Galaxy aggregates in the Coma cluster

Christopher J. Conselice* and John S. Gallagher, III

Department of Astronomy, University of Wisconsin, 473 N. Charter Street, Madison, WI 54706, USA

Accepted 1998 March 20. Received 1998 March 17; in original form January 20

ABSTRACT

We present evidence for a new morphologically defined form of small-scale substructure in the Coma cluster, which we call galaxy aggregates. Aggregates are dominated by a central galaxy, which is on average 5 mag 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: two dominated by the S0 galaxies RB 55 and RB 60, and one by the starbursting SBb NGC 4858.

RB 55 and 60 are both equidistant between the two dominant D galaxies NGC 4874 and 4889, while NGC 4858 is located near the large 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 gravitational potential.

Key words: galaxies: clusters: individual: Abell 1656 – galaxies: clusters: individual: Coma – galaxies: formation – galaxies: interactions.

1 INTRODUCTION

Due to its proximity and high density, the Coma cluster is a good location in which to investigate evolutionary effects in galaxy clusters, and to derive certain cosmological parameters (Dutta 1995; Crone, Evard & Richstone 1996). Coma is the closest rich cluster (Abell class 2), and considerable attention has been directed towards understanding its nature and deciphering its structure. One result is that 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 methods have been used to show that this substructure exists.

The Coma cluster contains subcondensations visible in X-rays first described in the work of Johnson et al. (1978). Later studies showed that the X-ray distribution is centred 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, Forman & Jones 1997). In addition, a recent study using redshifts has found that the velocity distribution of Coma members can be divided into two components centred around NGC 4874 and 4889 (Colless & Dunn 1996). This velocity difference is interpreted as the result of the merger of two clusters. Evidence also exists for subconcentrations centred on the most massive galaxies (Baier 1984; Meillier et al. 1988; Gurzadyan & Mazure 1998).

Given its current complex state, it would not be surprising if interactions were affecting individual galaxies in the Coma cluster. These interactions would occur through collisions either with other cluster members, or with structures within the cluster. The impact of collisions within clusters might be minimal owing to the high relative velocities between individual galaxies that are expected in a virialized galaxy cluster; however, observations indicate that galaxy–galaxy interactions are 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 & Mobasher 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 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 images 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 disc galaxies within the Coma cluster. We further suggest that such objects are likely to be found only in clusters actively accreting field galaxies.

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.

2 OBSERVATIONS

Our images of the Coma cluster that contain examples of galaxy aggregates were taken with the WIYN 3.5-m, f/6.5 telescope located at Kitt Peak National Observatory between the nights of 1997 May 31 and June 2. 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 $\times$ 6.8 arcmin$^2$. Broad-band B and R images were obtained for eight different regions of the cluster. Exposure times were 900 s for the B band and 600 s for the R band. The seeing ranged from 0.7 to 1 arcsec full width at half-maximum. During a preliminary examination of the images, it became clear that they contained remarkable systems consisting of several luminous condensations around medium-luminosity disc systems.

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

In addition to our morphological studies, aperture photometry was performed on the aggregates using the IRAF package APPHOT. The images were placed on the Landolt BR magnitude system using observations of his equatorial standard star fields (Landolt 1992). We found the B and R magnitudes of all aggregate members with small apertures at the centre of each object, chosen to maximize our signal-to-noise ratio.

3 DEFINITION AND MORPHOLOGY

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 five distinct knots distributed asymmetrically within 2–3 optical radii of the primary.

(2) The primary of a galaxy aggregate is not a dominant 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 (Figs 1 and 2) and RB 60 (Fig. 3) are located between the two central D galaxies in Coma, NGC 4874 and 4889. Both of their 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 is around 4 \( h^{-1} \) kpc \((h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1})\). The redshifts of RB 55 and 60 are 7905 and 9833 km s\(^{-1}\) respectively, where the mean redshift for the Coma cluster is 7200 km s\(^{-1}\) (Colles & Dunn 1996). The aggregate with the higher radial velocity, RB 60, is more than 1 \( \sigma \) above the mean Coma velocity dispersion, and could therefore be 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 that morphologically qualifies as a galaxy aggregate is the Coma cluster member NGC 4858 (Fig. 4), a starburst SBb galaxy located 13 \( h^{-1} \) kpc away from the larger E0 galaxy NGC 4860. The redshifts for these members are 9436 and 7864 km s\(^{-1}\) respectively. Towards the interface between NGC 4858 and 4860 are knots, or dwarf galaxies distributed almost symmetrically about NGC 4858 (Fig. 4). The average distance of the knots from NGC 4858 is 6 \( h^{-1} \) kpc.

The luminosity functions of the aggregates are shown in Fig. 5. RB 55 and 60 are both dominated by a galaxy of \( R \) magnitude around 17, with the 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. We could, however, be biased by completeness, as galaxies fainter than magnitude 22 could possibly be missed, owing to detection limits.

The \((B-R)\) versus \( R \) plots (Fig. 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, Harris & Plummer 1997).

Narrow-band WIYN images of the aggregates RB 55 and 60 taken under mediocre conditions do not show high amounts of Hβ emission from the smaller members.

5 RESULTS AND ANALYSIS

5.1 Chance alignments

In a dense cluster like Coma, galaxy aggregates could 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 the Coma cluster away from the aggregates on our 6.7 arcmin field CCD images is 4.7 galaxies arcmin⁻². The surface densities of knots in the aggregates are 36 galaxies arcmin⁻² for RB 55, 32 galaxies arcmin⁻² for RB 60 and 38 galaxies arcmin⁻² in NGC 4858: objects of extremely high number density. 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 and Perseus. Our images of these clusters contain most of the inner cores, about 47 arcmin², with Perseus having 92 arcmin² of covered area. For Coma, our eight images cover almost the entire core, as well as some outer core regions. We, however, find nothing approaching the similarity of the Coma aggregates in these other images.

In our eight Coma fields, there are about 225 galaxies with sizes similar to, or greater than, the aggregates. Except for the aggregates, only a few examples exist of galaxies that have even a slight overdensity of smaller, nearby objects in our Coma images. Based on these numbers, only about 1.3 per cent of all moderately large Coma core galaxies show any overdensity of small companions. If chance superpositions were the cause, we would expect to see the phenomenon in various degrees centred about other galaxies, but we find only aggregates, or no significant overdensities. These objects 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. 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 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 disc of the central galaxy or in surrounding dwarf satellites might be triggered via interactions with other cluster members, or as an effect of the cluster’s overall gravitational potential. Evidence for star formation induced by interactions within clusters comes primarily from the presence of blue disc 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 characteristic of recent infall 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 (e.g. Bothun & Dressler 1986; Caldwell et al. 1993). 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 (Moore et al. 1996).

A more general mechanism for perturbing infalling galaxies and producing unusual stellar clumps may come from interactions with the cluster’s overall tidal field. In Merritt’s (1984) model, galaxies that 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 v₀ and that of the cluster v_cl. The minimum tidal radius r_T then varies approximately with the cluster core radius R_c as

\[ r_T = R_c \frac{1}{2} \frac{v_0}{v_cl} \]

Galaxies with disc or satellite system radii that exceed r_T may experience significant distortion from the cluster tides.

In Coma, R_c = 0.15 and v_cl = 1062 km s⁻¹ (Kent & Gunn 1982). Adopting 100 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 kpc. In the RB 55 and 60 systems the faint knots are found at about this radius.

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

5.3 Ram pressure stripping

Ram pressure is a primary environmental influence exerted by a rich cluster 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, remains uncertain.

6 DISCUSSION

Three galaxy aggregates centred around NGC 4858, RB 55 and RB 60 have been found in the Coma cluster. These consist of moderate-
sized disc galaxies nested in several luminous knots or dwarf galaxy-like objects, which in RB 55 and 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 overdensities 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 gravitational interactions with neighbouring galaxies or with the cluster as a whole during the infall of disc 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 disc galaxy or its companions, then their radial velocities will be close to those of the primary galaxy, and the spread in velocities will be $100-300$ km s$^{-1}$, typical of internal motions in small galaxy groups.

If these aggregates were real physical associations then the knots, at the distance of the Coma cluster, would have absolute magnitudes between $-12$ and $-14$. If these objects were sites of recent star formation, they could be progenitors of dE or dSph galaxies with these magnitudes, after fading from the initial star formation events. These faded objects would then have magnitudes overlapping those of local group dSphs. If these galaxy aggregates were proven to be real physical entities, it would give a strong indication of the dynamic evolutionary state of Coma.

ACKNOWLEDGMENTS

We thank D. J. Pisano and Keivan Stassun for assistance with the photometry. We also thank the referee for useful comments which improved the presentation of this paper.

The WIYN Observatory is a joint facility of the University of Wisconsin–Madison, Indiana University, Yale University and the National Optical Astronomy Observatories.

REFERENCES

Baier F. W., 1984, Astron. Nachr., 305, 175
Sarazin C. L., 1986, Rev. Mod. Phys., 58, 1