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A SURVEY OF RICH CLUSTERS OF GALAXIES WITH *HEAO 1*. II.

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ABSTRACT

We present the results of surveying about 1900 Abell clusters with the NRL large-area X-ray detectors on *HEAO 1*. From this survey we derived the following results:

1. There are exponential and power law fits to the luminosity functions.
2. The resulting contribution of rich clusters to the local X-ray volume emissivity is ~3–10% of that required to produce the diffuse X-ray background.
3. We tentatively suggest a correlation between the optical radius of the cluster (R_0) and the X-ray luminosity, L_x, i.e., $L_x \propto R_0{}^{\delta}$, where $\delta \approx 2$.
4. We found no strong correlation between L_x and the Bautz-Morgan class, the richness class, or the 26 MHz radio power; but the B-M type I and Abell richness class 3 do seem more likely to be strong X-ray sources.
5. A2218, a cluster with a "microwave dip", is such a weak X-ray source that simple models for the system produce a value of the Hubble constant, $H_0 < 10$ km s^{-1} Mpc^{-1}, which is not plausible. We conclude that the simple models are not valid.

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

I. INTRODUCTION

The *HEAO 1* satellite provided a unique opportunity to survey the entire X-ray sky down to a factor of 2–10 better than previous work. We report here the second in a series of papers devoted to the X-ray survey of Abell clusters of galaxies (Abell 1958). In the first paper (Ulmer *et al.* 1980*a*, hereafter Paper I), we demonstrated the sensitivity of the experiment and gave results of scanning $\sim \frac{1}{30}$ of the Abell catalog. Here we have greatly increased our sample from 70 to 1900 Abell clusters. With these results, we are able to search for correlations reported in previous work (Jones and Forman 1978; McHardy 1978), as well as examine the question of luminosity evolution between distance class 4 and distance class 6.

This work complements the *HEAO 2* surveys (Henry *et al.* 1979; Jones *et al.* 1979) which looked at a small number of clusters selected mainly for their optical and radio properties.

II. OBSERVATIONS AND ANALYSIS

The satellite scan motion has been described in Paper I and by Ulmer *et al.* (1980*b*). The new portion of the sky that we covered can be best described in ecliptic coordinates, i.e., ecliptic longitude ranges 80°–180° and 260°–360°. We analyzed the data in a manner similar to that described in Paper I, and we have produced a list of about 1400 X-ray upper limits which will be published elsewhere (Kowalski *et al.* 1980).

We subdivided our remaining sample of ~ 500 clusters as follows: (1) sources so weak that source confusion (more than one source in the field of view) would prevent us from determining an accurate position; (2) sources in the ecliptic range −25° to +25°; (3) mid-ecliptic latitude sources 25°–65°; and (4) ≥ 65° ecliptic latitude. This division proved useful because it was not worthwhile to try to determine error boxes for confused sources—the error boxes were generally too large; also, the satellite coverage required different positional determination techniques in the different ecliptic latitude ranges. At this time, we have determined error boxes only for the ±25° ecliptic latitude data; however, combined with Paper I, we now have a survey with a comparable number of Abell clusters as McHardy (1978) or Jones and Forman (1978). The "confusion limit" we used for this survey was $\sim 1.2 \times 10^{-3}$ counts cm^{-2} s^{-1} in the initial 4 day averages and $\sim 1.5 \times 10^{-3}$ counts cm^{-2} s^{-1} for 1 day averages (1–10 keV). The net result of using this cutoff is a survey that is complete down to $\sim 2 \times 10^{-3}$ counts cm^{-2} s^{-1}.

III. LUMINOSITY CALIBRATION

Previously (Paper I), we used 10^{-3} counts cm^{-2} s^{-1} = (3.2×10^{-12} ergs cm^{-2} s^{-1}). Erroneously, we implied that the 3.2×10^{-12} factor applied to the same energy range as the counts (1–10 keV). In fact, the 3.2×10^{-12} value is for the 2–6 keV range. Also, we have reconsidered the conversion and suggest a slightly differ-

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ent one: 10^{-3} counts cm^{-2} s^{-1} ($\sim$ 1–10 keV) = 3.4×10^{-12} ergs cm^{-2} s^{-1} (2–6 keV), which is accurate for a thermal bremsstrahlung spectrum of 6.5 keV. Deviations of about 1.5 from the true flux should be expected due to spectral uncertainties.

In Table 1, we compare our derived luminosities with others (*Uhuru*, *Ariel 5*, and *HEAO A-2*), assuming a 6.5 keV spectrum to obtain luminosities in the same 2–10 keV band (Jones and Forman 1978; McHardy 1978; McKee *et al.* 1980). The values for the three sources A85, A754, and A2319, observed by all four satellites, compare fairly well. We attribute the differences among the values in Table 2 to spectral differences and to source confusion. For simplicity and because few data are available regarding the spectra of faint clusters, we have not allowed for spectral differences in deriving luminosities. As noted above, we expect luminosity to be in error on this account by a factor less than 1.5. Source confusion, whose effect depends on the area of the collimator field, should be less of a problem for *HEAO 1 when viewing sources detected by earlier satellites*, which probably explains the larger anomalies in Table 1. Using these considerations as a guide, we feel that the luminosities of the clusters listed in Table 2 are in error by a factor which in most cases is less than 1.5. The conclusions we reach here are not sensitive to errors of this magnitude.

IV. DISCUSSION

a) *Luminosity Function*

We have used the V/V_m test described by Schmidt (1968) to test for completeness of our sample of X-ray emitting clusters (Table 2), and found that it was complete ($V/V_m \approx 0.5$) in the range of luminosities 10^{43}–10^{45} ergs s^{-1}. A luminosity function of the clusters has been derived, using the following expression (Huchra and Sargent 1973) in calculating the density of galaxies, in specified luminosity intervals:

$$\rho = \frac{3H_0{}^3}{c^3\Omega} \sum_i \left(\frac{F_e}{F_i}\right)^{3/2} \frac{1}{Z^3} \qquad \mathrm{Mpc}^{-3} ,$$

where Hubble's constant $H_0 = 75$ km s^{-1} Mpc^{-1}, c is the speed of light, Z is the redshift, Ω is the solid angle of the surveyed field, F_e is the minimum detectable flux of the survey (2×10^{-3} counts cm^{-2} s^{-1}; see § II), and F_i is the measured flux from cluster i. Two data sets have been considered in the analysis. The first uses those clusters in Paper I and in Table 2, which are in Abell's complete sample and which are of richness class 1 or higher. In the second set we added to this list all richness class 0 clusters in Paper I and Table 2, again restricting ourselves to the field of Abell's complete sample. The list of clusters that we used, including those from Paper I, is given in the final Note to Table 2. The resulting luminosity functions are shown in Figure 1.

Above a luminosity of 10^{45} ergs s^{-1} the effects of incompleteness must become evident, because the limiting sensitivity allows the A-1 instrument to reach beyond the maximum redshift ($Z_{\rm max} \approx 0.25$) of Abell's survey. Therefore we have calculated a corrected value of ρ in the luminosity interval 10^{45}–$10^{45.5}$ ergs s^{-1}, by assuming $F_e = 5.7 \times 10^{-3}$ counts cm^{-2} s^{-1}, which corresponds with the lowest F_i in this interval. As shown in Figure 1, this correction indicates that the apparent decline in the luminosity function above 10^{45} ergs s^{-1} is probably due to selection effects. There are other methods of correction. For example, the density in the interval 10^{45}–$10^{45.5}$ ergs s^{-1} might be calculated by dividing the number of clusters found, N, by the volume of space bounded by $Z_{\rm max}$:

$$\rho = \frac{3H_0{}^3}{c^3 Z_{\rm max}{}^3 \Omega} N .$$

This second method of correction produces a value $\sim 30\%$ lower than the first. The 30% difference is small compared to that created by uncertainties in $Z_{\rm max}$ and by the statistical certainty of the data, and none of our results are sensitive to these errors in the $10^{45.5}$–10^{45} ergs s^{-1} data point. In Paper I, the probability that the distance class 5 and 6 clusters have been properly identified with X-ray sources was shown to be about 70%. At this writing we are aware of only two distant clusters found by *HEAO 1*, A2163 (Paper I) and A1413 (this work), which have been observed by *HEAO 2*. Both clusters were detected at the expected level (Ulmer, private communication, for

TABLE 1

LUMINOSITY COMPARISON
(log $(L_x)^a$ 2–10 keV)

Name	*Ariel 5*	A-5/A-1	*Uhuru*	*U/A-1*	*Heao* A-2	A-2/A-1	*Heao* A-1
A85	44.58	1.17	44.59	1.20	44.49	0.95	44.51
A754	44.67	1.26	44.76	1.55	44.64	1.17	44.57
A1367	43.38	0.72	43.73	1.62	...	...	43.52
Virgo	43.00	1.02	43.12	1.35	...	...	42.99
A2204	44.78	0.50	...	...	...	...	45.08
A2244	44.82	1.26	...	...	...	...	44.72
A2319[b]	44.89	1.26	44.79	1.00	44.84	1.12	44.79
A2440	44.86	2.88	44.89	3.09	...	...	44.40
A2589	43.95	1.58	44.19	2.75	...	...	43.75

[a] Assumes spectrum, $I = \exp(-E/6.5\ \mathrm{keV})E^{-0.4}$ keV keV^{-1} s^{-1}.
[b] Not from present survey, included as a calibrator, assumed $Z = 0.0549$.

1981ApJ...243..681U

TABLE 2

HEAO A 1 X-Ray Clusters

Name	Optical[a] Center (1950) α/δ	X-Ray Center (1950) α/δ	Error Box				Area (sq. deg.)	D^b	R^c	B–M[d]	Z	Z Ref.	F_x[e]		Log L_x[f]	X-ray Ref. Notes
A14	3.18 −24.17	3.16 −24.12	2.68 −24.67	3.93 −24.12	2.39 −24.12	3.64 −23.57	0.77	3	0	...	0.064	1	2.81 ±	.48	43.84	
A85	9.78 −9.63	9.77 −9.66	9.72 −9.75	9.87 −9.69	9.67 −9.63	9.82 −9.57	0.02	4	1	I	0.0556	1	12.3	.30	44.37	8, 9
A586	112.27 31.74	112.11 31.75	111.76 31.46	112.34 31.38	111.88 32.12	112.46 32.05	0.34	6	3	I	0.172	2	4.10	.30	44.87	
A754	136.61 −9.45	136.54 −9.35	136.19 −9.61	136.67 −9.77	136.42 −8.94	136.89 −9.10	0.38	3	2	I–II	0.054	3	14.9	.10	44.42	8, 9
A970	153.77 −10.46	153.71 −10.15	153.20 −10.25	153.99 −10.57	153.42 −9.72	154.21 −10.04	0.52	5	1	III	0.115	4	4.10	.50	44.52	
A992	154.95 20.76	154.87 20.48	154.49 20.18	154.93 20.02	154.81 20.93	155.25 20.77	0.36	6	1	III	0.247	4	5.70	.40	45.32	
A1030	156.95 31.27	157.51 31.36	156.71 31.25	157.97 30.79	157.05 31.92	158.31 31.46	0.92	6	1	...	0.180	5	3.00	.50	44.77	g, h
A1045	158.04 30.96	157.51 31.36	156.71 31.25	157.97 30.79	157.05 31.92	158.31 31.46	0.92	5	1	II–III	0.170	4	3.00	.50	44.72	g, h
A1164	165.97 2.34	166.54 2.09	165.77 1.96	166.98 1.45	166.09 2.73	167.30 2.22	1.09	6	1	II–III	0.179	4	2.30	.40	44.65	
A1181	166.75 −19.51	166.46 −19.07	165.67 −19.22	166.86 −19.74	166.06 −18.41	167.26 −18.93	1.11	6	1	...	0.180	3	2.60	.50	44.72	
A1367	175.48 20.12	175.48 20.11	175.20 20.00	175.59 19.84	175.38 20.38	175.77 20.22	0.17	1	2	II–III	0.0205	1	9.60	.60	43.37	8, 9, 10
A1413	178.20 23.66	179.02 23.45	178.28 23.51	179.55 22.96	178.50 23.94	179.77 23.39	0.62	5	3	I	0.143	2	2.70	.50	44.53	10
A1459	180.42 2.79	180.13 3.01	179.37 2.92	180.58 2.39	179.68 3.62	180.88 3.10	1.01	5	1	III	0.147	4	3.70	.80	44.69	
Virgo	186.75 12.50	186.78 12.48	186.39 12.30	186.91 12.07	186.65 12.89	187.18 12.66	0.34	0	0	III	0.0036	6	86.5	.75	42.84	8, 9, 11
A1601	190.25 9.26	189.81 9.77	188.82 9.95	190.61 9.17	189.00 10.36	190.80 9.58	0.89	5	1	II	0.169	4	3.70	.10	44.81	
A2330	313.73 −22.24	314.11 −22.16	313.52 −22.56	314.84 −22.21	313.38 −22.10	314.70 −21.75	0.61	6	2	II–III	0.197	4	4.10	.70	44.99	
A2338	319.52 −26.34	319.16 −26.03	319.07 −26.91	319.81 −26.70	318.52 −25.36	319.26 −25.15	1.13	5	1	III	0.160	4	2.80	.30	44.64	
A2344	320.70 −21.01	321.45 −21.37	321.15 −21.79	321.96 −21.55	320.93 −21.19	321.74 −20.94	0.51	6	1	II	0.180	4	2.80	.40	44.74	
A2349	322.22 3.73	322.16 3.93	321.67 3.49	322.82 3.89	321.50 3.97	322.65 4.37	0.66	5	1	III	0.123	4	2.10	.40	44.29	
A2355	323.21 1.17	323.36 1.59	322.81 .91	324.21 1.40	322.50 1.79	323.90 2.28	1.40	6	2	III	0.251	4	2.30	.50	44.94	i
A2356	323.29 −0.11	323.07 −.84	322.73 −1.43	323.70 −1.09	322.44 −.58	323.41 −.25	0.95	5	2	II–III	0.125	4	2.40	.30	44.36	j

TABLE 2—*Continued*

Name	Optical[a] Center (1950) α/δ	X-Ray Center (1950) α/δ	Error Box				Area (sq. deg.)	D^b	R^c	B–M[d]	Z	Z Ref.	F_x[e]		Log L_x[f]	X-ray Ref. Notes
A2384	327.37	327.29	326.76	327.84	326.73	327.81	0.10	4	1	II–III	0.094	4	3.40	.50	44.26	
	−19.79	−20.04	−20.26	−19.90	−20.17	−19.81										
A2415	330.69	330.61	330.16	331.24	329.99	331.07	0.55	4	0	III	0.069	4	3.40	.50	43.99	
	−5.84	−5.73	−6.16	−5.76	−5.71	−5.31										
A2440	335.32	335.74	335.33	336.48	335.00	336.15	1.11	4	0	II	0.088	4	3.80	.70	44.25	
	−1.86	−1.53	−2.17	−1.72	−1.33	−.88										
A2485	341.47	341.66	341.26	342.23	341.08	342.06	0.45	5	0	...	0.140	5	1.90	.50	44.35	
	−16.38	−16.35	−16.75	−16.36	−16.34	−15.95										
A2507	343.55	343.59	342.85	344.39	342.79	344.32	0.27	6	2	II–III	0.196	4	6.70	1.70	45.19	
	5.24	5.43	5.03	5.68	5.18	5.82										
A2550	347.22	347.41	346.86	348.11	346.72	347.97	0.41	5	2	II–III	0.166	4	3.30	.60	44.74	g
	−22.02	−22.11	−22.52	−22.01	−22.22	−21.71										
A2556	347.59	347.41	346.86	348.11	346.72	347.97	0.41	5	1	II–III	0.133	4	3.30	.60	44.55	g
	−21.90	−22.11	−22.52	−22.01	−22.22	−21.71										
A2572	348.98	349.74	349.40	350.34	349.14	350.09	0.61	3	0	III	0.039	7	3.20	.50	43.47	
	18.47	18.70	18.23	18.65	18.76	19.17										
A2589	350.36	350.67	349.96	351.69	349.66	351.38	1.35	3	0	...	0.042	1	3.70	.90	43.60	8, 9
	16.55	16.59	15.89	16.65	16.53	17.29										
A2593	350.49	350.47	349.74	351.50	349.44	351.20	1.37	3	0	II	0.046	4	2.30	.60	43.47	
	14.37	14.44	13.73	14.50	14.38	15.14										
A2597	350.69	350.06	349.53	350.91	349.21	350.58	1.18	5	0	III	0.075	4	3.60	.80	44.09	
	−12.40	−12.63	−13.29	−12.71	−12.56	−11.98										
A2657	355.58	355.64	355.33	356.12	355.16	355.95	0.36	3	0	II–III	0.041	7	5.10	.80	43.72	9, k
	8.88	8.92	8.56	8.90	8.94	9.28										

[a] All from Sastry and Rood 1971 except Virgo cluster (de Vaucouleurs 1961).
[b] Distance class (Abell 1958).
[c] Richness class (Abell 1958).
[d] Bautz-Morgan class (Leir and van den Bergh 1977; Corwin 1974).
[e] F_x = 2–6 keV flux in 10^{-3} counts cm^{-2} s^{-1}. Uncertainties are 1σ.
[f] L_x = X-ray luminosity in ergs s^{-1}; $H_0 = 75$ km s^{-1} Mpc^{-1}.
[g] A2550 and A2556 are contained in the same error box. The same remark applies to A1030 and A1045.
[h] Error box also contains QSO 1028+313 (Burbidge *et al.* 1977).
[i] Error box too large for formal identifications. It is included due to proximity with A2356, but it is not used in the calculations.
[j] The error box also contains the globular cluster NGC 7089, but NGC 7089 is not the X-ray source (Grindlay, private communication).
[k] Error box also contains the QSO 2344+092 (Burbidge *et al.* 1977).

NOTE.—The following clusters were used to calculate the X-ray luminosity functions (see IV*a*): 85, 480, 508, 521, 992, 1164, 1367, 1413, 1459, 1601, 2177, 2178, 2235, 2244, 2252, 2330, 2338, 2344, 2355, 2356, 2384, 2507, 2550, 2597.

REFERENCES.—(1) Thuan and Gunn 1980. (2) Kristian *et al.* 1978. (3) Gunn and Oke 1975. (4) Leir and van den Bergh 1979. (5) Abell 1958. (6) Sandage and Tammann 1976. (7) Corwin 1974. (8) Cooke *et al.* 1978; McHardy 1978. (9) Forman *et al.* 1978; Jones and Forman 1978 (10) Jones *et al.* 1979; Henry *et al.* 1979. (11) Ulmer *et al.* 1980*b*; Davison 1978; Lawrence 1978.

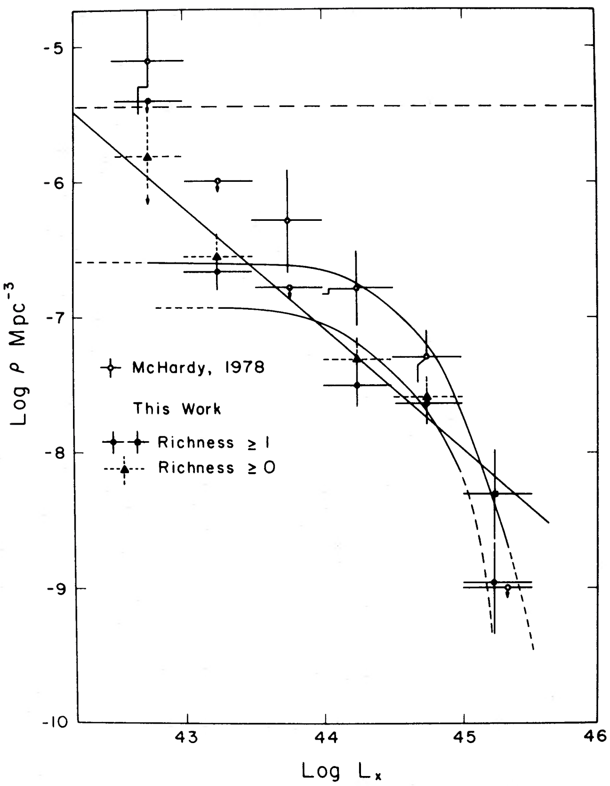

FIG. 1.—The volume density of X-ray emitting clusters plotted against X-ray luminosity. The clusters surveyed were drawn from Abell's (1958) complete sample, and we have plotted data points which show the effect of adding richness class 0 clusters to this sample. McHardy's (1978) data have been adjusted to the 2–6 keV energy band, assuming a 6.5 keV thermal bremsstrahlung spectrum and $H_0 = 75$ km s^{-1} Mpc^{-1}. The curved lines are exponential fits, and the straight line is a power-law fit to the data (see text). The point represented by a filled-in square, in the 10^{45}–$10^{45.5}$ ergs s^{-1} luminosity interval, is a correction of the data point below, made to allow for selection effects (see text). The dashed line measures the space density of clusters in Abell's complete sample.

A2163; see Henry *et al.* 1979 for A1413). Thus we feel confident that most of our identifications will prove to be correct. Misidentifications primarily effect the luminosity function above $\sim 3 \times 10^{44}$ ergs s^{-1}, as below this limit most of the clusters are distance class 4 or less and each has been identified in more than one satellite observation. Above the limit, the measured densities (Fig. 1) may be too low by no more than 30%. We can find no difference (Fig. 1) between our results for luminosities greater than 3×10^{44} ergs s^{-1}, which depend primarily on observations of distance class 5 and 6 clusters, and those of McHardy (1978), which relied on observations of clusters in distance class 4 or less. In Figure 1, we have corrected McHardy's results, assuming a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1} and the energy range 2–6 keV. The results show no evolutionary variation in the luminosity function between $Z \approx 0.07$ and $Z \approx 0.18$. This is in agreement with all the evolutionary models summarized by Henry *et al.* (1979), with the possible exception of the "all gas" model (Silk 1976).

We fitted both power law and exponential forms (cf. Schwartz 1978) to two data sets: (1) richness ≥ 1, 10^{45} ergs s^{-1} $> L_x \rangle 10^{43}$ ergs s^{-1}, set A; (2) all richness classes, plus the corrected data point above 10^{45} ergs s^{-1}, set B. We found for the exponential fits:

$$f_{AE}(L_{44}) = 3.7 \times 10^{-7} \exp(-L_{44}/1.3 \pm 1.4) \times (10^{44} \text{ ergs s}^{-1})^{-1} \text{ Mpc}^{-3} ,$$

$$f_{BE}(L_{44}) = 7.53 \times 10^{-7} \exp(-L_{44}/2.3 \pm 2.2) \times (10^{44} \text{ ergs s}^{-1})^{-1} \text{ Mpc}^{-3} ,$$

for data sets A and B, respectively. These are shown in Figure 1. Our best fits for a power law are:

$$f_{AP}(L_{44}) = 8.5 \times 10^{-8} L_{44}{}^{-1.7 \pm 0.3} \times (10^{44} \text{ ergs s}^{-1})^{-1} \text{ Mpc}^{-3} ,$$

$$f_{BP}(L_{44}) = 10^{-7} L_{44}{}^{-1.9 \pm 0.15} \times (10^{44} \text{ ergs s}^{-1})^{-1} \text{ Mpc}^{-3} .$$

The uncertainties are the estimated 90% confidence limits. We show only f_{BP} in Figure 1. The statistical uncertainties of the coefficients in these equations all are about ±20%.

In order to estimate the contribution of clusters to the diffuse X-ray background, we calculated

$$\int_0^\infty f_E L dL = V_E \quad (2\text{–}6 \text{ keV}) .$$

We found using f_{AE}, $V_E = 5.9 \times 10^{37}$ ergs s^{-1} Mpc^{-3}, and using f_{BE}, $V_E = 4.0 \times 10^{38}$ ergs s^{-1} Mpc^{-3}. Comparing the logarithmic average of these two values, $\langle V_E \rangle = 1.5 \times 10^{38}$ ergs s^{-1} Mpc^{-3}, with the local volume emissivity required to explain the diffuse X-ray background, $B_E = 2.0 \times 10^{39}$ ergs s^{-1} Mpc^{-3} (2–6 keV, $H_0 = 75$ km s^{-1} Mpc^{-1}, $q = 0.5$), we find that Abell clusters contribute about 7%. Calculating V_E by integrating Lf_{AP} and Lf_{BP} between $10^{42.5}$ and $10^{45.5}$ ergs s^{-1}, we found that in this case V_E contributes about 3% to B. Given the uncertainties in cross-calibration between experiments and in the absolute determination of B, we feel that our data are compatible with $0.03 \leq V_E/B_E \leq 0.10$. Marshall *et al.* (1980) argue that clusters do not contribute more than about 3% to the diffuse X-ray background. Even if we have overestimated the Abell cluster volume emissivity, the contribution from all clusters of galaxies is probably not quite as low as 3%. This is because some of the more numerous poor clusters are also X-ray emitters, with luminosities of order 10^{43} ergs s^{-1} (cf. Kriss *et al.* 1980; see also Bahcall 1979). A contribution as low as 3% might be compatible with our results if low-luminosity clusters all have low temperatures. However, it is beyond the scope of this work to make a detailed calculation of the impact of a temperature-luminosity relation on the 2–6 keV diffuse X-ray background.

An extrapolation of the power law fit to luminosities less than $10^{42.5}$ ergs s^{-1} implies a space density higher than that of Abell clusters. Therefore, as suggested by

McHardy (1978), we believe that the curve of the luminosity function flattens somewhere between 10^{43} and 10^{42} ergs s^{-1}. As the nominal X-ray luminosity per galaxy is about 10^{39} ergs s^{-1} (cf. Worrall, Marshall, and Boldt 1979) and the nominal number of galaxies in an Abell cluster is on the order of 10^3 (cf. Bahcall 1977*a*), we would expect there to be no Abell clusters with a luminosity less than about 10^{42} ergs s^{-1}. Hence the luminosity function for Abell clusters probably terminates near 10^{42} ergs s^{-1}.

b) *Correlation of Luminosity and Radius*

Leir and van den Bergh (1977, hereafter LV) determined the radius of each cluster by visual inspection of the Palomar Sky Survey. If the galaxy surface density determines both the optical cluster size R_0 and the X-ray surface brightness, then we might expect to see a correlation between the optical radius and the X-ray luminosity. The best fit to the data of a power law, $L_x \propto R_0{}^{\delta}$, shown in Figure 2, gives for the exponent, $\delta = 1.9 \pm 1.6$ (90% confidence level). We have taken $R_0 = R_L$ $1.3(Z + Z^2/2)/(1 + Z)^2$ Mpc, where R_L is the radius in millimeters measured by Leir, and we have assumed $q_0 = 0$, $H_0 = 75$ km s^{-1} Mpc^{-1}. The correlation coefficient between log L_x and log R_0 is 0.36. Formally this means that log L_x is correlated with log R_0 at the 95% confidence level. We remark that LV used R_0 as one of three distance indicators. Hence, some of the values of R_0 that we used were implicitly assumed, not measured. Also, although one might expect some systematic distance-dependent error in R_0, LV assure us that any such effects are small. With these caveats in mind, we

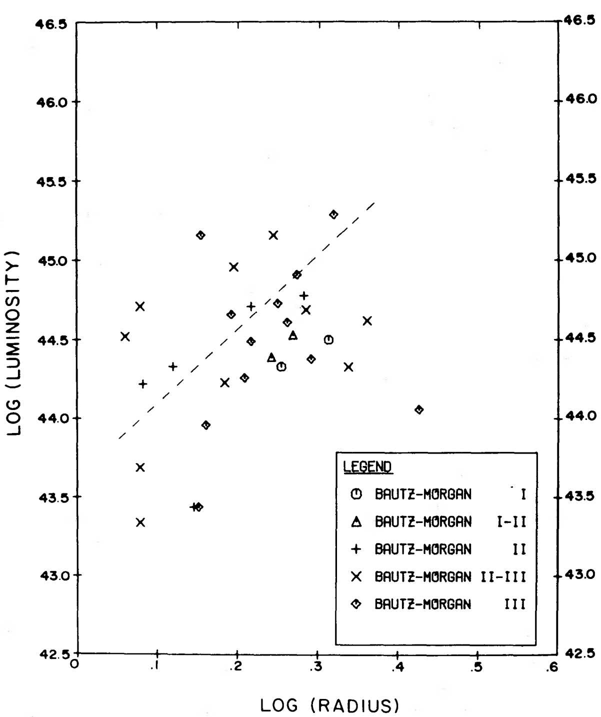

FIG. 2.—X-ray luminosity (2–6 keV) plotted against cluster radius (Leir and van den Bergh 1977). The dashed line is the best-fit power law.

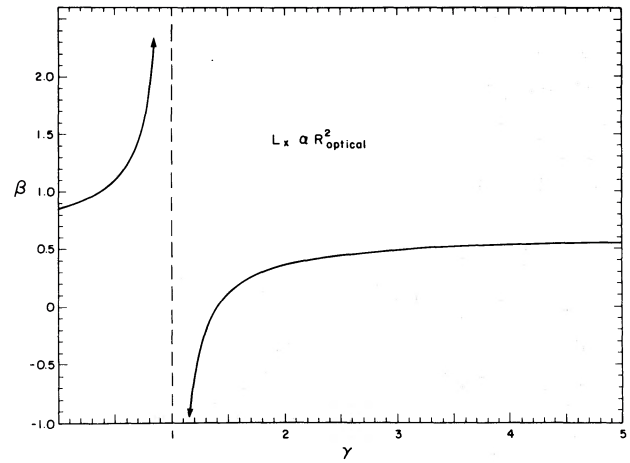

FIG. 3.—A plot of β against the exponent, γ, in a polytropic model of the gas ($P \propto n^{\gamma}$). β relates the X-ray and optical radii of clusters through the relation, $R_x \propto R_0{}^{\beta}$. The plot assumes that the X-ray luminosity, L_x, and the optical radius are related by the best fit in Fig. 2, $L_x \propto R_0{}^{\delta}$.

examine now the implications of a relation between L_x and R_0.

We applied two consistency checks: (1) as Bahcall (1977*b*) found that L_x and N_0 (the galaxy density) are related, we expect N_0 and R_0 to be related as well. R_0 and N_0 are correlated, although there is a large scatter in a plot of R_0 versus N_0. (2) Mitchell *et al.* (1979) and Mushotzky *et al.* (1978) reported $L_x \propto T^{11/2}$, and we sought to determine whether it is possible to find polytrope models which obey this relation and allow $L_x \propto R_0{}^{\delta}$ as well. It is assumed that $T \propto n^{\gamma - 1}$, although this is valid only if conditions in different clusters may be related to some common initial or reference state n_0, T_0 (see, for example, Bahcall and Sarazin 1977). Assuming that $L_x \propto n^2 T^{1/2} R_x{}^3$ and $R_x \propto R_0{}^{\beta}$, we obtain:

$$\beta = \frac{1}{3}\left[\delta - \left(2 + \frac{\gamma - 1}{2}\right)\left(\frac{2\delta}{11\gamma - 11}\right)\right].$$

We plot β as a function of γ in Figure 3. The relation $L_x \propto R_0{}^{\delta}$ appears to be consistent with previous results, although Figure 3 implies that R_x is correlated only weakly with R_0 ($\beta = 0.0$–0.3) for adiabatic conditions ($\gamma = \frac{5}{3}$), or that, if R_x is strongly dependent on R_0 ($\beta = 0.5$–1.5), the intracluster gas is cooling or convectively unstable.

c) *Correlation of Richness with Luminosity*

Figure 4*a* shows a plot of richness against luminosity. On the *average*, richness class 0 sources seem to be less luminous, but the scatter is so large that we hesitate to say there is a physical connection between the richness of the cluster and its luminosity (see also Pravdo *et al.* 1979). Further, the richness class 0 sample is not complete, and there is the possibility that the detection of richness class 0 clusters is distance dependent (cf. Abell 1958). Thus, correlations of richness with luminosity which depend upon using richness class 0 must be treated with caution.

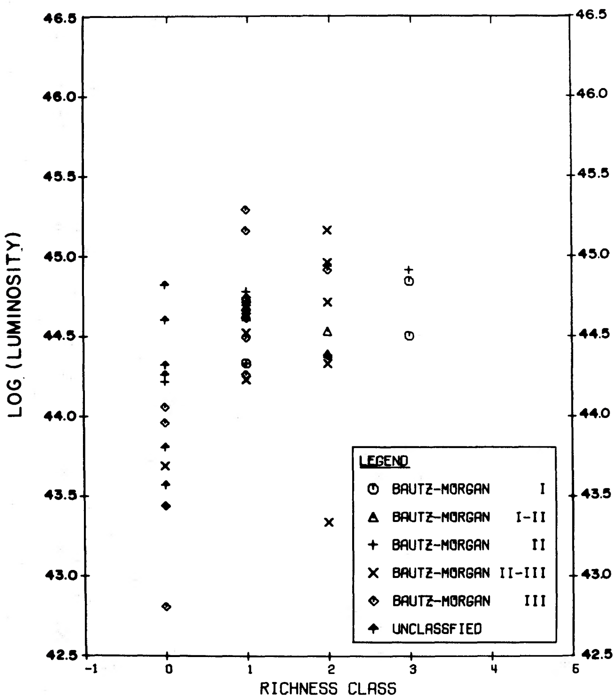

FIG. 4a

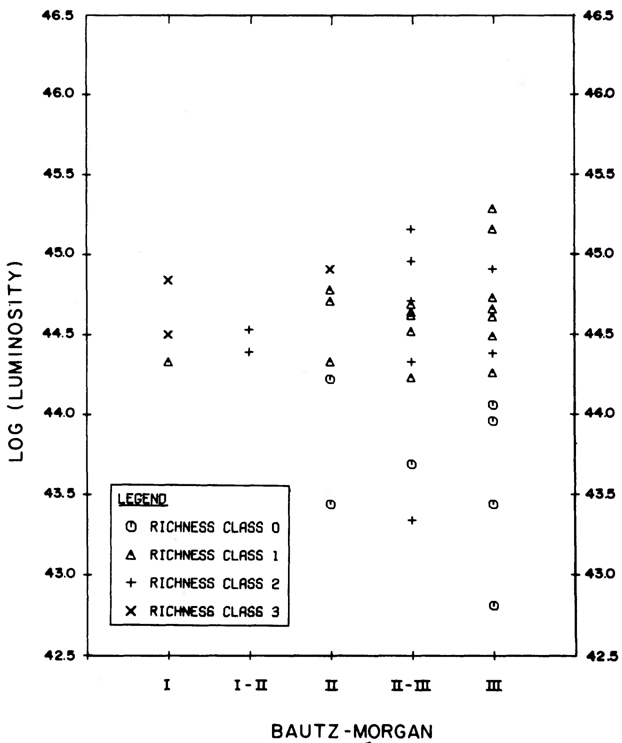

FIG. 4b

FIG. 4.—(*a*) X-ray luminosity (2–6 keV) plotted against cluster richness. (*b*) X-ray luminosity (2–6 keV) plotted against the Bautz-Morgan classification of the clusters.

Figure 5*a* shows the fraction of bright X-ray clusters ($L_x \geq 10^{44}$ ergs s^{-1}) in each richness class, and we see that there is a trend, in which richer sources are more likely to be bright X-ray sources. This is similar to the result of Jones and Forman (1978). As poorer clusters also can be bright X-ray sources, the physical connection between richness and L_x remains unclear.

Finally, we calculated the relative luminosity densities (i.e., ρ/ρ_0; cf. McHardy 1978) for richness classes 0, 1, and 2 in the range $10^{45} \geq L_x \geq 10^{44}$ ergs s^{-1}, and found 0.09 ± 0.05, 0.08 ± 0.02, and 0.12 ± 0.05, respectively. The space density of clusters, ρ_0, in each richness class was estimated by counting the number of different cluster types within the 2319 Abell clusters, which are in the portion of the sky of the complete sample. In this sample, richness class 1 objects are the most numerous, whereas clusters of distance class 3 or less are mostly of richness class 0. Hence, at least part of our apparent disagreement with McHardy (1978) may be attributed to the assumed space densities (we used $\rho_0 = 1.2 \times 10^{-6}$, 2.3×10^{-6}, and 7.2×10^{-7} Mpc^{-3} for $R = 0$, 1, 2 and $H_0 = 75$ km s^{-1} Mpc^{-1}). Furthermore, the statistical uncertainties are so large that the disagreement between us and McHardy is not statistically significant.

d) *Correlation of Bautz-Morgan Class and Luminosity*

McHardy (1978) and Jones and Forman (1978) have discussed why they thought Bautz-Morgan (B-M) type I clusters might be strong X-ray emitters. However, a plot

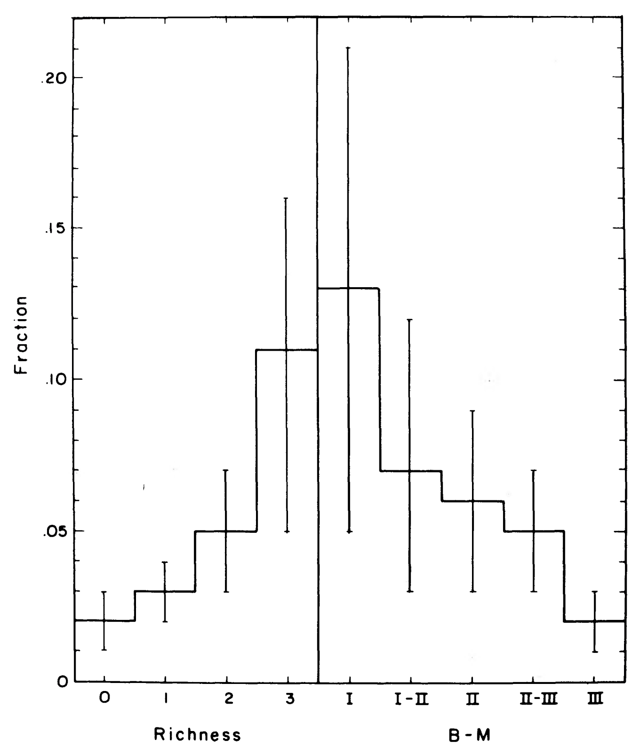

FIG. 5.—The fraction of clusters in the surveyed sample, with X-ray luminosities greater than 10^{44} ergs s^{-1}, plotted against: (*a*) richness class, (*b*) Bautz-Morgan class.

of B-M type against luminosity (Fig. 4*b*) shows no obvious trend. LV have shown that the frequency distribution of B-M type III is much higher in distance classes greater than 4 compared with those of 4 or less, and they suggest that many distant B-M I clusters have been misclassified as B-M III. Thus any correlations found between B-M type and L_x must be treated with caution. For completeness, we show a plot of the fraction of clusters that are X-ray bright ($L_x \geq 10^{44}$ ergs s^{-1}) as a function of B-M class (Fig. 5*b*). We have calculated the ratio ρ/ρ_0 in three Bautz-Morgan groups, for the luminosity interval 10^{44}–10^{45} ergs s^{-1}:

B-M I, I–II, and II: $\rho/\rho_0 = 0.11 \pm 0.04$;

B-M II–III: $\rho/\rho_0 = 0.17 \pm 0.07$;

B-M III: $\rho/\rho_0 = 0.03 \pm 0.02$.

There is a slight trend suggesting that lower B-M types are, on the average, more luminous than higher B-M types.

e) Correlation of 26 MHz *Power and X-Ray Luminosity*

Erickson, Matthews, and Viner (1978) suggested (see also Lea and Holman 1978) that L_x and $P_{26.5}$ (power at 26 MHz) might be correlated. Furthermore, they listed several radio-bright sources which were likely to be strong X-ray sources. We have used the data in Table 3, taken from Erickson, Matthews, and Viner (1978) and from our survey, to plot Figure 6. The correlation proposed by Erickson, Matthews, and Viner (1978) does not agree with the added data. The dominant source of the X-ray emission in most clusters is probably hot gas, and the correlation between L_x and $P_{26.3}$ would be tight if the radio emission and hot gas had the same origin and were always in the same proportion. The true situation appears to be more complicated, however.

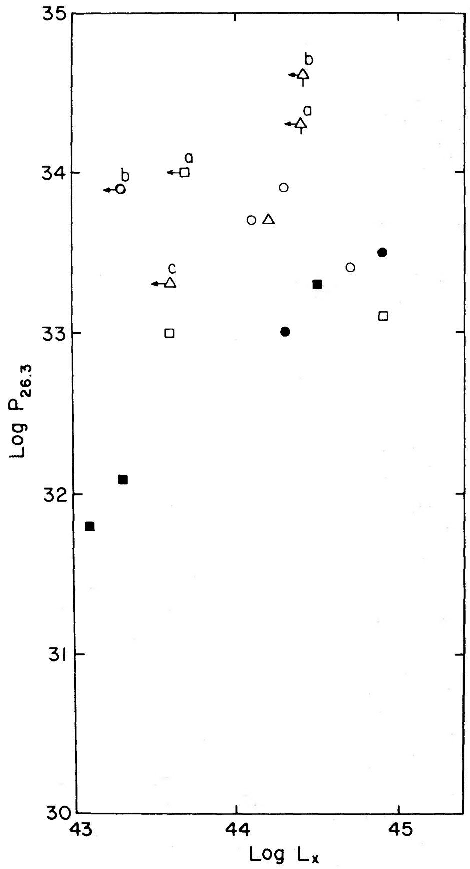

FIG. 6.—The radio power of clusters at 26 MHz plotted against X-ray luminosity (2–6 keV). The units of power are W m^{-2} s^{-1} Hz^{-1}; those of X-ray luminosity, ergs s^{-1}. The symbols denote the Bautz-Morgan classification of a cluster: *open circle*, BM I; *triangle*, BM I–11; *filled circle*, BM II; *open square*, BM III; *triangle with tail*, unclassified. The left-pointing arrows indicate that the X-ray luminosities are upper limits, and the letters have the same meaning as those in Table 3.

f) A2218 and the Microwave Dip

A2218 is interesting because it is a cluster that has been observed extensively in the microwave regime (for example, see Pravdo *et al.* 1979 and references therein). The hot gas in the cluster should produce a diminution in the microwave background, and an observation of this effect has been reported (cf. Birkinshaw, Gull, and Northover 1978). Pravdo *et al.* quote an X-ray upper limit of ~ 0.9 μJy and imply that $H_0 \approx 30$ km s^{-1} Mpc^{-1} $(F_x/0.9\ \mu\text{Jy}) \times (T/3 \times 10^8\ \text{K})^{3/2}$ where F_x is the observed X-ray flux. The source is below our nominal confusion limit detection level and we have not detected the source at a statistically significant level. The 2σ upper limit is ~ 0.2 μJy, and, taking the equation of Pravdo *et al.* (1979), we find $H_0 < 10$ km s^{-1} Mpc^{-1} $\times (T/3 \times 10^8\ \text{K})^{3/2}$. This value of H_0 is too small unless T is assumed to be unreasonably high, and therefore the correlation of microwave with X-ray measurements needs further refinement.

TABLE 3

RADIO/X-RAY POWER

Cluster	Log P26.3[a]	Log L_x[b]
A566	34.0	43.7[c]
A1682	34.6	44.4[d]
A2396	34.3	44.2[c]
A2622	33.3	43.6[e]
A2626	33.9	43.3[d]

[a] From Erickson *et al.* 1979, except $H_0 = 75$ km s^{-1} Mpc^{-1}.

[b] L_x in ergs s^{-1}, all upper limits.

[c] 2σ upper limit.

[d] Twice the measured value of a weak source within the 0°6 × 4° error box which also includes the cluster.

[e] Confused, upper limit based on twice the apparent strength of a source from that direction.

V. SUMMARY AND CONCLUSION

To summarize: (1) The luminosity function of Abell clusters probably turns over at low luminosities (10^{43} ergs s^{-1}), and the total contribution to the volume emissivity of the diffuse X-ray background is between 3 and 10%. (2) We find no strong correlation between the X-ray luminosity and Bautz-Morgan class, richness class, or low frequency (26 MHz) radio power; however, both B-M type I clusters and Abell richness class 3 clusters appear more likely to be bright X-ray sources. (3) Tentatively, we find a correlation between the optical radius as determined by Leir and van den Bergh and the X-ray luminosity—the higher the optical radius, the brighter the cluster in the X-rays. Future work with *HEAO 2* should elucidate this relationship.

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Note added in manuscript.—We have preliminary observations from the *Einstein* Observatory (*HEAO 2*) which indicate that about 70% of our proposed identifications are good, as predicted; however, A480 was not detectable at all as an X-ray source, and A508 was found to be very weak. This does not change any of the basic conclusions, except that A480 was the highest-luminosity richness-0 cluster in our survey.

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