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AN X-RAY SURVEY OF DISTANT RICH CLUSTERS OF GALAXIES WITH *HEAO 1*

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ABSTRACT

We present a 1–10 keV survey of distance class 4, 5, and 6 Abell clusters using the *HEAO 1* NRL large area survey experiment. The survey is a little less than 1/30 of the Abell catalog. Eleven clusters are identified with X-ray sources, and X-ray upper limits are provided for 60 others.

Subject headings: galaxies: clusters of — X-rays: sources

I. INTRODUCTION

Several surveys of X-ray emitting clusters of galaxies have been reported (McHardy 1978; Smith, Mushotzky, and Serlemitsos 1978; Mitchell, Ives, and Culhane 1977; Jones and Forman 1978, and references therein). The surveys concentrated on distance class $\lesssim 4$ Abell clusters. Here we report the first results based on the *HEAO 1* NRL large area X-ray detector survey (see Ulmer *et al.* 1979). These results cover $\lesssim 1/30$ of the Abell catalog, and they extend previous work out to distance class 6 clusters.

II. OBSERVATIONS AND RESULTS

The *HEAO 1* satellite has produced a deep X-ray survey of the entire sky. This was done $\sim 2\frac{1}{2}$ times in an 18 month period starting in 1978 August. The scan lines were always $\sim 90°$ from the satellite–Sun vector; hence, regions near the north and south ecliptic poles received greater coverage. This is demonstrated in Figure 1, which shows the sky coverage of our survey. The field of view of the detectors was $1° \times 4°$ (rectangular, full width at half-maximum). The satellite motion was such that a 360° great circle was scanned every $\frac{1}{2}$ hour in a direction perpendicular to the 4° field of view. The data base we used was the superposition of these 360° scans made over 1 and 4 day intervals. We first searched the 4 day "sums" for evidence of X-ray sources within $\sim 0\overset{\circ}{.}5$ of all the Abell clusters (Abell 1958) scanned by the satellite. This was about 70 clusters total for the work reported here. We fitted three X-ray sources plus a background level to 5° intervals of these "sums." The intervals were centered on the Abell cluster positions. The positions of two sources were left free, whereas the other position was taken to be that of the cluster (Sastry and Rood 1971). We also visually examined plots of these data. A potential candidate list was then made, and individual 1 day sums were fitted. The intensities and the derived positions were recorded, and these data were used to derive an average position in both the 1° direction and the 4° direction of the collimator field of view. In Table 1, we list the X-ray sources we found and the cluster identification. The initial criteria used were that the cluster be within $0\overset{\circ}{.}2$–$0\overset{\circ}{.}3$ of the 90% confidence error box and that the error box have an area of less than one square degree (see Bahcall and Bahcall 1975). We relaxed the error box size criterion slightly to include A508; however, the average size of the error boxes in Table 1 is still less than one square degree. All the sources except A2177 satisfy the criterion that they lie within one Abell radius ($R_A \approx 1.7Z^{-1}$ arc min) of the error box (cf. Bahcall and Bahcall). A2177 is $\sim 2R_A$ from the error box. *A priori* we expected that $\sim 70\%$ of the proposed identifications should be valid at the 90% confidence level.

We used the 4 day "sums" to provide sensitive, explicit upper limits to the other Abell clusters covered by this survey. These limits are given in Table 2, and they are 2–5 times lower than what could be inferred implicitly from the production of a general X-ray catalog. This is because the general catalog is based on a search for positive detections at a nominal 5 σ level. The energy range of the survey is $\sim$1–10 keV.

The normalization we used is based on the measurements of the Crab Nebula and the Perseus Cluster. The conversion we derived is 10^{-3} counts cm^{-2} s^{-1} = 3.2×10^{-12} ergs cm^{-2} s^{-1}. The uncertainty in this conversion for the data here is $\pm 50\%$; it is due to

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TABLE 1

ABELL CLUSTER X-RAY SOURCES

Name Optical Center 1950	X-Ray Center (α, δ, 1950)	Error Box (90% confidence)					Error Box Area (sq. deg.)	D	R	B-M[a]	z[a]	F_x[b]	$\log_{10}(L_\lambda)$[c]
A480 $04^h12^m.5$, 00°53′	$04^h14^m.4$ 00°59′	$04^h12^m.9$ 0°42′	$04^h12^m.6$ 01°06′	$04^h16^m.0$ 01°15′	$04^h16^m.3$ 00°52′		0.35	6	0	...	0.180	3.4 ± 0.4	45.17
A508[d] $04^h43^m.3$, 01°56′	$04^h39^m.6$ 02°04′	$04^h37^m.0$ 01°08′	$04^h36^m.0$ 02°47′	$04^h42^m.1$ 03°01′	$04^h43^m.1$ 01°21′		2.59	6	2	III	0.156	1.7 ± 0.3	44.73
A521[e] $04^h51^m.8$, −10°20′	$04^h52^m.0$ −10°07′	$04^h49^m.5$ −10°32′	$04^h49^m.1$ −09°53′	$04^h54^m.5$ −09°42′	$04^h54^m.8$ −10°21′		0.87	6	1	III	0.200	2.3 ± 0.4	45.08
A2159[f] $16^h09^m.3$, 17°07′	$16^h03^m.4$ 17°48′	$15^h58^m.8$ 17°50′	$15^h59^m.3$ 18°18′	$16^h08^m.0$ 17°46′	$16^h07^m.5$ 17°19′		0.98	4	0	...	0.090	3.9 ± 1.5	44.61
A2163 $16^h12^m.9$, −06°01′	$16^h12^m.5$ −06°01′	$16^h11^m.1$ −06°11′	$16^h11^m.5$ −05°44′	$16^h13^m.8$ −05°50′	$16^h13^m.4$ −06°18′		0.28	6	2	...	0.180	4.5 ± 0.4	45.29
A2177[d,g] $16^h18^m.9$, 25°52′	$16^h22^m.2$ 25°59′	$16^h20^m.1$ 25°42′	$16^h20^m.9$ 26°27′	$16^h24^m.3$ 26°16′	$16^h23^m.5$ 25°31′		0.59	6	0	...	0.180	2.1 ± 0.2	44.95
A2178[d] $16^h19^m.4$, 24°46′	$16^h21^m.1$ 24°45′	$16^h19^m.4$ 24°47′	$16^h19^m.5$ 24°55′	$16^h22^m.9$ 24°44′	$16^h22^m.8$ 24°36′		0.11	5	1	II	0.157	1.5 ± 0.2	44.68
A2204[d,h] $16^h30^m.3$, 05°41′	$16^h29^m.2$ 05°41′	$16^h27^m.6$ 05°34′	$16^h27^m.9$ 05°56′	$16^h30^m.8$ 05°48′	$16^h30^m.6$ 05°27′		0.27	5	3	II[i]	0.152[i]	6.1 ± 0.6	45.26
A2235 $16^h53^m.3$, 40°07′	$16^h52^m.3$ 39°51′	$16^h51^m.2$ 39°37′	$16^h51^m.9$ 40°10′	$16^h53^m.4$ 40°06′	$16^h52^m.6$ 39°33′		0.16	5	1	III	0.175	7.9 ± 0.3	45.51
A2244 $17^h00^m.9$, 34°07′	$17^h02^m.8$ 34°08′	$17^h01^m.3$ 33°58′	$17^h01^m.6$ 34°24′	$17^h04^m.3$ 34°18′	$17^h03^m.9$ 33°52′		0.24	5	2	I–II?	0.104	5.4 ± 0.4	44.88
A2252[j] $17^h12^m.6$, 49°27′	$17^h13^m.5$ 48°49′	$17^h10^m.9$ 48°28′	$17^h12^m.3$ 49°19′	$17^h16^m.0$ 49°09′	$17^h14^m.8$ 48°19′		0.55	6	1	II–III	0.188	2.1 ± 0.02	44.99

[a] z is estimated; taken from Leir and van den Bergh (1977) along with the Bautz-Morgan class (B-M), when available, except A2204. Otherwise, we used the average redshift for the distance class (Abell 1958).

[b] $F_x \equiv$ counts $cm^{-2}\,s^{-1} \times 10^3$, 1–10 keV.

[c] $L_x \equiv$ ergs s^{-1}, 1–10 keV, see text.

[d] Member of possible binary cluster, i.e. another Abell cluster is less than ~1° away—see Ulmer *et al.* 1979.

[e] Member of super cluster candidate, see Murray *et al.* 1978; see also Pravdo *et al.* 1977 and Ricketts 1978.

[f] Source existence $\approx 4\,\sigma$, the uncertainty in the intensity is due to the uncertainty in the aspect corrections.

[g] The source is strong, but we assign a detection significance of only $2\,\sigma$ due to potential source confusion effects which dominate in this case.

[h] *Ariel 5* source, Cooke *et al.* 1978.

[i] Corwin 1974.

[j] Error box also contains Arp peculiar galaxy Arp 102 (Arp 1966).

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TABLE 2

X-RAY UPPER LIMITS FOR SURVEYED CLUSTERS

Name	D	R	$B-M$	Z	F_x	Log (L_x)
A427	6	1	...	0.180	2.00	44.93
A429	6	2	...	0.180	1.00	44.63
A439	5	0	...	0.140	2.00	44.71
A455	6	1	III	0.234	1.00	44.85
A465	6	1	II–III	0.185	1.00	44.65
A466	6	1	...	0.180	1.00	44.63
A476	6	1	II–III	0.197	1.00	44.70
A481	6	0	...	0.180	2.00	44.93
A482	6	1	II–III	0.138	1.00	44.39
A487	5	1	II–III	0.126	2.00	44.62
A489	6	0	III	0.203	1.00	44.73
A495	5	0	...	0.140	2.00	44.71
A497	5	0	...	0.140	1.50	44.59
A498	5	1	...	0.140	2.00	44.71
A499	6	0	...	0.180	4.00	45.23
A501	6	1	...	0.180	0.50	44.33
A503	6	1	III	0.205	1.50	44.91
A504	6	1	...	0.180	1.00	44.63
A506	6	2	III	0.148	1.00	44.46
A507	6	1	II–III	0.220	1.00	44.80
A510	6	1	I	0.151	2.00	44.77
A511	5	0	...	0.140	1.00	44.41
A512	5	1	III	0.118	2.00	44.56
A513	6	0	II–III	0.186	2.00	44.95
A515	5	1	III	0.154	1.00	44.49
A516	6	1	II?	0.165	0.50	44.25
A517	6	2	III	0.179	0.50	44.32
A522	5	1	III	0.153	0.50	44.18
A524	5	1	III	0.130	2.00	44.64
A528	6	0	...	0.180	1.00	44.63
A2123	6	0	...	0.180	1.00	44.63
A2153	5	0	...	0.140	1.00	44.41
A2170	4	0	III?	0.098	1.00	44.10
A2186	5	0	...	0.140	1.00	44.41
A2200	5	0	...	0.140	1.00	44.41
A2205	5	0	III	0.122	1.00	44.29
A2214	6	0	...	0.180	1.00	44.63
A2217	5	1	III	0.152	1.00	44.48
A2221	6	1	III	0.236	1.00	44.86
A2223	5	0	III	0.109	2.00	44.49
A2233	6	0	III	0.167	0.50	44.26
A2238	6	1	II–III	0.152	1.00	44.48
A2241	3	0	...	0.068	1.00	43.78
A2249	3	0	...	0.068	5.00	44.48
A2253	5	0	III	0.135	0.50	44.07
A2268	6	1	II–III	0.234	1.00	44.85
A2269	6	0	...	0.180	1.00	44.63
A2270	6	0	...	0.180	0.50	44.33
A2275	5	0	II–III	0.126	0.50	44.01
A2280	6	1	II–III	0.259	1.00	44.94
A2281	6	0	...	0.180	0.50	44.33
A2299	6	1	...	0.180	2.00	44.93
A2305	5	1	III?	0.149	0.50	44.16
A2306	5	0	III?	0.152	0.50	44.18
A2308	4	0	II–III	0.096	1.00	44.08
A2310	5	1	II	0.148	1.00	44.46
A2311	4	1	III	0.090	2.00	44.36
A2318	5	1	III	0.156	1.00	44.50
A2323	6	0	...	0.180	0.50	44.33
A2373	6	1	III?	0.198	1.00	44.71

typical range of X-ray cluster spectra (cf. Smith *et al.*) and the broad energy band of the survey. For comparison with *Uhuru* observations, we also derived the conversion of 0.1 *Uhuru* counts at $\sim 5 \times 10^{-4}$ counts $cm^{-2}\ s^{-1}$. This also has an associated uncertainty of $\pm 50\%$.

III. DISCUSSION

a) Source Identification

Because of the large number of distance class 5 and 6 Abell clusters and the large number of weak background X-ray sources, we examined the probability that the proposed identifications are valid. Two major uncertainties are inherent in this estimate: (1) The source counts from the X-ray surveys are not known to better than a factor of 2 (cf. Fabian and Rees 1978), and (2) the Abell cluster centers are not necessarily the X-ray center of the emission (Ulmer *et al.* 1979; Cooke *et al.* 1977) which required including clusters just outside the error boxes. Within these uncertainties, however, we came to the following conclusions: (1) From the source counts, we estimated that only one of candidate clusters in Table 1 would be confused with a 0.1 *Uhuru* count background source within a 0°.5 radius. (2) Similarly, we estimated that one false source could exist in Table 1 due to finding two 0.1 *Uhuru* count sources within a 0°.5 radius of all the 71 cluster positions. (3) We empirically tested for accidental identification by creating false "catalogs" generated by moving the centers of the X-ray error boxes by various amounts. The false "catalogs" were searched for Abell cluster identifications, and either one or zero "X-ray clusters" were found with each false "catalog." From these tests, we found the probability that one of the entries in Table 1 is due to such an accidental identification of an X-ray source with a cluster is 30%. The net result of our calculations is that probably one or two of the 11 proposed identifications are invalid, but a 90% probability that seven to eight out of the 11 are valid.

b) Sizes—Extension

With the exception of A480 and A2235, all the clusters had X-ray emission consistent with that detected from a point source by our instrument. We estimate that the 95% confidence upper limit to the X-ray radii of the other clusters given in Table 1 is 30′. On the basis of the statistics of background sources, we would expect one or two out of the 11 to exhibit apparent extension due to source confusion. Therefore, the existence of extended emission (on the order of 30′) from A480 and A2235 must be treated with caution.

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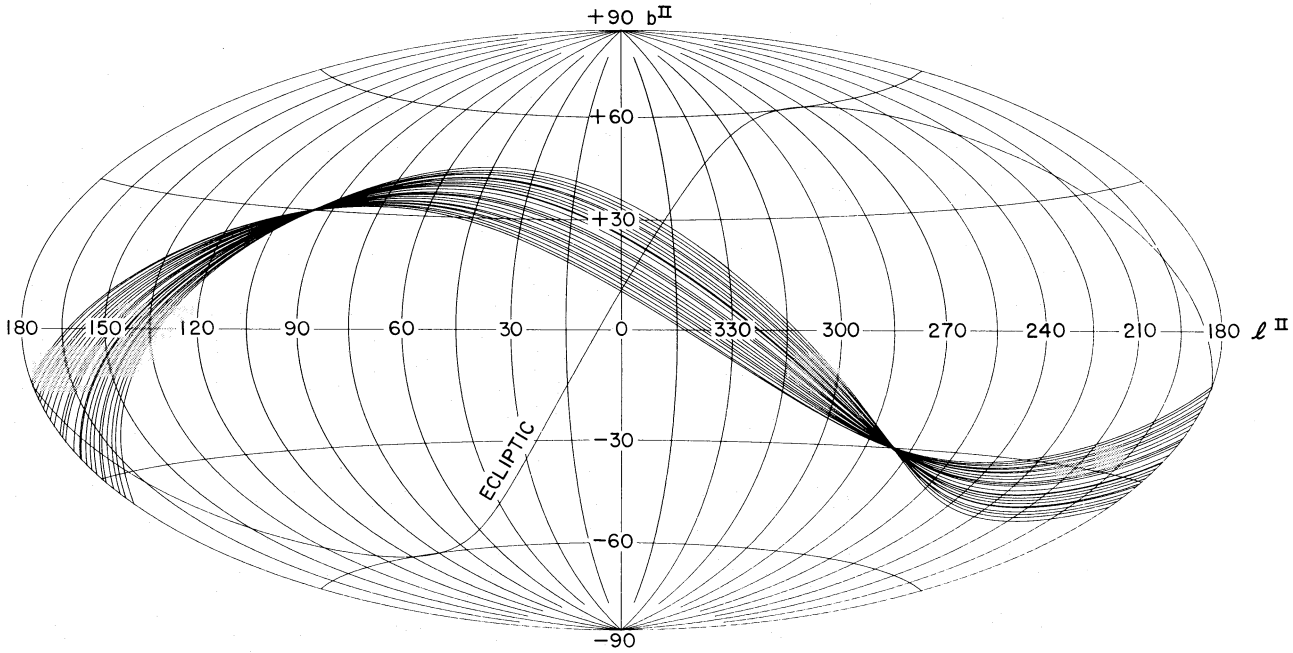

FIG. 1.—Sky coverage, in galactic coordinates of the *HEAO* A 1 experiment from 1977 August 19 to September 10

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