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MEASUREMENTS OF X-RAY SOURCE POSITIONS BY THE SCANNING MODULATION COLLIMATOR ON *HEAO 1*

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ABSTRACT

This paper reports preliminary results on the positions of X-ray sources obtained with the modulation collimator on the first NASA *High Energy Astronomy Observatory*, *HEAO 1*. Calibration on Sco X-1 establishes the experiment capabilities to be within 7″ as limited by aspect errors. For the reported X-ray sources we resolve certain ambiguities in their positions and confirm the previous optical identifications of four sources, two of which are X-ray bursters and one of which is the black hole candidate Cir X-1. We also present an accurate position for a new transient source.

Subject headings: X-rays: general — X-rays: sources

I. INTRODUCTION

NASA's *High Energy Astronomy Observatory*, *HEAO 1*, was successfully launched on 1977 August 12. The satellite contains four independent experiments of much greater size than have been orbited to date. The experiments are intended to provide a broad range of observational capability in the area of X-ray astronomy. We report here on the scanning modulation collimator (MC) experiment, whose prime objective is to measure the positions of X-ray sources over the whole sky with high angular precision in order to permit their optical or radio identification. We will also study the angular size and structure to elucidate the nature of the radiation mechanisms in certain systems.

This paper describes briefly the essential features of the experiment hardware, operation, analysis, and calibration. This is relevant information to establish the results of previous papers on the identification of the flarelike, burstlike source in Norma (Fabbiano *et al.* 1978), on the Ophiuchus transient (Griffiths *et al.* 1978), and on the rapid burster (Doxsey *et al.* 1978), as well as to be used in subsequent papers by the group. We also present location error boxes of a few tenths arcmin^2 size for seven strong sources in the galactic center region. Two of these regions are heavily obscured and devoid of optical candidates. Four of the sources have suggested optical identifications which are consistent with our measurements. One is a newly discovered transient X-ray source (Kaluzienski and Holt 1977*a*, *b*; Doxsey *et al.* 1977*b*). The position determinations obtained here with limited "quick look" analysis are of equal or greater precision than the best final results (e.g., Wilson *et al.* 1977; Doxsey *et al.* 1977*a*) from earlier satellite missions and appear to resolve certain conflicting reports on positions.

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II. INSTRUMENTATION—THE SPACECRAFT AND THE EXPERIMENT

HEAO 1 is in a circular ($\epsilon = 0.001501$) orbit at 432 km altitude and 22°.76 inclination. The satellite z-axis is maintained within 1° of the Sun, and the observatory spins about this axis at a rate of about 12′ s^{-1}. The MC looks along the y-axis and on any day scans a band centered at 90° from the Sun. In 6 months this band sweeps out the entire sky. The spacecraft can also be pointed, in principle, to any arbitrary direction with about ½° accuracy. In practice, thermal constraints restrict the point directions in such a way that the z-axis remains within 5°–10° of the Sun. Further discussion of the satellite and the four experiments is given by Dailey and Parnell (1977).

The MC experiment contains two four-grid modulation collimators. The angular response of this kind of collimator is a series of transmission bands separated by 8 times the FWHM of each band. In our case the bands are 30″ and 2′ FWHM, separated by 4′ and 16′, respectively, for the individual collimators. Each collimator measures position in one dimension, perpendicular to its transmission bands. The collimators are not coaligned but are mounted so that their transmission bands tilt +10° or −10° to the spacecraft scan circle. Such a mounting scheme reduces the telemetry sampling requirements, since the time a source takes to undergo one modulation cycle is proportional to csc 10°. An egg-crate collimator limits the overall field of view to 4° × 4° (FWHM). Properties of modulation collimators have been discussed generally by Bradt *et al.* (1968). The present instrument is very similar to one used in 1966 to measure the angular size and position of Sco X-1

(Gursky *et al.* 1966*a*, *b*) and the structure of the Crab Nebula (Oda *et al.* 1967); many of the details presented in the earlier papers are relevant here.

The X-rays are detected by four sealed proportional counters placed behind each collimator. The 30″ collimator (MC1) has a net effective area of 400 cm^2 maximum. One of the MC2 counters failed 2 weeks after launch, giving it a net area of 300 cm^2. The spectral response is defined by the 2.5 μm thick Mylar thermal shield, the 43 μm thick Be counter windows, and the filling gas of 855 mm argon and 70 mm CO_2, to be greater than 10% between 1.4 and 16 keV. Pulse height analysis sorts acceptable X-ray counts into three energy channels, which are 0.90–2.6, 2.6–5.4, and 5.4–13.3 keV according to prelaunch calibration. Pulse shape discrimination is used to reject non–X-ray events (long rise time), and is effective in removing 93% of the background while accepting 85% of all X-rays as determined in orbit. Two image-dissector star cameras, identical to those used on the *SAS 3* mission, provide individual star measurements to an accuracy of 10″–20″ rms. Rate-integrating gyros on the spacecraft give rates of motion accurate to approximately 0°.05 $hour^{-1}$.

Residual non–X-ray background in MC1 is about 11 s^{-1}: 1.5, 3.0, and 6 s^{-1} in the three respective pulse height channels; the MC2 background is slightly less than $\frac{3}{4}$ that on MC1. These rates remain stable within 30% around the orbit, and are independent of Earth or sky view as expected, since our small aperture has a negligible response to the diffuse X-ray background. We currently estimate that our ultimate sensitivity will be about 1.5–2 *Uhuru* counts s^{-1} (3 σ significance)[1] for sources at the equator during our initial 6 month scan and correspondingly lower if the mission life is longer. During two orbits of pointing operations, we should be able to achieve sensitivity of $\sim$1 *Uhuru* count s^{-1}. This sensitivity should be sufficient to detect any 1–10 keV X-ray source now cataloged. For these faintest sources, the positional uncertainty will be $\sim$2 $arcmin^2$.

We telemeter the total accepted X-ray count in each of the three energy channels every 40 (160) ms for MC1 (MC2). In each case this amounts to motion by about $\frac{1}{6}$ of the FWHM for the nominal scan rate. We also receive one readout from each star-tracker and each of three gyros every 0.32 s. As in previous X-ray experiments, the X-ray counts are binned and projected onto the sky on the basis of an aspect solution, i.e., post facto knowledge of the instantaneous orientation of the spacecraft. In our case, we use the body rates as determined from the gyros to generate the aspect solution. Star sightings as found in the star sensor are used to tie the aspect solution to the sky and to determine the best values of the gyro parameters. Alignments of the gyros, X-ray collimators, and star-trackers are established on-orbit. We correct the gyro data relative to aspect sensor and X-ray data to account for the effects of the aberration of starlight.

Two potential difficulties in analyzing modulation collimator data are that fine angular resolution requires a large number of resolution elements on the entire sky to be searched for the existence of X-ray sources, and that multiple positions are produced corresponding to the periodicities of 4′ and 16′. Both of the problems are greatly alleviated by use of the data provided by the Naval Research Laboratory from the 1° × 4° mapping modules of their large-area sky survey (LASS) experiment on *HEAO 1*. We analyze these data for the existence of X-ray sources above the MC experiment threshold of about 1 *Uhuru* count s^{-1} (about 10 times larger than the ultimate LASS experiment threshold) and obtain a line of position accurate to about 10′ in azimuth. Further reduction of ambiguities may be obtained from previous X-ray catalogs, from special maneuvers to scan through the source at offset phase angles, or from monitoring the source as the LASS experiment scans it in elevation over an 8 day period.

Further details of the MC hardware and operation are given by Roy *et al.* (1977) and Schwartz *et al.* (1978).

III. CALIBRATION AND POSITION MEASUREMENTS

For each collimator we must determine three parameters on-orbit: the actual value of the spacing of the transmission bands, the inclination of the transmission bands to the scan direction, and the angular separation of the star-tracker boresight in the direction normal to the transmission bands. Because of the thermal stability, we expect these parameters to remain constant, at least on a time scale of several weeks. The measurements are made by observing a source that has a precisely located optical counterpart. Figure 1 shows the actual raw counts from a transit of Sco X-1, which satisfies this condition (cf. Fig. 2 of Gursky *et al.* 1966*a*). By now, there are sufficient identified sources around the sky to assure good calibrations during the entire mission.

The periodic spacing and the inclination of the transmission bands are of greatest influence when one is trying to superpose the repeated transits of a source near the edge of the field of view, $\sim$4° away from the scan circle. We adjust these parameters to give a minimum width to the superposed triangle. The error in inclination also gives a systematic phase change as a function of source elevation that provides an initial estimate for the above refinements. The apparent position of Sco X-1 in each collimator then defines the phase of the aspect-solution boresight perpendicular to the transmission bands. We measure an apparent position of Sco X-1 for each individual rotation of the satellite. The rms deviations derived from this process are about 5″ in MC1 and 7″ in MC2, much larger than the 1″ that would be estimated from statistics alone. These numbers are also larger than our *a priori* estimate of the net aspect solution, since the rms residuals of *individual* star sightings from the aspect solution are typically 8″–15″. Therefore, we are using 5″ and 7″ as our current estimate of the 1 σ error in

[1] One *Uhuru* count s^{-1} = 1.7×10^{-11} ergs cm^{-2} s^{-1} between 2 and 6 keV.

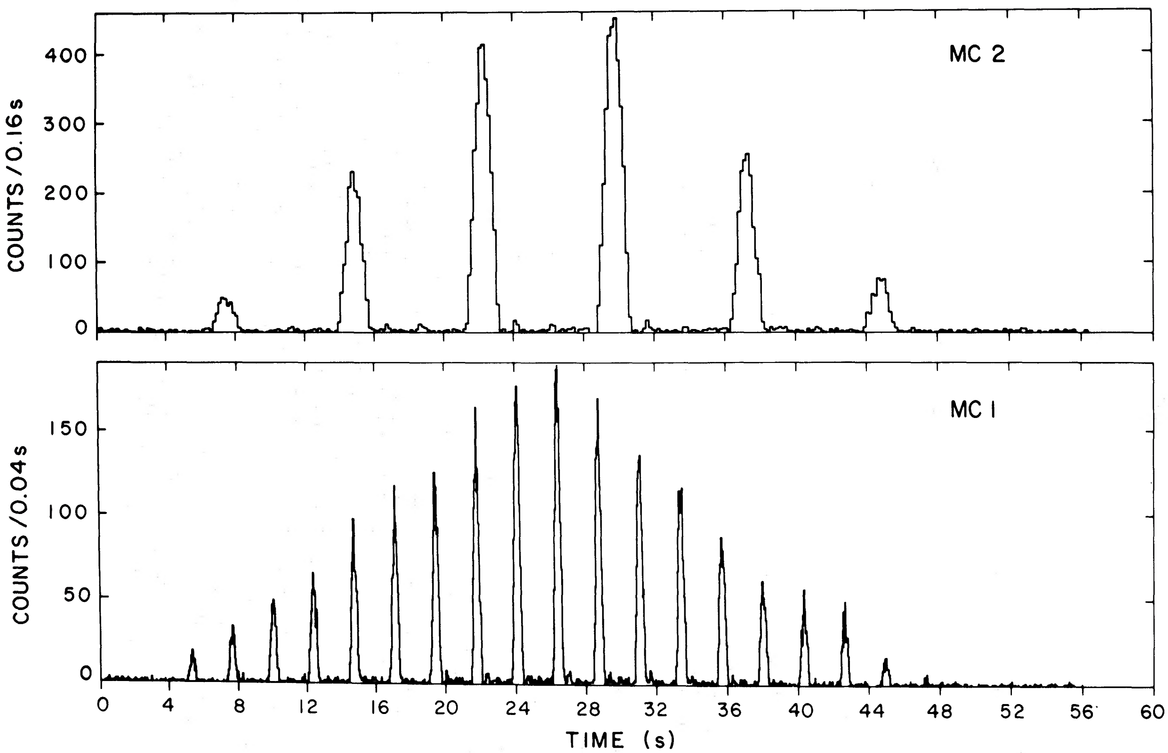

FIG. 1.—Raw count data summed over the three pulse height analyzer channels. The six large peaks in MC2 and the 18 in MC1 represent the transit of Sco X-1 through the transmission bands of the modulation collimators. The amplitude of the individual peaks changes according to the source orientation of the 4° × 4° coarse collimator. Small peaks can be seen in MC2 between the main peaks (e.g., at 17, 24, and ~32 s) and result from leakage through the collimator. (The ratio of the MC2 to MC1 band separations in time is not 4, owing to the +10°/−10° alignment offsets and to the spacecraft drift which tilts the apparent source motion by 2°.)

the aspect solution with respect to the individual collimators.

IV. X-RAY SOURCE POSITIONS

We derive the positions discussed below (and those in our other papers) from a best line of position for each collimator by converting it to a 90% (1.6 σ) probability band using the aspect error (5″ or 7″), combined (root-sum square) with the statistical error based on the number of accumulated counts. The intersection of the two bands that falls within the boundary of previously determined error boxes is a diamond which is our best estimate of the position. The area of these diamonds is between 0.3 arcmin^2 and 0.4 arcmin^2, depending on the statistical errors. In discussing these sources we have adopted the following nomenclature. For internal purposes and for previously unknown sources, we use the designation *Hxxxx*±*yyy*, where *xxxx* is the R.A. in hours and minutes and ±*yyy* is the declination in degrees to one decimal place. *H* refers to the spacecraft. For known sources, we use the common designation, generally the discovery name or one assigned during an early survey.

We show positions for six known X-ray sources in Figure 2 and for one transient source in Figure 3, along with other X-ray position determinations and positions for candidate optical identifications. The sources in Figure 2 have been subject to intensive investigations, as is seen by the variety of available positions. Of special importance, each of these sources has been observed by the rotating modulation collimator on *SAS 3*, which is the only other experiment of angular resolution comparable to our own and is especially designed to measure positions. Our positions, the *diamonds*, intersect the *SAS 3* positions in every case. We determined the rms offset between the lines of position of MC1 and MC2 and the centers of the *SAS 3* positions (similar to our calibration on Sco X-1) to be 4″.5. This number should have been substantially larger, since our average 1 σ error for single lines of position is about 6″.5 and that of *SAS 3* is 9″ for these sources. Thus it is likely that both we and *SAS 3* are overestimating our errors; in any event, it is obvious that any systematic errors are limited to ~5″ and cannot affect the results.

V. DISCUSSION

The conclusion of this analysis is that the *SAS 3* and the MC positions form a self-consistent set of data and that the intersecting regions can be taken to represent the best position for a given X-ray source

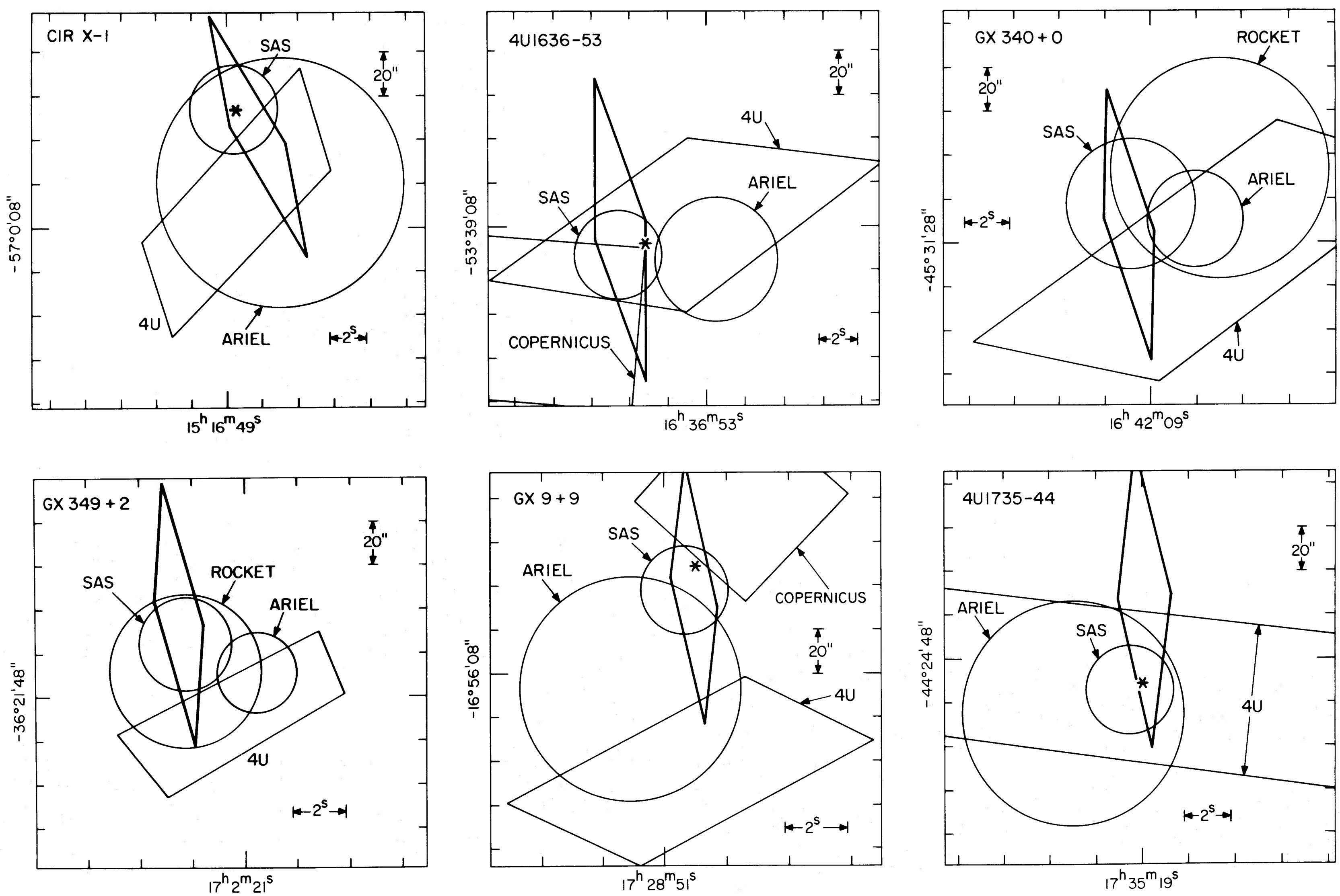

FIG. 2.—Position of six X-ray sources. North is up and east is on the left in these figures. The MC positions are the diamonds. The 4U positions are taken from Forman *et al.* (1978). The *SAS 3* positions are taken from Bradt *et al.* (1977) for Cir X-1, from Jernigan *et al.* (1977) for 4U 1636−53 and 4U 1735−44, from Doxsey *et al.* (1977*a*) for GX 9+9, and from Apparao *et al.* (1978) for GX 340+0. The *Ariel* positions are from Wilson *et al.* (1977) and Wilson and Carpenter (1976); the *Copernicus* positions are from Willmore *et al.* (1974); and the rocket positions are from Rappaport *et al.* (1971). The candidate optical identifications are indicated by stars. Those for 4U 1735−44 and 4U 1636−53 are from McClintock *et al.* (1977); for Cir X-1, from Mayo, Whelan, and Wickramasinghe (1976); and for 4U 1728−16, from Davidsen, Malina, and Bowyer (1976).

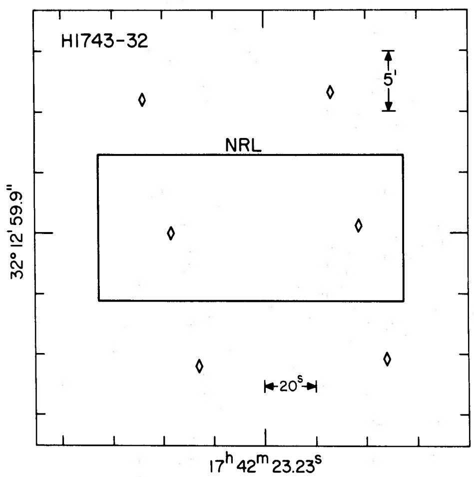

FIG. 3.—The two diamonds inside the heavy rectangle give the position of H1743−322 as found by *HEAO 1* using LASS and MC data. The positions of these diamonds are as follows: center $17^h43^m0^s.05$, −32°13′0″; corners $17^h43^m0^s.36$, −32°12′0″; $17^h43^m0^s.94$, −32°12′53″; $17^h42^m59^s.76$, −32°13′59″; $17^h42^m59^s.18$, −32°13′7″; and center $17^h41^m46^s.10$, −32°12′24″; corners $17^h41^m46^s.42$, −32°11′24″; $17^h41^m47^s.00$, −32°12′17″; $17^h41^m45^s.82$, −32°13′24″; $17^h41^m45^s.24$, −32°12′31″.

with a high degree of confidence. This is of particular importance in the case of Cir X-1, 4U 1636−53, GX 9+9, and 4U 1735−44, all of which have candidate optical identifications within this intersecting region. Only for 4U 1735−44 is the candidate star consistent with all previous positions; in contrast, the candidate star for GX 9+9 is outside the 4U, the *Ariel*, and the *Copernicus* positions. For 4U 1636−53 it is outside the *Ariel* and *Copernicus* positions, and for Cir X-1 it is outside the 4U position. Similarly, in the case of the two unidentified sources, GX 340+0 and GX 349+2, the *SAS 3*/MC intersecting region is disjoint from what might otherwise be considered the best position, on the basis of the overlap of previous positions.

The position shown in Figure 3 for the transient source H1743−322 illustrates the importance of the NRL data in reducing the positional ambiguity in the MC position. We obtained the box labeled NRL using the data from the NRL experiment. Clearly, only two of the six possible MC positions shown in the figure can contain the source.

Several of the identifications discussed here may ultimately be of the first rank in importance. Cir X-1 in many respects is similar to Cyg X-1, since it exhibits erratic, very short, time variability and exhibits a two-state instability. Thus the system may contain a black hole as is believed to be the case for Cyg X-1, and the optical data are the only means for determining its mass. The sources 4U 1636−53 and 4U 1735−44 may be the steady counterparts of X-ray bursters. So far, an understanding of the bursters eludes us. A key point is whether these objects are in a binary system. For example, it is generally agreed that demonstrating a binary companion to the burster would allow us to distinguish between the massive black hole model suggested by Grindlay and Gursky (1976) and the neutron star model discussed by Lamb *et al.* (1977) and others. Since the X-ray data have provided no evidence that the burster has a companion, we must turn to the optical data for the answer to this key question.

The experiment described here, representing as it does extensive hardware flown on a complex space vehicle along with the requisite software for data processing, was successful only because of the skill and perseverance of hundreds of individuals. The MC was the joint responsibility of X-ray astronomers at MIT and SAO, although it had its beginnings in 1970 when the SAO participants were at American Science and Engineering (AS&E). We acknowledge our gratitude to Frank McDonald, the NASA project scientist and one of the individuals responsible for the inception of the HEAO program; Richard Halpern, the Program Manager at NASA headquarters; Fred Speer, under whose direction the project was managed at Marshall Space Flight Center; Richard Whilden, who directed the preparation of the spacecraft at TRW; and Philip Gray, who directed the preparation of the MC experiment at AS&E. We are also especially grateful to Mark Levine of AS&E, and to Gregorz Madejski and Roger Hauck of SAO for activities related to preparing the experiment hardware and the data processing software. We thank Dr. Herbert Friedman for permission to use NRL data in support of our analysis. Also, it was a great pleasure to have had the assistance of Kathleen Smith in preparing the manuscript. This work has been supported in part by NASA contracts NAS 8-30453 and NAS 8-27972.

REFERENCES

Apparao, K. M. V., Bradt, H., Dower, R. G., Doxsey, R., Jernigan, J. G., and Li, F. 1978, *Nature*, **271**, 225.
Bradt, H., Apparao, K. M. V., Dower, R., Doxsey, R., Jernigan, J. G., and Markert, T. H. 1977, *Nature*, **269**, 496.
Bradt, H., Garmire, G., Oda, M., Spada, G., Sreekantan, B. V., Gorenstein, P., and Gursky, H. 1968, *Space Sci. Rev.*, **8**, 471.
Dailey, C., and Parnell, T. 1977, NASA TMX-73396.
Davidsen, A., Malina, R., and Bowyer, S. 1976, *Ap. J.*, **203**, 448.
Doxsey, R., Apparao, K. M. V., Bradt, H., Dower, R. G., and Jernigan, J. G. 1977*a*, *Nature*, **270**, 586.
Doxsey, R., *et al.* 1977*b*, *IAU Circ.*, No. 3113.
Doxsey, R., Bradt, H., Gursky, H., Johnston, M., Schwartz, D., and Schwarz, J. 1978, *Ap. J.* (*Letters*), **221**, L53.
Fabbiano, G., Gursky, H., Schwartz, D., Schwarz, J., Bradt, H., and Doxsey, R. 1978, *Ap. J.* (*Letters*), **221**, L49.
Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., and Giacconi, R. 1978, in preparation.
Griffiths, R. E., *et al.* 1978, *Ap. J.* (*Letters*), **221**, L63.
Grindlay, J., and Gursky, H. 1976, *Ap. J.* (*Letters*), **205**, L131.
Gursky, H., Giacconi, R., Gorenstein, P., Waters, J. R., Oda, M., Bradt, H., Garmire, G., and Sreekantan, B. V. 1966*a*, *Ap. J.*, **144**, 1249.
———. 1966*b*, *Ap. J.*, **146**, 310.

Jernigan, J. G., Apparao, K. M. V., Bradt, H., Doxsey, R., and McClintock, J. E. 1977, *Nature*, **270**, 321.
Kaluzienski, L., and Holt, S. S. 1977*a*, *IAU Circ.*, No. 3099.
———. 1977*b* *IAU Circ.*, No. 3106.
Lamb, F. K., Fabian, A. C., Pringle, J. E., and Lamb, D. Q. 1977, *Ap. J.*, **217**, 197.
Mayo, S. K., Whelan, J. A. J., and Wickramasinghe, D. T. 1976, *IAU Circ.*, No. 2957.
McClintock, J. E., Canizares, C., Bradt, H. V., Doxsey, R., Jernigan, J. G., and Hiltner, W. A. H. 1977, *Nature*, **270**, 320.
Oda, M., *et al.* 1967, *Ap. J.* (*Letters*), **148**, L5.
Rappaport, S., Zaumen, W., Doxsey, R., and Mayer, W. 1971, *Ap. J.* (*Letters*), **169**, L93.
Roy, A., Ballas, J., Jagoda, N., McKinnon, P., Ramsey, A., and Wester, E., 1977, *IEEE Trans.*, **NS24**, No. 1, 804.
Schwartz, D., Schwarz, J., Gursky, H., Bradt, H., and Doxsey, R. 1978, *Proc. AIAA 16th Aerospace Conf.*, Paper 78–34.
Willmore, A. P., Mason, K. O., Sanford, P. W., Hawkins, F. J., Murdin, P., Penston, M. V., and Penston, M. J. 1974, *M.N.R.A.S.*, **169**, 7.
Wilson, A. M., and Carpenter, G. F. 1976, *IAU Circ.*, No. 2965.
Wilson, A. M., Carpenter, G. F., Eyles, C. J., Skinner, G. K., and Willmore, A. P. 1977, *Ap. J.* (*Letters*), **215**, L111.

Note added in proof.—As this paper was going to press, we discovered an error in the Fig. 2 display of the *Ariel* error circle Cir X-1. The circle's center should be moved 30″ to the north.

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