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

DOI: 10.1017/S174392130400081X

Spectroscopic signatures of galaxy evolution in Cl0024+16 at z∼0.4

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Abstract. We report the first results from a panoramic spectroscopic survey of galaxies in the rich cluster Cl0024+1654 ($z \simeq 0.4$). Using HST imaging we examine the properties of early-types as a function of cluster radius. At all cluster radii, our sample lies on a self-consistent Fundamental Plane whose zero point implies evolution since $z = 0$ corresponding to $\Delta[\log(M/L_V)] = 0.14 \pm 0.06$, an overall trend consistent with previous work. Using diagnostic [O II] emission and Balmer absorption lines, we locate a population of intrinsically faint galaxies at 1–2.4 Mpc radius undergoing a period of star formation. The luminosity-dependent radial trends are suggestive of the gradual quenching of star formation for infalling galaxies. We discuss physical mechanisms that may be responsible for this environmental evolution.

1. Introduction

Environmental processes have played a significant role in shaping the morphological evolution of galaxies in clusters. Galaxy clusters at intermediate redshift provide excellent laboratories to study these environmental effects, at a time when they were perhaps most active. At $z \sim 0.4$, clusters were still actively forming, with a much higher fraction of blue, star-forming galaxies than is seen today (Butcher & Oemler 1984). Yet the morphology–density relation was already in place (e.g. Treu et al. 2003), suggesting that environmental processes were already working to curtail star-formation within infalling galaxies. Compared to the local universe, there seems to be a deficit of S0 galaxies that nearly matches an excess of spirals (Dressler et al. 1997). As a result, it is thought that environmental processes may work to transform spiral galaxies into S0s, though the physical mechanisms responsible are still poorly understood.

Spectroscopy of cluster members at various stages of infall into the cluster can provide a key to the dominant environmental processes. Depending on the process at work, different physical mechanisms will leave different spectral and dynamical signatures in the affected galaxies. While many physical processes occur simultaneously in the central 0.5–1 Mpc of a cluster, the various mechanisms can be disentangled by contrasting differences observed across the entire cluster, from the periphery where galaxies are just beginning to feel the cluster potential, through the transition region near the virial radius, and into the virialized core.

We present here the first results from a wide-field spectroscopic study of Cl0024+1654 at $z \sim 0.4$, which complements the *Hubble Space Telescope (HST)* imaging on this cluster presented in Treu et al. (2003). Making use of the morphological classifications of Treu et al. (2003), we analyze spectral features and kinematics of confirmed cluster members.

By dividing our galaxies according to morphology, we can better trace how the cluster environment affects each class of galaxies, independently of spectral classification. Previous spectroscopic studies of moderate redshift clusters have either focused on the cluster core, where morphologies are available (e.g., Poggianti et al. 1999), or have relied on spectral types or colors to trace the effects of environment out to the cluster periphery (e.g. Fisher et al. 1998). With our more extended sample, we can trace the detailed spectral properties and kinematics of both early and late type galaxies across the cluster, providing a more complete picture of how infalling galaxies are affected by the cluster environment.

We focus here on cluster members classified as E+S0 by the HST imaging survey. A future paper will address the properties of spiral galaxies in Cl0024.

2. Observations

Treu et al. (2003) presented the results of a wide-field HST imaging survey of Cl0024+16. The survey includes 39 sparsely-sampled WFPC2 images taken in the F814W filter ($\sim I$ band), providing good coverage of the cluster field out to radius > 5 Mpc. Treu et al. (2003) reports morphological classifications down to $I = 22.5$. Classifications to a limiting magnitude of $I = 21.1$ were found to be very reliable. For galaxies between $I = 21.1$ and $I = 22.5$, broad classification as early or late type is still reliable, though differentiating between E and S0 galaxies, for example, is less certain.

In October 2002, and again in October 2003, we used the DEIMOS spectrograph on *Keck II* to obtain deep (2.5 hrs) spectra of ~ 1000 galaxies in the field of Cl0024. Selection priority was given to known cluster members with *HST* images, followed by unknown galaxies in the *HST* survey with $I < 21.0$; galaxies without *HST* images, or those with magnitudes $21.0 < I \leqslant 22.5$ filled the slit mask gaps. Spectra were reduced using the DEEP2 DEIMOS data pipeline. In total, we have obtained spectra of over 200 cluster members to $I = 22.5$. We present initial results on 74 E+S0 galaxies, with 54 of these having high quality spectra.

In our sample, no galaxy dimmer than $I \sim 21$ yielded a high quality spectrum. This roughly matches the magnitude limit of Treu et al. (2003) for precise morphological classification. We therefore divide our E+S0 galaxies into a sample that is brighter than $I = 21.1$ and one that includes all observed E+S0 members down to $I = 22.5$. An M_V^* galaxy in Cl0024 corresponds to $I = 19.5$ for ΛCDM cosmology with $h = 0.72$ (Smail et al. 1997; Treu et al. 2003), such that our two samples represent galaxies brighter than $M_V^* + 1.6$ and $M_V^* + 3.0$, respectively.

3. Results

3.1. *Fundamental Plane of Cl0024*

For our brighter sample, we are able to study galaxy kinematics via velocity dispersions. With the addition of surface photometry from the *HST* images, we can derive the parameters of the fundamental plane (FP) in Cl0024: effective radius R_e, mean surface brightness SB_e, and central velocity dispersion σ_0 (Djorgovski & Davis 1987; Dressler et al. 1987). We study the mass-to-light ratio of cluster galaxies as a function of cluster environment and galaxy sub-class (elliptical or S0).

Previous studies have traced a mild shift in the intercept of the FP with redshift (e.g. Wuyts et al. 2004; Kelson et al. 2000c). This seems to be consistent with passive luminosity evolution of stellar populations with a high redshift of formation (Wuyts et al. 2004), though biases due to morphological evolution are difficult to quantify. All such studies, however, have focused on the central regions of the clusters studied, or on a small field sample. With our broader spatial coverage, we can uncover any significant difference

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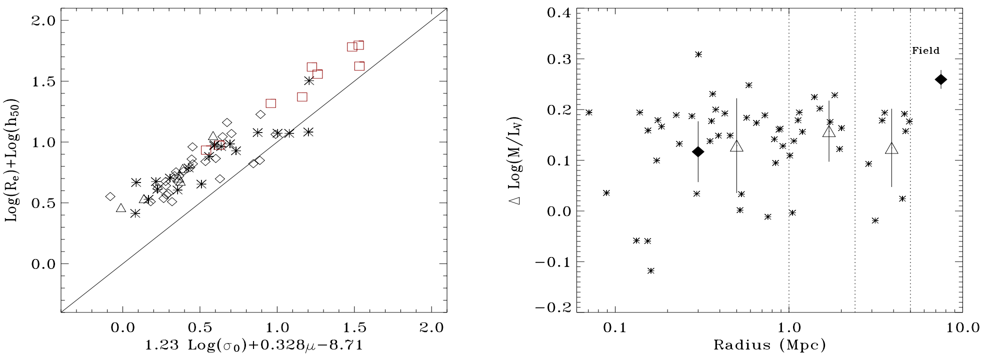

Figure 1. Left: FP of Cl0024+16, compared to Coma cluster (solid line). Asterisks are galaxies classified as E, open diamonds are S0, and open triangles are E/S0. Open squares are from van Dokkum & Franx (1996). **Right:** Change in M/L_V ratio for galaxies in Cl0024, with respect to $\langle M/L_V \rangle$ for Coma. Asterisks represent individual galaxies. Open triangles: averages for the three radial zones indicated. Error bars reflect the rms scatter. Filled diamonds: points from van Dokkum & Franx (1996) and Treu et al. (2001) for cluster core and field, respectively.

in the mean M/L_V of early types as a function of radius. Our sample also extends to fainter magnitudes than previous studies at $z \sim 0.4$, allowing us to probe M/L_V for smaller early-types that perhaps formed later than the most massive cluster ellipticals.

In order to determine velocity dispersions for early-types with high quality spectra, we fit them to a grid of stellar templates degraded to the instrumental resolution and smoothed to various velocity dispersions (Van der Marel 1994). We apply a 5% correction to match a 3.4″ aperture at the distance of Coma (Jørgensen, Franx, & Kjærgaard 1996). In addition, *GALFIT* (Peng et al. 2002) was used to derive effective radii and surface brightnesses for all galaxies with velocity dispersions.

Figure 1 presents the FP of Cl0024 compared to that of the Coma cluster. We find that the average offset from the Coma FP implies a change in the M/L_V ratio between $z = 0.4$ and $z = 0.02$ of $\langle \Delta \log (M/L_V) \rangle = 0.139 \pm 0.06$. This is a slightly smaller evolution than found in the field at $z \sim 0.4$ by Treu et al. (2001), though it is in excellent agreement with the offset determined by Kelson et al. (2000c) for a cluster at $z = 0.33$.

Red squares in Figure 1 indicate points from van Dokkum & Franx (1996), who also measured the FP in Cl0024. The two sets of data fall on the same plane, and our inferred $\langle \Delta \log (M/L_V) \rangle$ is consistent with their work. Combining our two datasets, we find that, within the errors, the tilt (Ciotti, Lanzoni & Renzini 1996) of the FP of Cl0024 matches that of the Coma cluster FP. This suggests that the tilt of the FP cannot be explained by a simple relation between galaxy age and mass (Treu et al. 2001).

When dividing our sample into three subclasses (E, S0, and E/S0), we find no evidence of significant variation between the populations, either in scatter, intercept, or tilt of the FP. Furthermore, the mean M/L_V does not vary with cluster radius, as shown on the right-hand side of Figure 1. However, the uncertainties in these preliminary results preclude us from identifying any subtle differences or trends that may exist.

3.2. *Radial trends in spectral features*

To probe for star formation in cluster early-types, we examine diagnostic spectrum lines as a function of cluster radius, both taking ensembles and galaxy-by-galaxy. This is done for the entire sample to $I = 22.5$. [OII] emission is sensitive to ongoing star formation

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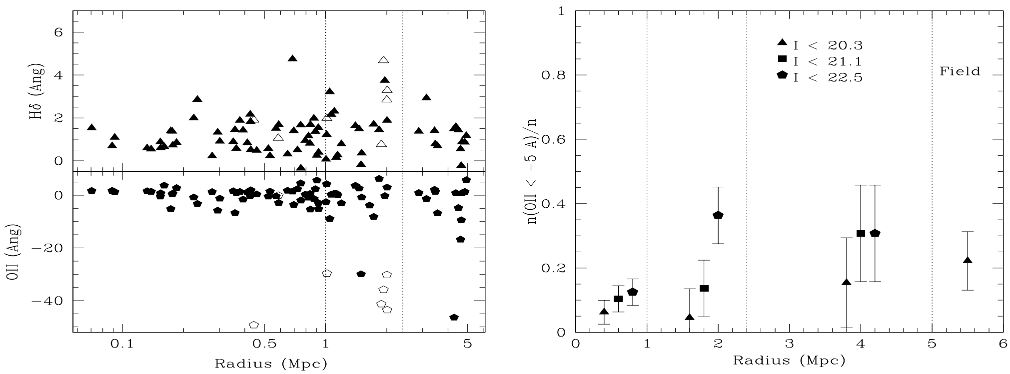

Figure 2. Left: Hδ and [OII] EWs for all E+S0 members as function of radius. Dotted lines delineate the core, transition region, and periphery. Open symbols: $21.1 < I < 22.5$. Filled symbols: $I < 21.1$. **Right:** Fraction of E+S0 galaxies with EW([OII]) < -5Å, as a function of radius. Triangles represent fraction for galaxies with $I < 20.3$. The field value is from Treu et al. (2002). Squares and pentagons are the same measure, but to $I = 21.1$ and $I = 22.5$, respectively.

and indicates the presence of gas, whereas the Balmer absorption line $H\delta$ is indicative of recently-completed activity.

Figure 2 shows these two diagnostics, measured as equivalent widths, as a function of radii, both on an individual galaxy basis and as means. On the left is a split plot with EW(Hδ) on top and EW([OII] 3727Å) below it. On the right, we plot the fraction of all E+S0 galaxies with EW([OII])< -5Å, averaged across each of the radial zones indicated. Figure 3 shows the coadded spectra of all early-types binned by radial zone; top to bottom, they trace the mean early-type spectrum from the periphery to the core. All galaxies with EW(OII) < -15Å were coadded separately; see Figure 3, right panel.

Examining individual measurements of EW([OII]), we find a population of galaxies with strong emission, which are concentrated in a narrow range in radius, close to the virial radius at 1.7 Mpc. The spectra of these galaxies are dominated by emission lines, including [OIII] and several Balmer lines (see Figure 3, right panel). These emission line galaxies are preferentially dim; as denoted by the un-filled pentagons in Figure 2, most are in the magnitude range $21.1 < I \leqslant 22.5$. Previous studies have not been sensitive to early-type cluster galaxies at these magnitudes and in this radius range. If this emission is due to star formation, these galaxies could be undergoing mergers or some interaction with the ICM.

In addition to the emission line galaxies, we see a gradual trend of increasing [OII] emission and, to a lesser extent, Balmer absorption with increasing radius. This suggests an encounter with the cluster environment which serves to suppress star formation gradually during infall. Co-added spectra of 'normal' E+S0 members in Figure 3 show a clear increase in an average galaxy's OII emission with radius, but little difference in the average galaxy's $H\delta$ line strength.

On closer examination, there is a luminosity trend in the fraction of E+S0 galaxies with EW([OII]) < -5. (Figure 2). For the brightest galaxies, $I < 20.3$, the fraction of [OII]-emitters decreases monotonically, from the field measurement of Treu et al. (2002) to the cluster core. However, when we include slightly dimmer galaxies, to $I = 21.1$, we see an enhanced fraction of emitters in the cluster periphery, though [OII] emission is still rare within 2.4 Mpc. Now including our full sample to $I = 22.5$, the fraction of star-forming galaxies in both the transition region and periphery are higher than expected. In the transition region, the jump represents the addition of the dim but strongly emitting

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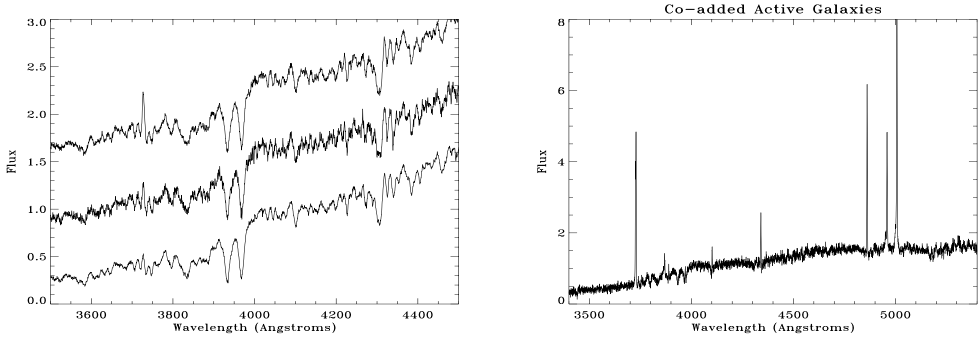

Figure 3. Left: Coadded spectra for all E+S0 members, divided by distance from cluster core. From top to bottom: periphery, transition region, and cluster core. **Right:** Coadded spectrum of all E+S0 cluster members with EW(OII) < -15Å. Wavelengths in rest frame.

galaxies discussed above. The overall trend suggests that the star formation observed in the outskirts of this cluster is suppressed earliest in the largest and brightest E+S0s.

4. Discussion

The brightest galaxies in our sample ($I < 20.3$) follow the FP and show few signs of star formation. Similarly, galaxies to $I = 21.1$ lie on the FP and exhibit star formation only in the periphery. Perhaps star formation is quenched early during infall of these galaxies, with passive luminosity evolution from that point. Because the dimmest galaxies seem to undergo big bursts of star formation (though AGN activity has yet to be ruled out) near the virial radius, it could be that they are simply swallowing small satellite galaxies. In the dimmest hosts, the addition of a small satellite with ongoing star-formation will be the most obvious. This could also happen with the slightly brighter star-forming galaxies in the periphery, but the observable effect of swallowing a satellite is smaller.

We have presented evidence for a population of actively star-forming early type galaxies, concentrated in distance from the cluster center. In addition, moderate star formation is seen across a range of radii. The radius at which this star formation disappears seems to be correlated with galaxy luminosity, possibly due to galaxy cannibalism of small satellites. We intend to expand this analysis to the spiral cluster members, in the hopes of obtaining a more complete picture of how the cluster affects infalling galaxies.

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