OBSERVATIONAL EVIDENCE FOR SPECTRAL EVOLUTION OF CLUSTER GALAXIES

Alan Dressler
Mount Wilson and Las Campanas Observatories
813 Santa Barbara Street
Pasadena, CA 91101

James E. Gunn
Peyton Hall
Princeton University
Princeton, NJ 08544

1. USING CLUSTER POPULATIONS TO INVESTIGATE GALAXY EVOLUTION

The study of galaxy evolution with large lookback times is dominated by two difficult issues. The first is a technical matter. Even the most luminous galaxies are faint ($m_r < 19$) at significant lookback times ($z \gtrsim 0.5$), and so spectrophotometric observations of average galaxies challenge our present telescope and detector technology. The second issue is the selection of objects in an unbiased way in order to assemble a representative sample of galaxies at the remote epoch. It is far too easy to chase only exotic objects whose very peculiarity has brought them to our attention. Though observations of such objects may be fascinating and revealing, they may tell us little about the evolution of an typical galaxy like our own.

Spurred on by the photometric observations of Butcher and Oemler (1978,1984) which indicated a dramatic evolution of cluster galaxies in only the last 5 Gyr, we began in 1981 to make spectroscopic observations of a sample of galaxies in distant clusters. With a high efficiency spectrograph and CCD detector on the Palomar 5m Hale telescope, we are able to obtain useful low-resolution spectra of normal galaxies even up to z = 0.8 with exposure times of less than 10 hours. An aperture mask of ~10 small slits thus enables, but by no means makes easy, the study of typical galaxies at cosmologically significant lookback times.

Observations of galaxies in clusters provide a practical though imperfect solution to the problem of selection effects. Because of their high densities and predominance of early type galaxies, clusters do not offer us a sample of average galaxies in typical environments, but they do offer us a volume limited sample of

J. Audouze et al. (eds.), Large Scale Structures of the Universe, 311–319.

galaxies under similar conditions for a range of epoch $z \lesssim 1$. Though there may have been some question at first as to whether distant clusters were, by selection, all extraordinarily rich or dense, more complete surveys like that done by Gunn, Hoessel, and Oke (1986), have identified clusters that appear, based on their space densities and luminosity functions, to be the ancestors of at least the richer present-epoch clusters like Coma or Hercules. We will return to this question of the representativeness of the cluster sample later.

Our present sample consists of 7 intermediate redshift clusters in the range $0.37 < z < 0.55$ and 4 high redshift clusters $0.65 < z < 1.0$. We typically have photometry of 100-300 galaxies with $18.5 < m_r < 23.5$ in fields of size 5' x 5'. For the intermediate redshift sample we have collected usable spectra of 20-50 galaxies with typical magnitudes of $20 < m_r < 22$ in each of these fields but we are are just beginning to accumulate a reasonable number of spectra for the high-z sample. We also have available a low-z sample of roughly 1000 spectra of galaxies in clusters with $z < 0.06$, obtained by Dressler and Shectman.

2. A HIGHER FRACTION OF ACTIVE GALAXIES IN HIGH REDSHIFT CLUSTERS

Turning first to the intermediate-z sample, we have redshifts for 236 objects in the following 7 clusters:

TABLE 1: The Intermediate Redshift Sample

Designation	z	f (%)	E+A	em+AGN
9HFCL27	z = 0.38	27±15	3	1
9HF$\alpha\beta$	z = 0.39	27±8	2	10
Cl0024+24	z = 0.40	22±9	6	1
3HFCL2	z = 0.42	34±17	1	4
3C295	z = 0.46	39±18	3	3
Cl0016+16	z = 0.54	31±10	7	5
16HF$\beta\beta$	z = 0.54	37±15	3	5

Of these 236 objects, 163 are members of the seven clusters and 73 are "field galaxies". This averages out to 15-30 members per cluster over an area which, at this redshift, corresponds to about two square megaparsecs.

Although Butcher and Oemlers' claim of significant evolution was based on a distinction between "red" and "blue" galaxies, our data lend themselves better to a separation into what we call "passive" and "active" galaxies. "Active" galaxies are those with signs of recent star formation or an active nucleus. These are to be contrasted with "passive" galaxies, those with a K-giant spectrum typical of an old stellar population, rest frame B-V ≈ 0.9, and little or no sign of star formation within the previous 5 Gyr. At the present epoch these are the spectral characteristics of E or S0 galaxies which account for about 95% of the galaxies in the inner regions of dense, concentrated clusters. As we will see, by z ~ 0.5 this fraction has dropped to about 70%.

The spectra of the "active" population can itself be divided into those with and without emission lines. Those with emission lines include galaxies with long-term, relatively steady star formation like spirals, "starburst" galaxies with greatly enhanced star formation rates (SFRs), and high-excitation spectra typical of active nuclei (AGNs). Examples of these are shown in Dressler, Gunn, and Schneider (1985). The other common type, first noted in our study of 3C295 (Dressler and Gunn 1983) is a basically old stellar spectrum, perhaps about 0.2 mag bluer in rest frame B-V than a typical passive galaxy, with strong Balmer absorption lines and little or no emission. We call these "E+A" spectra because they are well matched by adding the spectra of A stars to an elliptical-type (passive) spectrum. We have from time to time also called these "post-starburst galaxies", based on our interpretation that many of these galaxies had a significant increase in the SFR which subsided about 1 Gyr before the epoch of observation.

We have calculated the active fraction in each cluster based on both the spectral and photometric data in the following way. We divide the g-r histogram for each field studied into a red, yellow, and blue region. The contamination by field galaxies obviously increases substantially as one moves from red to blue. For each zone we use the spectral data to predict the cluster-to-field ratio, and then multiply this fraction by the total number of galaxies in the bin to the approximate magnitude limit sampled by the spectroscropic sample. This gives us a predicted cluster membership of red, yellow, and blue galaxies. We then use the spectral data to predict the active fractions in each bin based on the active-to-passive ratio for the spectroscopic sample. By dividing the predicted number of cluster members by the predicted number of active galaxies we derive the active fraction f given in Table 1. This procedure corrects for the bias we introduced by preferentially selecting bluer galaxies for spectroscopic study, although in practice this bias was almost entirely offset by the fact that the majority of these are not cluster members.

From Table 1 we see that the active fraction averages 30% with deviations that are consistent with counting statistics. It therefore appears that with this still small sample of 7 clusters we have found a significant fraction of active galaxies which, within the errors, does not vary from cluster to cluster. Note that this is true even for the often-cited cluster Cl0016+16, which was claimed by Koo (1981) to be a counterexample to the Butcher and Oemler effect of a greater fraction of blue galaxies at high redshift. Koo suggested that this distant cluster was like the low-redshift Coma cluster, but our discovery of a large population of E+A galaxies demonstrates that this is not the case. While it is true that there are few very blue galaxies in this cluster, as Koo reported, this difference may not be very significant. If, for example, many galaxies in a given cluster experience a simultaneous but temporary increase in star formation activity, the blue population could rise for a few Gyrs. Afterwards, the cluster may return to a redder color distribution but still harbor signs of a very active period. Thus the accident of the epoch of observation may make two phases of the same activity appear different and unconnected. Moreover, a breakdown of the numbers of E+A vs. emission-line galaxies, also given in Table 1, reveals that the statistics are still too poor to even substantiate a true difference in this ratio from cluster to cluster.

How does this fraction of active galaxies of 30% compare to the populations of present-epoch clusters of similar richness and density? The ~16% fraction of emission-line galaxies is significantly higher than the value of 7% found by Dressler, Thompson, and Shectman (1985) in a sample of about 1000 galaxies in low-z clusters. The distribution of luminosity and average surface brightness for this low-z sample studied by Dressler and Shectman, is very similar to the characteristics of the high-z sample, but the area survey extends to larger radii in each cluster. Dressler has redone the analysis with an area similar to that surveyed for the distant clusters and finds an emission-line frequency of a bit less than 5%. Thus an increase of at least a factor of three in the frequency of emission-line galaxies at z ~ 0.5 is implied.

The E+A case is more dramatic. Dressler identified 20 candidate objects from about 1000 low signal-to-noise spectra from the Dressler-Shectman sample, and then obtained better spectra for these with the du Pont telescope at Las Campanas Observatories. He found only 3 or 4 that were comparable to the high-z E+A galaxies, a fraction of less than 1%! Therefore, an order of magnitude increase is found in the frequency of E+A galaxies in high-z clusters. While it is true that there are examples of such galaxies in both clusters and the field at low-z, we stress that they are relatively rare.

Thus it seems clear that Butcher and Oemler were on the right track when they identified a change in cluster populations since z ~ 0.4. Although it is too early to settle the nature of this difference, there is a strong indication in our work, as well as studies by Couch and Sharples (1987) and Lavery and Henry (1986), that starbursts in some of these cluster galaxies are partly or wholly responsible for the change in spectral characteristics. We came to this conclusion for the E+A galaxies by a rough modeling of the Balmer absorption lines and continuum color (Dressler and Gunn 1983, Dressler 1987) and recently Couch and Sharples have made more detailed models of the same sort. Although it was our original interpretation that most of the objects with moderately strong emission-lines were likely to be normal spirals (e.g., Dressler, Schneider, and Gunn 1985), it is plausible that a significant number of these are starbursts caught in the act rather than spirals forming stars vigorously and continuously.

What might trigger such an increase in star formation? We have advanced the idea that a sudden increase in the SFR may be triggered in a gas-rich galaxy if it falls into the dense, high pressure intercluster gas for the first time. While ram pressure may serve to sweep out the warm intercloud medium, the dense, cold clouds may be relatively unaffected by this and instead induced to collapse by the sudden and significant increase in pressure. We have some evidence, admittedly circumstantial, from the observations that tends to support this model: (1) the active galaxies appear to preferentially populate a zone approaching but always avoiding the cluster center; (2) the typical velocities of active galaxies are ~50% higher, on average, than those of passive galaxies. Additional support for this hypothesis may be available in the analysis of high-resolution images of such galaxies that will be possible with the Hubble Space Telescope.

Consideration of an alternate hypothesis, that the starbursts might be triggered by mergers or tidal encounters, has prompted us to visually inspect all the galaxy images on our CCD frames and classify them as to whether they are isolated, have close companions, or look tidally disturbed. This classification (blind with respect to the colors or spectra of the galaxies) revealed no increase at all in the fraction of galaxies with companions or disturbed shapes for those with active spectra. One might not be surprised in the case of E+A galaxies since a merger might be well calmed after a Gyr or more, but we expect that some reasonable fraction of the emission-line galaxies, which are observed closer to the event, should have shown an increased incidence. The poor statistics of our small sample prevent us from ruling out such a model, but it is certainly clear that our data provide no support, as it probably should were this the correct interpretation.

Nor can we rule out the possibility that such evolution is independent of the cluster environment and instead reflects a time evolution of galaxies in general. Detailed comparison of cluster samples to representative field samples, like the one being assembled by Kron and Koo, should be decisive on this point.

In summary, we have strong evidence that cluster galaxies do evolve. In each of our 7 clusters at $z \sim 0.5$ we see a significant increase in the fraction of galaxies in which recent star formation has been important. The interpretation of this result remains in question, but perhaps not too far beyond our reach.

Finally, the issue of selection effects deserves further attention. Koo (1987) has argued that the reported increase in blue or active galaxies does not necessary imply that these galaxies are actually located *in the core* of the cluster. His principal concern is that interlopers *in the vicinity of* but not actually in the core are included because the redshift range covered by the velocity dispersion admits a volume hundreds of times larger than the core volume. This effect becomes more serious with increasing redshift. It is straightforward to show that this is not an important effect for the kind of sampling we have been doing. Even a volume hundreds of times larger would provide negligible contamination if the surrounding volume had the average field density (at the present epoch, $\sim 5 \times 10^{-3}$ gal Mpc^{-3} for $L_{gal} > 0.1 L_*$) because the average density contrast of the central regions of clusters is typically $\sim 10^4$.

It is likely to be the case, however, that rich clusters are imbedded in superclusters in which the density is much higher. We take a value of ρ = $\sim 10^{-1}$ from present-epoch examples like the Coma and the Local Supercluster, and a thickness of the supercluster of about 5 Mpc (see, for example, the "cone-diagrams" of deLapparent, Geller, and Huchra 1986). With these typical parameters it is clear that our 2 Mpc^2 areas will typically have ~1 supercluster galaxy superposed on the central part of the cluster. Even if the supercluster is seen edge-on (a chance occurrence of $\lesssim$10% unless selection effects are important) the contamination is ~5 interlopers. This is still small compared to the 20-30 active galaxies, but it may be large enough to be important. Therefore, it is important to know if such edge-on alignments have been preferentially selected. This is surely not the case for 5 out the 7 clusters in our sample. Four of these are from the Hoessel, Oke, and Gunn catalog, for which the critical selection criterion is the density contrast of a region of radius of 1-2 core radii, i.e., a fraction of a Mpc^2. Contamination by supercluster galaxies is totally unimportant in such small areas, as evidenced by the fact that nearly the entire core population of these clusters is red, passive galaxies, far different from the supercluster population. Attention was drawn to the 3C295 cluster by the very strong radio source, so this case too is immune from such a bias. As for the other two clusters, they were selected on photographic plates covering a large area so that a supercluster projection bias could have played a role. However, Koo himself has noted that Cl0016+16 has practically no blue population in the central region, therefore it seems unlikely that there is any serious contamination from a bluer supercluster population. Cl0024+24, which interestingly enough has the largest population of very blue, emission-line galaxies of any of our sample, may be the only good case for supercluster contamination.

While it is true, as Koo points out, that many of the first clusters studied may be unusual in one way or another (e.g., richness, color, density) it seems to us important that these selection biases appear to vary from cluster to cluster but the "active fraction" we find does not. We think this in itself is a strong argument for the universality of the effect and the relative unimportance of the selection bias.

3. THE 4000 ANGSTROM BREAK AS AN INDICATOR OF GALAXY EVOLUTION

It is not clear how germane are the results just discussed to the general issue of galaxy evolution. It is possible that the Butcher-Oemler effect is quite environment specific and may tell us little about the history of star formation in the more typical galaxies not in rich clusters. This limitation has encouraged us to address the more general question of the history of star formation in the <u>passive</u> galaxies. Because these are likely to be among the "oldest" (least amount of late star formation) of any galaxies regardless of environment, they should be good cases in which to try and estimate the critical epoch of star formation when these oldest galaxies converted much of their gas into stars.

The diagnostic we are using for this study is the 4000 Å break amplitude introduced by Spinrad (1980,1986) and recently studied by Hamilton (1986). A new study by Dressler and Shectman (1987) shows, for a sample of ~800 galaxies in present-epoch clusters, that the break amplitude is a weak function of galaxy luminosity (as claimed by Hamilton) but a strong function of star formation history. These are exactly the desired characteristics for the task at hand.

Our distant cluster sample provides a good arena in which to investigate this issue because it is, in some ways, a volume limited sample free of the more troublesome selection effects. We have shown (see Dressler 1987) that the maximum break amplitude does not change significantly from the z ~ 0 to the z ~ 0.5 sample. This alone implies that there has been little significant star formation for some 10 Gyr in ~70% of our cluster galaxies. Just for a point of comparison, we can parameterize this result in terms of Bruzual's (1983) models of the evolution of coeval stellar populations. For example, with $H_o = 50$, $q_o = 0$ and an epoch of formation $z_f = 4$, this implies a model of $\mu \geq 0.3$, i.e., an exponential decay in the star formation rate with 30% of the star formation occurring within 1 Gyr of formation. In such a model, 80% of the stars have formed by z = 2. This has obvious implications for models of the growth of structure in the early universe, especially if they predict a good deal of galaxy formation at a relatively late epoch. A parameterization of the observations that is less model-dependent would, of course, be desirable.

We have a small amount of data which, if representative, provides an even stronger constraint. These are the 15 spectra of cluster members in 13HFKPα, a rich, concentrated cluster at z = 0.75 that we are studying. As discussed in Dressler (1987), these appear to have a genuine drop of about 10% in the maximum break amplitude relative to the z = 0 sample. One might be concerned that aperture effects are responsible since the distant galaxies are studied using apertures that cover more of the galaxy than for the low-z sample. However, we are reassured by the fact that the change in the break amplitude shows up between the intermediate-z sample and the high-z cluster, over which the change in covered area is negligible. The Bruzual model which is appropriate for this amount of evolution in the break amplitude is $\mu = 0.7$. In such a model 90% of the stars have formed 2 Gyr after formation, which, for the cosmological parameters given above, corresponds to z = 2.3. At least 30% of the galaxies in 13HFKPα seem to fit into this category. This result, similar to what has been found for the reddest field galaxies by Lilly and Longair (1984) and Djorgovsky et al. (1987) and implies an early and rapid formation of at least some galaxies.

4. SUMMARY

Cluster galaxies do evolve. There is a higher fraction of active galaxies in clusters at $z \gtrsim 0.4$, although these clusters are still dominated by passive galaxies. Judging from the amplitude of the 4000 Å break, even the passive galaxies show evidence for evolution by $z = 0.75$.

Cluster-to-cluster variations in the types of active galaxies may be significant, but could be a only an accident of the epoch of observation of transient populations. For example, many of the AGN and active starburst galaxies may signal an epoch of activity (like the infall of a subcluster of gas-rich galaxies), which is later seen as an increase in E+A galaxies. We have suggested that E+A galaxies are post-starburst galaxies, perhaps produced by ram-pressure induced star formation. Our data do not give any support for the model that mergers or tidal encounters are responsible for the increased star formation, though they may not be able to rule it out. A model in which such activity is independent of environment can be tested by comparing cluster and field samples.

In terms of future observations, we are turning more of our attention to the difficult task of getting spectra for galaxies in the high-z clusters. We are hopeful that evidence for galaxy evolution will be evident in *all* of the galaxies in such clusters, and that this, combined with long-awaited images from HST, will help in deciphering the nature of the evolution we have observed.

REFERENCES

Bruzual A., G. 1983, *Ap. J.*, **273**, 105.
Butcher, H., and Oemler, A. 1978, *Ap. J.*, **219**, 18.
Butcher, H., and Oemler, A. 1984, *Ap. J.*, **285**, 426.
Couch, W., and Sharples, R. M. 1987, preprint.
de Lapparent, V., Geller, M. J., and Huchra, J. P. 1986, *Ap. J. Lett.*, **302**, L1.
Dressler, A. 1987, in *Nearly Normal Galaxies*, ed. S. M. Faber, (New York: Springer-Verlag) p. 265.
Dressler, A., Gunn, J. E., and Schneider, D. P. 1985, *Ap. J.*, **294**, 70.
Dressler, A., and Gunn, J. E. 1983, *Ap. J.*, **270**, 7.
Dressler, A., and Shectman, S. A. 1987, *A. J.*, in press.
Dressler, A., Thompson, I. B., and Shectman, S. A. 1985, *Ap. J.*, **288**, 481.
Djorgovski, S., Spinrad, H., and Dickinson, M. 1987, *Ap. J.*, submitted.
Gunn, J. E., Hoessel, J. G., and Oke, J. B. 1986, *Ap. J.*, **306**, **30**.
Hamilton, D. 1985, *Ap. J.*, **297**, 371.

Koo, D. C. 1981, Ap J. Lett, **251**, L75.
Koo, D. C. 1987, Erice Workshop on Spectral Evolution, to appear in Towards Understanding Galaxies at Large Redshift, eds. R. Kron and A. Renzini (Reidel).
Lavery, R. J., and Henry, J. P. 1986, Ap. J. Lett., **304**, L5.
Lilly, S. J., Longair, M. S. 1984 M.N.R.A.S., **211**, 833.
Spinrad, H. 1980, "Spectroscopy and Photometry of Faint Galaxies" in G. O. Abell and P. J. E. Peebles, eds.: IAU Symposium 92, Objects of High Redshift, pp. 39-48 (Reidel, Dordrecht).
Spinrad, H. 1986, P. A. S. P., **98**, 269.