1981ApJ...243L.133F

THE ASTROPHYSICAL JOURNAL, 243:L133–L136, 1981 February 1

EINSTEIN IMAGING OBSERVATIONS OF CLUSTERS WITH A BIMODAL MASS DISTRIBUTION

W. FORMAN, J. BECHTOLD, W. BLAIR, R. GIACCONI, L. VAN SPEYBROECK, AND C. JONES
Harvard-Smithsonian Center for Astrophysics
Received 1980 July 23; accepted 1980 October 21

ABSTRACT

A morphologically distinct class of clusters characterized by a double structure in their X-ray surface brightness distribution has been identified from imaging observations made with the *Einstein* Observatory. In the context of hierarchical models for cluster formation, we suggest these double clusters represent an intermediate stage of dynamical evolution.

Subject headings: galaxies: clusters of — galaxies: evolution

I. INTRODUCTION

Uhuru observations showed evidence for extended X-ray emission from nearby rich clusters of galaxies (Gursky *et al.* 1971; Forman *et al.* 1972; Kellogg *et al.* 1972). Subsequent spectral observations (Mitchell *et al.* 1976; Serlemitsos *et al.* 1977) confirmed that this emission was produced by thermal bremsstrahlung from an optically thin gas with temperatures from 2 to 10 keV and roughly solar abundances of iron. Jones *et al.* (1979) discussed the first *Einstein* X-ray images of nearby clusters in terms of dynamical evolution in a hierarchically clustering universe. The X-ray observations allow clusters of galaxies to be divided into two distinct morphological classes—those with dominant, centrally located galaxies characterized by centrally peaked X-ray emission and those with broader X-ray distributions. Within these two classes, different stages of dynamical evolution can be identified. For the class of clusters having dominant X-ray galaxies, these stages have properties ranging from those of an unevolved system like Virgo to the evolved cD cluster A85. Coma and A2256 are evolved clusters with no dominant galaxy.

In this *Letter* we present observations of four X-ray double clusters which appear as an intermediate phase of dynamical evolution among those clusters lacking a dominant galaxy. These clusters, A98, A115, A1750, and SC 0627−54 were all selected optically as single clusters by either Abell (1958) or Duus and Newell (1977), but are characterized by a double structure in their X-ray surface brightness distribution and, therefore, in their mass distribution.

II. OBSERVATIONS

In a survey of nearly 50 clusters detected with the Imaging Proportional Counter (IPC) on the *Einstein* Observatory, we have observed the clusters A98, A115, A1750, and SC 0627−54, whose X-ray surface brightness distributions exhibit two enhancements. Figure 1 (Plate L7) shows the X-ray images along with a one-dimensional projection of the surface brightness distributions which emphasizes the double structure of each cluster. In Figure 2 (Plate L8) the X-ray isointensity contours are superposed on optical prints.

We have calculated in several different ways the probability that the double clusters are chance superpositions. We have used the separation of the pairs in both velocity and angle and assumed that our population of objects was detectable out to a distance corresponding to $z = 0.2$ (the redshift of the most distant cluster in our sample). Using the Smirnov-Cramer-Von Mises test (Eadie *et al.* 1971), we computed a probability of less than 10^{-3} that the double clusters consist of a coincidence between a known cluster with another uniformly distributed population. We have made a second calculation and compared the volumes containing each cluster pair to the volume within which we could have detected such a pair (within $z = 0.2$ and the central $34' \times 34'$ of the IPC). In this test, the probability that all four are chance coincidences and lie within a fraction of space equal to the largest double cluster volume is 2×10^{-5}. Therefore, we conclude that these double clusters cannot all be random coincidences and that they represent a class of clusters with physically associated subclusters.

To compare the properties of the components of the double clusters to those of previously studied objects, their radial distributions have been fitted to a King approximation of an isothermal sphere model (Lea *et al.* 1973) convolved with the instrument response of the IPC (approximately a Gaussian of width $0'.6$). None of the eight cluster components is consistent with a single point source. The parameters of these fits are given in Table 1 with 1 σ errors computed using the prescription of Avni (1976). The core radii vary from 0.53 to 0.80 Mpc with uncertainties of up to 30%. These sizes are similar to the 0.6 Mpc core radii found for evolved clusters with no dominant galaxy. In computing both the core radii and the luminosities, we have assumed $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

We have used the radial profiles to compute the luminosities by assuming that the opposite halves of each subcluster are equally luminous. The counts per

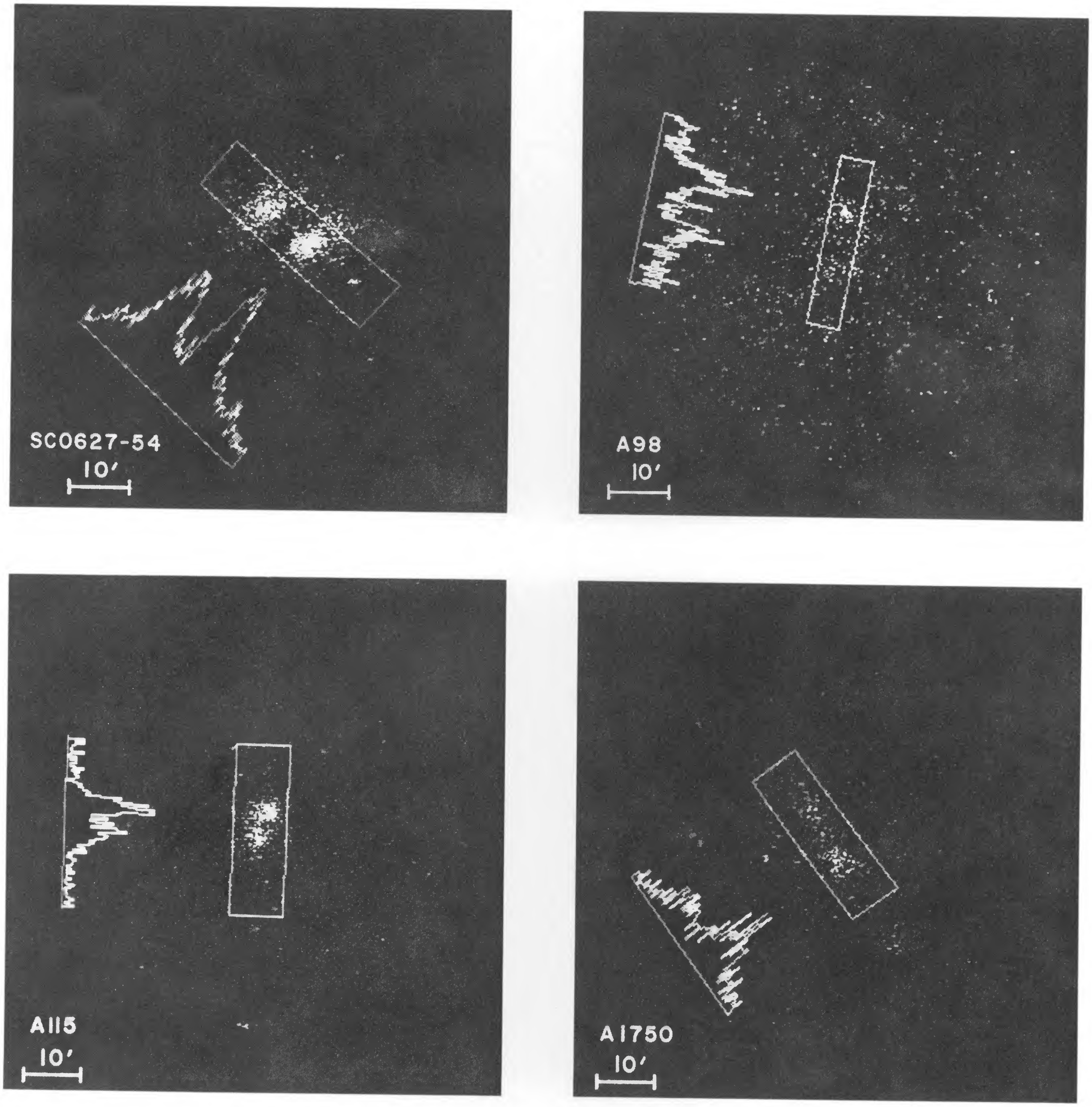

FIG. 1.—The X-ray images of SC 0627−54, A98, A115, and A1750 are shown as observed by the IPC in the energy band 0.5–3.0 keV. The one-dimensional projections include only those photons inside the rectangular boxes superposed on each image.

FORMAN *et al.* (*see* page L133)

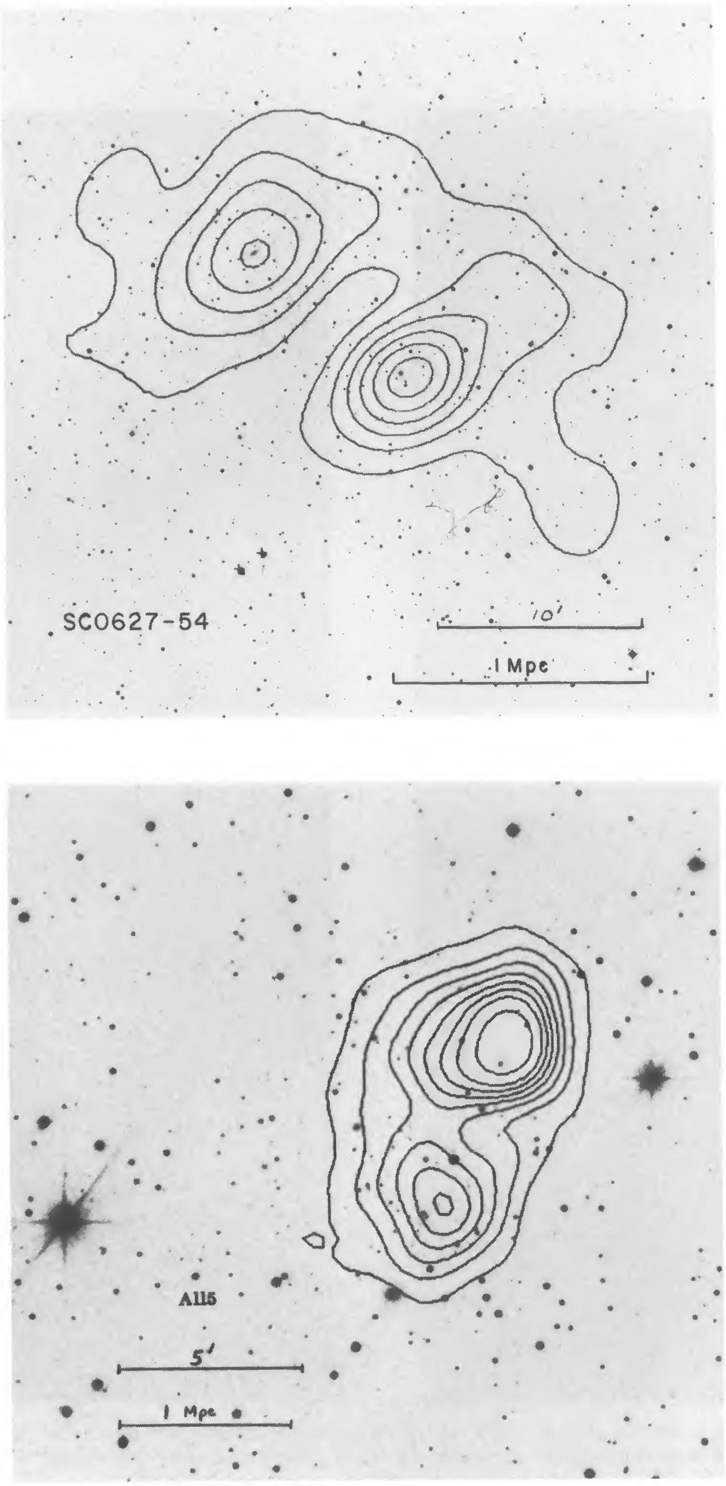

FIG. 2.—The X-ray isointensity contours are shown superposed on the Palomar Sky Survey prints (A98, A115, A1750) and on the European Southern Observatory print (SC 0627−54). The X-ray contours have been generated by deconvolving the image data with a Weiner filter, which smooths on a scale comparable to the detector's resolution. The contour levels are given as the number of counts in each 64″ × 64″ bin—SC 0627−54: 12.0, 21.4, 30.2, 39.1, 48.5, 57.3; A98: 5.2, 7.0, 8.8, 10.8, 12.6; A115: 5.3, 7.7, 10.5, 13.3, 16.1, 18.9, 22.1, 27.3; A1750: 3.9, 6.8, 9.6, 12.6, 15.5. The background levels in the fields in the same units are 2.0, 1.1, 5.5, and 0.6 for SC 0627−54, A98, A115, and A1750, respectively.

FORMAN *et al.* (*see* page L133)

1981ApJ...243L.133F

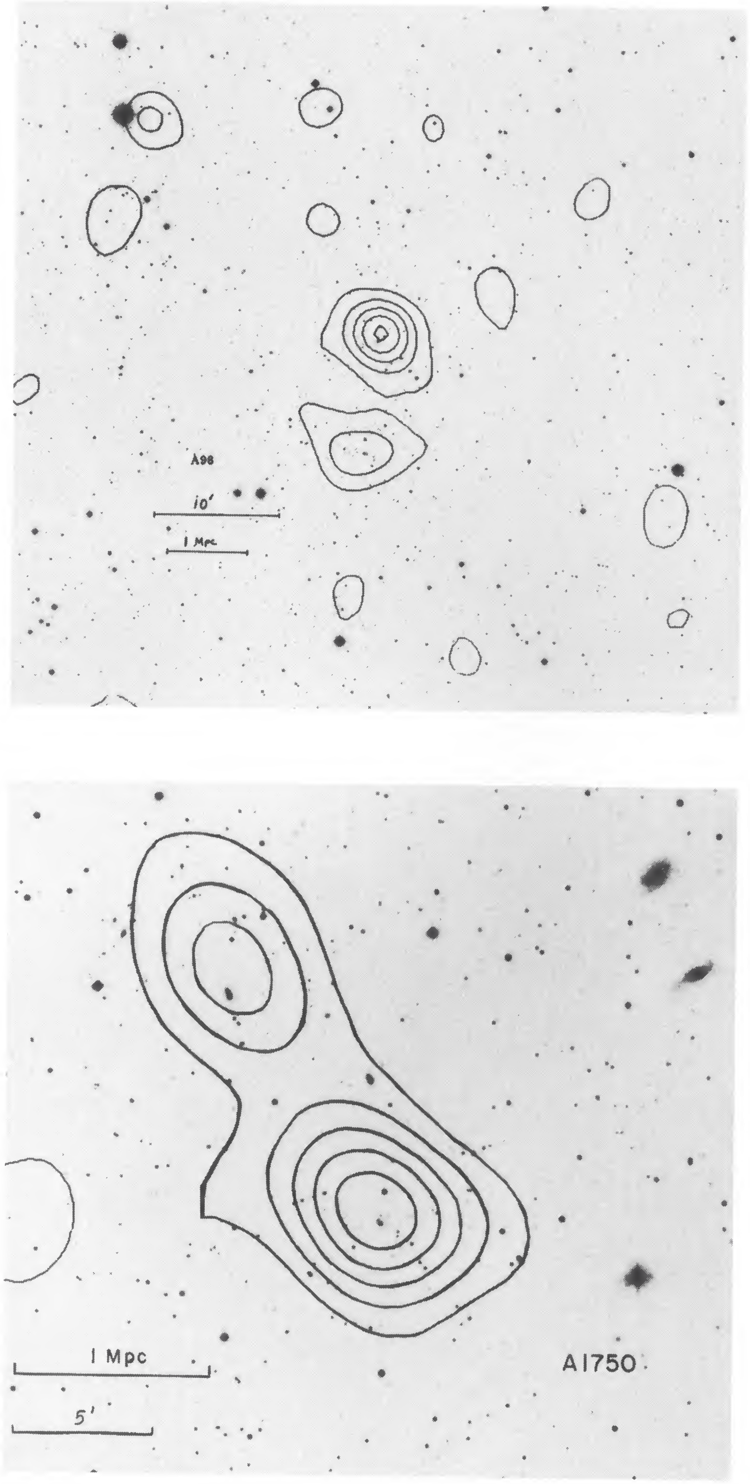

FIG. 2.—*Continued*

FORMAN *et al.* (*see* page L133)

TABLE 1

X-RAY PROPERTIES OF DOUBLE CLUSTERS

Cluster	z	R.A. (1950 coordinates)	decl. (1950 coordinates)	L_x ($\times 10^{43}$ ergs s^{-1})	Size (Mpc)	n_0	Separation (Mpc)
A98	0.104[a]	$00^{\mathrm{h}}43^{\mathrm{m}}.76$	+20°20′.9	5.3±0.7	5′.1±0.5 (0.80)	4.9×10^{-4}	8′.93(1.40)
		00 43.84	+20 12.0	3.9±0.6	3′.5±1.0 (0.55)	7.4×10^{-4}	
A115	0.1959[b]	00 53.15	+26 09.9	32±3	2′.3±0.3 (0.61)	1.8×10^{-3}	5′.05(1.33)
		00 53.29	+26 04.3	19±2	2′.5±0.5 (0.67)	1.2×10^{-3}	
SC 0627−54	0.051[c]	6 26.48	−54 25.4	8.9±0.2	8′.0±0.2 (0.66)	8.5×10^{-4}	8′.61(0.70)
		6 25.74	−54 31.1	9.8±0.3	8′.0±0.5 (0.66)	8.9×10^{-4}	
A1750	0.086[d]	13 28.55	−1 28.0	7.9±0.8	5′.0±1.0 (0.67)	7.8×10^{-4}	9′.39(1.25)
		13 28.27	−1 36.4	11±1	4′.0±0.5 (0.53)	1.3×10^{-3}	

[a] Faber and Dressler 1977.

[b] Schmidt 1965.

[c] Danziger 1980.

[d] Davis and Huchra 1980.

second are converted to fluxes from 1.0 to 3.0 keV using the calibration,

$$1 \text{ IPC count s}^{-1} = 2.5 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$$

(Giacconi *et al.* 1979), then to luminosity from the expression given by Tananbaum *et al.* (1979). The luminosities range from 0.8 to 3.2×10^{44} ergs s^{-1}, which are typical of rich clusters. The central gas densities, assuming isothermal gas distributions with temperatures from 2 to 10 keV, are approximately 10^{-3} particles cm^{-3} and are similar to those found for evolved clusters without dominant galaxies.

While spectral information is available from the IPC, the detector has not been sufficiently calibrated for us to make any quantitative statements about temperatures of the X-ray-emitting gas. Therefore, we have assumed temperatures in the range 2–10 keV, consistent with the determination by Mushotsky (1980) of 6 ± 3 keV for SC 0627−54.

The X-ray surface brightness can be used to trace the distribution of the total cluster mass regardless of its contribution to the visible light of the galaxies for gas in hydrostatic equilibrium (Fabricant, Lecar, and Gorenstein 1980). Since the dynamical time scale varies slowly with mass, the assumption of hydrostatic equilibrium for the double clusters may not be valid (Cavaliere 1980). However, in the absence of observational evidence against the assumptions of hydrostatic equilibrium and an isothermal temperature distribution, we have computed the masses of each subcluster. We find masses within 1 Mpc of 4–5 $\times 10^{14}$ $M_\odot$—typical of the values obtained for bound and virialized clusters (we have chosen $kT = 7$ keV, but note that the mass scales linearly with the gas temperature). If these masses are correct then, as for other X-ray-emitting clusters, the gas contributes only ~10% of the total inferred mass.

Four of these subclusters are associated with radio sources (see Table 2). While some portion of the X-ray emission may be produced in a compact region related to these radio sources, it is more likely that the contribution is small, as in most other clusters containing radio sources of comparable luminosities. If a substantial portion of the X-ray luminosity were a result of strong nuclear activity in the central galaxies, we would expect to observe unusual optical emission lines, but none have been observed.

The double clusters differ substantially from typical superclusters (Karachentsev, Tsarevskaya, and Scherbanovskii 1976), since their sizes are more than 10 times smaller and, hence, their densities are about 1,000 times larger. Therefore, superclusters composed of a few clusters would not be at the same dynamical phase as the double clusters (see eq. [2] below).

In addition to the two peaks of emission identified with SC 0627−54 and shown in Figures 1 and 2, there is a third region of extended emission about 50′ to the north which is centered on the brightest galaxy in the cluster 0626−536 (Duus and Newell 1977). This third system has a redshift which differs by less than 1500 km s^{-1} from the pair in SC 0627−54 (Danziger 1980), while its separation from them is about 4 Mpc on the plane of the sky. These three systems may be members of a supercluster similar to those discussed by Rood (1976). In addition, the diffuse background in this region from 1.0 to 3.0 keV is 50% higher than the average background in the over 100 fields used in the medium sensitivity survey by Maccacaro *et al.* (1980) and is 20% higher than the highest background observed in that survey. This unusually high background is seen in two separate observations made 6 months apart with pointing directions differing by 20′. Further analysis of the IPC spectral behavior is required before this background can be attributed to a celestial phenomenon.

III. DISCUSSION

One highly developed theory of cluster and galaxy formation has been that characterized by hierarchical clustering in which relaxation first occurs on a small scale, and each subsequently larger scale can be modeled by N-body gravitational clustering. In this

TABLE 2

Optical and Radio Properties of Double Clusters

Cluster	Bautz-Morgan and Abell Richness[a,b]	Cluster Component	Velocity of Central Galaxy in Subcluster (km s^{-1})	Radio Sources
A98............	II–III, 3	N	30,752[c]	00 44.0+2019[d]
		S	30,805[c]	00 43.9+2012[d]
A115...........	III, 3	N	58,770[e]	3C 28.0
		S		
SC 0627−54....	Late[f], 2	SW	15,855[g]	PKS 0625−545
		NE	14,750[g]	
A1750..........	II–III, 0	SW	26,350[h]	<0.1 f.u. at 1400MHz[i]
		NE	25,075[h]	

[a] Leir and van den Bergh 1977.

[b] Bahcall (1977*a*) and Lugger 1978.

[c] Faber and Dressler 1977.

[d] Owen 1975.

[e] Schmidt 1965.

[f] The two dominant galaxies are nearly the same magnitude.

[g] Danziger 1980.

[h] Davis and Huchra 1980.

[i] Owen 1974.

scheme, the spectrum of density fluctuations at the epoch of recombination is usually given by a power law,

$$\delta\rho/\rho \propto M^{-\alpha}\,, \tag{1}$$

where ρ is the mean density, $\delta\rho$ the overdensity of the perturbation, M the mass, and α ranges from $\frac{1}{3}$ to $\frac{1}{2}$ (Peebles 1974; Gott and Rees 1975). Thus, the largest overdensities are concentrated in the smallest mass scales, and since the dynamical time scale depends on the density of the perturbation as

$$\tau_D \propto [G(\rho + \delta\rho)]^{-1/2}\,, \tag{2}$$

then on the average, the smallest mass scales will undergo the most rapid dynamical evolution. This scenario is in basic agreement with the dynamical evolution observed in clusters.

Hierarchical gravitational clustering has been analyzed through numerical simulations by Peebles (1970), Aarseth (1969), and White (1976), among others. These numerical experiments have shown that an initially expanding cloud of galaxies will collapse and eventually reach equilibrium with an extended halo surrounding a denser core. White (1976) has shown that during this evolution subclustering occurs about the more massive galaxies. Subclusters continue to merge into a few large concentrations before their final coalescence.

The observation of double X-ray clusters provides additional support for hierarchical clustering. We suggest that the X-ray double clusters represent an intermediate evolutionary stage before the final merger of the subclusters into a relaxed Coma-type cluster. The observed subcluster separations of 1 Mpc (a minimum separation since projection effects cannot be removed) as well as the 0.6 Mpc core radii agree with those expected from White's (1976) model for an intermediate dynamical phase. White assumed that the initial mass function is derived from a Schechter luminosity function with a constant mass-to-light ratio, and his analysis did not allow for galactic cannibalism or for tidal disruption of massive halos. Therefore, his simulation is most appropriate to those clusters with no dominant galaxy. The interval during which clusters exhibit a bimodal distribution is substantial since free-fall times for subclusters with 1 Mpc separations are $\sim 10^9$ yr. Gingold and Perrenod (1979) have studied the properties of the intracluster medium during the final subcluster merger. They calculated that the X-ray-emitting gas should have the same bimodal distribution exhibited by the galaxies. White (1976) and Cavaliere (1980) also noted that after the merger a residual asymmetry may remain in the galaxy distribution. Such asymmetries are reflected in the X-ray surface brightness distributions of some relaxed clusters lacking dominant galaxies (see Jones *et al.* 1979 and Ku and Abramopoulus 1980).

The optical support for our dynamical classification of these double clusters is scant, primarily because the clusters are distant. A velocity dispersion of 793 (+159, −198) km s^{-1} is available only for A98 (Faber and Dressler 1977); and while the value itself is intermediate between those of the unevolved cluster A1367 (634 ± 110 km s^{-1}; Yahil and Vidal 1977) and the evolved system A2256 (1274, +131, −280 km s^{-1}; Faber and Dressler 1977), the uncertainties are too large to confirm the intermediate state of A98. The luminosity function of A98 derived by Dressler (1976) is similar to that of the Coma-type cluster A2256, but is significantly flatter than that of the evolved cD cluster A2029. The late Bautz-Morgan type (see Table 2) for these bimodal clusters agrees with our suggestion that these clusters belong to the evolutionary branch of clusters without a dominant galaxy.

While the double clusters contain no single dominant galaxy, the presence of a bright galaxy near the center of each subcluster provides some evidence of galactic cannibalism or a similar process. However, while galaxy mergers may have occurred in the early evolutionary phases, it is unlikely that this process is presently occurring in these clusters at a significant rate. A dominant galaxy develops most rapidly in the early stages of hierarchical clustering when galaxies are members of small groups which have larger-than-average densities and, therefore, short dynamical time scales. Furthermore, the relaxation time for these groups is shortened by both a short dynamical time scale and the small number of galaxies involved before the groups have coalesced (Ostriker 1978). A second reason for the reduced rate of cannibalism at later evolutionary stages is that, as White (1978) has argued, the massive dark halo initially associated with each galaxy must have been stripped to become part of the general cluster background. This process reduces the mass and size of each galaxy and, thereby, the effectiveness of dynamical friction (Ostriker and Tremaine 1975). Thus, the time scales for cannibalism have been increased, and, therefore, double clusters with properties similar to those discussed above are not the progenitors of the X-ray-dominant cD clusters.

We have shown that the X-ray observations are useful as an indicator in determining a cluster's dynamical state. Optical galaxy counts should confirm the bimodal mass distributions, as has been done for A98 (Henry *et al.* 1980). Further detailed optical analyses are necessary to understand the processes that occur as evolution proceeds. In particular, studies of spiral fractions, galaxy colors, and cluster velocity dispersions will aid in understanding the ram-pressure stripping of galaxies and the evolutionary effects of the cluster environment on individual galaxies. Numerical experimentation could better define the importance of the initial conditions upon the final state of the cluster and the appearance of the double clusters. As these investigations proceed, it may be possible to use the observed distribution of cluster evolutionary states to help clarify the initial spectrum of density fluctuations in the early universe on mass scales appropriate to clusters of galaxies.

We would like to thank M. Davis, J. Huchra, and J. Danziger for providing redshifts of galaxies in two of the double clusters. H. Tananbaum provided a useful stimulus for completing this project. We would like to acknowledge stimulating and helpful discussions with M. Rees, A. Cavaliere, and S. Strom. We thank K. Gilleece for help in preparing this manuscript. This research was supported by NASA contract NAS8-30751.

REFERENCES

Aarseth, S. 1969, *M.N.R.A.S.*, **144**, 537.
Abell, G. O. 1958, *Ap. J. Suppl.*, **3**, 211.
Avni, Y. 1976, *Ap. J.*, **210**, 642.
Bahcall, N. 1977, *Ap. J. (Letters)*, **217**, L77.
Cavaliere, A. 1980, in *Proc. NATO Advanced Study Institute, Erice, Italy, July 1979*, ed. R. Giacconi and G. Setti (Dordrecht: Reidel).
Danziger, I. J. 1980, private communication.
Davis, M., and Huchra, J. 1980, private communication.
Dressler, A. 1976, Ph.D. thesis, University of California, Santa Cruz.
Duus, A., and Newell, B. 1977, *Ap. J. Suppl.*, **35**, 209.
Eadie, W. T., Drijard, D., James, F. E., Roos, M., and Sadoulet, B. 1971, in *Statistical Methods in Experimental Physics* (London: North-Holland), p. 268.
Faber, S. M., and Dressler, A. 1977, *A.J.*, **82**, 187.
Fabricant, D., Lecar, M., and Gorenstein, P. 1980, *Ap. J.*, **241**, 552.
Forman, W., Kellogg, E., Gursky, H., Tananbaum, H., and Giacconi, R. 1972, *Ap. J.*, **178**, 309.
Giacconi, R., *et al.* 1979, *Ap. J. (Letters)*, **234**, L1.
Gingold, R., and Perrenod, S. 1979, *M.N.R.A.S.*, **187**, 371.
Gott, R., and Rees, M. 1975, *Astr. Ap.*, **45**, 371.
Gursky, H., Kellogg, E., Murray, S., Leong, C., Tananbaum, H., and Giacconi, R. 1971, *Ap. J. (Letters)*, **167**, L81.
Henry, J. P., Henriksen, M. J., Charles, P. A., and Thorstensen, J. R. 1981, *Ap. J. (Letters)*, **243**, L137.
Jones, C., Mandel, E., Schwarz, J., Forman, W., Murray, S. S., and Harnden, F. R. 1979, *Ap. J. (Letters)*, **234**, L21.
Karachentsev, I. D., Tsarevskaya, R. L., and Scherbanovskii, A. L. 1976, *Soviet Astr.*, **19**, 606.
Kellogg, E., Tananbaum, H., Giacconi, R., and Pounds, K. 1972, *Ap. J. (Letters)*, **174**, L65.
Ku, W. H. M., and Abramopoulus, F. 1980, presented at AAS meeting, San Francisco.
Lea, S. M., Silk, J., Kellogg, E., and Murray, S. 1973, *Ap. J. (Letters)*, **184**, L105.
Leir, A., and van den Bergh, S. 1977, *Ap. J. Suppl.*, **34**, 381.
Lugger, P. 1978, *Ap. J.*, **221**, 745.
Maccacaro, T., Feigelson, E., Fener, M., Giacconi, R., Griffiths, R., Murray, S., Schwartz, D., and Zamorani, G. 1980, in preparation.
Mitchell, R. J., Culhane, J. L., Davison, R. J. N., and Ives, J. C. 1976, *M.N.R.A.S.*, **176**, 29P.
Mushotsky, R. F. 1980, in *Proc. NATO Advanced Study Institute, Erice, Italy, July 1979*, ed. R. Giacconi and G. Setti (Dordrecht: Reidel).
Ostriker, J. P. 1978, in *IAU Symposium 79, The Large Scale Structure of the Universe*, ed. M. S. Longair and J. Einasto (Dordrecht: Reidel), p. 357.
Ostriker, J. P., and Tremaine, S. D. 1975, *Ap. J. (Letters)*, **202**, L113.
Owen, F. N. 1974, *A.J.*, **79**, 427.
———. 1975, *A.J.*, **80**, 263.
Peebles, P. J. E. 1970, *A.J.*, **75**, 13.
———. 1974, *Ap. J.*, *(Letters)*, **189**, L51.
Rood, H. J. 1976, *Ap. J.*, **207**, 16.
Schmidt, M. 1965, *Ap. J.*, **141**, 1.
Serlemitsos, P. J., Smith, B. W., Boldt, E. A., Holt, S. S., and Swank, J. H. 1977, *Ap. J. (Letters)*, **211**, L63.
Tananbaum, H., *et al.* 1979, *Ap. J. (Letters)*, **234**, L9.
White, S. D. M. 1976, *M.N.R.A.S.*, **177**, 717.
———. 1978, *M.N.R.A.S.*, **179**, 33.
Yahil, A., and Vidal, N. 1977, *Ap. J.*, **214**, 347.

J. Bechtold, W. Blair, W. Forman, R. Giacconi, C. Jones, and L. Van Speybroeck: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138