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HEAO 2 X-RAY OBSERVATIONS OF CLUSTERS OF GALAXIES

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ABSTRACT

We provide a summary of results of our *Einstein* satellite observations of clusters of galaxies. We report X-ray luminosities or upper limits for 27 clusters. Newly reported clusters with interesting morphologies are presented, and a brief discussion of the data in relation to theories of cluster formation and evolution is given.

Subject headings: galaxies: clustering — galaxies: X-rays

I. INTRODUCTION

Prior to the launch of the *Einstein* satellite (*HEAO 2*), we made an X-ray survey of rich clusters of galaxies with the *HEAO 1* A-1 experiment (see Kowalski *et al.* 1984, and references therein). We selected objects from this list to observe with the *Einstein* satellite for the following reasons: (1) to search for direct evidence of superclustering, (2) to make morphological studies of X-ray sources discovered by the *HEAO 1* survey, (3) to determine if only rich clusters, or Bautz-Morgan type I clusters, or both are X-ray bright, and (4) to determine the reliability of the identifications of the *HEAO 1* survey identifications. Most of the results for (1) and (2) have been reported previously (Ulmer, Cruddace, and Kowalski 1985; Ulmer 1984; Kowalski, Ulmer, and Cruddace 1983; Ulmer and Cruddace 1982). Here we report cluster data that have not been published (17 clusters) and combine results of the entire sample of 27 clusters.

II. OBSERVATIONS AND RESULTS

The observations were all made with the *Einstein* satellite IPC (Gorenstein, Harnden, and Fabricant 1981). The net observing time per cluster was typically 1200 s. The data were reduced in the standard manner of background subtraction, smoothing, and energy range selection to optimize the signal-to-noise ratio (Ulmer and Cruddace 1982). In Table 1 we present the quantitative results, and in Figure 1 contour plots of selected clusters from Table 1 are shown. For simplicity, the images for all but A1560, A2356, and A2384 were fitted with a radially symmetric model: a Gaussian, or two Gaussians with a common center but different widths. At least one of the models produced an adequate fit with a reduced χ^2 of close to unity. The Gaussian was chosen for convenience. In some cases, although a good fit was produced, inspection of the data indicates 2–3 σ deviations from a symmetrical shape; see Table 1 and § III.

III. DISCUSSION

Several studies of clusters based on large samples have already been published (see Abramopoulos and Ku 1983; Kowalski *et al.* 1984; Jones and Forman 1984; Sarazin 1985), and our present sample does not constitute a statistically significant increase. Therefore, we confine ourselves to describing general trends in our data in relationship to the points mentioned in § I. We also comment on a few clusters that are reported here for the first time.

An examination of Table 1, Figure 1, and Jones and Forman (1984) reveals that about 10% of all the clusters are 'clumpy' (have more than one peak flux center), and that it seems that clumpy or centrally condensed clusters form over a wide range in z, e.g., A1560, A2384 (clumpy), and A2390 or A2204 (centrally condensed). Unfortunately, a more quantitative value than *about* 10% clumpy cannot be given, as no complete sample of morphological studies of clusters has yet been published. We estimate that the true fraction of clumpy X-ray clusters could be as low as 3% and as high as 15%. Those in our sample that we classify as clumpy are A1560, A2356, and A2384. The statistical reality of the clumps in these clusters is discussed in Ulmer and Cruddace (1982). The probability of a line-of-sight object making the clumps is less than 10^{-3} in all three cases.

Theoretical work by Carnevali, Cavaliere, and Santangelo (1981) and White (1976) have indicated that clusters can evolve from clumpy to smooth on the time scale of $\sim 10^9$ yr over the $z = 0.2$–0.1 range spanned by our data. This suggests that clumpy clusters should have smoothed out by $z = 0.1$. Although the cluster mass density may be the basic reason why some clusters are beginning to collapse now and therefore appear clumpy (see Sarazin 1985, and references therein), we note that there is no direct evidence that clumpy clusters which formed over 10^9 yr ago have actually smoothed out by now; our data are consistent with the hypothesis that clumpy clusters may have some other inherent property (besides galaxy or mass density), such as angular momentum or turbulence, that prevents them from evolving into centrally condensed clusters.

The data in Table 1 are also consistent with previously reported trends that richer clusters are more likely to be brighter in X-rays. No richness (R) class 0 clusters are seen to be strong X-ray sources in this limited sample, although some richer clusters that are not X-ray bright were found. Also, the only Bautz-Morgan (B-M) I cluster in our sample, A994, is an upper limit, whereas A2204 (B-M II) is bright and centrally condensed. Other counterexamples to a correlation between B-M type and X-ray brightness can be found in Table 1. The correlation or lack of correlation of B-M type with X-ray luminosity has been discussed extensively in Kowalski *et al.* (1984) and Abramopoulos and Ku (1984), and references

TABLE 1

CLUSTER OBSERVATIONS

NAME	OPTICAL POSITION (1950)		X-RAY POSITION (1950)		F_x (0.7–3.5 keV) (10^{-13} ergs cm^{-2} s^{-1})	L_x (0.7–3.5 keV) (10^{43} ergs s^{-1})	X-RAY RADIUS	R_o[a]	z[b]	B-M[a]	R[a]	REFERENCE	NOTE
	R.A.	Decl.	R.A.	Decl.									
A58	$00^{\rm h}31^{\rm m}.5$	−07°02′	...	...	<4.0	<2.0	N.A.	15	0.1600	III	1		
A230	01 37.0	−11 38	...	...	<2.0	<2.4	N.A.	8	0.2500	III	2		
A236	01 38.0	−12 07	$01^{\rm h}38^{\rm m}4^{\rm s}.6$	−12°07′08″	4.7 ± 1.6	3.0 ± 1.0	<3′.0	8	0.1840	II–III:	1		
A239	01 38.9	−12 02	...	...	<2.0	<1.3	N.A.	16	0.1820	III	2		
A320	02 10.3	+25 10	...	...	<3.0	<3.1	N.A.	15	0.2320	III	1		
A480	04 12.5	+00 53	...	...	<2.0	<0.1	N.A.	N.A.	0.0473	N.A.	0		
A508	04 43.3	+01 56	04 43 18.3	+01 56 13	1.9 ± 0.6	0.8 ± 0.3	< 3.0	12	0.1479	III	2	1	
A509	04 45.1	+02 13	04 44 54.2	+02 08 11	2.2 ± 0.6	0.3 ± 0.1	<3.0	15	0.0836	III:	1	1	
A521	04 51.8	−10 20	04 51 46.2	−10 17 41	21.0 ± 2.0	16.1 ± 1.5	<1.0	9	0.2000	III	1	2	c
A970	10 15.1	−10 27	10 14 55.2	−10 25 27	46.0 ± 3.0	11.6 ± 0.8	1.8 ± 0.2	13	0.1150	III	1	2	c, d
A994	10 20.1	+19 36	...	...	<2.0	<0.3	N.A.	16	0.0940	I:	1		
A1560	12 31.6	+15 27	12 31	+15 29 59	13.5 ± 1.3	17.5 ± 2.0	<3.0	N.A.	0.2700	N.A.	2	3	
A1701	13 11.6	+61 17	...	...	<2.0	<0.7	N.A.	N.A.	0.1350	N.A.	0	2	c
A1754	13 29.4	−11 25	...	..	<1.0	<0.4	N.A.	12	0.1390	II–III	1		
A2163	16 12.9	−06 01	16 13 4.8	+06 00 46	7.7 ± 0.4	4.2 ± 0.2	<3.0	N.A.	0.1698	N.A.	2	2	c
A2177	16 18.9	+25 52	16 18 56.8	+25 52 36	4.5 ± 0.6	0.5 ± 0.1	<2.0	N.A.	0.0769	N.A.	0	2	c, e
A2178	16 19.4	+24 46	16 19 24.0	+24 46 10	3.5 ± 1.2	0.6 ± 0.2	< 3.0	8	0.0928	II	1	1, 2	c
A2204	16 30.3	+05 41	16 30 21.8	+05 40 50	182.0 ± 8.6	80.8 ± 3.8	See comment	N.A.	0.1524	II	3	1, 2	c, f
A2210	16 32.3	+05 36	16 32 00.6	+05 36 53	9.7 ± 0.2	4.0 ± 0.1	<3.0	N.A.	0.1465	N.A.	1	1	
A2339	21 18.3	+21 40	21 18 13.6	−21 43 31	6.1 ± 1.7	1.5 ± 0.4	<3.0	12	0.1128	II–III	1	1	
A2349	21 28.9	+03 44	21 28 22.5	+03 49 00	9.4 ± 0.4	2.7 ± 0.1	< 2.0	12	0.1230	III	1	2	c, g
A2355	21 32.8	+01 10	21 32 43.5	+01 11 01	6.0 ± 1.8	1.8 ± 0.5	<2.0	8	0.1244	III	2	1	
A2356	21 33.2	−00 07	21 33 05.4	−00 04 59	21.7 ± 2.9	5.6 ± 0.8	<3.0	16	0.1161	II–III:	2	1, 2	c
A2372	21 42.5	−20 12	21 42 26.4	−20 13 40	1.1 ± 0.3	0.2 ± 0.1	< 3.0	N.A.	0.1000	N.A.	0		h
A2378	21 44.5	−20 14	21 44 53.5	−20 12 28	5.8 ± 0.1	1.1 ± 0.02	<2.0, see comment	N.A.	0.1000	N.A	0		i
A2384	21 49.5	−19 48	21 49 34.6	−19 48 06	88.0 ± 5.0	15.0 ± 0.9	See comment	16	0.0943	II–III	1	2, 3	c, j
A2390	21 51.2	+17 27	21 51 13.6	+17 27 19	64.2 ± 4.2	46.7 ± 3.1	Point source (0.7 ± 0.2) and 7.0 ± 5.0	N.A.	0.1950	N.A.	2	2	k

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[a] R_0, B-M from Leir and van den Bergh 1977; R from Abell 1958; see also Kowalski *et al.* 1984.

[b] From Kowalski *et al.* 1984.

[c] *HEAO 1* A-1 source.

[d] An IPC rib is ~3′.0 south. No correction for this was applied.

[e] Note the source may be partially under the IPC rib. No correction for this was applied. The small "blob" is at $16^{\rm h}19^{\rm m}4^{\rm s}.2$, 25°46′2″.5; $F_x = 1.8 \pm 0.3 \times 10^{-13}$ ergs cm^{-2} s^{-1}.

[f] Poor image due to distortion caused by position of source in field of view. Poor fit to the data, but an extended ~2′ source with a central condensation <0′.7 seems likely.

[g] Position is off from Abell 1958 by about 9′, but galaxy counts by eye on POSS plates do not favor the optical over the X-ray position.

[h] *HEAO 1* A-1 confused region. Alternate identification is OX 271.

[i] Average radius is small; see Fig. 1*j*, however. *HEAO 1* A-1 confused region.

[j] See Fig. 1*k*; position is given for peak flux.

[k] 60% of flux is associated with "point" source, which is probably associated with MC3 2151+174 ($21^{\rm h}51^{\rm m}14^{\rm s}.31$, 17°27′42″.9). The χ^2 for a single diffuse source was 46, 17 degrees of freedom vs. 19.8 (15 dof) for the model which included a point source at the center of the diffuse source.

REFERENCES.—(1) Ulmer *et al.* 1985. (2) Kowalski *et al.* 1984. (3) Ulmer and Cruddace 1982.

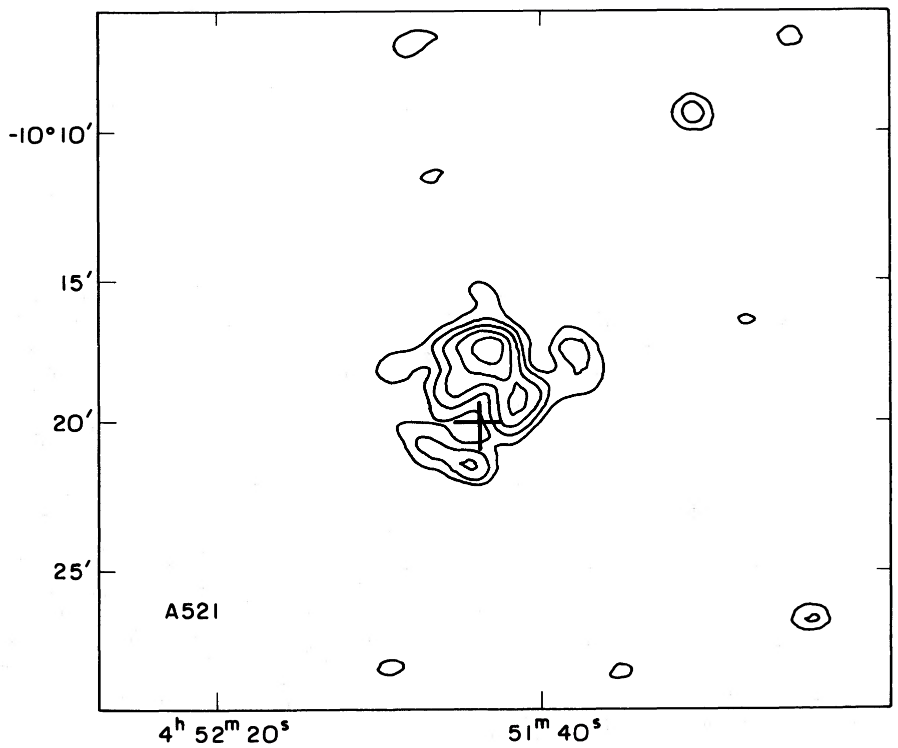

FIG. 1*a*

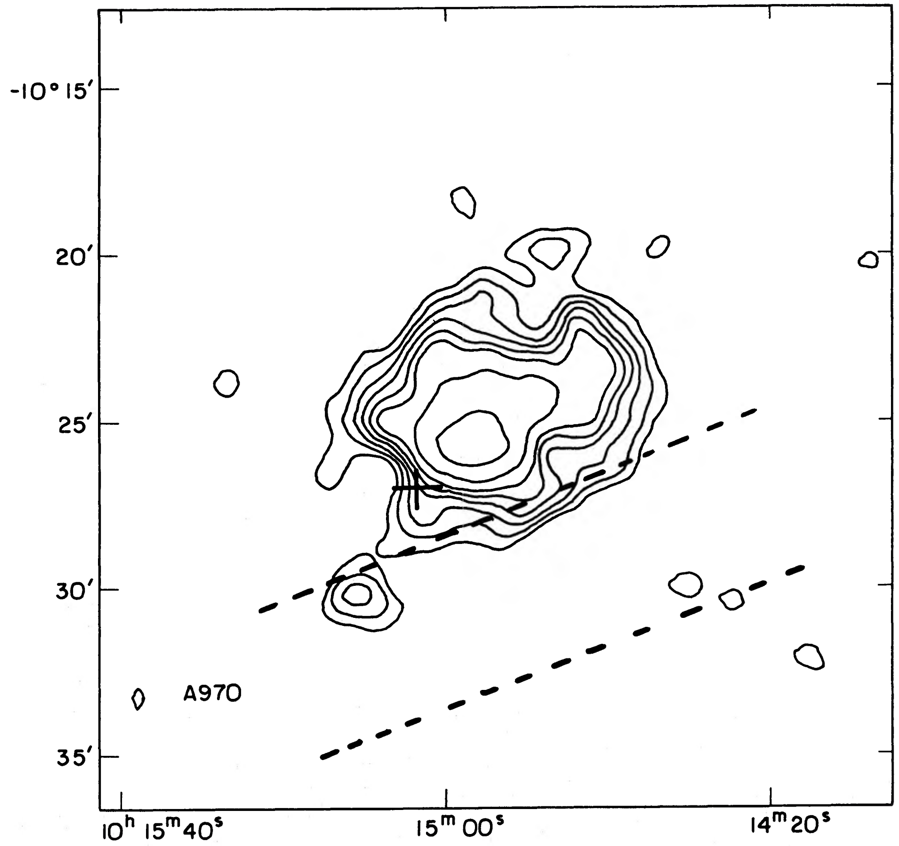

FIG. 1*b*

FIG. 1.—Contour levels of various Abell clusters of galaxies. The data were first background-subtracted, corrected for vignetting, and smoothed with a $\sigma = 30''$ Gaussian. The shaded circle in Fig. 1*c* is the full width at half-maximum effective resolution beam. The energy range for these data is ~0.75–3.5 keV. The cross on each figure denotes the optical center of the cluster from Abell (1958).

FIG. 1*a*.—The levels are 3, 4, 5, 6, 7, and 8 times the rms background fluctuation of 0.42 counts arcmin^{-2}

FIG. 1*b*.—The levels are 3, 4, 5, 6, 7, 8, 10, and 13 times the rms fluctuation of 1.2 counts arcmin^{-2}. Portion of IPC ribs (*parallel lines*) partially distorts image.

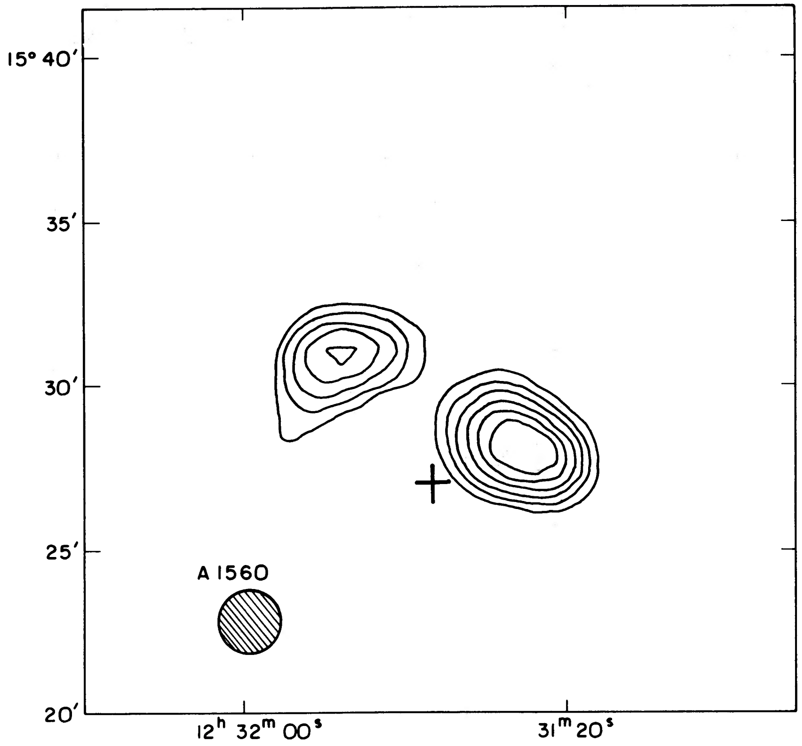

FIG. 1c

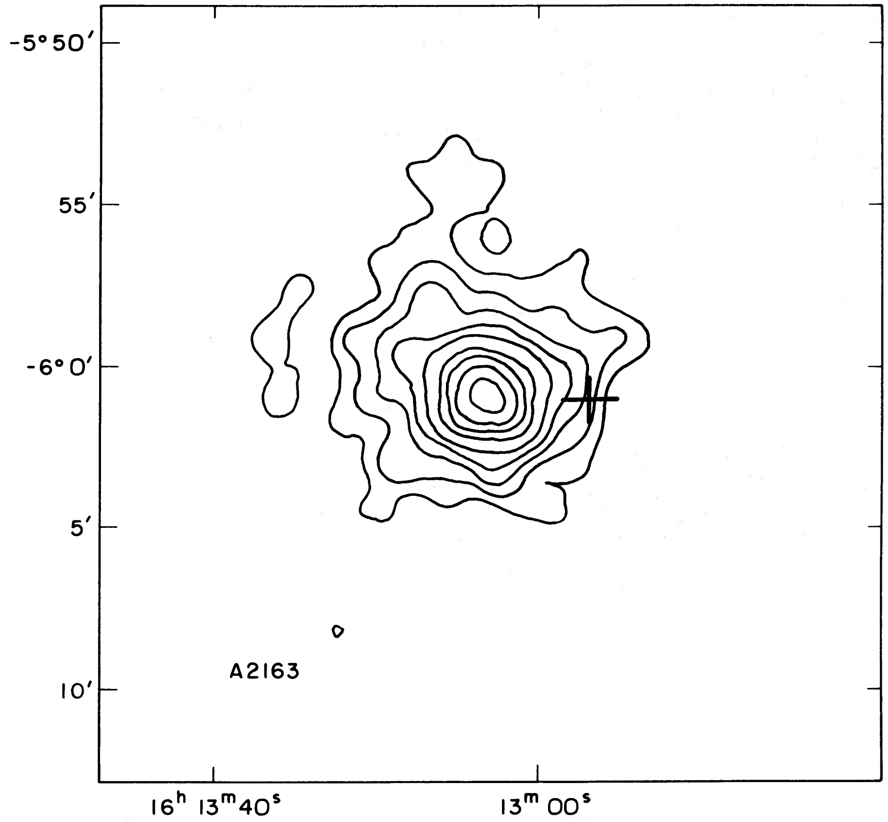

FIG. 1d

FIG. 1c.—The levels are 2.5, 3, 3.5, 4.5, and 5 times the average rms fluctuation of 0.50 counts arcmin^{-2}
FIG. 1d.—The levels are 3, 5, 7, 9, 11, 14, 16, 18, and 20 times the rms fluctuation of 0.91 counts arcmin^{-2}

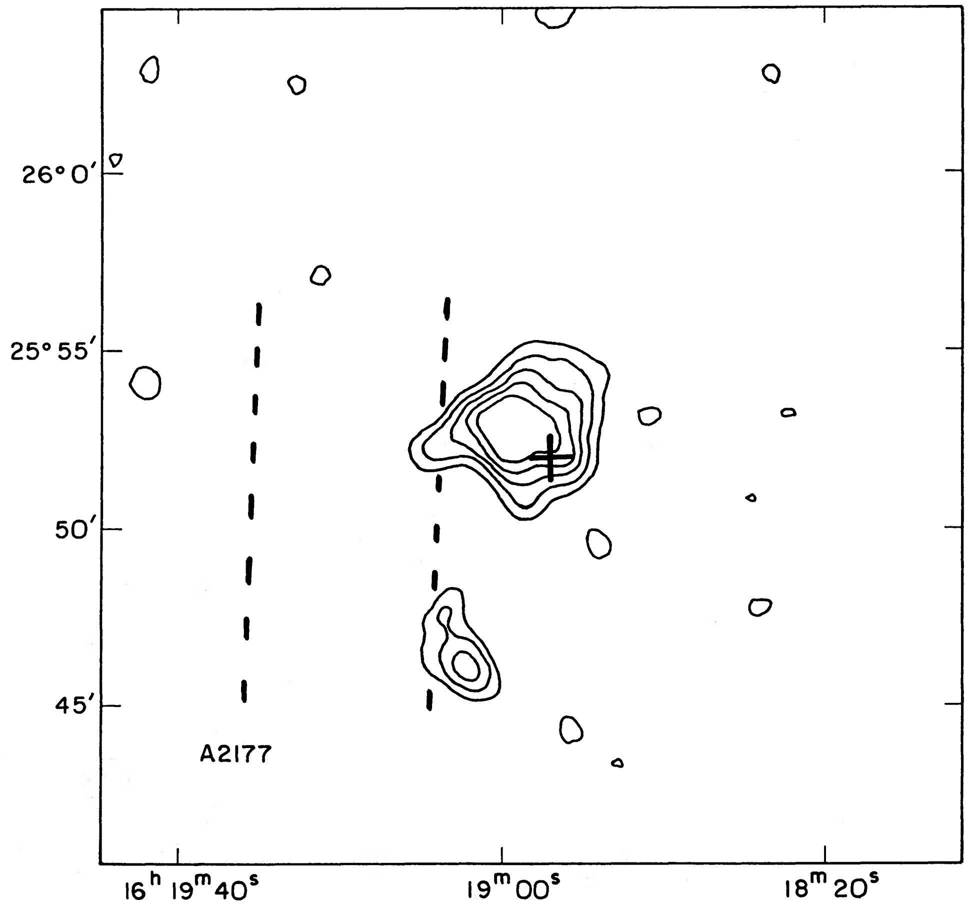

FIG. 1e

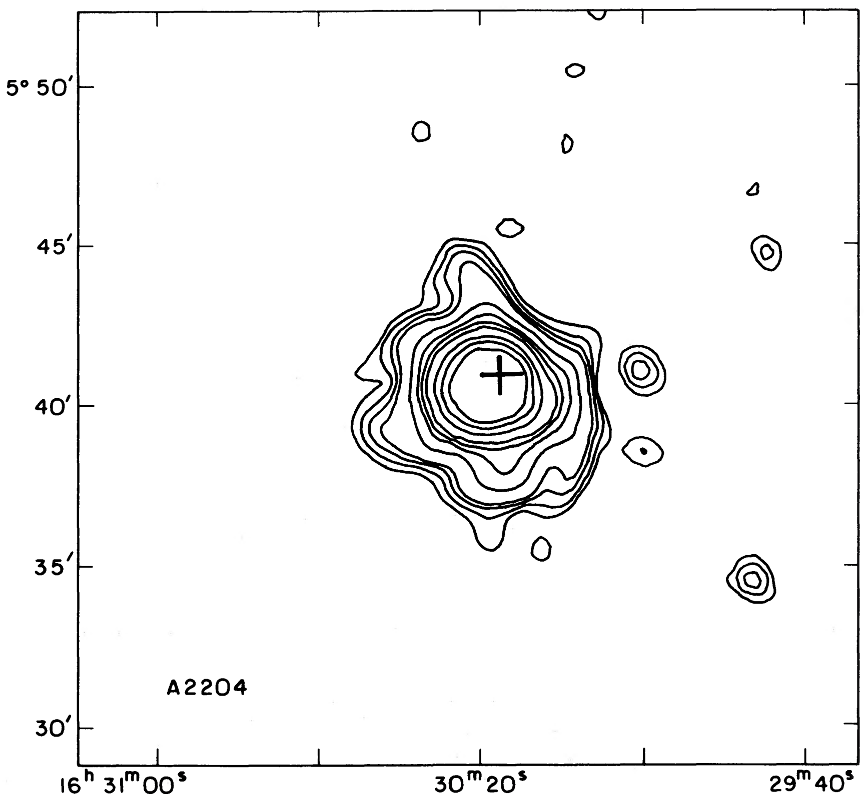

FIG. 1f

FIG. 1e.—The levels are 3, 4, 5, 6, and 7 times the rms fluctuation of 0.76 counts arcmin^{-2}. Note that the flux is probably diminished due to the IPC ribs (*parallel lines*).

FIG. 1f.—The levels are 3, 4, 5, 6, 9, 12, 14, 16, 20, 23, and 27 times the rms fluctuation of 2.0 counts arcmin^{-2}. Due to an error, this one figure was made over the entire pulse height analysis energy range of the IPC ($\sim$0.2–4.5 keV); however, the dominant X-ray flux is in the $\sim$0.75–3.5 keV range. Note that the image is distorted due to being on the very edge of the field of view.

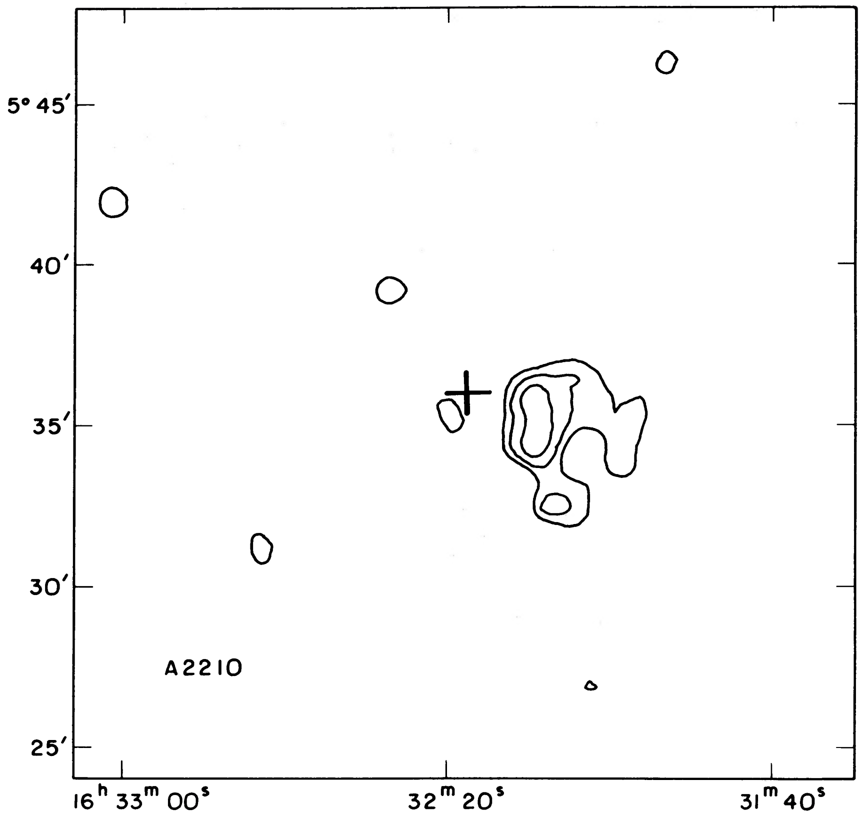

Fig. 1*g*

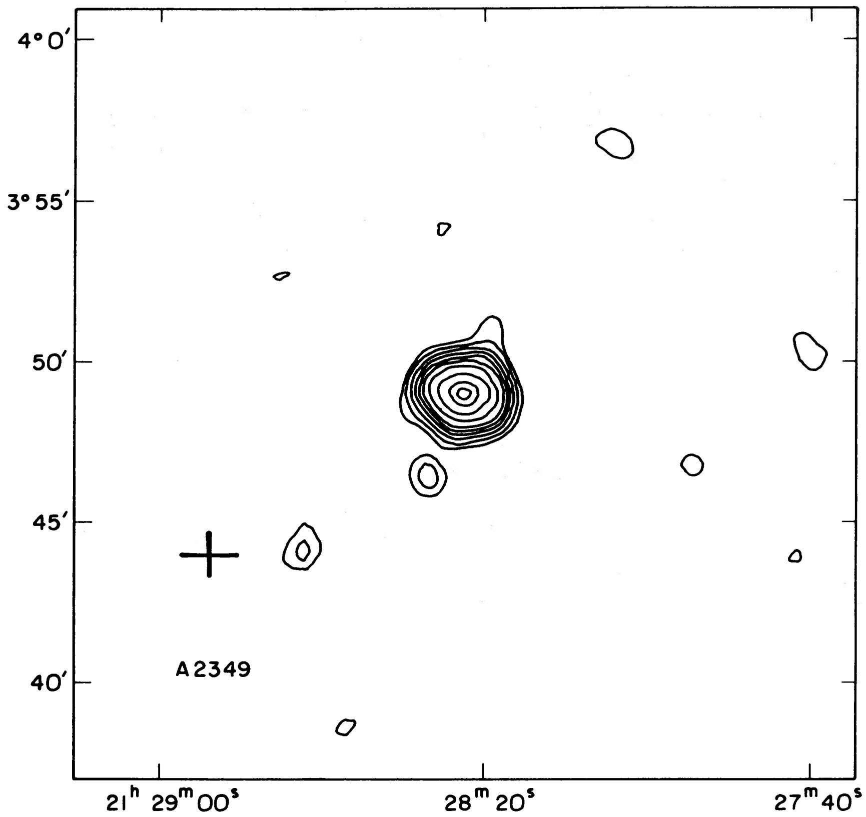

Fig. 1*h*

Fig. 1*g*.—The levels are 3, 4, 5, and 6 times the rms fluctuation of 0.73 counts arcmin^{-2}

Fig. 1*h*.—The levels are 3, 4, 5, 6, 7, 8, 10, 12, 14, and 15 times the rms fluctuation of 0.43 counts arcmin^{-2}. See the comment in Table 1 regarding the optical vs. X-ray position.

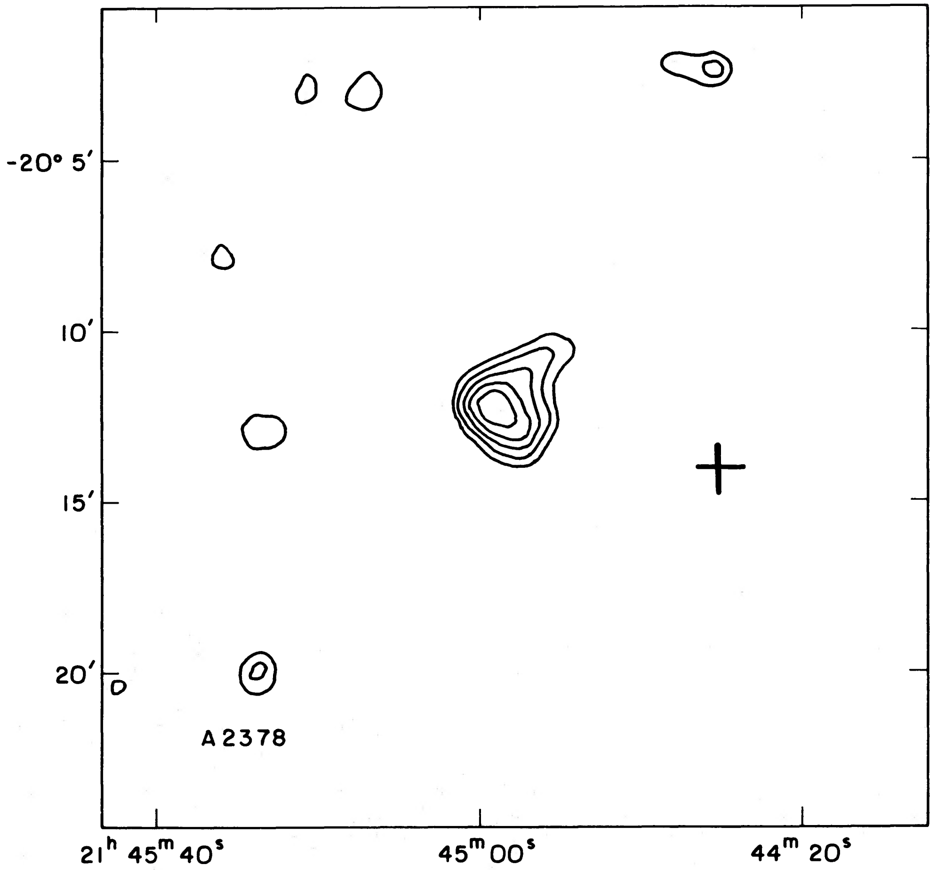

FIG. 1*i*

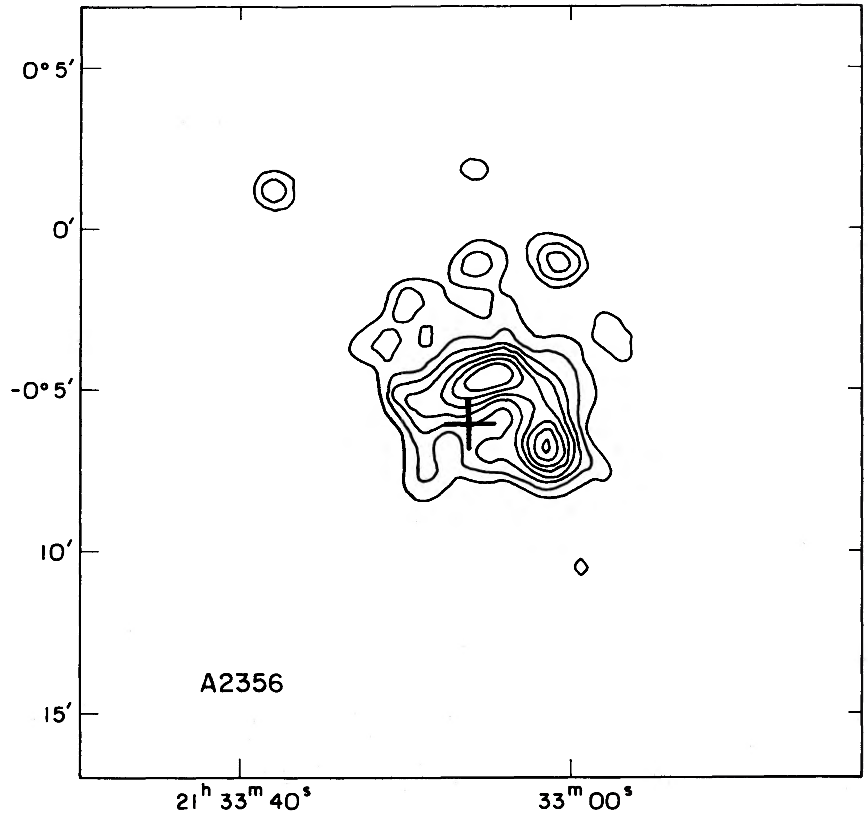

FIG. 1*j*

FIG. 1*i*.—The levels are 3, 4, 5, 6, 7.5, 9, and 9.5 times the rms fluctuation of 0.75 counts arcmin^{-2}

FIG. 1*j*.—The levels are 2, 3, 4, 5, 6, and 7 times the rms fluctuation of 0.78 counts arcmin^{-2}

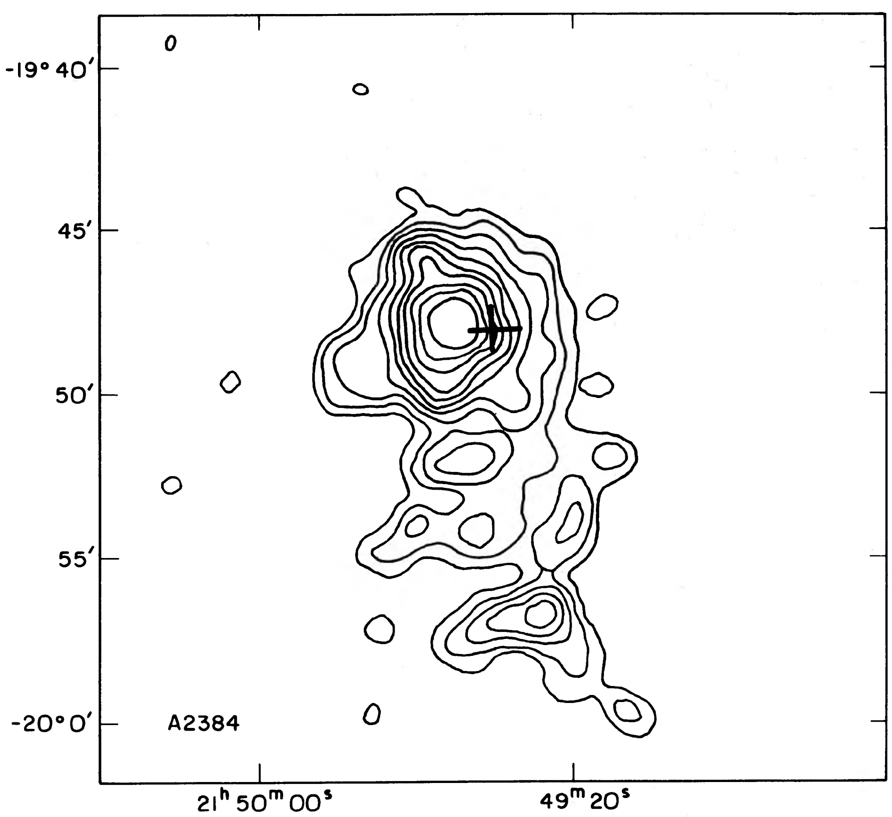

FIG. 1k

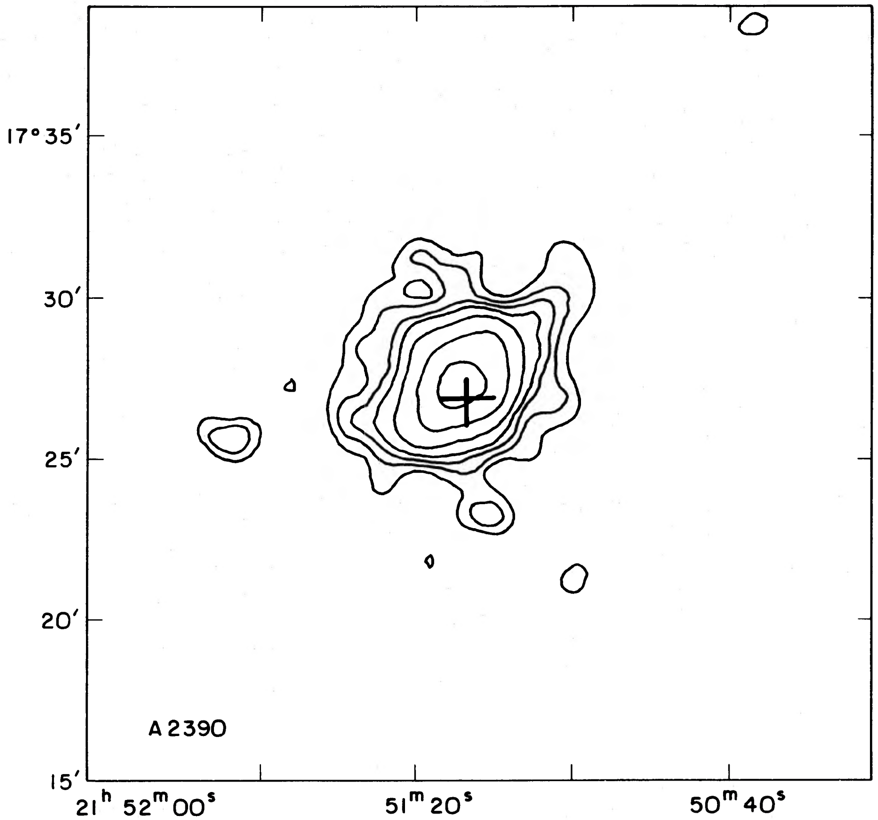

FIG. 1l

FIG. 1k.—The levels are 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11 times the rms fluctuation of 1.0 counts arcmin^{-2}

FIG. 1l.—The levels are 3, 4, 5, 6, 8, 12, 18, and 21 times the rms fluctuation of 0.51 counts arcmin^{-2}

therein. A few counterexamples do not disprove a correlation, but they do demonstrate that there is not a simple relationship between these two cluster characteristics.

In a series of papers (Kowalski *et al.* 1984), and references therein), we have estimated the probability that some of the *HEAO 1* A-1 clusters were misidentifications. For distance class 5 or more clusters, the estimated probability for a misidentification was approximately 30%. In Table 1 only one of the nine upper limits (with fluxes less than the *HEAO 1* A-1 flux limit of $\sim 10^{-12}$ ergs cm^{-2} s^{-1}) is an *HEAO 1* A-1 identification, which is consistent with our estimate of the fraction of the misidentification rate. Differences between the measured X-ray fluxes by the two experiments from source to source (see Ulmer, Cruddace, and Kowalski 1985) are due to: the different energy range of the measurements; the loss of flux in the *HEAO 2* observations that were off axis due to flux being outside the field of view or partially under a rib (the detected fluxes were corrected for vignetting); and to contamination of the *HEAO 1* A-1 data by line-of-sight objects in the field of view of the A-1 detector.

Finally, we discuss three clusters that have some potentially interesting morphology, but have not been described previously.

A2204.—The image was distorted due to being on the very edge of the IPC field (Ulmer, Cruddace, and Kowalski 1985), and so the fitted results are not firm; however, the best fit is for a diffuse source and a central point source ($<2'$). Further, we note that the source has a dominant galaxy, and the cluster is $R = 3$. We suggest, therefore, that A2204 is a centrally condensed, relaxed cluster.

A2378.—The source image presented in Figure 1*j* is clearly out of round. The northeast portion of the flux that produces the "tail" in the image is only 3 σ above the background, however. Tentatively, then, this cluster has a peculiar morphology.

A2390.—This source clearly has a centrally condensed core of X-ray emission, as the data are best fitted by a central point source (consistent with the point response of the IPC) and a diffuse source. The origin of the point-like emission is unclear, but it is likely to be related to the radio source that is within the error radius of the peak flux from *A*2390. This radio source is called MC3 2151 + 174 (Sutton *et al.* 1974), and it has a flux of 0.6 Jy at 408 MHz. We suspect that the source is associated with a cD or NGC 1275–like object and that the centrally peaked emission has the same origin as in other clusters with the similar morphology (see Fabian, Nulsen, and Canizares 1984 for an explanation of this morphology based on cooling flows).

IV. SUMMARY

We have presented X-ray luminosities and morphologies for 27 clusters of galaxies. We have found examples of clumpy clusters over a range of z from ~ 0.1 to 0.2. This is consistent with at least two hypotheses (1) that less dense clusters take longer to collapse; (2) these clumpy clusters formed clumpy and have not evolved to smooth clusters on time scales between 10^9 and 10^{10} yr. Our results are also consistent with previous analyses that show a dependence of cluster X-ray luminosity on richness class and with the previously calculated *HEAO 1* A-1 survey misidentification rate of $<30\%$ for distance class 5 and 6 clusters. We have also presented three new clusters whose X-ray morphology makes them particularly worthy of follow-up studies: A2204, A2378, and A2390.

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