Part 3

FORMATION AND TRANSFORMATION OF GALAXIES

Section A

Nurture and genetics of galaxies

Outskirts of Galaxy Clusters: Intense Life in the Suburbs
Proceedings IAU Colloquium No. 195, 2004
A. Diaferio, ed.

DOI: 10.1017/S1743921304000717

The properties of galaxies on the outskirts of clusters

Erica Ellingson

Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309, USA email: elling@casa.colorado.edu

Abstract. The outskirts of clusters are dynamically complex regions populated by galaxies falling into the cluster potential for the first time as well as some which have already visited the cluster core. Addressing the properties of galaxies in these transition regions requires the integration of cluster dynamics, an understanding of environmental influences on galaxies at both high and low densities and hierarchical scenarios of cluster formation and growth. In this review I describe some recent observational results on galaxies in the outskirts of clusters, and the evolution of galaxies in clusters as a function of local density and radius.

1. Introduction

The regions between the central virialized cluster cores and the general field hold special interest for both galaxy evolution and cosmological investigations. While the over densities measured on large scales in this region are small, these regions provide constraints on environmental mechanisms which might occur in lower-density environments prior to infall into clusters. The infall regions at the edges of clusters also form a direct link between the cluster and the rest of the universe, sampling the filamentary structures that eventually flow into clusters.

The standard portrait of massive galaxy clusters is on the surface quite simple. The cores are dominated by red, early-type galaxies containing very little new star formation. Observations at both low and high redshifts indicate that the stars in many of these galaxies formed at very high redshifts ($z > 2$; Bower, Lucey & Ellis 1993, Stanford et al. 1998, van Dokkum et al. 1998 and others) and have been evolving passively since then. Later type galaxies are found more commonly at larger radii (e.g., Dressler 1980, Whitmore et al. 1993), with spatial and dynamical properties consistent with being relatively new arrivals into the cluster potential well. This phenomenon was shown exceptionally well by Biviano & Katgert 2004, in these proceedings, who show that both red and blue populations are in dynamical quasi-equilibrium with the cluster potential, but that the red galaxy population is a much better spatial tracer of the underlying mass distribution. Blue galaxies show a broader spatial extent, but are in equilibrium with the same gravitational potential. These blue galaxies are expected over time to transform into a less-active population due to some environmental process associated with the cluster environment which curtails star formation. The ensuing gradients in cluster populations, from red cores to bluer outskirts, reflect the balance between the infall of star-forming galaxies and the efficiency with which star formation is squelched.

The physical mechanisms which may be responsible for the lower fraction of star-forming galaxies in dense environments include attacks on both the physical structure and gas content of the galaxies. Individually or in combination, they appear to be sufficient to transform normal field spirals into the observed cluster core populations. Possible mechanisms include galaxy-galaxy mergers, "harassment", ram-pressure stripping of gas from infalling galaxies by a dense intra-cluster medium, the disruption of halo gas reservoirs and tidal disruption from the cluster potential (e.g., Lavery & Henry 1986, Dressler & Gunn 1983, Moore et al. 1996, Fujita 1998 and others). Despite this litany of violence, the mechanisms which dominate galaxy evolution in and near clusters are not well constrained. Studies of galaxies in the regions intermediate between cluster and field provide more specific clues as to which mechanisms dominate in which environments.

2. Properties of galaxies in the outskirts of clusters

Until recently, comprehensive studies of the outskirts of galaxy clusters have been difficult. At lower redshifts, the large field sizes required have been a poor match to previous instrumentation, and at higher redshifts (or fainter magnitudes at lower redshift), contamination from unrelated galaxies overwhelms the low-density cluster counts. Wide field detectors, photometric redshift techniques and very large spectroscopic surveys have made extraordinary advances in the past few years, producing detailed inventories of cluster outskirts.

Results from the 2dF Survey (Lewis et al. 2002) provided a first spectroscopic measure of star formation in cluster galaxies to very large radii (up to 10 times the virial radius). They found strong gradients in the star formation rates as measured via Hα emission, with cluster cores containing very little star formation, and a smooth gradient leading to field galaxy levels. Somewhat unexpectedly, star formation in galaxies was measurably suppressed well beyond the cluster virial region, where the most powerful environmental processes are expected to occur. Gradients in galaxy star formation rates via [OII] were also measured for intermediate redshift clusters, with qualitatively similar findings, to about twice the virial radius (Balogh et al. 1997).

Gradients in galaxy properties have also been measured by several investigations based on the Sloan Digital Sky Survey (SDSS) database. Gomez et al. (2003) found that star formation rates in clusters at $3-4$ virial radii were suppressed relative to the field population. Goto et al. (2003) traced gradients in the morphologies of galaxies in clusters using SDSS data, finding that elliptical galaxies dominate the cores, but that intermediate-type morphologies (generally S0 galaxies according to their classification scheme) are seen at $0.2-2$ virial radii. This scenario appears to be consistent with the paradigm where field spirals are transformed to S0 galaxies via some environmental mechanism.

It has long been known that cluster spirals are deficient in their HI gas content (Giovanelli & Haynes 1985; see also Solanes et al. 2001). As with star formation rates and galaxy morphologies, radial gradients show a smooth transition from gas-poor cores to the properties of normal field galaxies, possibly also with an extension beyond the virial radius (Sanchis et al. 2004, Mamon et al. 2004).

3. Suburban lifestyles near the big city

These detailed studies suggest, unsurprisingly, that cluster environments are hazardous for gas-rich, star-forming and disk galaxies, and that one or more of the mechanisms suggested for affecting galaxy properties is at work in and near the clusters. The large radial range of affected galaxies, well beyond the virial region, suggests that these effects may begin to occur well before galaxies are incorporated into the cluster potential, thus diminishing the roles of ram-pressure stripping and other mechanisms which require a dense intra-cluster medium or a deep gravitational potential and promoting galaxy interactions and other mechanisms which dominate in small group environments.

https://doi.org/10.1017/S1743921304000717 Published online by Cambridge University Press

However, the transition regions between the cluster virialized region and the general field are dynamically complex and the galaxies in these regions are a mixture of both infalling objects and objects which have passed once through the inner regions and have scattered out again. Timescales for travel in and through the clusters are generally shorter than the stellar evolution timescales which govern the wholesale spectral and morphological changes seen from field to cluster core. This will inevitably produce a blurring in the galaxy populations near the virial radius. Within the suburban analogy, galaxies in cluster outskirts correspond to residents of small communities near the big cities. Local teenagers have certainly visited the city at some point and returned home (at least for awhile). While their present observed environment may seem tame and suburban, it is not unsurprising that many of them will have purple hair, tattoos and pierced tongues.

How many of the galaxies in the infall regions have actually fallen through the central core regions and are outside the virial radius as "backsplash?" Balogh, Navarro & Morris (2000) suggested roughly 50% of galaxies between 1 and 2 virial radii were previously inside the virial radius (see also Moore et al., in these proceedings). A detailed dynamical simulation of the Virgo cluster by Mamon et al. (2004) also showed some scatter beyond the virial radius, but very little outside of 2 virial radii. Clearly, some of the decrease in star formation in cluster galaxies near the virial radius may still be due to deep-potential mechanisms.

Galaxies which are truly infalling for the first time probably dominate at radii larger than 2 virial radii. However, these galaxies are also not expected to be identical to an untouched field population. The well-established morphology-density effect (Dressler 1980) shows a continuous decline in the spiral population throughout several orders of magnitude in projected galaxy density. While density is degenerate with radius for massive, regular clusters, studies of irregular clusters and groups suggest that local density is a primary driver in galaxy evolution. In hierarchical scenarios, clusters grow via the merging of these smaller structures, implying that a significant amount of pre-processing may occur in the galaxy population while they live in group-sized structures and before they are incorporated into a massive system. Thus the outskirts of clusters should be composed of a dynamic mixture of both infalling and back-splashing galaxies, each of which will have stellar populations and morphologies which are different from a pristine field population, but which may reflect the effects of very different environmental mechanisms.

The apparent strength of the influence of local density on galaxy properties begs the question: do cluster-scale environments matter at all? If the infall and merging process allows galaxies in general to retain their local density, then the observed cluster radial gradients could simply be a spatial restructuring of the morphology-density effect with no additional environmental influence required from the cluster itself. Several recent studies suggest that there are small but detectable differences in the morphology-density relation depending on whether the galaxies are near massive clusters. Balogh et al. (2002) found that high X-ray luminosity (presumably more massive) clusters had a marginally smaller fraction of star forming galaxies at a given local galaxy density than did clusters with lower X-ray luminosities. Subsequent studies of SDSS clusters (Balogh et al. 2004) suggested that star formation rates are primarily correlated with local density, but that galaxies in the densest regions in and near clusters show lower star formation rates than more isolated systems of similar density. These studies suggest that cluster-scale structures do indeed have an additional effect on galaxy star formation rates.

https://doi.org/10.1017/S1743921304000717 Published online by Cambridge University Press

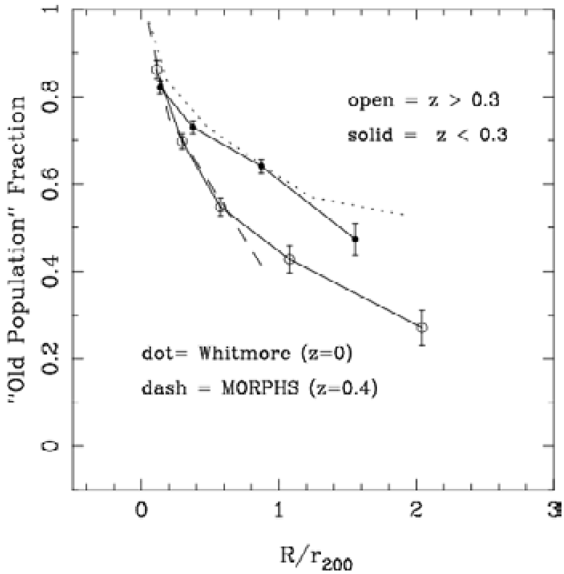

Figure 1. Fraction of cluster galaxies with old (early-type) spectral features, as a function of radius for $\sim$ 900 galaxies in 16 clusters from the CNOC sample at $0.2 < z < 0.55$ (Ellingson et al. 2001). The cores of the clusters are consistently dominated by old, red galaxies, while the outskirts have a higher fraction of star forming and intermediate age galaxies at higher redshifts. Data from $z = 0$ (Whitmore et al. 1993) and regular clusters from $z = 0.4$ (MORPHS; Dressler et al. 1997) are overplotted, assuming that their morphological elliptical and S0 types correspond to old spectral types. Note that for this composite cluster radius and density are essentially degenerate.

4. Evolution in cluster population gradients

These results from the low density outskirts of cluster reinforce the concept that clusters are not closed boxes, and that understanding even the core cluster properties requires an understanding of the structures from which the cluster was created. Studies of clusters at intermediate and high redshift suggest significant evolution in cluster properties since $z \sim 1$, which may be related to changing infall rates and the evolving field and infalling population more than evolution of the physical cluster environment.

The Butcher-Oemler effect is a classic measure of cluster evolution; the fraction of blue galaxies within clusters is seen to increase from a few percent at $z = 0$ to a substantial fraction of the cluster population at $z \sim 0.5$ and higher (e.g., Butcher & Oemler 1978, 1984; and many others). The origin of this effect can be constrained by examining the radial gradients in these clusters as a function of redshift. Figure 1 shows the fraction of spectroscopically-identified old (early-type spectra) population galaxies as a function of radius for clusters in the CNOC cluster sample (Canadian Network for Observational Cosmology; Yee, Ellingson & Carlberg 1996). The Butcher-Oemler effect is confirmed explicitly in the sample photometry; here the evolution is seen to be dominated by changes in the cluster outskirts. While the core regions appear to evolve very little, the gradients between 0.3 and 1.5 r_{200} are steeper at higher redshift. This suggests that cluster evolution even within the virial radius is most likely related to changes within the infalling population rather than physical properties of the core region.

Radial distributions of the galaxies in this sample show that the old population has a remarkably constant profile, while the remaining galaxies (star-forming and intermediate age populations) form a spatially broader profile that declines over time. This pattern

https://doi.org/10.1017/S1743921304000717 Published online by Cambridge University Press

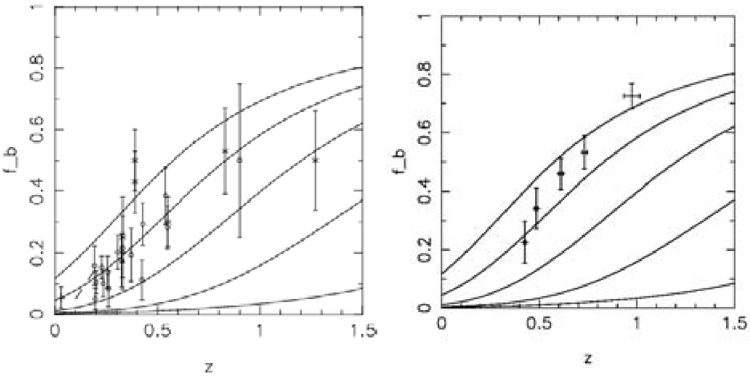

Figure 2. (a, left) The Butcher-Oemler effect from CNOC clusters and clusters gathered from the literature. Measures of galaxy properties, counting radii and magnitude limits are roughly similar for different investigations, but please note that the data are still somewhat inhomogeneous. Model curves are for expected infall rates and transformation timescales of 0.5, 1.0, 1.5, 2.0 and 2.5 Gyr, from lower to upper (see text for details). (b, right) Preliminary results from 85 clusters from the RCS survey with richness > Abell class 0. Average blue fractions in the highest redshift bin are corrected for the slight selection effect expected from a red-sequence-selected cluster sample; corrections at lower redshift are expected to be minimal.

mirrors that from dynamical studies of clusters at lower redshift (e.g. Biviano & Katgert 2004, in these proceedings), which identify spatially broad, bluer galaxy populations as newly infalling galaxies. These results suggest that the Butcher-Oemler effect is driven primarily by a decline in the cluster infall population over time.

Such a decline in the overall infall rates is expected for currently accepted cosmological models. Figure 2a shows the fraction of blue galaxies within the virial radius as a function of redshift for a number of clusters. Model curves show the expectation from extended Press-Schechter (Lacy & Cole 1993) infall rates through the cluster virial radii for a Λ–CDM cosmology. The infalling galaxy population is modeled after an evolving field population. After infall, galaxies are transformed from "blue" to "red" on a given exponential timescale. These models are very simple, but illustrate that the Butcher-Oemler effect is generally consistent with expected infall rates and a constant transformation timescale of about 2 Gyr. This timescale seems short; even with an abrupt halt to star formation at the virial radius, stellar evolution timescales would still require at least $1-1.5$ Gyr. Significant pre-processing of the infalling galaxies could (and probably does) lengthen this timescale to allow for one or two crossing-times to pass before star formation is completely quenched.

Figure 2b shows a similar plot using 85 clusters in the optically-selected cluster sample from the Red Sequence-Cluster Survey (Gladders & Yee 200). These results suggest an even steeper Butcher-Oemler effect at $z > 0.5$. While these results are very preliminary, they can be used to frame the pertinent questions. A steeper relation could mean that inner-cluster mechanisms are less efficient in quenching star formation in the infalling galaxies. This would correspond to a longer transformation timescale due to either a changing physical environment or more resilient galaxies with deeper gas reservoirs at higher redshifts. The other possibility is that less pre-processing is in effect at higher redshift.

Evolution in the morphology-density relation at lower densities indeed supports a scenario where at least part of the explanation is due to less pre-preprocessing. Morphological studies of intermediate redshift clusters (Dressler et al. 1997, Treu et al. 2003) show a

https://doi.org/10.1017/S1743921304000717 Published online by Cambridge University Press

significant morphology-density relation which, like the low-redshift relation, appears to be broadly consistent for a given local projected density, regardless of whether the galaxy is in the throes of the cluster core environment or in its outskirts. The intermediate redshift relation is offset towards a lower fraction of early-type galaxies at a given density relative to the $z = 0$ relation, particularly at the group/poor-cluster densities which form the likely infalling population.

However, linking this evolution specifically to the evolution of populations within clusters requires a more detailed understanding of the structures falling into clusters as a function of redshift. Tracing the low-density filamentary structures around clusters is a very difficult observational task, particularly at higher redshifts where foreground/background contamination dominates the galaxy counts. Photometric redshift techniques show significant promise in tracing this structure beyond the cluster core. Kodama et al. (2001, in these proceedings; see also Gray et al., and Li et al., in these proceedings) have traced groups and substructures around clusters at intermediate redshifts, confirming a correlation of galaxy colors with galaxy surface density. Such studies provide critical observational tests of hierarchical cluster formation.

5. Summary

Like their suburban counterparts, the outskirts of clusters are complicated regions where inner-city and rural populations blend. New wide-field surveys of low-redshift clusters have documented an extension of environmental effects on galaxies to very low density regions around clusters. These results underscore the need for detailed dynamical modeling of the clusters to several virial radii in order to disentangle galaxies falling into the cluster for the first time from those who have already visited the denser regions. The strong influence of local density on infalling galaxies provides a basis for evaluating the amount of pre-preprocessing in groups and lower-density structures, and the additional effects of mechanisms at work within the deep cluster potential. At this point, evidence for additional damage by the cluster is becoming well-established, but may be subordinate to the effects of local environment before and during the infall phase. If this is the case, then substructure must be retained to a significant extent during and after infall.

The evolution of cluster properties, particularly in the outskirts, appears to be strongly dependent on the infalling population, both in terms of infall rates and the properties of the infalling galaxies. As at low redshift, understanding the correlations of galaxy properties and local density at low densities is necessary for assessing the relative importance of environmental mechanisms inside and outside of the cluster virial regions. Currently our picture of cluster evolution is incomplete, with significant uncertainties in the infall rates, the amount of pre-processing, and the efficiency of the cluster core at diminishing star formation. New clusters samples at high redshift and ongoing work on measuring cluster properties to higher redshifts currently hold promise for providing the necessary context for tracing cluster evolution in a fully cosmological context.

References

Balogh, M. L., et al., 1997, ApJ, 527, 54
Balogh, M. L., Navarro. J., Morris, S. L., 2000, ApJ, 540, 113
Balogh, M. L., et al. 2002, MNRAS, 335, 10
Balogh, M. L., 2004, MNRAS, 348, 1355
Bower, R. G., Lucey, J. R., Ellis, R. S. 1992, MNRAS, 254, 601
Butcher, H., & Oemler, A., Jr. 1978, ApJ, 226, 559

https://doi.org/10.1017/S1743921304000717 Published online by Cambridge University Press

Butcher, H., & Oemler, A., Jr. 1984, ApJ, 285, 426
Dressler, A. 1980, ApJ, 236, 351
Dressler, A., et al. 1997, ApJ, 490, 577
Ellingson, E., Lin, H., Yee, H. K. C., Carlberg, R. G., 2001, ApJ, 547, 609
Fujita, Y. 1998, ApJ, 509, 587
Giovanelli, M.P. & Haynes, M., 1985, ApJ, 292, 404
Gladders, M. D., Lopez-Cruz, O. Yee, H. K. C., Kodama, T., 1998, ApJ, 501, 571
Gladders M. D. & Yee, H. K. C., 2000, AJ, 120, 21
Gomez, P., et al., 2003, ApJ, 584, 210
Goto, T., et al, 2004, MNRAS, 348, 515
Kodama, T., et al. 2001, ApJ, 562, 9
Lacey, C. & Cole, S., 1993, MNRAS, 262, 627
Lavery, R. J., & Henry, J. P. 1988, ApJ, 330, 596
Lewis, I. et al., 2002, MNRAS, 334, 673
Mamon, G., 2004, A&A, 414, 445
Moore, B., et al., 1996, Nature, 379, 613
Sanchis, T., et al., 2004, A&A, 418, 393
Solanes, J. M., 2001, ApJ, 548, 97
Stanford, S. A., Eisenhardt, P. R., Dickinson, M., 1998, ApJ, 492, 461
Treu, T., et al., 2003, ApJ, 591, 53
van Dokkum, P. G., et al., 1998, ApJ, 504, L17
Whitmore, B. C., Gilmore, D. M., Jones, C. 1993, ApJ, 407, 489