Galaxy Aggregates in the Coma Cluster

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ABSTRACT

We present evidence for a new morphologically defined form of small-scale substructure in the Coma Cluster, which we call galaxy aggregates. These aggregates are dominated by a central galaxy, which is on average three magnitudes brighter than the smaller aggregate members, nearly all of which lie to one side of the central galaxy. We have found three such galaxy aggregates dominated by the S0 galaxies RB 55, RB 60, and the star-bursting SBB, NGC 4858.

RB 55 and RB 60 are both equi-distant between the two dominate D galaxies NGC 4874 and NGC 4889, while NGC 4858 is located next to the larger E0 galaxy NGC 4860. All three central galaxies have redshifts consistent with Coma Cluster membership. We describe the spatial structures of these unique objects and suggest several possible mechanisms to explain their origin. These include: chance superpositions from background galaxies, interactions between other galaxies and with the cluster gravitational potential, and ram pressure. We conclude that the most probable scenario of creation is an interaction with the cluster through its potential.

Subject headings: galaxies - clusters - individual (Coma, Abell 1656): galaxies - formation: galaxies- interactions.

1. INTRODUCTION

Due to its proximity and high density, the Coma Cluster is a good location to investigate evolutionary effects in galaxy clusters, and for deriving certain cosmological

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parameters (Crone et al. 1996; Dutta 1995). Coma is the closest rich cluster (Abell class 2) that can be studied in detail, and considerable attention has been directed towards understanding its nature, and deciphering its structure. The model of Coma and other galaxy clusters as simple, virialized systems has been overthrown in the last few decades after the detection of significant substructure in a large number of clusters (e.g. West 1994). These features indicate that clusters have not had time to fully relax, and are likely to still be in the process of formation.

The Coma cluster is now recognized as one of the best examples of a cluster with substructure, and several method have been used to show that this substructure exists.

The Coma cluster contains sub-condensations visible in X-Rays first described in the work of Johnson et al. (1978). Later studies showed that the X-Ray distribution is centered around two point sources in the cluster (Davis & Mushotzky, 1993; Sarazin, 1986). As observing techniques and satellites improved, more X-Ray inhomogeneities were detected (Briel et al. 1992; White et al. 1993; Vikhlinin et al. 1997). A recent study using redshifts found that the velocity distribution of Coma members can be divided into two components centered around NGC 4874 and NGC 4889 (Colless & Dunn, 1996). This velocity difference is interpreted as the result of the merger of two clusters. Evidence also exists for sub-concentrations centered on the most massive galaxies (Meillier et al. 1988; Baier 1984). It is therefore no longer possible to think of Coma as a single relaxed physical system.

Given its current complex state, it would not be surprising if interactions are affecting individual galaxies in the Coma Cluster. These interactions would occur either through collisions with other cluster members or with structures within the cluster. In the past, the impact of collisions within clusters was thought to be minimal due to the high relative velocities between individual galaxies that are expected in a virialized galaxy cluster. However, the observations indicate that galaxy-galaxy interactions are relatively frequent in some regions of the Coma cluster. In addition evidence for damaging collisions within Coma in the form of a giant stellar debris arc has recently been discovered (Trentham et al. 1998). If a cluster is not virialized, then strong local interactions can occur between galaxies that are just falling into the cluster, as well as from more global tidal effects (Valluri 1993, Henriksen & Byrd 1996).

In this paper we present images of yet another curious form of galaxy within the Coma cluster. These consist of galaxies surrounded by numerous small companions. We call these objects ”galaxy aggregates” so as not to prejudice their physical interpretation. However, we argue that at least some galaxy aggregates result from the disruption of disk galaxies within the Coma cluster.
Section 2 presents our new imaging observations of the Coma Cluster. In section 3 we describe the galaxy aggregates, present photometry for these objects, and quantify their positions within the Coma Cluster. The possible origins of galaxy aggregates are reviewed in Section 4, and we suggest that such objects are likely to be found only in those clusters which are actively accreting field galaxies.

2. OBSERVATIONS

Our images of the Coma Cluster which contain examples of galaxy aggregates were taken with the WIYN 3.5m, f/6.5 telescope located at Kitt Peak National Observatory between the nights of May 31 to June 2, 1997. The thinned 2048\(^2\) pixel S2kB charged coupled device (CCD) produced images with a scale of 0.2 arcsec per pixel. The images cover a field-of-view of 6.8 x 6.8 arcmin. Broad-band B and R images were obtained for six different regions of the cluster. Exposure time are 900s for the B-band and 600s for the R-Band. The seeing ranged from 0.7 to 1 arcseconds full width at half maximum.

These data are part of a larger study of the influence of cluster environments on low luminosity galaxies (Gallagher, Han & Wyse 1997). During a preliminary examination of the images, it became clear that they contained remarkable systems consisting of several luminous condensations around medium-luminosity disk systems.

Two of our galaxy aggregates are centered around the Coma S0 cluster members RB 55 and RB 60 (Rood & Baum, 1967). The third galaxy aggregate is NGC 4858, whose central galaxy is a starbursting SBb member of the Coma cluster (Gallego et al. 1996).

In addition to our morphological studies, aperture photometry was performed on the aggregates using the IRAF package apphot. These were placed on the Landolt BR magnitude system using observations of his equatorial standard star fields (Landolt 1992).

3. DEFINITION AND MORPHOLOGY

\(2\)The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.
Galaxy aggregates have distinctive appearances in our images. They therefore at least merit a morphological definition, even if they turn out not to be a unique physical class of galaxy system. We define a “galaxy aggregate” as follows:

1. A galaxy aggregate consists of a primary lenticular (S0) or spiral galaxy that contains at least 5 distinct knots distributed asymmetrically within 2-3 optical radii of the primary.

2. The primary of a galaxy aggregate is not a dominate member of a galaxy cluster, such as a cD or D galaxy. This is to avoid confusion with central galaxies in clusters which often are surrounded by dwarfs (e.g. in the Coma cluster).

3. The number of knots around the primary of an aggregate must be statistically in excess over that seen in the surrounding region.

4. PROPERTIES OF COMA AGGREGATES

The two galaxy aggregates associated with RB 55 (Figure 1 & 2) and RB 60 (Figure 3) are located between the two central D galaxies in Coma, NGC 4874 and NGC 4889. Both of these S0 primary galaxies appear to be embedded in regions containing several compact, high surface brightness knots. The average separation of the knots from the central galaxies for both RB 55 and RB 60 are around 4h⁻¹ kpc. The redshifts of RB 55 and RB 60 are 7905 km s⁻¹ and 9833 km s⁻¹ respectively, where the mean redshift for the Coma cluster is 7200 km s⁻¹ (Colless & Dunn, 1996). The higher radial velocity aggregate, RB 60, is more than 1σ above the mean Coma velocity dispersion, and could therefore be in-falling into the cluster core. Ulmer et al. (1994) find dwarf galaxies to group in the Coma cluster, and suggest that RB 60 is a possible effect of this clumping.

A third object which morphologically qualifies as a galaxy aggregate is the Coma Cluster member, NGC 4858 (Figure 4), a starburst SBb galaxy located 13h⁻¹ kpc away from the larger E0 galaxy NGC 4860. The redshifts for these members are 9436 km s⁻¹ and 7864 km s⁻¹ respectively. Towards the interface between NGC 4858 and NGC 4860 are knots or dwarf galaxies distributed almost symmetrically about NGC 4858 (Figure 3). The average distances of the knots from NGC 4858 is 6h⁻¹ kpc.

The luminosity function of the aggregates are shown in Figure 5. RB 55 and RB 60 are both dominated by a galaxy of R magnitude around 17 with NGC 4858 aggregate having
a central galaxy of magnitude 18.6. The NGC 4858 and RB 55 aggregates have similar luminosity functions, which rise at fainter magnitudes. RB 60 has a luminosity function which peaks between 22 and 22.5 and falls off at fainter magnitudes.

The (B-R) vs. R plots (Figure 6) show that two of the aggregates contain knots covering a wide range in brightness, while those in NGC 4858 are near our faint limits. The colours of the knots in NGC 4858 and RB 60 are very red, while those in RB 55 are bluer and close to the colour of the primary galaxy and have similar colours to the dE galaxies in the Coma cluster (Secker 1996).

Images of the aggregates RB 55 and RB 60 do not show significant amounts of H\(\alpha\) in the smaller members.

5. RESULTS AND ANALYSIS

5.1. Chance Alignments

In a dense cluster like Coma, there is a possibility that galaxy aggregates result from chance alignments of galaxies at different distances. To test this possibility, the number density of galaxies detected in several fields in Coma, and the densities of the two aggregates are computed. The mean number density of detected galaxies in Coma cluster away from the aggregates on our 6.7 arcmin field CCD images is 4.7 galaxies arcmin\(^{-2}\). The surface density of knots in the aggregates is 36 galaxies arcmin\(^{-2}\) for RB 55, 32 galaxies per arcmin\(^{-2}\) for RB 60 and 38 galaxies per arcmin\(^{-2}\) in NGC 4858. The galaxy aggregates are effectively 6 \(\sigma\) fluctuations, which have less than a 0.01% chance of occurring due to a random superposition of Coma galaxies. Further evidence against the random hypothesis is our failure to observe similar superpositions in other regions of Coma, or in the clusters: Abell 2199, AWM 5, AWM 3, or Perseus. These aggregates are therefore relatively unusual, whatever their origin may be.

Secker et al. (1997) consider galaxies with colours of (B-R) > 2 or (B-R) < 0.9 as either too red, or too blue to be dwarf members of the cluster, and rejected such objects as being in the background or foreground. Based on these criteria, most of the knots in the NGC 4858 and RB 60 aggregates could be background galaxies. Perhaps these are examples of foreground S0 systems superimposed on a distant poor galaxy clusters or groups? We suspect that this is not a universal explanation as we do not find examples of such background clusters without a foreground object in our images. Therefore, some
special effect would have to be invoked to amplify background objects near the S0s. The one candidate for such a process, gravitational lensing, is unlikely on geometrical grounds; the images are neither distorted along arcs nor at small angles from the nuclei of the S0 primaries.

5.2. Gravitational Interactions

The morphologies of the Coma galaxy aggregates are suggestive of a central galaxy surrounded by dense knots of stars, which could have been produced by recent unusual events, such as a first passage through the Coma cluster. Under these conditions star formation in the disk of the central galaxy or in surrounding dwarf satellites might be triggered via interactions with other cluster members, or as an effect of the clusters overall gravitational potential. Evidence for star formation induced by interactions within clusters comes primarily from the presence of blue disk galaxies responsible for the Butcher-Oemler effect seen most prominently in moderate redshift galaxy clusters (e.g., Dressler & Gunn 1983, Lavery & Henry 1988, 1994, Couch et al. 1994). A high fraction of these blue galaxies show signs of recent gravitational interactions with nearby galaxies, and have the expected kinematics of recent infalls into their clusters.

Despite its proximity and the dominance of early-type galaxies in its core, the Coma cluster also contains a population of blue galaxies (Bothun & Dressler 1986, Caldwell et al. 1993 and references therein). Thus, this cluster may also contain galaxies that are responding to interactions within the cluster. The only likely binary aggregate pair is NGC 4858 whose nearby E companion NGC 4860 is at a 1572 km s\(^{-1}\) lower radial velocity. Such large velocity differences will reduce the severity of galaxy-galaxy collisions, but they may still be able to produce a significant starburst as is seen in NGC 4858 (Moore et al. 1996).

A more general mechanism for perturbing infalling galaxies and producing unusual stellar clumps may come from interactions with the clusters overall tidal field. In Merritt’s (1984) model, galaxies which are close to the cluster core will experience maximal tidal forces from the cluster potential. The tidal disruption experienced by a galaxy depends on the velocity dispersion of the galaxy \(v_g\) and that of the cluster \(v_{cl}\). The tidal radius \(r_T\) then varies with the cluster core radius \(R_c\),

\[
r_T = R_c \frac{1}{2} \frac{v_g}{v_{cl}}.
\]
Galaxies whose disk or satellite system radii exceed $r_T$ may experience significant distortion from the cluster tides.

In Coma $R_c = 0.15^\circ$ and $v_{cl} = 1062 \text{ km s}^{-2}$ (Kent & Gunn 1982). Adopting $100 \text{ km s}^{-1}$ for the equivalent velocity dispersion of a moderate luminosity S0 galaxy, the condition for tidal disruption at the Coma cluster core becomes $r_T > 8 \text{ kpc}$. In the RB 55 and RB 60 systems the faint knots are found at about this radius.

A possibly more attractive way the cluster could produce an aggregate is as a result of the reaction of galaxy disk to external tidal forces. This process may lead to an epoch of enhanced star formation activity as well as thickening of the stellar disk, as discussed by Valluri (1993) and Henriksen and Byrd (1996). However, none of these models lead in a transparent way to the production of knots of stars which are the morphologically defining characteristic of galaxy aggregates.

5.3. Ram-Pressure Stripping

Ram-pressure is the second primary type of environmental influence that a rich cluster may exert on its members. This effect was initially described by Gunn & Gott (1972) as a means to convert spirals into S0 galaxies within rich galaxy clusters. While there is now extensive observational evidence that gas is stripped from spirals in galaxy clusters (e.g., Vigroux et al. 1986, Haynes & Giovanelli 1986) the details of this process are still debated (see Nulsen 1982, Gaetz, Salpeter, & Shaviv 1987, Henriksen & Byrd 1996).

Certainly the copious hot intracluster medium in the Coma cluster will have an effect on its member galaxies (White et al. 1993). However, whether this also can yield clump formation, as in the case of tidal interactions, also remains uncertain.

6. DISCUSSION

Three galaxy aggregates centered around NGC 4858, RB 55 and RB 60 have been found in the Coma cluster. These consist of moderate-sized disk galaxies nested in several luminous knots or dwarf galaxy-like objects, which in RB 55 and RB 60 are not emission line regions. The number densities of objects in the aggregates are seven times larger than for small objects in surrounding regions of the Coma cluster. The large over-densities
in the aggregates and the absence of galaxy aggregates in other nearby galaxy clusters suggest that they are statistically unlikely to be chance alignments. However, projections of background objects possibly combined with weak gravitational lensing cannot be excluded.

The most likely model for the creation of the knots or dwarf galaxies in aggregates is through gravitational interactions with neighboring galaxies or the cluster as a whole during the infall of disk galaxies into the cluster. Tests of possible models require spectroscopy to determine the stellar content, kinematics, and redshifts of the knots within the aggregates. If the aggregates are background objects, then this will be immediately clear from their redshifts, while if, as we believe, they are produced by disturbances in a disk galaxy or its companions, then their radial velocities will be close to those of the primary galaxy, and the spread in velocities will be \( \approx 300 \text{ km s}^{-1} \) or less, as is typical of internal motions in small galaxies. In this model the presence of galaxy aggregates in the Coma cluster would then be another indication of the dynamic evolutionary state of this cluster.

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FIGURE CAPTIONS:

Fig.1 — The Coma field with the Aggregate RB 55 at centre. The high surface brightness, almost linear knots, close to the central S0 stand out as being unique. The size of the image is 4.3 arcmin on each side.

Fig.2 — A close up view of Aggregate RB 55. The image is 1’ on each side, with a scale of 0.2” per pixel.

Fig.3 — The aggregate RB 60. This 1’ by 1’ image shows the large central S0 galaxies surrounded by smaller dwarf galaxies or semi-stellar knots.

Fig.4 — The aggregate NGC 4858. This aggregate is unique from the other two in that it is close to another galaxy, NGC 4860. The knots in this image are all redder than NGC 4858. The image size is 1’ by 1’.

Fig.5 — The luminosity function for the Aggregates. The magnitudes for NGC 4858, RB 55 and RB 60 are 18.6, 17.0, and 17.4. The luminosity function for NGC 4858 and RB 55 both rise at fainter magnitudes, whereas the RB 60 function peaks near magnitude 22.

Fig.6 — The colour (B-R) vs. R relation. The colours of the central galaxies are (B-R)=0.9, 1.4, and 1.5, these are denoted on the figure as a dashed line. For NGC 4858 and RB 55 a slight trend towards bluer colours at fainter magnitudes is detected. The colours of the objects in RB 60 tend to be a bit redder than the central galaxy but have no particular trend. The colours and magnitudes for NGC 4858 are similar and the RB 55 colours are almost all bluer than the central galaxy.
