A MORPHOLOGICAL CLASSIFICATION OF CLUSTERS OF GALAXIES FROM EINSTEIN IMAGES

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The earliest Uhuru observations showed that cluster X-ray sources were not associated with single individual galaxies but were extended sources (Gursky et al. 1971, Kellogg et al. 1972, and Forman et al. 1972). The detection of iron line emission from X-ray spectroscopic observations (Mitchell et al. 1976 and Serlemitsos et al. 1977) showed both that the dominant X-ray emission process was thermal bremsstrahlung and that the gas had been processed through stellar systems before being injected into the intracluster medium.

Various optical classification systems have been developed for clusters with the goal of providing dynamical information. Properties of cluster member galaxies have been suggested as indicators of dynamical evolution. For example, relaxed, evolved clusters tend to be characterized by lower fractions of spiral galaxies, higher velocity dispersions and larger central densities (see Bahcall 1977 for a review). Hausman and Ostriker (1978) suggested that the Bautz-Morgan system is directly related to cluster evolution with type I systems -- those with optically dominant cD galaxies -- the most highly evolved.

Although ten years have passed since clusters of galaxies were discovered to be X-ray sources, it has only been with the advent of the Einstein X-ray imaging observatory that a first look at cluster X-ray morphology and classification has been possible. The proposed classification system divides clusters into two families -- those with and those without X-ray dominant galaxies. Within each family, the dynamical indicators display a full range of values.

One subgroup of clusters is those whose X-ray emission is not regular and which do not contain an X-ray dominant galaxy. The luminosities of these irregular clusters are low by classic cluster standards (10^{42} to 10^{44} ergs/sec). One of the brighter, nearer and best studied members of this class is A1367. Bechtold et al. (1981) have discussed the Einstein observations of this cluster.

In the IPC image of A1367, Figure 1, the cluster fills most of the field and has an elongated central region. At the southeast is a bright elliptical galaxy which contains a 3C radio source with a radio tail (Gavazzi 1978) and a nuclear X-ray source (Elvis et al. 1981). Figure 2 shows contours of the X-ray emission on an optical photograph.

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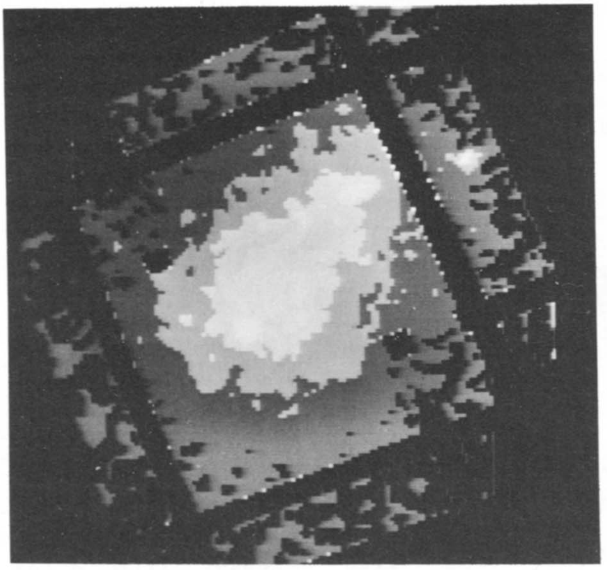

Figure 1: A1367 observed in two offset IPC fields in the energy range 0.5-3.0 keV.

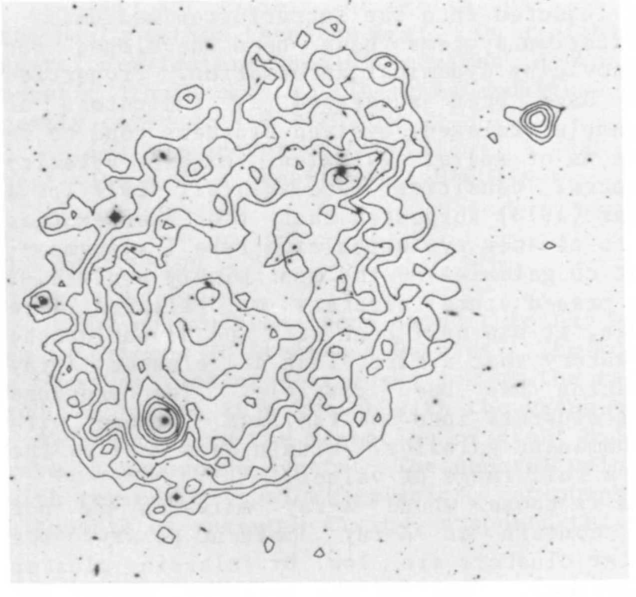

Figure 2: The X-ray iso-intensity contours of A1367 snow the elongatation oi the central region ot the cluster and the ga-axy associated with 3C284 in the southeast.

Using an isothermal sphere model Bechtold et al. obtained core radii of 0.80 Mpc for the long axis and 0.42 Mpc for the short axis. Carter and Metcalf (1980) have measured the cluster ellipticity from optical galaxy counts and find a ratio of .5 ± .1 with a similar position angle to the x-ray.

The IPC image was suggestive that the emission was not smooth

(Jones et al. 1979). Therefore, we performed a long (37K second) HRI observation of the central region. Since the background varies over the field of view due to the cluster emission, Bechtold et al. calculated the background locally in regions adjacent to the candidate source locations and searched the field with various detection cell sizes ranging from 12" to 2′ on a side. For comparison, the same analysis was performed on the Cetus deep survey.

With the 1′ cell Bechtold et al. detected ten extended regions in A1367 compared to one in Cetus. The one in Cetus is associated with a poor group of galaxies. To demonstrate that these clumps of emission were not an artifact of extended cluster emission, Bechtold et al. repeated the analysis on the Columbia Einstein observations of the Coma cluster. Both Coma and A1367 lie at the same distance and both are richness class 2, so their X-ray morphologies may be easily compared. In Coma two sources were detected, compared to the ten in A1367. One is a strong point source 5′ from the cluster center with no obvious optical counterpart. The second corresponds to the peak of the cluster emission at the cluster center. Although clumped emission is observed in A1367 and not in Coma, clumps such as those found in A1367 could exist in Coma but would remain undetected due to the higher level of general cluster emission in Coma.

In A1367 about 5% of the total cluster emission is in blobs. Oemler (1980), in a magnitude limited sample counted 19 galaxies in the central region. The extended X-ray sources occupy 5% of the area and include six of Oemler′s galaxies. The probability of finding this association by chance is 2×10^{-4}. A seventh galaxy, below Oemler′s magnitude limit coincides with one additional source. Thus, there is a significant association of these extended sources and cluster galaxies. However, three sources are not near galaxies. One contains several faint objects and may be a distant cluster.

At the distance of A1367, the X-ray luminosities of these blobs are 10^{40} to 10^{41} ergs/sec. which is five to fifty times the X-ray luminosity of our galaxy. Bechtold et al. considered several scenarios for maintaining the hot corona. In the core of the cluster, mass loss rates from ram pressure stripping and evaporation are ten to one hundred times the maximum gas replenishment rate postulated for normal galaxies. But these excessive galactic winds are not required if the galaxies have massive halos.

While the observation of coronas around approximately one third of the core galaxies suggests that massive halos may be a common property of galaxies in A1367, for the remaining galaxies Bechtold et al. did not detect hot coronas. These galaxies appear to be of the same galactic types as those with coronas so that the mass injection rate which varies with galactic type is not apparently the deciding factor.

Observations suggest that A1367 is a young, dynamically unevolved cluster. Its irregular appearance and low central concentration both optically and in X-rays indicate that it has not fully relaxed. Its low X-ray temperature (Mushotsky and Smith 1980) implies a weak cluster potential, characteristic of a system in an early stage of collapse.

White (1976) has modelled the dynamical evolution of clusters. In his numerical simulation, the galaxies first separate out from the general Hubble expansion and form small groups. These groups may merge into two large subclusters which condense to form a relaxed cluster.

From the X-ray imaging observations, four clusters have been discovered to have double structure in their surface brightness distributions (Forman et al. 1980). Figure 3 shows a mosaic of fields around the southern double cluster SC0627-54. The extended source to the north is another cluster at the same redshift as the double cluster, separated by ~4 Mpc.

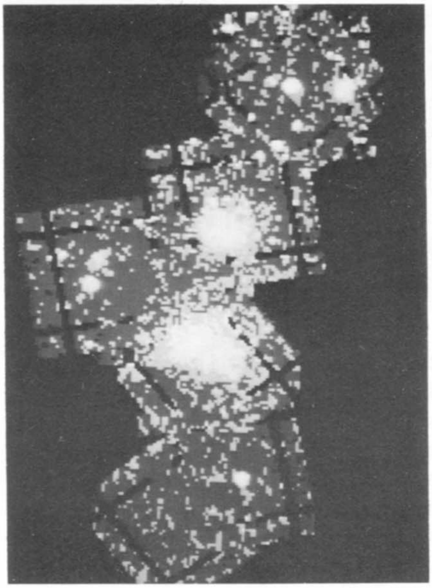

Figure 3: The 0.5-3.0 keV image around SC0627-54 showing the double cluster and a cluster to the north.

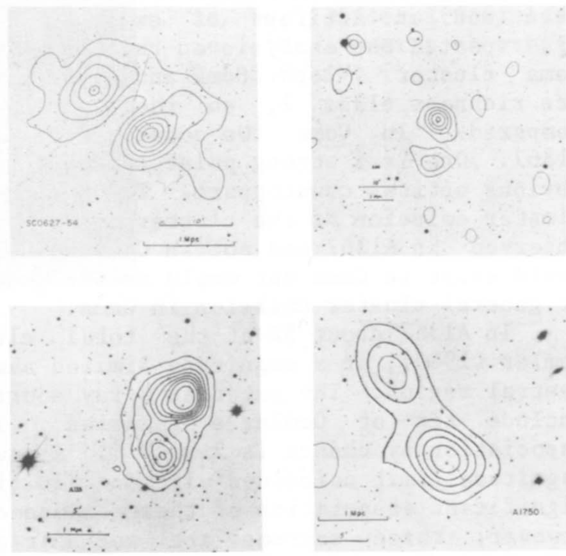

Figure 4: Iso-intensity contours for four double clusters superposed on optical photographs.

Figure 4 shows the X-ray iso-intensity contours for the four double clusters superposed on optical photographs. Each subcluster is centered on one of the bright cluster galaxies. Redshifts of each pair are consistent with the doubles being physically associated. Forman et al. have shown that all of the cluster components are extended with core radii similar to those of A1367. Their luminosities are also typical for rich clusters.

Unfortunately, there is no precise information for any of the dynamical indicators including spiral fractions, X-ray temperatures or accurate subcluster velocity dispersions. The observed subcluster separations and core radii agree with those expected from White's model for an intermediate dynamical phase. When the cluster survey is completed, the frequency of double clusters combined with numbers of clusters in each subgroup, should allow an estimate of how often the evolution proceeds through a double phase.

The Coma cluster is the archtype of an evolved, fully relaxed cluster. A Coma-type cluster A2256 is shown in Figure 5. The X-ray emission in these clusters is smooth and can be well-described by an isothermal sphere. The X-ray luminosities of these clusters are high and the X-ray temperatures are hot.

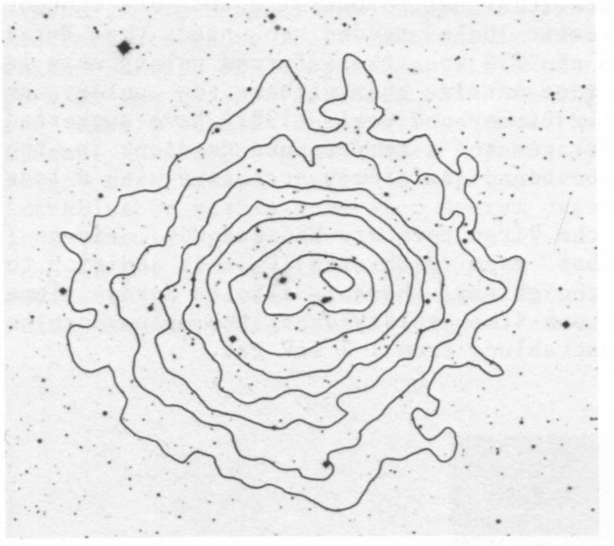

Figure 5: The X-ray iso-intensity contours of A2256 superposed on the PSS photograph.

In a parallel structure to the family of clusters from A1367 to Coma are those which contain a dominant galaxy. One such dynamically unevolved cluster is Virgo. Figure 6 shows the Virgo cluster in X-rays. Most of the bright sources in this figure are associated with

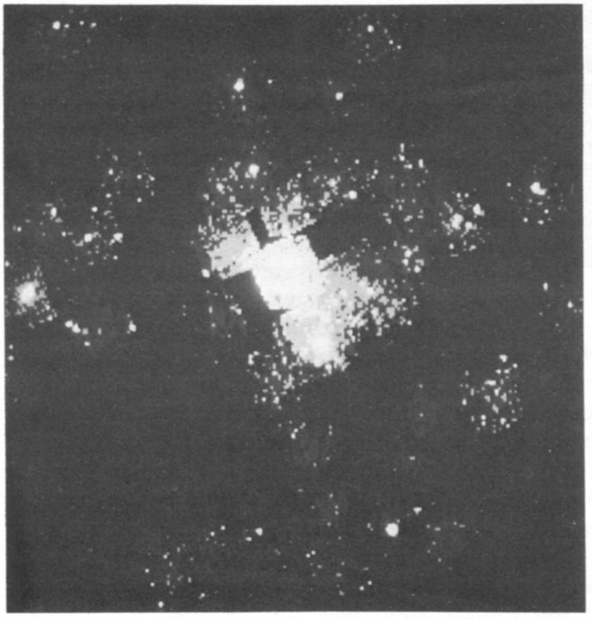

Figure 6: The 0.5-3.0 keV image of the Virgo cluster. X-rays from M87 dominate the central region. Each field is a single 1° x 1° IPC image.

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galaxies. Dominating the central region is M87. Although much of the emission is associated with the gas halo around M87, there is extended cluster emission which is not symmetric about M87 but brighter to the north and west.

Fabricant, Lecar, and Gorenstein (1980) have used the IPC observations to trace the gravitational potential of M87 and thereby determine the mass of the galactic halo needed to bind the X-ray emitting gas. To a distance of ~230 kpc, the inferred galaxy mass is several x 10^{13} $M_{\odot}$ - ten times more massive than either the galaxy or the X-ray gas. Alternatively Binney and Cowie (1981) have suggested that the pressure of the cluster gas and a temperature gradient in the halo gas may allow the gas to be bound and slowly accreting with a less massive halo.

Two other ellipticals in the Virgo core are M86 and M84. Figure 7 shows an observation of these made with the IPC. In addition to extended emission centered on the galaxy, there is also an X-ray plume or tail. The spectra of both the galaxy and the plume can be characterized by thermal bremsstrahlung from 1-2 keV gas.

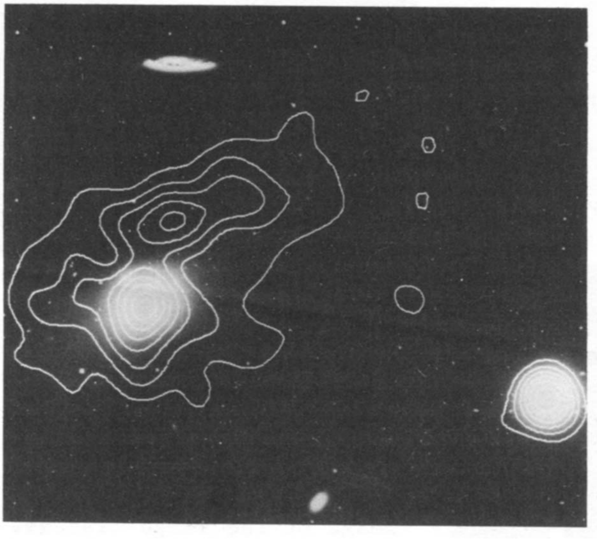

Figure 7: The X-ray image of M86 shows a central region with a detached plume to the north. M84 is to the west.

The key to understanding M86 is its high velocity of approach - nearly 1500 km/sec with respect to the Virgo cluster. Forman et al. (1979) suggested that the gas we presently see associated with M86 was accumulated during the intervals between the periodic passages of M86 through the Virgo core. M86 spends about five billion years between the time it exits the core, rises to its maximum height above the core and then falls back to the cluster center. M86 is now well into the Virgo core. The plume is gas that has been ram pressure stripped from the envelope around M86 by the intracluster medium but not yet heated and incorporated into that medium.

M84 is a less luminous X-ray source. Since it contains a 3C radio source, it was possible that the emission was associated with a compact nuclear source. However, HRI observations showed that the M84 X-ray source was extended on a scale of about 20 seconds, smaller than that around M86. M84 has a velocity which is equal to the mean of the Virgo cluster. Therefore, M84 appears to be a permanent resident of the cluster core where it is continually exposed to the intracluster gas which strips or evaporates its outer envelope. We observe only the core of the gas distribution which is tightly bound to the galaxy. As for A1367, these observations show that hot X-ray coronas are not an unusual feature of galaxies in dynamically unevolved clusters. The Virgo observations provide strong evidence that at least some of the intracluster gas is generated by ram pressure stripping of gas produced in the member galaxies.

In the family of clusters with dominant galaxies, we have in addition to young clusters like Virgo, dynamically evolved clusters, which are exemplified by A85 whose X-ray contours are shown in Figure 8.

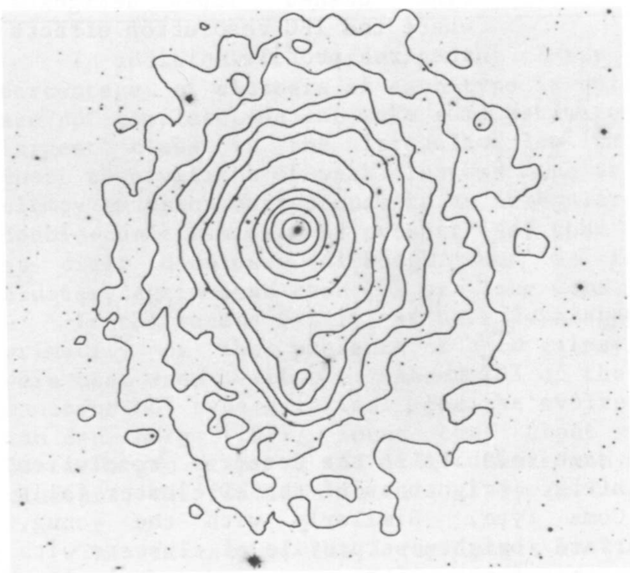

Figure 8: The X-ray iso-intensity contours of A85. The lowest contour is 3σ above background.

The emission is sharply peaked towards the center and coincides with the bright cD galaxy that sits at the bottom of the cluster's potential well. The X-ray gas in these clusters is hot and is associated with the cluster as a whole, not with individual galaxies. The x-ray emission is quite smooth in contrast to the irregular emission seen in A1367 type clusters. The X-ray surface brightness distribution of cD clusters is quite symmetrical suggesting relaxed systems.

Figure 9 shows the radial surface brightness profiles for four types of clusters. The first two are A1367 and A262 (like M87) which are the dynamically less evolved clusters and the last two - the Coma-type and the cD's are the more evolved clusters. Each evolved cluster has its progenitor - the M87-type for the cD clusters and the irregular A1367-type for the Coma-type clusters.

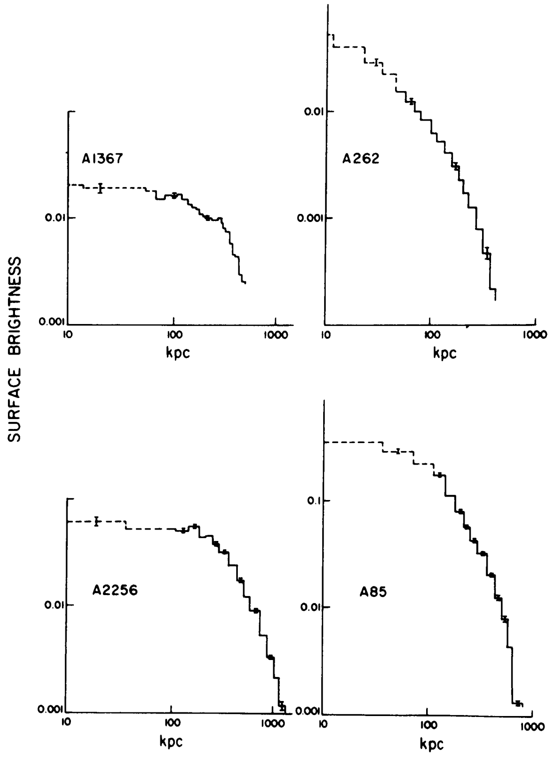

Figure 9: The 0.5-3.0 keV X-ray surface brightness profiles of A1367, A262, A85, and A2256. (The dashed lines designate where the IPC resolution effects the true profile.)

A85 and A2256 are at the same redshift so the detector resolution is the same for both. The surface brightness of the cD cluster falls much faster than that of the Coma type. Similarly with the young, unevolved clusters, the surface brightness profile of clusters with dominant galaxies falls faster than those without dominant galaxies. The clusters with steep slopes are both cD clusters and M87 type systems. The flatter distributions are both dynamically young A1367 systems and relaxed Coma-type clusters. The X-ray surface brightness distribution can be used to place the cluster in its family, then optical and X-ray indicators are used to determine the relative evolutionary stage.

Table 1 summarizes the dynamical indicators. The low X-ray temperature of A1367, its irregular X-ray and optical appearance and high spiral fraction indicate a relatively unevolved system. Similarly Virgo and A262 are in early stages. In contrast, Coma and A85 with their high X-ray temperatures, high central concentrations, and low spiral fractions are more evolved systems.

TABLE 1 - Cluster Classification

X-ray Dominant (XD) Systems		Non XD Systems	
A262	Cool X-ray gas 2.4±0.8 keV Emission around single galaxy Low velocity dispersion 478^{+183}_{-110} km/sec High spiral fraction 45%	A1367	Cool X-ray gas 2.8±1.0 keV Clumpy emission around galaxies Low velocity dispersion 694±75 High spiral fraction 40%
A85	Hot X-ray gas 6.8±0.5 keV Smooth emission centered on single dominant galaxy Low spiral fraction ≤22%	A2256/Coma	Hot X-ray gas 7^{+3}_{-2}/7.9±.3 keV Smooth, "isothermal sphere" emission High velocity dispersion 1274±250/900±63 Low spiral fraction ?/13%

In addition to defining the X-ray classes of clusters, the percentage of clusters of each type is relevant. Although our samples are not complete, we can make some estimates. In the first family, the largest class is the irregular, low luminosity A1367-type clusters. Short observations of weak clusters make it difficult to determine if clumpy emission corresponds to an irregular cluster or a cluster with a double condensation. At present less than 10% of all clusters appear as clear doubles. Although Coma is thought of as the "classical" cluster, again less than 10% are like Coma.

In the second family, we have separated the two main classes based primarily on the presence of a cD galaxy although X-ray temperatures were used when available. About 20% of the clusters are unevolved with dominant M87 type galaxies. For the evolved dominant systems, Leir and van den Berg (1977) found that about 10% of the clusters were Bautz-Morgan types I and I-II. Since many of these appear as cD X-ray clusters, the fraction in this class is also about 10%.

The efficacy of the X-ray images in cluster classification studies derives from their sensitivity in mapping the mass distribution within clusters. The studies of gaseous corona around individual cluster galaxies suggest the existence of massive halos. This analysis applied to entire clusters gives masses in good agreement with the virial mass. Although only about 10% of the total cluster mass is in the form of hot X-ray gas, it is a remarkably sensitive tracer of the unseen material defining the cluster potential.

In summary the cluster images are useful in determining the cluster family and the cluster's dynamical state. However, further detailed analysis is necessary to understand the processes that occur as evolution proceeds.

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