminous object in the LMC which we previously noted as peculiar and now identify with the x-ray source H0453-75.

Three scientific papers are in progress which will present a total of 39 new quasar and Seyfert ID’s. Photographic work for these papers is also underway.

The two Century disk drives were adjusted and heads realigned after both malfunctioned simultaneously. Both are back on line now. We await the installation of a “new” (hand-me-down) dual-density DG tape drive to replace one with a burnt-out power supply.

August 1989

A Cerro Tololo nine-night observing run yielded 36 objective prism plates and 8 uv-blue direct plates of A-3 x-ray source fields. These plates were scanned, and interesting objects
marked for further observations at the Anglo-Australian Telescope in September.

Rebinning of the original A-3 data at new interesting locations continues, and is about 5/8 complete. Mapping of the A-3 x-ray diamonds is now done on the MIT SUN system, and figures are thereby camera-ready from the laser printer.

Three papers of A-3 identifications are underway. These include 35 emission-line AGN’s, 6 cataclysmic variables and 2 BL Lac’s.

October 1989

Work progresses on the final LASS/A-3 survey Ingres database, with approximately 75% of the identified source information complete. Appropriate query and report forms are being built for each spectral class to facilitate access by the community.

Approximately thirty new x-ray sources have been identified during two recent observing runs. Three new publications of previous identifications are in progress.

April 1990

Work continues on the final HEAO-1/MC LASS catalog of identified x-ray sources, both the hardcopy version for publication, and the Ingres data-base version. At present the catalog contains 660 identifications.

A recent A-3 observing run yielded 20 new identifications whose exact positions will be measured. Approximately 300 sources with A-3 results remain unidentified. Of these, the brighter LASS detections are undergoing A-3 LASS analysis to confirm the LASS positions.

Fortran 5 .dx file analysis source programs have been ported to the SUN system, and are undergoing conversion to SUN Fortran 77. The .dx files and resulting answer.ct files are presently being written to WORM disks. A C program has been written to read the answer.ct’s as well as many interesting and previous x-ray catalogs, and to output a SMONGO-readable file.

The DG computer was found to have blown a fuse due to a power glitch. The fuse has been replaced and no other problems were found. A high voltage power supply was replaced in the Versatec printer. Other DG system hardware continues to function satisfactorily.

August 1990

All .dx file analysis source programs have been successfully converted to f77 and ported to the SUN/UNIX system. The programs will undergo final testing during the next month to ensure compatibility. The INGRES data base of final A-3 results in on-line and will be updated one last time. All DG equipment is functional.

October 1990

The A-3 data reduction and analysis has been completed after 13 highly successful years. We have shutdown all Data General and associated equipment, which are now awaiting return shipment to NASA. A-3 raw tapes are expected to be stored until they can conveniently be transferred to DAT tapes; binned data tapes are currently being WORMed at Penn State;
All A-3 software has been archived on 9-track tapes; all other obsolete 9-track tapes are ready for shipment to Goddard's Tape Retrieval Center.

The A-1/NRL catalog of final results is available in hard-copy format, and as an INGRES database on the SUNS. Two more A-3 papers which document identification of 37 new AGN's are about to be submitted of publication. A-3 data analysis of sources from the three binning catalogs is now fully supported by the SUN/UNIX system. Software necessary for the rebinning of raw data has been converted to AOS format, assuring that the tapes will be readable via "AOSLOAD" directly to the SUNS.

Subsequently, all equipment and magnetic tapes have been officially returned to NASA.

3 Summary of Scientific Results

Table 3.1 summarizes the A-3 locations of hard x-ray sources identified with optical objects. The table omits about 200 A-3 locations of x-ray sources which do not yet have firm identifications. Objects are in nine categories as follows: AC=Active Coronal star, usually an RS CVn type object; AGN=active galactic nuclei, emission line objects; BL=BL Lac type object; CG=cluster of galaxies; CV=cataclysmic variable; Misc.=miscellaneous, including nearby galaxies, and galactic objects; SNR=supernova remnant; XRB=classical x-ray binaries, neutron star or black hole accreting from an OB supergiant or low mass companion; and XRB-Be=x-ray binary accreting from a Be star companion.
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# TABLE 3.1
HEAO-1 SCANNING MODULATION COLLIMATOR IDENTIFICATIONS OF HARD X-RAY SOURCES

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4 Guest Collaborator Program

Long before the HEAO-1 launch we realized that the primary scientific return of the MC experiment would not be the plots of allowed x-ray source locations in celestial coordinates, but rather would be the publication of each astronomical identification, with appropriate discussion of the physical characteristics of the system. It was obvious this must involve extensive participation by many astronomers outside of our MC x-ray experiment team. Well planned, deliberate studies were needed to make significant progress.

We perceived some major differences from the traditional Guest Investigator programs being set up for both the HEAO-1 and HEAO-2 missions. Accessing and analyzing raw x-ray data is not generally a task in which an optical astronomer is skilled or interested. HEAO-1 was originally defined as a six month, solely PI mission, and the MC data system, designed in the 1974 to 1976 time frame, was intended for operation only by computer specialists guided by the MC experiment scientific team. The baseline HEAO-1 mission was a six month all-sky scan without pointing, so that 4 to 8 full days of the real-time telemetry stream must be processed for each source position. The key fact is that essentially all astronomers are interested in particular types of objects, whereas a priori the identification type of an arbitrary, weak x-ray source cannot be anticipated.

Therefore we initiated an active Guest Collaborator Program. (Einstein used a similar collaborative program for their identifications of deep and medium survey sources, cf. Giacconi et al. 1979). In this program we freely collaborated with any astronomer in the world on specific x-ray identifications according to their interests. Typically, they provided detailed or repeated spectra, polarization, photometry, and astronomical interpretation, after our indication of the identification type. Their data might be in any electromagnetic band: optical, ultraviolet, infrared, radio, or x-ray.

Table 4.1 provides details on the collaborations which resulted in publications. People from CfA and MIT are only listed during periods of time when they were not actually employed on the MC project. Several of these people have worked on more than one publication, and each publication has many co-authors. We have additional publication with 10 other members of the HEAO-1 A-1, A-2, and A-4 teams.

We effectively organized and carried out a substantial guest observer program, at no additional cost to NASA.
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HEAO-1 A-3 GUEST COLLABORATORS

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18
5 Publications

5.1 Articles


5.2 Abstracts of Talks


1979 Location of variable x-ray sources near southern clusters of galaxies using the scanning modulation collimator on HEAO-1 (D. Schwartz, M. Couroy, M. Garcia, E. Ralph,


Appendix A: Description of the MC Experiment
APPENDIX A

We summarize here a review of the scanning modulation collimator hardware and data processing. This appendix is reproduced from sections 1.2 and 1.3 of our proposal P1192-6-82 of June 1982, to NASA, to "Preserve the Scientific Data Base of the HEAO-1 Scanning Modulation Collimator (MC) Experiment."

A-1 Description of the Experiment Hardware

The MC instrument contained two modulation collimator banks, each a stack of four planes of wire grids. Each grid was a set of regularly spaced wires, with the spaces nominally equal to the wire diameters. In a four-grid collimator (cf. Bradt et al. 1968), the acceptance of the outer grid pair has a repeating triangular pattern. Each of the two inner grids shadows every other remaining triangle (i.e., reduces their response to zero) so that the overall acceptance pattern, as a function of the azimuth angle in a plane perpendicular to the wires, is a set of triangles of half-width δ and spaced 8 apart. On-orbit
The instrument also contained two image dissector star cameras, rigidly mounted to the same optical bench as the modulation collimators. Along with rate integrating gyro data from the spacecraft, we used our star camera data and the Smithsonian Observatory catalogue of star positions to calculate the instantaneous field of view on the celestial sphere.

The experiment functioned flawlessly on-orbit, except for the failure of one of the four proportional counters in MC2 after about 3 weeks. This degraded the MC2 area to 300 cm² for most of the mission. Throughout the mission, no changes in our aspect or alignment parameters occurred.

There is a systematic aspect displacement with elevation that has been calibrated to be about 4 arcsec per degree in elevation from the scan plane. This correction is applied by the software which sums data from different scans.

Published descriptions of the experiment hardware appear in Roy et al. (1977), Gursky et al. (1978), and Schwartz et al. (1978).

A-2 Data Reduction and Analysis

Figure 2 shows a schematic block diagram of our data reduction programs. Although we processed quick look data to monitor the experiment and obtain some science results, the same data was reduced sequentially when received as a production data tape; therefore, only production data is relevant to this proposal. The key "scientific" steps are the calculation of the
calibration gives $\delta_1 = 28.86$ arcsec for the "30 arcsec" collimator (MC1) and $\delta_2 = 115.61$ arcsec for the "2 arcmin" collimator (MC2). In addition to the grids each has an egg-crate collimator which limits the overall field of view to $7\,\text{.}\,6 \times 7\,\text{.}\,6$, full width at zero response. The net open area on-axis was about 400 cm$^2$ per collimator.

The grid wires of MC1 and MC2 are respectively tilted $-10.265^\circ$ and $+9.821^\circ$ with respect to the spacecraft scan circle. The egg-crate collimator is aligned parallel and perpendicular to the scan. Figure 1 shows the collimators' responses to Sco X-1. One second of time represents $0.2^\circ$ in scan angle. The figure illustrates the $30^\prime$ and $2^\prime$ FWHM response, the $4^\prime$ and $16^\prime$ spacing between triangles, and the coarse collimator envelope.

Four sealed proportional counters, behind each modulation collimator, sort X-ray events into three channels with pulse height boundaries equivalent to 0.9-2.6, 2.6-5.4, and 5.4-13.3 keV. The overall spectral response is defined by the 2.5 micron thick mylar thermal shield and 43 micron thick Be window to be above about 1.5 keV (10% quantum efficiency), and by the filling gas of 855 mm argon and 70 mm CO$_2$ to be below about 16 keV. The total counts from MC1 and MC2 in 0.040 and 0.160 second intervals, respectively, are telemetered. At the nominal scan rate, these correspond to angles of 5 and 20 arcsec, in MC1 and MC2 respectively. Pulse shape discrimination (PSD) is used to reject non-X-ray events, and the PSD and other auxiliary rates are telemetered.
Sco X-1 AS SEEN BY SCANNING MODULATION COLLIMATOR
7 OCTOBER 1977

MC 2

COUNTS / 0.16 s

MC 1

COUNTS / 0.04 s

TIME (s)
Figure 2

MC DATA REDUCTION
"fine aspect" solution, and the binning of the X-ray data. The aspect solution is merely an intermediary used to bin the X-ray data. We will document it further with our data submission, but need not discuss it here. However, understanding the X-ray binning procedure is prerequisite to understanding what scientific data base is practical and meaningful for delivery to the NSSDC.

We will discuss the 30 arcsec collimator (MC1) in detail. For MC2, multiply all sample times and angles by 4. We read out the total counts in each pulse height channel every 40 milliseconds. This corresponds to about 5 arcsec perpendicular to the modulation collimators at the nominal spacecraft scan rate of 0.2 deg/sec; i.e., \((0.040 \text{ seconds}) \times (0.2 \text{ deg/second}) \times \sin 10° = 0.0014 \text{ degrees} = 5 \text{ arcsec}\). If we had tried to bin all the X-ray data we would have required \((3600 \text{ arcsec/degree}) \times (360 \text{ degrees/circle}) \times (2 \text{ circles/day}) \times (182 \text{ days/sky scan})/(5 \text{ arcsec/bin}) = 9.4 \times 10^7 \text{ bins on the sky, times (3 energy channels + 1 exposure time array)} = 3.8 \times 10^8 \text{ total bins}\. (Add 25% to account for MC2.) In terms of 1974 technology, and our available computer hardware and programming resources, this was a preposterous number. However, since our investigation proposed only to locate (and not to discover) cosmic X-ray sources; i.e., sources known to exist, it was obvious that we need only bin our X-ray data in the relatively small sky regions around each X-ray source in some catalogue.

As a complication, the successive 30 minute spacecraft
rotations did not precisely reproduce a single scan circle. To handle this rigorously within the general motions allowed by the spacecraft specification would have required a two-dimensional binning approach. Instead, our binning preserves each rotation individually, along with parameters, the "jitter angles", which allow superposition in later analysis. We thus bin in one dimension only, each bin representing 1/60 of the periodicity of the modulation collimator response. The approximations inherent in this scheme cause the X-ray signal to begin to wash out when the true source position is more than ±1° from the trial binning position. Therefore we often insert multiple trial binning positions for one X-ray source, if its previous location is not established to better than a 1° radius in any direction.

Another complication is that most X-ray sources are quite variable in time, at least potentially. Therefore we could not use a predetermined, fixed catalogue for our binning. At launch we did have a master X-ray source catalogue (MCAT) containing all published X-ray sources, plus private and pre-print data from experiments at MIT (OSO-7 and SAS-3), SAO (the fourth Uhuru catalogue), and the University of Leicester (the Ariel V Sky Survey Instrument, or 2A, catalogue). During our first reduction effort we added sources which we noted in the A-1 raw data, which was generously provided to us by Dr. H. Friedman of NRL in order to reduce our multiple source positions. Subsequent to the end of the mission, in February 1979, we created a new binning catalogue (BCAT), utilizing all the A-1 data which we had, plus
published and some private A-2 results on new sources, and a pre-publication version of the final Ariel V catalogue (3A). One major limitation of our use of A-1 data was that we could not superpose it perpendicular to the scan circle. We therefore had lines of position up to 8° in length, along which we defined multiple binning positions. BCAT contained about 1200 positions, representing an estimated 600 distinct sources, with an estimated number of 400 above the A-3 sensitivity threshold of roughly 1 Uhuru flux unit. \( (1 \text{UFU} = 1.7 \times 10^{-11} \text{ergs cm}^{-2} \text{s}^{-1}, 2-6 \text{keV}; \approx 1.6 \mu\text{Jy at 3.6 keV.}) \)

As a simplification and for further compression, we "fold" the data modulo the 4 or 16 arcmin periodicity of each collimator. In Figure 1 all the triangles would be added together to form a single triangle, plus flat background, for each collimator. Figure 3 illustrates the data after folding.

The structure is 60 angular bins of size 4 arcsec and 16 arcsec for MCl and MC2, respectively, representing the mean phase of the modulation collimator relative to the binning position during the data integration time. The raw counts in each of the three energy channels, and the integer number of readouts (in units of the integration times of 40 msec and 160 msec for MCl and MC2, respectively) are incremented accordingly.

During the spacecraft "pointed" mode one target remains within the field of view for an extended period of time (except for earth occultations). For HEAO-1 the pointings have a very
coarse deadband of \( \pm 1/2^\circ \), and the rates within that deadband are not controlled. The jitter of the spacecraft in response to magnetic, gravity gradient, and aerodynamic torques causes an X-ray source to be swept through the full modulation cycle of the collimators. The data reduction proceeds largely as in the case of scanning with two principal exceptions. First, the records during which data is folded are set at exactly 64 seconds (200 minor frames) instead of being one spacecraft rotation. Second, the PSD data is sorted into a parallel binning structure and those files are saved to be used in the data analysis.

The time resolution of the binned, scanning data is the 30 minute rotation period. We have lost time resolution in the 2 to 20 second range by folding modulo the collimator periodicities. For both pointing and scanning data we still preserve some information on variability in the 40 to, say, 640 millisecond range, because these are the time intervals between the successive angular bins.

Figure 4 shows a schematic block diagram of our data analysis computer programs. Data analysis is discussed in more detail in Part II. We include it here to guide scientists who may wish to use our reduced data base, and because we propose that it is the analyzed data, to the extent available, which most economically contains the meaningful and useful flight data.

The key feature of data analysis is that each modulation collimator gives a regularly spaced set of lines, with 86 (4 or 16 arcmin) separation. The two sets of lines intersect at
Figure 4

MC DATA ANALYSIS
20° angles, forming a regular grid of "diamonds" which contain the true X-ray source position, to better than 90% confidence. To the eye, this grid appears almost rectangular with spacing of 15 by 11 arcmin. We can almost always use either the A-1 data provided to us, or the forthcoming A-1 catalogue (made available to us in October 1981) as well as any other previous error locations, to reduce the possible locations to one or two rows of diamonds.

A key feature of data analysis is the fact that non-X-ray background sampling is interspersed with the X-ray source signal, as shown in Figure 1. Effectively, each collimator is a narrow band receiver, where the frequency is known a priori and it is our measurement of the phase which relates the set of lines to the celestial sphere. This makes the modulation collimator an extremely "clean" instrument. In the case of pointed data, we use the binned PSD data to "flatten" apparent angular structure in our X-ray data which in reality arises from temporal variations in the non-X-ray background (cf. Dower et al. 1980).