Enhanced interactions, mergers and starbursts in dense cluster environments

C. Moss
Astrophysics Research Institute, Liverpool John Moores University,
Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD, U.K.

Abstract.
Optical and X-ray studies have established the prevalence of significant substructure in clusters of galaxies, indicating that clusters are young systems, and that recent major mergers have occurred in many clusters. Numerical simulations show that sub-cluster merging will result in significant tidal forces on disk galaxies in accreting sub-groups, which is likely to lead to the transformation of spirals to S0s in clusters. Simulations predict simultaneous moderate starbursts in gas-rich disk galaxies in clusters which show on-going or recent merger activity, as well as enhanced galaxy–galaxy interactions and mergers. Observational data from studies of spectral indicators, both of starburst activity in late-type galaxies in nearby clusters, and of poststarburst activity in early-type galaxies in nearby and intermediate redshift clusters, support this scenario.

1. Introduction: sub-cluster merging and cluster disk galaxy evolution

Both optical studies of sky-projected cluster galaxy distributions (e.g. Baier 1979; Geller & Beers 1982) and studies of cluster X-ray morphologies (e.g. Mohr, Fabricant & Geller 1993; Buote & Tsai 1996) reveal the presence of significant substructure in clusters of galaxies. Subgroup velocity statistics (e.g. Dressler & Shectman 1988; Bird 1994; Girardi et al. 1997; Solanes, Salvador-Solé & González-Casado 1999) confirm these results, and are in substantial agreement in showing that some 30–40% of clusters have statistically significant substructure.

Numerical simulations also show that subclustering is a typical property of cluster formation in hierarchical theories of structure formation. Such subclustering is expected for a broad range of cosmologies, and its predicted extent is in agreement with that observed (e.g. Knebe & Müller 2000). Its prevalence indicates that clusters are young objects, since such substructure is expected to be smoothed out over a few cluster crossing times. Moreover the existing substructure indicates that recent major mergers have occurred in many clusters.

The evolution of cluster substructure is potentially of great importance for its influence on the star formation histories and morphological evolution of cluster galaxies (e.g Tully & Shaya 1984; Lavery & Henry 1988; Gnedin 1999; Bekki 1999). However, until very recently this potential influence has largely been neglected (cf. Bekki 1999). Of particular interest, is its relevance to the evolution of disk galaxies in clusters.
As is well known, Butcher & Oemler (1978) found that the cores of intermediate redshift clusters contain a higher fraction of blue, star-forming galaxies than similar environments at the present. These galaxies have been shown to be normal spiral or irregular galaxies, a fraction of which are obviously interacting or disturbed (e.g. Dressler et al. 1994; Oemler, Dressler & Butcher 1997; Smail et al. 1997). In rich clusters they constitute up to 50% of the population, but by the present epoch have been depleted by a factor of two and replaced by a corresponding increase in S0s (e.g. Dressler et al. 1997). Wang & Ulmer (1997) have found a correlation between the fraction of blue galaxies in intermediate redshift clusters and the cluster X-ray ellipticities. They interpret the latter as an age sequence, and conclude that the younger clusters have a higher fraction of blue, star-forming galaxies. As the authors note, this interpretation is in accord with a hierarchical clustering scenario, in which a typical distant cluster is assembled from smaller units which tend to contain more gas-rich, late type galaxies. The relative depletion of such star-forming galaxies in older, more relaxed clusters, suggests that the process of sub-cluster merging plays a crucial role in the transformation of an initial population of cluster spirals to a subsequent S0 population.

What effect is the sub-cluster merging process likely to have on a population of gas-rich, star-forming disk galaxies? Bekki (1999) using numerical simulation of a merger between a small group of galaxies and a cluster, shows that the time-dependent tidal gravitational field of the merger gives strong nonaxisymmetric perturbations to the disk galaxies in the group, inducing simultaneous moderate secondary starbursts in the central regions of the galaxies.

Similarly, Gnedin (1999) using self-consistent cluster simulations, demonstrates that for substantial infall of additional material into a cluster, the time-varying gravitational potential causes a sequence of tidal shocks on individual galaxies over a wide area of the cluster. These shocks enhance galaxy–galaxy interactions as well as amplifying galaxy merger rates. Again the effect is also likely to induce simultaneous starbursts in gas-rich infalling disk galaxies over a wide area of the cluster. Moreover, the tidal shocks are shown to typically thicken the disks of large spirals by a factor of two, making it unlikely that spiral structure and gaseous shocks in the inner regions of the galaxies will form. A significant amount of the dark matter halo is stripped, possibly removing the reservoir of fresh gas which maintains the star formation activity (cf. Larson, Tinsley & Caldwell 1980). While gas in the outer regions of the disk can be stripped by the ram pressure of the ambient medium, interpenetrating collisions with neighbouring galaxies could remove all their gas. The effect of all these tidal transformations is the conversion of spirals to S0s.

2. Observational evidence for tidally-induced starbursts in cluster galaxies

The theoretical considerations discussed above suggest that (moderate) tidally-induced starbursts should be widespread in cluster gas-rich disk galaxies in clusters which show evidence of on-going or recent merger activity. Together with enhanced starburst activity, enhanced galaxy–galaxy interactions and mergers are also expected. In fact, there is considerable observational evidence to support
this scenario, both from studies of early-type and late-type galaxies in nearby clusters, and from evidence of poststarburst galaxies in intermediate redshift clusters. This evidence is now briefly reviewed.

Caldwell et al. (1993) have surveyed early-type galaxies in the Coma cluster and found an unusually high number with spectra that reflect recent enhanced star formation activity in a substructure of the cluster. As noted by Bekki (1999), this may readily be explained as due principally to tidal gravitational effects of a group-cluster merger with rather large relative velocity. Caldwell & Rose (1997) also found a larger fraction of poststarburst galaxies in nearby clusters with obvious double structure. In a similar fashion, Bekki notes that these results can also be explained by the tidal effects of cluster mergers.

Moss & Whittle (2000) have undertaken an Hα survey of a magnitude-limited complete sample of 320 galaxies of types Sa and later within 1.5h^-1 Mpc of the centres of 8 nearby Abell clusters. Some 116 of the sample were detected in emission. A subset of the emission-line galaxies are found to have tidally-induced circumnuclear starburst emission, as evidenced from the particular Hα morphology, and its strong correlation with a disturbed galaxy morphology. Starburst emission is found to be most prevalent in the richest clusters in the survey. The percentage of the total sample of late-type galaxies with starburst emission is ~ 40% for the two richest clusters, Coma and Abell 1367. In contrast, the corresponding percentage for field galaxies in the sample is only a few percent. Moreover X-ray morphologies and temperature structures for Coma and Abell 1367 indicate that both these clusters are recent post-merger systems (cf. Donnelly et al. 1998; Honda et al. 1996). Again, a plausible explanation for the enhanced starburst activity seen in the clusters, is tidal effects of subcluster merging.

Moss & Whittle also identify a class of late-type galaxies in their sample which are likely to be on-going mergers, in which the companion is indistinguishable from its merger partner. These on-going mergers are most prevalent in the Coma cluster. They are likely to represent a later stage of close double, interacting systems with tidally induced emission which comprise a significant fraction (~ 14%) of the galaxies they detect with starburst emission.

For intermediate redshift clusters, there is also evidence of an enhancement of starburst emission. Galaxies with spectra showing strong Balmer lines in absorption, indicative of a poststarburst phase, are an order of magnitude more frequent in the cluster environment as compared to the high redshift field (e.g. Dressler et al. 1999; Poggianti et al. 1999). A surprising fraction of the star-forming galaxies at intermediate redshift show signs of morphological disturbance, of which many are suggestive of merging systems, virtually always involving a disk galaxy (cf. Ellis 1999). This suggests a tidal origin for the starburst phase, although no clear difference in the incidence of disturbed morphology between the high redshift field and cluster environments has been established (cf. Dressler et al. 1999).

3. Conclusion

Strong theoretical and observational data suggest that sub-cluster merging plays a crucial role in the transformation of spirals to S0s in the process of cluster for-
mation, due to the strong tidal forces on the disk galaxy members of an accreting sub-group. Theoretical studies predict simultaneous moderate starbursts in disk galaxies of the accreting sub-group due to tidal forces. This prediction is supported by observational data for both nearby and intermediate redshift clusters. Tidal shocks due to the time-varying potential associated with sub-cluster merging are expected to effect morphological transformation of star-forming disk galaxies to S0s. Thus these can explain the transformation of the majority of the spiral population in younger, less relaxed clusters to a population of S0s in older, more relaxed clusters as an integral part of the process of cluster formation.

References

Baier, F. 1979, Astron. Nachr., 300, 85
Bekki, K. 1999, ApJ, 510, L15
Bird, C.M. 1994, ApJ, 107, 1637
Buote, D.A. & Tsai, J.C. 1996, ApJ, 458, 27
Butcher, H. & Oemler, A. 1978, ApJ, 219, 18
Caldwell, N. & Rose, J. 1997, AJ, 113, 492
Caldwell, N., Rose, J., Sharples, R.M, Ellis, R.S. & Bower, R.G. 1993, AJ, 106, 473
Donnelly, R.H. et al. 1998, ApJ, 500, 138
Dressler, A. & Shectman, S.A. 1988, AJ, 95, 985
Dressler, A., Oemler, A., Butcher, H.R. & Gunn, J.E. 1994, ApJ, 430, 107
Dressler, A. et al. 1997, ApJ, 490, 577
Dressler, A. et al. 1999, ApJS, 122, 51
Ellis, R.S. 1999, in IAU Symp. 183, The Formation and Evolution of Galaxies, ed. K. Sato, (Dordrecht: Boston), 107
Geller, M.J., & Beers, T.C. 1982, PASP, 94, 421
Girardi, M. et al. 1997, ApJ, 482, 41
Honda, H. et al. 1996, ApJ, 473, L71
Gnedin, O.Y. 1999, Ph.D. Thesis, Princeton Univ.
Knebe, A. & Müller, V. 2000, 354, 761
Larson, R.B., Tinsley, B.M. & Caldwell, C.N. 1980, ApJ, 237, 692
Lavery, R.J. & Henry, J.P. 1988, ApJ, 330, 596
Mohr, J.J., Fabricant, D.G. & Geller, M.J. 1993, ApJ, 413, 492
Moss, C., & Whittle, M. 2000, MNRAS, 317, 667
Oemler, A., Dressler, A. & Butcher, H.R. 1997, ApJ, 474, 561
Poggianti et al. 1999, ApJ, 518, 576
Smail, I., Dressler, A., Couch, W.J., Ellis, R.S., Oemler, A., Butcher H. & Sharples, R.M. 1997, ApJS, 110, 213
Solanes, J.M., Salvador-Solé, E. & González-Casado, G. 1999, A&A, 343, 733
Tully, R.B. & Shaya, E.J. 1984, ApJ, 281, 31
Wang, Q.D. & Ulmer, M.P. 1997, MNRAS, 292, 920