A wide field survey of the distant rich cluster Cl0024+1654

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Abstract. We describe the first results from a comprehensive study of the distant cluster Cl0024+1654 (z = 0.39) based upon a pattern of 38 mosaiced HST-WFPC2 images extending to radii ~ 5 Mpc. These are being analysed in conjunction with extensive spectroscopy conducted with the CFHT, WHT, and Keck Telescopes. The overall goal is to understand the morphological transformations and associated short-term star formation histories of representative numbers of infalling field galaxies in the context of the cluster potential as defined by weak lensing studies. Our HST database contains over 2000 galaxy morphologies to $I = 22.5$. Spectroscopic data and HST morphologies are currently available for about 215 members over an unprecedented range of environments. We confirm the existence of a well-defined morphology-density relation over a large dynamic range within a single system at a significant look-back time. Tentative trends in the E/S0 fraction as a function of radius are discussed. A weak lensing signal in the background galaxies has been detected at the cluster periphery and its inversion demonstrates only marginal substructure. A statistically-significant galaxy-galaxy lensing signal has also been seen for the cluster members. Further work will relate radial dependencies in the dark matter and halo masses in the context of spectroscopic and morphological diagnostics of truncated star formation.
1. Introduction

The ability of the Hubble Space Telescope (HST) to resolve galaxy morphologies at cosmologically-significant look-back times has enabled great progress in understanding the origin of the morphology density relation and, \textit{inter alia}, the influence of the environment on galaxy morphology. On the basis of HST images of several clusters at \( z \sim 0.3 - 0.5 \), the Morphs team (Dressler et al. 1997) determined a remarkable decline with redshift in the fraction of S0s with a corresponding rise in that for spirals. They deduced that spirals were transformed to S0 galaxies remarkably recently, most likely because their gas was removed by processes such as tidal effects and ram pressure stripping.

Alongside this evolutionary signal, strong evolution is also found in star formation and morphological characteristics of field galaxies (Glazebrook et al. 1995; Lilly et al. 1996). Understanding the role that gas-rich field galaxies play in fueling the transformations inferred in cluster cores remains an interesting issue. As field galaxies most likely fall into clusters at all epochs, the origin of the recent demise of spirals is puzzling.

A promising way forward is to study, in considerable detail, the transformations occurring \textit{in situ} in a single system from the virialised core to the periphery where field galaxies infall on radial orbits. This is preferable to drawing deductions based on studies of many clusters, observed at different redshifts, each at an unknown stage in its evolutionary history.

Because of the small field of view of WFPC-2, most morphological studies have been limited to the very central regions of distant clusters (e.g. Smail et al. 1997), and correspondingly little is known about the properties of the infalling galaxy population at large radii. Ground based studies (Abraham et al. 1996a) have explored the \textit{integrated} properties of galaxies to large cluster radii, finding evidence for radial trends in diagnostics of recent star formation. It seems likely that star formation is suppressed as galaxies infall, although the physical mechanisms and timescales are still quite controversial (Poggianti et al. 1999; Balogh et al. 2000). These latter uncertainties may be overcome if the timescales of stellar activity/truncation can be linked to those determined dynamically in a known gravitational potential (e.g. from weak lensing signal).

We present the first results from a wide field HST survey of the rich cluster Cl0024+1654 (hereafter 0024; \( z = 0.39 \)) whose goal is to address many of the above questions. In the following, the Hubble constant is \( H_0 = 50 h_{50} \text{km s}^{-1} \text{Mpc}^{-1} \), assuming \( h_{50} = 1.3 \) when necessary. The matter density of the Universe and the cosmological constant are \( \Omega = 0.3 \) and \( \Omega_\Lambda = 0.7 \) respectively.

2. Overview of Database

0024 (\( z = 0.39 \)) is an ideal cluster with which to begin a detailed dynamical, morphological and stellar population study of this type. The results can be contrasted with similar pioneering ground-based studies of the Coma cluster by Kent & Gunn (1982) and Colless & Dunn (1996) and of Abell 2390 (\( z = 0.23 \)) by Abraham et al. (1996a). The distance to 0024 is sufficient that only a relatively modest number (38) of WFPC2 images is needed for a well-sampled study almost to the turn-around radius. The cluster appears regular and symmetric in
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Figure 1. WFPC2 pointings and available redshifts (open circles). The working database of cluster 0024 ($z = 0.39$) contains $\sim 2000$ HST morphologies and $\sim 750$ spectroscopic redshifts.

both its galaxy distribution and X-ray morphology. The availability of over 600 spectroscopic redshifts from the CFHT/WHT (Czoske et al. 2001a) provides a major starting point for a comprehensive dynamical study. As is often the case with such extensive sampling of the velocity field (c.f. Coma), complications emerge. The redshift distribution of confirmed members already suggested the existence a foreground system of modest mass. However, recent work by Czoske et al. (2001b) suggests the dynamical distribution of the innermost galaxies is consistent, although not uniquely so, with a line-of-sight merger of two systems. In addition, the central mass distribution can be independently reconstructed from the quintuple gravitational arc system (Broadhurst et al. 2000).

The first component of our dataset is the wide-field WFPC2 data, providing galaxy morphology and the weak shear to $\sim 15'(\sim 5\text{Mpc})$ from the cluster center. The primary imaging was accomplished using 2 orbit exposures using the F814W filter, with parallel images taken using STIS in clear CCD mode. As of July 2001 when the conference was held, only 22/38 planned pointings had been observed. However, the remainder arrived soon after and this report presents the first preliminary analysis based on the entire dataset (see Fig. 1).
Via comparisons with both the Morphs and Medium Deep Survey data taken in the same F814W filter, it was determined that morphological classifications in 0024 could be reliably performed within the MDS classification system (Glazebrook et al. 1995, Abraham et al. 1996b) to a limiting magnitude of $I = 22.5$. The slightly deeper Morphs exposure in the cluster core permits a similar classification to $I = 23$ (Smail et al. 1997). Systematic classifications performed by one of us (RSE) yields a sample of 1800 objects ($\sim 600$ E/S0 $\sim 800$ S, $\sim 400$ Irr), in addition to $\sim 250$ already classified in the core. Independent classification is currently being performed by a second collaborator (AD).

The second component of our survey is the redshift survey. In the outer fields (>1-2 Mpc from the center), the galaxy excess above background per WFPC2 field to $I \sim 22.5$ is within the observed fluctuations in the field counts (Abraham et al. 1996a); to identify infalling members, spectra are crucial. So far, we have collated 718 redshifts (Dressler et al. 1999; Czoske et al. 2001a; Owen 2001; Metevier & Koo 2001) including 334 members. Further spectroscopy in the periphery is necessary because of the incomplete sampling by earlier studies.

The third component is a spectroscopic campaign with the Keck Telescopes, following up known members to $I = 21$ and extending the completeness of the redshift surveys to $I = 23$. These data represent a crucial part of the study of the infalling population providing diagnostics of recent star formation and dynamical masses either through stellar velocity dispersions or resolved emission line rotation curves. A first attack in Oct 2001 yielded spectra for $\sim 100$ objects.

3. First results

3.1. Galaxy population

Our dataset provides the first comprehensive and uniform set of morphological data across the range of environments from the cluster core out to $\sim 5$ Mpc ($\sim$ “field”). This has enabled us to examine the suggestion that there are strong radial gradients in the morphological mix and, in future, to tie these to spectroscopic diagnostics which can be used to understand the interplay between dynamical infall and the truncation of star formation.

Whereas photometric techniques are effective in addressing the statistical properties of background-subtracted galaxies in low densities (Kodama et al. 2001), we seek here to identify members individually so the dynamical and spectral diagnostics can be brought into play. As an illustration of the difficulties associated with statistical subtraction techniques, we show in Fig. 2, the run of morphological type with radius from the cluster core to regions of very low density. The left panel shows the $I < 22.5$ galaxy density as a function of cluster radius divided by broad morphological type. As expected, E/S0 are more centrally concentrated than spirals, while Irr/Unclass/Mergers show little evidence of any concentration. At radii $\gtrsim 2$ Mpc, the observed density lies within the random fluctuations of the average field density (dashed line; Abraham et al. 1996b), and the background contamination can no longer be reliably removed statistically. We can obtain a smoother morphology-radius relation by averaging azimuthally, as shown in the right panel of Fig. 2. The peaked distribution of E/S0s is now more prominent and an excess in both E/S0s and spirals is seen to the largest radius probed. However, this excess is critically dependent on the
assumed background count and its morphological distribution. Astonishingly, the morphological counts (Glazebrook et al. 1995, Driver et al. 1995) remain uncertain simply by virtue of the limited area sampled by HST. This emphasises the importance of a redshift survey (to a depth equivalent to that of local determinations) to construct a reliable morphology-density relation.

What does the extensive spectroscopic data tell us about the distribution of confirmed members in Figure 2? As discussed, the kinematic structure of 0024 is more complex than that of a single relaxed system. In particular, the distribution of radial velocities is double peaked, with a secondary peak blueshifted by 3000 km s$^{-1}$ with respect to the main peak (Czoske et al. 2001b). If we assign membership based on the redshift limits adopted in Dressler et al. (1999), there are currently 215 confirmed members within our WFPC2 survey, 115 of which are E/S0s.

The left panel of Figure 3 shows the fraction of E/S0s in 0024 ($I < 21.1$ equivalent to the luminosity limit of Dressler 1980) as a function of radius in comparison to a local relation and values reported at intermediate redshift by Couch et al. ($z = 0.31$) and van Dokkum et al. (2000; $z = 0.83$). Examining the trends across the various clusters, the fraction of E/S0s in the cluster cores increases with redshift, consistent with earlier findings by Dressler et al. (1997) and van Dokkum et al. (2000). However, perhaps surprisingly, in the outer regions of 0024, the fraction of E/S0s remains relatively high and consistent with the local value. Of course, the uncertainties are large as the number of spectroscopic redshifts beyond 2 Mpc remains small. If this result is borne out by enlarged spectroscopic samples, one possible explanation is that the growth of 0024 is fuelled from merging substructures containing spheroidals rather than solely via an abundant population of infalling isolated field galaxies. Alternatively, in the model proposed by Czoske et al. (2001b), some members of the core of the merg-
Figure 3.  

Left: The fraction of E/S0s as a function of radius (points with error bars) as compared to a local relation (open squares, Whitmore, Gilmore & Jones, 1993). Also shown are values reported at $z = 0.31$ (filled squares Couch et al. 1998) and at $z = 0.83$ (open stars; van Dokkum et al. 2000). Right: Shear map (solid sticks) computed from the faint galaxy catalogue (small ellipses). The cluster shear can be detected right to the periphery of our HST data.

3.2. Weak lensing

In classical studies of cluster dynamics, galaxies (or X-ray gas) have been regarded as tracers of the gravitational potential under a number of assumptions. Foremost it has been assumed that they are not biased in any respect with respect to the dominant dark matter potential. A significant advantage of studying in detail a cluster at $z \approx 0.4$ is that it lies $\approx$ half-way to the faint background population reached with a 2-orbit WFPC2 exposure.

It is possible, therefore, to contemplate combining the galaxy dynamical data with the dark matter distribution as revealed by the weak lensing induced by the cluster on the background population. As an illustration of where we have reached with the recently arrived data, Figures 3 and 4 show the first results arising from this important additional physical diagnostic.

The right panel of Figure 3 shows the weak shear as a function of position using a simple interpolation scheme to handle the sparse-sampling. Remarkably, the shear is detected right to the periphery of the HST mosaic where its value is typically $\sim 3\%$. Interestingly there is some discrepancy between the centre of the shear pattern and that of the visible light, the multiply-imaged arcs or the X-ray gas. This may be an artefact of the preliminary reduction or it could represent contamination from the foreground component. In the context of the model proposed by Czoske et al. (2001b) this seems unlikely.
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3.3. Galaxy-galaxy lensing

A final application of this rich dataset is in determining the halo properties of individual galaxies as probed by weak lensing induced by individual cluster members. In dense environments, dark matter halos of galaxies are likely to be truncated or stripped by environmental effects (e.g., Moore et al. 1996). Previous studies in the cluster AC 114 at $z = 0.31$ (Natarajan et al. 1998) suggested an apparent halo cutoff for cluster members not seen in the equivalent field population. While comprehensive measures of galaxy-galaxy lensing by field galaxies have been carried out recently (e.g., McKay et al. 2001), in clusters such studies have been limited by small sample sizes and sample inhomogeneities.

The 0024 dataset can, in principle, probe halo properties in a statistical sense from the high density core to the low density field thereby securing a direct unbiased test of the result claimed by Natarajan et al. A preliminary analysis of the 38 WFPC2 pointings yielded 137 cluster galaxies (71 with confirmed redshifts, 66 selected on the color-magnitude diagram) and a carefully constructed background galaxy sample of $\approx 11,000$ objects. The shear obtained by direct averaging (Natarajan & Kneib 1997) is plotted in Fig. 4.

A shear detection of $\tau = 0.18 \pm 0.08$ (1 $\sigma$) is observed in the innermost $2''$. Despite significant statistical uncertainties, the observed value is consistent with that expected for an isothermal mass distribution with $\sigma \sim 200$ km s$^{-1}$ (see caption for detail). Compared to Natarajan et al. (1998) who detected $\tau = 0.16^{+0.12}_{-0.13}$ (1 $\sigma$) in the innermost $1.5''$, the galaxy-galaxy lensing signal is
more clearly seen and to further radial distance (see plot). Although still a weak signal, the improved selection criteria and larger sample of spectroscopically confirmed E/S0 galaxies are major advances over the AC114 study. The signal will improve further when data from the Morphs field is used. Employing a detailed cluster mass model which incorporates strong lensing features, a maximum likelihood method (Natarajan & Kneib 1997) will be used to robustly extract halo parameters and look for radial trends in halo mass and size.

References

Abraham R. G. et al. 1996a, ApJ, 471, 694
Abraham R. G. et al. 1996b, ApJS, 107, 1
Balogh M., et al. 2000, ApJ, 540, 113
Broadhurst T., et al. 2000, 534, L15
Colless M. & Dunn A. 1996, ApJ, 458, 435
Czoske O., et al. 2001a, A&A, 372, 391
Czoske O., et al. 2001b, A&A, submitted, astro-ph/0111118
de Blok et al. 2001, ApJ, 552,L23
Dressler A. 1980, ApJ, 236, 351
Dressler A. et al. 1997, ApJ, 490, 577
Dressler A. et al. 1999, ApJS, 122, 51
Driver, S.P. et al. 1995, ApJ, 449, L23
Kent, S. & Gunn, J.E. 1982, AJ, 87, 945
Kodama T., et al. 2001, ApJ, 562, L9
McKay T.A. et al. 2001, submitted to ApJ, astro-ph/0108013
Moore B. et al. 1996, Nature, 379, 613
Natarajan P. & Kneib J.-P 1997, MNRAS, 287, 833.
Poggianti B., et al. 1999, ApJ, 518, 576
Smail I. R. et al. 1997, ApJS, 479, 70
van Dokkum P. G. et al. 2000, ApJ, 541, 95