HST OBSERVATIONS OF DISTANT CLUSTERS:
IMPLICATIONS FOR GALAXY EVOLUTION

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The “MORPHS” group has completed the cataloging, parameterization, and morphological classification of ∼2000 galaxies in 10 rich clusters from 0.36 < z < 0.56. From a weak lensing analysis using these data, which compares the X-ray properties (L_X) of the clusters with virial temperature estimates (T_v) from the lensing shear strength, we find little evidence for evolution in the L_X–T_v relation from that observed for local clusters. We discuss how this observation constrains models for the X-ray evolution of clusters. The data have also been used to study the color dispersion of bona-fide ellipticals in high-z clusters: we find the spread to be very small, suggesting an early formation epoch for the stellar populations of cluster ellipticals. This is consistent with the evolution of the morphology-density relationship, in which we find ellipticals to be as abundant at z = 0.5 as in clusters today, and already well ensconced in the dense regions. In contrast, S0’s are less plentiful and less well-concentrated compared to the present epoch, and spiral galaxies everywhere more abundant. Combined with other spectroscopic and morphological data, these observations suggest that most of these rapidly evolving systems are not likely to become bright ellipticals, which were more likely formed at early epochs. Cluster S0 galaxies, on the other hand, are likely to have been produced in large numbers in the recent past.

1 Introduction

Substantial progress has been made in the study of galaxy evolution through use of the lookback in cosmic time afforded by the observations of distant clusters and field galaxies. Very different histories of star formation produce spectral and integrated color characteristics that are essentially indistinguishable by the present epoch. Observations of the state of galaxies at much earlier times help break this degeneracy and offer a clearer picture of the evolutionary path taken by galaxies of various types and masses, and in different environments.

A group of us call the “MORPHS” — Richard Ellis, Warrick Couch, Gus Oemler, Harvey Butcher, Ray Sharples, Bianca Poggianti, Amy Barger, Visit Research Associate at the Carnegie Observatories.
and ourselves, has been using images from the Hubble Space Telescope Wide Field Planetary Camera 2 (WFPC-2) and extensive ground-based photometry and spectroscopy to study the properties of, and galaxy populations in, rich clusters of galaxies at $z \sim 0.5$. Here we report on various results from our group, which should be referred to by the specific papers named in each section.

2 Mass Estimates for Distant Clusters

Rich clusters of galaxies can be identified to high redshift and can thus be used as tracers of the evolution of structure in the universe. Moreover, as clusters represent the extreme tail of the mass fluctuation spectrum they provide a particularly sensitive probe of the form of the primordial power spectrum. One of the most widely used techniques to identify and study the masses of distant clusters is X-ray imaging of the hot intracluster gas bound to the cluster potential. Published X-ray surveys indicate a reduction in the volume density of luminous clusters at intermediate redshift. Unfortunately, without corroborating evidence it is difficult to determine if this arises from a real decline in the number of massive clusters in the past, or a change in the thermal properties of the cluster gas. The relatively new field of gravitational lensing provides an unique opportunity to tackle this issue by determining independent estimates of the cluster masses, from their effects on the shapes of background faint field galaxies. Using the homogenous, high-quality WFPC-2 imaging obtained for distant clusters by our collaboration, we have made a first attempt at combining X-ray and lensing observations of a large sample of distant clusters to determine the relative importance of cluster mass and the thermal history of the gas on the X-ray luminosities. The following discussion is abstracted from Smail et al. (1996a).

For the lensing analysis we have used deep WFPC-2 imaging of 12 distant clusters spanning the redshift range $z = 0.17–0.56$. Working from catalogs of faint galaxies ($I_{814} = 24.0–26.0$) detected in these fields we measure the mean shear strength — the average, coherent elongation of galaxy images around the cluster lens center — within a $200h^{-1}$ kpc aperture. We detect the signature of gravitational lensing in 11 of the 12 clusters; spanning nearly an order of magnitude in lensing strength. Moreover, the shear strength measured on these large scales correlates well with the presence of multiply-imaged arcs and pairs in the very central regions of the clusters, indicating that the clusters all share similar mass profiles. We have examined the correlation between the cluster X-ray luminosities and our mean gravitational shear strengths (linearly related to the central mass and the cluster virial temperature) and develop a model which allows us to predict the relationship expected from the properties.
Figure 1: The correlation between the cluster X-ray luminosity and the mean shear strength, \(<g_1>\), linearly related to central cluster mass. The error bars are 1\(\sigma\) boot-strap estimates and the solid line shows the best fit relationship for the data. The dotted line indicates the upper limit expected, assuming 100\% measurement efficiency, in the case of our simple model. The dashed line represents a 75\% efficiency. Filled symbols denote those clusters which have candidate strongly-lensed features.

of local clusters. After allowing for various observational effects, we find that the predicted correlation is a reasonable match to the available data (Fig. 1), indicating that there has been little evolution in the X-ray luminosity–central mass relationship between \(z \sim 0.4\) and now. Such limited evolution in the X-ray luminosity–central mass relation can be reproduced by models introducing a modest initial entropy into the gas prior to cluster formation, possibly resulting from pre-heating by AGN or galactic winds. Our results demonstrate the important role weak gravitational lensing can play in the study of the evolution of distant clusters, as the most direct and least biased probe of their growth.
3 The Ages of Elliptical Galaxies in Distant Rich Clusters

Elliptical galaxies are conventionally regarded as old galactic systems whose star formation history can be approximated as a single burst that occurred 12–16 Gyr ago. However, in recent years, this simple picture has been challenged from various viewpoints. Numerous cases have been found of ellipticals with intermediate-age stellar populations and dynamical arguments suggest that many peculiarities seen in ellipticals (shells and dust-lanes) are best explained via recent formation from the merger of gas-rich systems. Nevertheless, the small scatter observed for the \((U - V)\) colors of spheroidal galaxies in nearby clusters of galaxies still provides a basic constraint on the history of star formation in dense environments (Bower, Lucey & Ellis 1992). Using these local data and assuming the spheroids formed stochastically, it is possible to limit their formation epoch to \(z \geq 2\). However, introducing some degree of synchronicity serious weakens this limit, allowing the spheriodal population to form at more recent epochs.

In Ellis et al. (1996) we address this ambiguity using high precision rest-frame \((U - V)\) photometry of a large sample of morphologically-selected spheroidal galaxies in three \(z \sim 0.54\) clusters which have been observed as part of our HST program. We use our \(F555W\) and \(F814W\) imaging to determine accurate rest-frame \((U - V)\) colors for spheroidal galaxies in the three clusters: Cl0016+16 \((z = 0.55)\), Cl0054–27 \((z = 0.56)\) and Cl0412–65 \((= 0.51)\). Using these new data we repeat the color-scatter analysis conducted locally at a significant look-back time. Matching our aperture sizes, luminosity range and color system to those used locally we find a small scatter \((\leq 0.07\) mag rms, not much greater than that observed at \(z \sim 0)\) for galaxies classed as Es and E/S0s, both internally within each of the three clusters and externally from cluster to cluster. We do not find any trend for the scatter to increase with decreasing galaxy luminosity beyond that due to observational error. Our result thus provides a new constraint on the star formation history of cluster spheroids prior to \(z \sim 0.5\). Although we cannot rule out the continued production of some ellipticals, our results do indicate that the bulk of the stars seen in luminous elliptical cluster galaxies were formed by \(z \sim 3\).

4 The Morphology-Density Relation at High Redshift

A principal goal of our group has been to study the evolution of morphological types in the rich cluster environment. To this end we have morphologically classified 1857 objects brighter than \(R_{702} < 23.0\) or \(I_{814} < 23.5\), in the 11 fields, as described in Smail et al. (1996b) While the addition of spectroscopically-
derived parameters, such as cluster membership or stellar population, is important for understanding the evolutionary state of these populations. Photometric/morphological information alone allows a simple and important comparison with the properties of present day clusters. This comparison offers clues as to how clusters of galaxies came to hold their atypical complements of galaxy types.

With a resolution approaching 0.1″, our WFPC-2 images show detail at the level of 500 pc in the clusters, equivalent to observing galaxies in the Coma cluster with 1″ seeing. While cruder than the resolution usually available for morphological classification of nearby galaxies, it is sufficient for the identification of basic morphological information, and, in particular, is comparable to that presented by Dressler (1980) in the study of galaxy morphology in 55 low-redshift clusters. Our morphological samples in the distant clusters have also been selected in as similar a fashion as possible to the local data, for example, over the same area and to comparable absolute magnitude limits.

Dressler found a strong relation between the fractions of E, S0, and spiral galaxies with the local projected density where they were found, in the well known sense that ellipticals became more prevalent, and spirals less so, in regions of higher surface density. He concluded that, to first order at least, the morphology-density relation is universal, that is, representative of every cluster in the sample, regardless of its global properties.

Dressler’s original data have been reanalyzed and are presented in Dressler et al. (1996) along with the morphology-density relation for the HST sample described here. That paper also reviews some of the challenges to the morphology-density relation, for example, the contention by Whitmore, Gilmore, & Jones (1993) that the principal determinant of galaxy type within rich clusters is the radial distance from the cluster center. For our purposes here we simply analyze the morphology-density relation in our $z \sim 0.5$ sample.

In Fig. 2 we show the morphology-density relation for the entire $z \sim 0.5$ sample. The density range encompassed by the more distant sample is shifted by half a dex to higher density, probably reflecting the fact that these clusters are systematically richer than the typical clusters of Dressler’s local sample.

Before addressing the question of gradients in Fig. 2, we take note of differences between this and the nearby cluster sample. As is now well known, spirals are greatly overabundant at these high densities compared to present-epoch clusters, but, perhaps surprisingly, the difference seems to made up entirely by a paucity of S0 galaxies rather than an underabundance of both S0 and E galaxies. In fact, E galaxies appear to be in even greater abundance! At comparable densities, spirals are a factor of 2 overabundant, S0’s are a factor of 2-3 underabundant, and ellipticals are a factor of 1.5 overabundant in the
Figure 2: The morphology-density relation for 10 clusters at redshifts $0.36 < z < 0.57$. The plot shows the relative proportions of the different morphological classes (E, S0, Sp) as a function of projected density. The upper histogram shows the total number of galaxies in each bin.

$z \sim 0.5$ sample compared to Dressler’s sample of nearby clusters. The paucity of S0 galaxies is particularly noteworthy. As explained in Smail et al. (1996b), we have compared the distribution in flattenings of S0 galaxies in our sample with that for the Coma cluster, to see if we have systematically misclassified S0 galaxies as ellipticals, particularly for the face-on cases. The good agreement of these distributions indicates that this is probably not the case, but at any rate it is hard to see how we could be missing more than $\sim 25\%$, which is of little consequence to the gross deficiencies in S0’s found here.

We now ask whether any trend of morphology with density is apparent for the distant sample. From Fig. 2 it appears that a modest relation is present, but it is only for the bins of highest surface density — over the last factor of 5 in surface density. Over this range the spiral fraction plummet and the elliptical fraction rises sharply, but for the lower density zones, over which there is a very noticeable gradient in the nearby clusters, the relationships are basically flat. However, when the sample is divided by concentration and the degree of regularity, which to a large extent go together, a very different picture
emerges. Fig. 3 shows that, for the 4 highest concentration, regular clusters of the $z \sim 0.5$, the morphology-density relation is steep and well defined over the entire density range. In contrast, however, there are no correlations at all for the 4 lowest concentration, irregular clusters. This is a strikingly different result from the situation for present epoch clusters, for which Dressler found a strong morphology-density relationship for both irregular and regular clusters. A more detailed discussion of this difference can be found in Dressler et al. (1996).

Perhaps our most important result of this analysis, however, is simply that irrespective of whether the clusters appear dynamically “mature” or not, the incidence of elliptical galaxies is already very high, and independent of whether they are collected into dense, central regions or not. We suggest, based on this result, that elliptical galaxies predate, and are basically independent of, the virialization of a rich cluster. This is, of course, consistent with the Ellis et al. (1996) result described above of early formation of the stars in elliptical galaxies. Furthermore, we find that that the fractional representation of highly asymmetric or disturbed morphologies ($D > 1$, see Small et al. 1996b) with local surface density mirrors the S0 or spiral trend rather than the trend for el-
lipticals. Together, these three observations suggest that, for the environments of rich clusters at least, the stars seen in elliptical galaxies are not the result of mergers of starforming, gas-rich systems after a redshift $z = 3$. This does not preclude the possibility of dissipationless mergers at $z = 1$, say, when these clusters might have been in the process of amalgamating small groups with lower velocity dispersion, but both the distribution and numbers of ellipticals we have found here, and their photometric and spectral properties, suggest that the stellar populations of ellipticals in these regions are not produced by late mergers, or in any process that depended on the dynamical evolution of a rich cluster. Instead, gaseous mergers or coherent collapse at high redshift, or growth of spheroids through dissipationless mergers until later epochs, seems to be the history indicated for ellipticals. It is remarkable, we think, that the environment of proto-clusters of this richness was able to produce such a large population of ellipticals before the identities of the clusters themselves was well established.

The situation for the S0 galaxies seems to be just the opposite. Though the ones we find are, like the ellipticals, red and with little scatter in color, their numbers are so deficient as to suggest that many need to be added since $z = 1$, in order to reach the populations of present-epoch clusters. The source of these S0’s seems clear: the overabundance of spirals provides a reservoir of galaxies which may be stripped by ram pressure, tidally harassed (Moore et al. 1995) merged, or subject to strong 2-body gravitational interactions, with the result of producing today’s dormant disk galaxies in clusters. Our $z \sim 0.5$ cluster sample includes a significant number of disturbed, distorted morphologies, often with spectroscopic evidence of strong episodes of star formation. These may be the result of mergers, strong interactions, accretions, harassment, or stripping — we are still unable to tell which of these processes are responsible. But, we do know from our morphological classifications that most of these are disk systems — they do not seem destined to settle into ellipticals galaxies when their jostling and bursts of star formation have ceased. Though the exact mechanism(s) may be yet unspecified, it seems that at least half of the S0 galaxies in today’s clusters have been made by such processes since $z = 0.5$.

5 Conclusions

Our HST images of distant clusters exhibit robust shear fields due to gravitational lensing. These allow us to estimate the cluster mass (or virial temperature) and compare these to the cluster X-ray luminosity. The relation between $L_X$ and $T_v$ in these distant clusters is similar to that observed locally and we thus claim that there is no strong evolution in the $L_X$–$T_v$ relationship out to
We find a remarkably small scatter of restframe $(U - V)$ color for galaxies that we have classified as ellipticals. This suggests an early epoch of formation for the stars in these galaxies, and perhaps of the galaxies themselves. Furthermore, the large number of elliptical galaxies in these clusters, $\sim 40\%$, suggests that the formation of ellipticals predates cluster virialization. If mergers are responsible for making the ellipticals that now inhabit these rich clusters, they must have been dissipationless, in the “group phase” at $z \sim 1$, or much earlier, $z > 3$, if significant dissipation and star formation were involved. In contrast, the relative paucity of S0’s in the intermediate redshift clusters suggests that many of them have indeed been added since $z \sim 0.5$, by mechanisms that acted on the excessive numbers, compared to today’s clusters, of spirals and irregulars.

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