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The Evolution of [OII] Emission from Cluster Galaxies

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ABSTRACT

We investigate the evolution of the star formation rate in cluster galaxies. We complement data from the CNOC1 cluster survey ($0.15 < z < 0.6$) with measurements from galaxy clusters in the 2dF galaxy redshift survey ($0.05 < z < 0.1$) and measurements from recently published work on higher redshift clusters, up to almost $z = 1$. We focus our attention on galaxies in the cluster core, ie. galaxies with $r < 0.7h_{70}^{-1}$ Mpc. Averaging over clusters in redshift bins, we find that the fraction of galaxies with strong [OII] emission is $\lesssim 20\%$ in cluster cores, and the fraction evolves little with redshift. In contrast, field galaxies from the survey show a very strong increase over the same redshift range. It thus appears that the environment in the cores of rich clusters is hostile to star formation at all the redshifts studied. We compare this result with the evolution of the colours of galaxies in cluster cores, first reported by Butcher & Oemler (1984). Using the same galaxies for our analysis of the [OII] emission, we confirm that the fraction of blue galaxies, which are defined as galaxies 0.2 mag bluer in the rest frame $B - V$ than the red sequence of each cluster, increases strongly with redshift. Since the colours of galaxies retain a memory of their recent star formation history, while emission from the [OII] line does not, we suggest that these two results can best be reconciled if the rate at which the clusters are being assembled is higher in the past, and the galaxies from which it is being assembled are typically bluer.

Key words: galaxies: clusters: general — galaxies: evolution — galaxies: formation

1 INTRODUCTION

More than 20 years ago, Butcher & Oemler (1978) first reported a puzzling evolution in the colours of cluster galaxies (the "Butcher-Oemler effect"). Their results were surprising because they showed that galaxies in clusters could not have all formed at early times of the universe and subsequently evolved passively, which was a popular theory at the time (Eggen, Lynden-bell & Sandage 1962). The initial results have been confirmed in many subsequent studies (e.g., Butcher & Oemler 1984 [BO84]; Couch & Newell 1984; Kodama & Bower 2001; Ellingson et al. 2001; Margonnier et al. 2001). Despite the vintage of these results, there is still uncertainty over their interpretation. The result remains surprising since the cluster environment would seem hostile to star formation. Cluster galaxies undergo efficient ram pressure (Gunn & Gott 1972; Abadi, Moore & Bower 1999; Fujita & Nagashima 1999; Quilis, Moore & Bower 2000), suffocation due to removal of their gaseous halos (Larson, Tinsley & Caldwell 1980; Balogh, Navarro & Morris 2000; Drake et al. 2000; Diaferio et al. 2001; Okamoto & Nagashima 2003) and harassment due to the cumulative effect of fast encounters with other galaxies (Moore et al. 1996, 1999). Currently, the most popular explanation is that the blue galaxies are a galaxy population that has arrived only recently in the cluster. Even though their star formation may be suppressed, their previous star formation history will still be reflected in their blue colours (Kauffman 1996; Ellingson et al. 2001; for a recent review see Bower & Balogh 2004). This scenario also fits well with observations of a significant population of post-starburst galaxies in clusters at $z < 1$ (Dressler & Gunn 1992; Postman, Lubin & Oke 1998; Dressler et al. 1999; Poggianti et al. 1999).

On the other hand, the previous discussion does not address why the population of blue cluster galaxies evolves so strongly with redshift. Although the rate of infall into clusters does evolve with redshift (Bower 1991; Kauffmann 1996; Diaferio et al. 2001), on its own this effect seems insufficient to account for the rapid evolution. The additional component may come from the rapid change in the star formation rates of field galaxies over the same redshift range (Ellingson et al. 2001). It is then a matter of some debate whether the population of blue galaxies is a population of galaxies actually in the cluster itself, or whether they represent a population of infalling galaxies that have not yet reached the high density region in the cluster core.

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Furthermore, colours do not tell the complete story. In order to investigate the nature of the "Butcher-Oemler" effect more directly, we have set out to measure the star formation rate of galaxies in the cluster core. Hα is the preferred estimator of star formation in the optical, but a large homogeneous survey covering a wide range of redshifts has not yet been completed (see Balogh & Morris 2000; Couch et al. 2001; Balogh et al. 2002; Finn, Zaritsky & McCarthy 2004; Kodama et al. 2004 for some recent results on distant clusters). The best available alternative is to use the large and homogeneous sample of clusters that form the CNOC1 survey (e.g., Yee, Ellingson & Carlberg 1996). Although this survey lacks the wavelength coverage to measure the strength of Hα, we can investigate the evolution of star formation activity using the [OII] λ3727 emission line. This dataset allows us to investigate the evolution of the equivalent width of the [OII] line (EW[OII]) over the redshift range $0.15 < z < 0.6$. For a datum at lower redshift, we compare these measurements with the local 2dF data (Colless et al. 2001, 2003). At higher redshifts, we compare the trends seen in the CNOC1 data with publicly available catalogues of four clusters (Cl 1324+3011, Cl 1604+4304, Cl 1604+4321: Postman, Lubin & Oke 2001; MS 1054-03: van Dokkum et al. 2000).

There has been a recent realization that the galaxy population is strongly bimodal (Kauffman et al. 2003), with distinct 'active' star forming population and a 'passive' population with low levels of star formation. Within the active population the star formation rate seems to vary little with environment (Balogh et al. 2004b; Baldry et al. 2004) and that it is therefore more useful to characterise the galaxy population from the ratio of the active and passive populations. We follow this procedure here, focusing on the fraction of strongly star forming galaxies ($\mathrm{EW[OII]} > 10$Å) as a function of redshift.

This paper is structured as follows. In Section 2, we briefly describe data used for our analysis. In Section 3, we investigate the evolution of the fraction of strong star-forming galaxies at $z \lesssim 1$. We will show that there seems to be little evolution in the star formation activity within the clusters. Therefore in Section 4, we compare our results with the evolution of the blue galaxy fraction in the CNOC1 clusters. We consider the wider implication of these results in Section 5, and summarise our results in Section 6. Throughout this paper, we assume a cosmology with $\Omega_0 = 0.3$, $\lambda_0 = 0.7$, $H_0 = 70h_{70}^{-1}$ km s^{-1} Mpc^{-1}.

2 DATA

2.1 CNOC1

The CNOC1 catalogue (e.g., Yee et al. 1996) is a spectroscopic sample of 16 X-ray bright clusters at intermediate redshift ($0.15 < z < 0.6$), selected from the EMSS catalogue (Gioia & Luppino 1994). Our aim is to study star formation in high mass systems, thus we exclude E0906, for which a velocity dispersion could not be computed because of an apparent double component structure (Carlberg et al. 1996).

We calculate the K-corrected absolute B-magnitude in the rest frame using the K-corrections given in Fukugita, Shimasaku & Ichikawa (1995). They are based on Coleman, Wu & Weedman's (1980) and Kennicutt's (1992) spectral atlas. The completeness of catalogued objects is adopted from Balogh et al. (1999). We apply a magnitude dependent weight (W_m) to correct for galaxies which are omitted from the spectroscopic catalogue. Figure 1 shows the luminosity function (LF) of CNOC1 galaxies in the rest-frame B band. The dotted and the solid lines indicate the raw counts and the counts corrected for spectroscopic incompleteness, respectively. We include not only cluster galaxies but also field ones to check the completeness of the catalogue. The figure compares the CNOC1 LF with that of galaxies from the 2dF-galaxy redshift survey (2dFGRS) sample (see below). It is clear from Figure 1 that incompleteness in the input catalogues is significant below $M_B > -19.5$ (solid line). Therefore, we set a limiting magnitude of our analysis as $M_B = -19.5$, which corresponds to $\sim M^* + 1$.

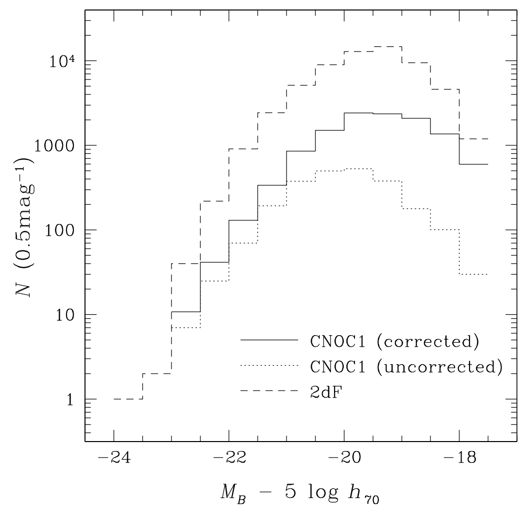

Figure 1. The luminosity functions of galaxies in the rest frame B band. The dotted and the solid line indicate the raw counts and the counts corrected for incompleteness for CNOC1 galaxies, respectively. The dashed line shows the LF of 2dF galaxies. Note that these LFs include field galaxies as well as cluster galaxies.

Cluster membership is based on the radial velocity difference from the brightest cluster galaxy, using the method described in Balogh et al. (1999). We estimate the (projected) radial dependence of the cluster velocity dispersion, $\sigma(r)$, from the average measured dispersion, σ_1, using the mass model of Carlberg, Yee & Ellingson (1997). Galaxies with normalized velocities less than $3\sigma(r)$ are considered cluster members. We also extract field galaxies from the same CNOC1 area. We treat galaxies with normalized velocities greater than $6\sigma(r)$ as field galaxies. We use only galaxies within $0.7h_{70}^{-1}$ Mpc radius, which is a characteristic value of the cut-off radius adopted by BO84. This facilitates direct comparison with the Butcher-Oemler effect. Table 1 summarises the sample we used. Column 1 indicates the data-set; column 2 shows the redshift bins into which the data have been split; column 3 shows the number of cluster galaxies within $0.7h_{70}^{-1}$ Mpc radius at $M_B < -19.5$; and column 4 indicates the number of field galaxies for which spectroscopy is available.

2.2 2dF

We use data from the 2dF galaxy redshift survey (Colless et al. 2001, 2003) to set a low redshift datum. We take a volume limited sample of the data in the redshift range $0.05 < z < 0.1$, and only galaxies brighter than $M_B = -19.5$ in order to match the limiting magnitude of the CNOC1 sample (Figure 1). The 2dF EW[OII] measurement is smoothed with a gaussian kernel of width 2Å to match the mean error on CNOC1 EW[OII] measurements.

The cluster sample is taken from the redshift space selected

Table 1. A summary of the sample.

	z	$N_{\rm cluster}$	$N_{\rm field}$	lim. mag	bands^a	spectroscopy aperture (kpc)^b	spectroscopy wavelength (Å)	Reference
2dF	$0.05 < z < 0.1$	366	12426	$M_B < -19.5$	$b_{\rm J} r_{\rm F}$	2.0-3.7	3600-8000	Colless et al. (2001,2003)
CNOC1	$0.15 < z < 0.3$	180	118	$M_B < -19.5$	gr	3.9-6.7	4350-5600	Yee et al. (1996)
	$0.3 < z < 0.4$	84	195	$M_B < -19.5$		6.7-8.1	4700-6400	
	$0.4 < z < 0.6$	74	197	$M_B < -19.5$		8.1-10.0	4700-7000	
Postman	$0.6 < z < 0.8$	22	48	$M_B < -19.5$	$BVRI$	6.7-10.5	4400-9500	Postman et al. (2001)
	$0.8 < z < 1$	34	23	$M_B < -20.5$		7.5-11.2		
MS1054	0.83	51	–	$M_B < -20$	F606W,F814W	9.1	5700-9500	van Dokkumn et al. (2000)

^{a} Imaging bands using for deriving the absolute B-magnitude in the rest frame of each galaxy
^{b} derived from the aperture size of the fibre (2dF) or the width of the slit (others)

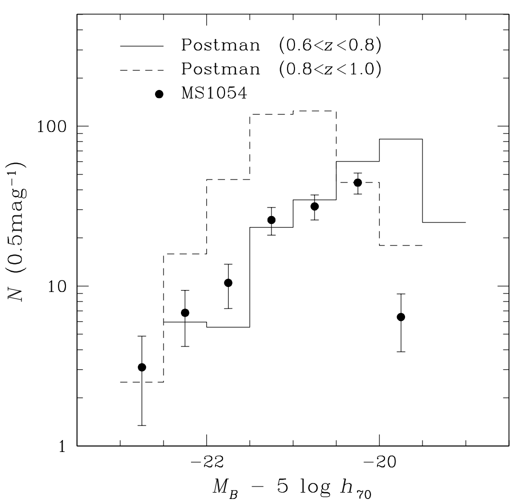

Figure 2. The LF of high-z galaxies in the rest frame B band. The solid and the dashed line indicate the LF of galaxies at $0.6 < z < 0.8$ and $0.8 < z < 1.0$, respectively, which is catalogued at Postman et al. (2001). The filled circles shows the LF of galaxies in MS 1054. The catalogue of the MS 1054 does not include field galaxies, while the LFs of Postman's catalogue include galaxies in both field and cluster environments.

2PIGGZ cluster and group catalogue (Eke et al. 2004). We only use those clusters, whose velocity dispersion is larger than 500 km/s, and also require that the number of member galaxies is larger than 30 in order to exclude poor systems with over estimated velocity dispersion. Note that even if we adopt more strict conditions for selecting cluster systems from the 2dF catalogue, the results we show do not change significantly. There are 366 galaxies within $0.7h_{70}^{-1}$ Mpc radius from the center of clustering systems we adopt, and there are 12426 field galaxies.

2.3 Higher redshift data sets

To investigate the effect of evolution at higher redshift, we added two publicly available catalogues: Cl 1324+3011 ($z = 0.76$), Cl 1604+4304 ($z = 0.90$) and Cl 1604+4321 ($z = 0.92$) are from Postman et al. (2001) and MS 1054-03 from van Dokkum et al. (2000). In addition to the cluster galaxies, the Postman data set provides a control sample of high redshift field galaxies. We refer to these catalogues as the high-z data sets. Figure 2 shows the LF of galaxies extracted from these catalogue. The incompleteness of each catalogue is corrected using literature (Figure 2 of Postman et al. 2001 and Figure 1 of van Dokkum et al. 2001). The solid and dashed lines indicate the LF of galaxies (in both cluster and field environments) at $0.6 < z < 0.8$ and $0.8 < z < 1.0$, respectively, extracted from Postman et al. (2001). We find that the incompleteness is small for $M_B < -19.5$ (the limiting magnitude of CNOC1 sample) for galaxies at a lower redshift bin ($0.6 < z < 0.8$), while it becomes large at $M_B > -20.5$ for galaxies in the higher redshift bin ($0.8 < z < 1.0$). Thus, we use only brighter galaxies ($M_B < -20.5$) at $0.8 < z < 1.0$. The filled circles of Figure 2 indicate the LF of cluster galaxies of MS 1054 extracted from van Dokkum et al. (2001) (this catalogue does not include field galaxies). Since the incompleteness is small to $M_B < -20$ for MS 1054 galaxies, we use galaxies in the full magnitude range. We summarise these high-z data-sets at the end of Table 1. Columns 3 and 4 indicate the number of galaxies at the core ($r < 0.7h_{70}^{-1}$ Mpc) of each cluster and field galaxies, respectively. The limiting magnitude of the sample is shown in column 5. We also show the observed imaging bands, which is used for deriving the M_B of each galaxy in column 6, spectroscopic apertures derived from the aperture size of the fibre (2dF) or the width of the slit (others) in column 7, and the spectral range covered by each observation in column 8.

3 THE EVOLUTION OF EW[OII] OF CLUSTER GALAXIES

As we discussed in the introduction, [OII] emission is a workable tracer of star formation in a statistical sense (e.g., Hopkins et al. 2003), nevertheless, we will avoid explicit conversion of EW[OII] into star formation rates. For our purposes, it is sufficient to compare the line emission properties of high/low redshift and cluster/field galaxies directly. This results in a comparison of well defined observational quantities.

Figure 3 shows the distribution of EW[OII] in 2dF, CNOC1 and high-z galaxies. There is a strong spike around $\mathrm{EW[OII]} = 0$Å for cluster galaxies at all redshifts. This is expected since star formation is known to be strongly suppressed in galaxy clusters. In contrast, the field galaxies have a much wider distribution.

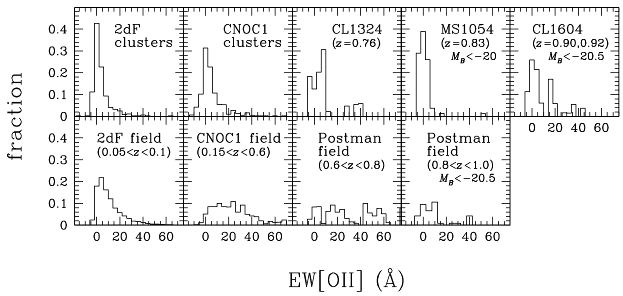

Figure 3. Distributions of EW[OII] of the 2dF, CNOC1 and high-z galaxies. Redshift is increasing from left to right, with $0.05 < z < 0.1$ (2dF), $0.15 < z < 0.6$ (CNOC1) and $0.6 < z < 1$ (high-z galaxies). The cluster galaxy sample is shown in the top panels, and the field sample in the bottom panels, respectively.

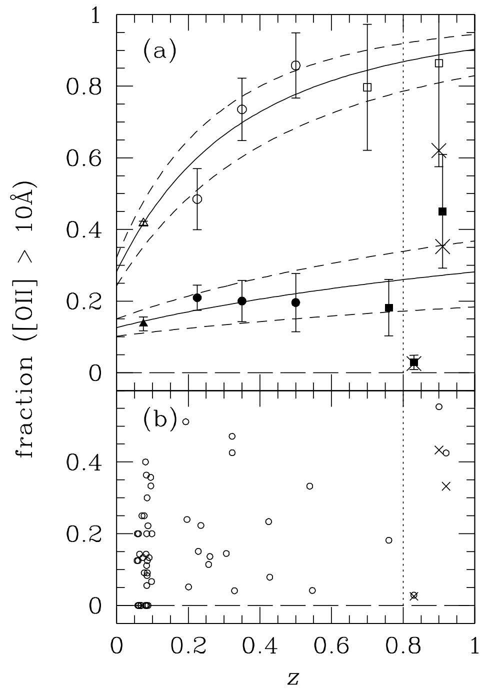

Figure 4. The fraction of galaxies with $\mathrm{EW[OII]} > 10\text{Å}$ as functions of redshift. (a) The triangles, circles and squares indicate the 2dF, CNOC1 and high-z galaxies, respectively. The filled and open symbols correspond to the cluster and the field galaxy samples, respectively. The error bars indicate the 1σ Poisson errors. The two solid lines indicate best fitted lines of the form $f_{10} = 1 - a(1+z)^{-b}$ fitted to cluster and field data, respectively, and the dashed lines show the 1σ error of the fits. (b) The open circle indicates the fraction of each cluster, which is binned at the panel (a). The vertical dotted line in the figure separates the data sets for where we have had to apply a correction to allow for the brighter limiting magnitude. The crosses illustrate the fraction before the correction was made. While the field galaxies show a rapid evolution in f_{10}, the fraction in clusters changes little out to $z \sim 1$.

As we have discussed, the Hα equivalent width distribution (Balogh et al. 2004b; Kauffmann et al. 2004) is strongly bimodal. The bimodality corresponds to a blue, star-forming population and a red population of galaxies no longer forming stars. The distribution of EW[OII] is less clearly bimodal due to the less direct and less sensitive relation between [OII] emission and star formation. Nevertheless, the distribution can still be usefully decomposed into two populations by separating the distribution at a particular EW[OII] value. We have chosen to make this separation at $\mathrm{EW[OII]} = 10\text{Å}$. The particular choice of 10Å is not crucial, but roughly separates the galaxies with strong star formation from the passive population. By examining the objects scattered to negative [OII] values, we can estimate the level of contamination. With the 10Å cut, less than 1% of galaxies with intrinsically low star formation rate scatter into the $\mathrm{EW[OII]} > 10\text{Å}$ population.

In order to investigate the redshift evolution of star formation activity, we determine the fraction of star–forming galaxies as those with $\mathrm{EW[OII]} > 10\text{Å}$ (hereafter f_{10}). As Balogh et al. (2004b) discusses, the evolution of this fraction provides a better indicator of the galaxy population than the median star formation rate. We have confirmed that similar trends are seen in the median, but they are more difficult to interpret due to the highly skewed distribution of $\mathrm{EW[OII]}$.

The evolution of f_{10} is shown in Figure 4(a). The triangles, circles and squares indicate the 2dF, CNOC1 and high-z data sets, respectively. The filled symbols correspond to the cluster samples, while the open symbols correspond to the field galaxy samples. The limiting magnitudes of the $z > 0.8$ data sets do not reach $M_B = -19.5$ (see §2.3). The fractions measured for these systems are shown by the crosses in the diagram. In order to compare these clusters with the other data points, we must make a correction for the additional contribution to f_{10} from galaxies below the magnitude limit. We estimate this by determining the dependence of f_{10} on limiting magnitude for CNOC1 galaxies at $0.3 < z < 0.6$ as described below (Figure 5).

As we should expect from previous work on the cosmic volume averaged star formation rate (Lilly et al. 1996; Madau et al. 1996; Madau, Pozzetti & Dickinson 1998; Hopkins 2004), field galaxies show a strong increase in the active galaxy fraction with redshift. In order to quantify the evolution in f_{10}, we perform least-squares fits using the equation $f_{10} = 1 - a(1+z)^{-b}$. For field galaxies, we find $a = 0.72 \pm 0.04$ and $b = 2.89 \pm 0.74$.

In contrast, the fraction of active galaxies is always low in the cluster galaxies, and there is little discernible increase with redshift as far as $z \sim 0.8$. In order to perform least-squares fits, we combine the distant clusters at $z > 0.6$ (Cl 1324, MS 1054, Cl 1604+4302, and Cl 1604+4321) from the different surveys into a single bin. We find that $a = 0.87 \pm 0.02$ and $b = 0.28 \pm 0.14$ for cluster galaxies. Thus, the parameter b, which indicates an evolutionary strength, of cluster galaxies is inconsistent with that of field galaxies with $\sim 3\sigma$ level. This result is in agreement with the weak evolution in the cluster core "emission" population (derived from a principle component analysis) reported for the CNOC1 alone clusters by Ellingson et al. (2001), but extends the trend to both lower and higher redshift. We will contrast this result with the evolution of the blue fraction in clusters reported by BO84 in the following section.

Figure 4(b) shows the fraction of star forming galaxies of each individual cluster. The variation in f_{10} is large at all redshifts due to the small numbers of galaxies in each individual cluster. It is possible to find individual clusters with f_{10} as low as 0, or as high as 0.6. From the limited data that is currently available, the scatter appears similar at both low and high redshift. The apparent inconsistency between MS1054 (which has a very low f_{10}) and the CL1604 clusters (which have significantly higher values) appears entirely consistent with the variations seen in lower redshift clusters. It is important to realise, however, that the highest redshift

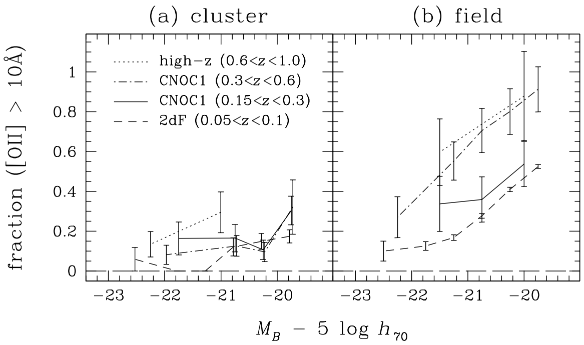

Figure 5. The fractions of galaxies with $\mathrm{EW[OII]} > 10$Å in the (a) cluster and (b) field as functions of the rest-frame B magnitude. The solid and dot-dashed lines indicate the CNOC1 galaxies at $0.15 < z < 0.3$ and $0.3 < z < 0.6$, respectively. The dashed and dotted lines show the 2dF and high-z galaxies, respectively.

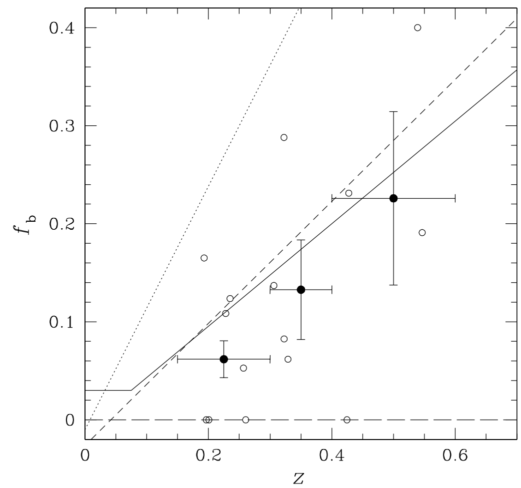

Figure 6. The blue galaxy fraction $f_{\rm b}$ for CNOC1 clusters as a function of redshift. The filled circles show the average blue fraction in each redshift bin. The small open circle indicates the fraction for each cluster. The solid line are extrapolations to higher redshifts of the observed evolution of $f_{\rm b}$ obtained by BO84. The dashed and dotted line indicate the $f_{\rm b}$ derived by Ellingson et al. (2001) and Margonnier et al. (2001), respectively.

sample is limited to only 4 clusters, and thus has limited sampling of the range of f_{10} in clusters at this redshift.

The fraction of emission–line or blue galaxies within a given projected radius is an overestimate of the blue fraction within the corresponding physical radius, because of the strong colour gradient in clusters. We can estimate the effect of projection from the simulations of Diaferio et al. (2001; their Figure 13). This work shows that within a projected radius of $\sim 0.7h_{70}^{-1}$ Mpc, the fraction of interlopers (defined as galaxies with physical distances beyond R_{200}) depends strongly on galaxy colour: ~ 60 per cent for blue galaxies and only ~ 10 per cent for red galaxies. Making a correction for these interlopers reduces our blue (or star–forming) fractions in clusters from ~ 20 per cent to ~ 10 per cent. Moreover, if the fraction of blue interlopers increases with increasing redshift (as expected due to the colour evolution in the field), this will make the observed trend of f_{10} with redshift in clusters *even weaker*. Thus accounting for projection effects only strengthens our conclusions.

In order to investigate the dependence on limiting magnitude in the data-sets we have used, we determined f_{10} for different luminosity bins. The result is shown in Figure 5. The solid and dot-dashed lines indicate the CNOC1 galaxies at $0.15 < z < 0.3$ and $0.3 < z < 0.6$, respectively, and the dashed lines show 2dF galaxies. We also show a result of high-z galaxies with the dotted lines. Because of the low numbers of galaxies and variable magnitude limits we only plot two points for high-z galaxies.

It is clear that the fainter galaxies in the field are more likely to be star forming and possess larger EW[OII] than brighter ones (Kauffmann et al. 2003; Baldry et al. 2004; Balogh et al. 2004a). On the other hand, the trend is much weaker for galaxies in cluster cores over the magnitude range probed by this data. The plot also confirms the trends seen in Figure 4: the fraction of star forming galaxies is always greater in the field than in the cluster and that the redshift evolution is seen for field galaxies, but not for cluster galaxies.

4 COMPARISON WITH BLUE GALAXY FRACTIONS

In the previous section we find that the EW[OII] of galaxies in clusters shows little evolution at $z < 1$. At face value, this result seems to be inconsistent with the Butcher-Oemler effect: the increase in the fraction of blue galaxies in cluster cores with redshift (Butcher & Oemler 1978; BO84; Couch & Newell 1984). The difference cannot be due to the cluster sample used by Kodama & Bower (2001) and Ellingson et al. (2001) both found a significant Butcher-Oemler effect using the CNOC1 clusters. However, among the sample used by Kodama & Bower (2001), only bright galaxies are spectroscopically confirmed requiring them to apply a foreground/background subtraction using a general field data for faint galaxies. This enabled them to reach $M_V < -20+5\log\,h_{50}$, consistent with the original definition of the limiting magnitude of Butcher-Oemler effect. Ellingson et al. (2001) investigate blue fractions of CNOC1 galaxies using spectroscopically confirmed members, however, the radius constraint they adopted is a dynamically determined value, R_{200}, the radius within which the average cluster density is 200 times the critical density (e.g., Carlberg et al. 1996, 1997). The R_{200} of CNOC1 clusters is 1.07-2.24 h_{70}^{-1} Mpc, which is wider than our radius constraints ($0.7h_{70}^{-1}$ Mpc). In order to eliminate the possibility that the increasing trend may be due to galaxies in the outer cluster region, we directly compare with measurements of the evolution in EW[OII], by recomputing the blue fraction only from the spectroscopically confirmed galaxies and adopting the same limiting magnitude and radial cut-off.

We use the $g - r$ colour in Thuan-Gunn system (Thuan & Gunn 1976), which is available in the CNOC1 catalogue to discriminate between blue and red galaxies. On the $g - r$ versus r diagram we fit the colour-magnitude relation for the early-type galaxies using a biweight fit (Beers, Flynn & Gebhardt 1990). Blue galaxies are defined as galaxies 0.2 mag bluer in the rest frame $B - V$ than the red-sequence of each cluster. We calculate the difference in $g-r$ colour in the observed bands corresponding to $\Delta(B-V) = -0.2$ in the rest frame (BO84; Kodama & Bower 2001). This corresponds to $\Delta(g - r)$ of 0.20-0.44 mag, depending on the cluster redshift. As discussed above, we fix the radial cut off at $0.7h_{70}^{-1}$ Mpc (this is typical of the R_{30} cut off used by BO84). Note that our magnitude limit is $M_B = -19.5$, which is brighter than the limit of BO84, $M_V = -19.3$.

Figure 6 shows the calculated blue fraction as a function of redshift. The filled circles show the average blue fraction from the CNOC1 data. The small open circles show the blue fraction of each individual cluster. The solid line in Figure 6 is a linear extrapolation to higher redshifts of the observed evolution of $f_{\rm b}$ obtained by BO84, while the dashed line and the dotted line indicate the best-fit lines from Ellingson et al. (2001) and Margonnier et al. (2001), respectively. In contrast to the results we obtained from our analysis of EW[OII], we see that the blue galaxy fraction of CNOC1 clusters has an increasing trend with redshift. Although the uncertainty is large, the slope of this relation is consistent with BO84, Kodama & Bower (2001) and Ellingson et al. (2001). Note that even if we make the colour boundary redder by 0.1 mag ($\Delta(B-V)=-0.1$), the increasing trend of the $f_{\rm b}$ does not change significantly. As the magnitude limits are different between our analysis and BO84, it is not surprising that our results fall slightly below the trend proposed by BO84. This reflects the trend for a larger fraction of fainter galaxies to have blue colours (Kodama & Bower 2001; Kauffmann et al. 2003; See also Figure 5). Our $f_{\rm b}$ values are also slightly lower than those of Ellingson et al. (2001), a difference that arises from the different radial constraints we have applied: we use only galaxies at the cluster core ($r < 0.7h_{70}^{-1}$ Mpc), while their sample include galaxies out to R_{200}. The extremely rapid change in $f_{\rm b}$ over the redshift range out to $z \sim 0.2$ reported by Margonnier et al. (2001) is not consistent with our study.

5 DISCUSSION

We set out to investigate the evolution of the [OII] line in cluster galaxies. We found that the fraction of cluster galaxies with strong [OII] emission was always small and evolved little with redshift. Viewed in isolation, this result is not surprising: the very dense environment in cluster cores is hostile to star formation. The commonly discussed environmental processes of ram-pressure (Gunn & Gott 1972; Abadi et al. 1999; Fujita & Nagashima 1999; Quilis et al. 2000), harassment (Moore et al. 1996, 1999) and strangulation (Larson et al. 1980; Balogh et al. 2000; Drake et al. 2000; Diaferio et al. 2001; Okamoto & Nagashima 2003) are all effective in this region. Our results are showing us that this environment has always been hostile even out to $z \sim 1$. The very dense environment of the cluster core becomes increasingly rare as we look back to higher redshift, but star formation is always highly suppressed there.

What is puzzling is to compare this result to the evolution in the colours of cluster galaxies. A long history of studies have reported an increase in the fraction of blue galaxies in cluster cores at higher redshifts (BO84; Kodama & Bower 2001; Ellingson et al. 2001; Margonnier et al. 2001). With the CNOC1 data set, we are able to compare the two measurements of galaxy star formation activity directly. Within the large uncertainties, the colours of the galaxies confirm the increase in blue fraction suggested by BO84.

First we consider two biases in the measurements that could affect this result. (1) Aperture effects are of course a worry in assessing these results. However, Appendix A of Wilman et al. (2004) makes a detailed study of the likely effect on [OII] emission by examining the radial dependence of the colours of galaxies in the Sloan Digital Sky Survey (hereafter SDSS; York et al. 2000; Stoughton et al. 2002; Abazajian et al. 2003). He concludes that there is currently no evidence that the fraction of [OII] emitting galaxies determined from relatively small apertures (eg., by the 2dF and SDSS fiber spectrographs) is substantially different from that determined through larger apertures. (2) If the measurement error on the [OII] emission was large, a weak trend in the fraction of [OII] emitters could be masked by objects with intrinsically low star formation rates being scattered into the $\mathrm{EW[OII]} > 10$Å region. However, the estimated errors in the CNOC1 equivalent widths are only 2Å on average, and thus the error is too small to account for the tail seen in Figure 3 as we have shown in §3.

If we reject both of these measurement biases, how can we reconcile these apparently contradictory results? The key may lie in the way the two measures of the galaxy activity are related to the star formation history. While the [OII] emission measures the radiation from short-lived hot stars, the $g-r$ colour contains a memory of the star formation rate over the previous few Gyr (eg., van Dokkum et al. 2000). Thus one possible explanation for the result is that while most galaxies in these central cluster regions currently have little star formation at all redshifts, more galaxies in the higher redshift clusters have experienced significant star formation within the last few Gyr, and have evolved from a bluer starting point. In Figure 7, we directly compare the EW[OII] with the offset of the galaxy from the dividing colour between blue and red galaxy, which is defined at §4 ($\Delta(g-r)$). At higher redshift, there is a greater spread in colour for the range of EW[OII] (due both to the K-correction, and the greater star formation rates of field galaxies) while the range in EW[OII] is roughly similar. Thus the star forming population in the lower redshift bin lie closer to the colour threshold than to the EW[OII] threshold, while the converse is true in the high redshift panel. This provides some support for the differential evolution of EW[OII] and colour that we have discussed.

If this is a satisfactory explanation for the different evolution of f_{10} and f_b, can we understand what drives it? Two possibilities stand out: (1) the more rapid assembly of clusters at higher redshift (Bower 1991; Kauffmann 1996) or (2) the star formation rates in the galaxies that are being accreted by the local clusters are lower than in their high redshift counter parts. In the first case, the mass assembly history of clusters differs between low and high redshift because clusters are much rarer objects at $z \sim 0.5$ than at the present-day, and because the cosmic time available to build the cluster is less at higher redshift. In the second case, the reduction in the star forming fraction of the infalling galaxies is clearly shown by our data on the field galaxies. As a result the galaxies which are accreted by the local clusters are much less likely to have significant star formation in the first place. It is likely that both effects contribute, and hard to disentangle them.

An alternative possibility is that the [OII] emission is powered by AGN activity rather than by star formation. In this case, the fractions would reflect very different physical processes, whose evolution might very well differ. The scenario naturally explains the existence of red galaxies with detectable [OII] seen in the first panel of Figure 7. Martini et al. (2004) show from X-ray observations that clusters may contain a significant population of AGN. Often these galaxies cannot be recognised as AGN from their optical spectra alone, yet they are clearly luminous point sources in the X-ray data. Their results suggest that the active systems are over represented in clusters compared to the field. It is thus possible that an underlying trend in the star formation rates of cluster galaxies is masked by a opposing trend in the fraction undergoing AGN activity. It should be noted, however, that the average AGN fraction is significantly less that 5% in their data.

In future, it will also be possible to carry out this programme using other indicators of star formation and to investigate other galaxy environments. Wilman et al. (2004) have used [OII] to investigate the evolution of galaxies in groups. Interestingly, they find

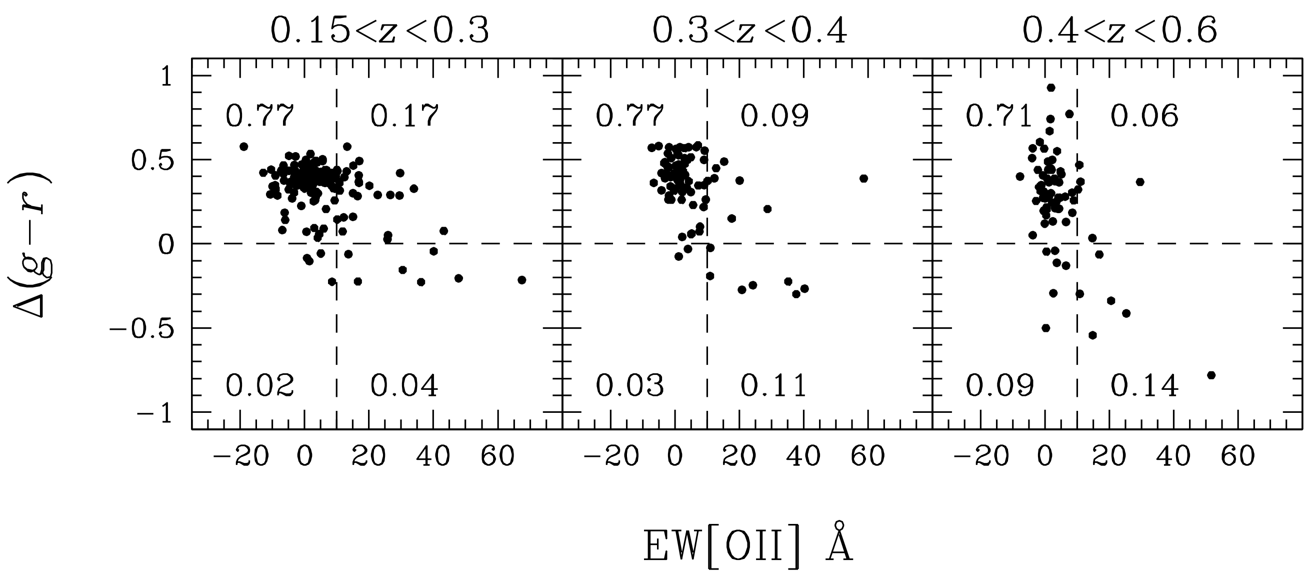

Figure 7. EW[OII] versus $\Delta(g-r)$ diagrams of the CNOC1 cluster galaxies. The vertical axis shows the 'differential colour', defined as the observed colour minus the dividing colour between blue and red galaxy (see text for detail) at the same M_B magnitude. The sequence of panels shows clusters at increasing redshift. At higher redshift, the blue galaxy population becomes increasingly offset from the red colour sequence. We also show the fraction of galaxies in each of the four regions.

that the fraction of star forming galaxies in the group environment increases significantly over the redshift range $z = 0$ to 0.5, suggesting that group galaxy properties are much more closely tied to galaxies in the field than galaxies in cluster cores. While the [OII] line is conveniently placed in the optical spectral window, it suffers the disadvantage of being sensitive to dust and metallicity as well as the star formation rate. The Hα line gives a cleaner measure of the star formation rate. For example, Finn et al. (2004) report measurements of Hα emission from a poor cluster (Cl J0023+0423B) at $z = 0.845$. Although their measure of activity is not directly comparable to the one we use here, they find a much higher incidence of star formation activity than any of our clusters, or that of our Hα measurements in the rich cluster Cl0024+1652 (Kodama et al. 2004). At present, however, the sample of clusters with well sampled Hα determinations is too small to make an accurate test of the rate of evolution. Furthermore, it is harder to measure over a wide range of redshifts because it is redshifted out of the optical window. Nevertheless, new multi-object spectrographs working in the near infrared, such as MOIRICs, will allow us to probe the star formation rates in distant clusters with much greater accuracy using Hα emission. Alternatively, it will be possible to use the Spitzer satellite to measure the star formation rates in clusters on the basis of their far infra-red dust emission (Duc et al. 2002; Stanford et al. in prep). The prospects look extremely good for extending the work we have described here.

6 CONCLUSIONS

By compiling a homogeneous sample of the clusters with extensive spectroscopic measurements of the [OII] emission line, we have presented an analysis of the evolution of the fraction of strongly star forming galaxies in cluster cores as a function of redshift. Our sample is based on the CNOC1 cluster survey (Yee et al. 1996), but extends this data set to lower and higher redshift using the 2dF-GRS (Colless et al. 2003) and spectroscopic surveys of higher redshift clusters by Postman et al. (2001) and van Dokkum et al. (2000).

Our results show little evolution in the fraction of galaxies with EW[OII] > 10Å. We constrain the rate of evolution to be $\Delta f_{10}/\Delta z < 0.2$. This result suggests that the cluster environment has always been hostile to star formation, at least for $z < 1$. Many mechanisms have been proposed to explain the hostility of the cluster environment at low redshift. Our results show that the same mechanisms also operate effectively in this special environment at higher redshift, despite the higher rates of galaxy infall that are expected (Kaufman 1996) and the higher fraction of star forming galaxies in the field population. It is important to note, however, that there is extensive scatter between individual clusters at all redshifts; thus individual clusters may pass through episodes with higher rates of field galaxy accretion.

The slow evolution of f_{10} we report, initially seems at odds with the strongly increasing fraction of blue galaxies in clusters reported in previous papers (eg. BO84); however, we confirm that the fraction of blue galaxies increases strongly with redshift using the same galaxies for our analysis of the [OII] emission. We consider how the results can be reconciled. Since the [OII] emission line is an instantaneous measure of the star formation rate, while galaxy colour reflects the average star formation rate over the previous few Gyr, the two observations may be compatible if the rate at which clusters are assembled is sufficiently high at high redshift and the galaxies from which the system is assembled are initially much bluer. Another possibility is that the [OII] emission line galaxies that we see in the low redshift systems may be powered by AGN activity rather than by AGN activity. A larger compilation of deep X-ray data is required to exclude this possibility.

The results we present are limited by the small numbers of clusters which have been extensively surveyed at high redshift, and by the limitations of the [OII] emission line as a star formation rate indicator. The prospects for extending this work using Hα line strengths, SPITZER mid-IR fluxes and GALEX ultra-violet photometry as star formation rate indicators look very encouraging.

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REFERENCES

Abadi, M. G., Moore, B., Bower, R. G. 1999, MNRAS, 308, 947
Abazajian, K. et al. 2003, AJ, 126, 2081
Baldry, I. K., Glazebrook, K., Brinkmann, J., Ivezić, Ž., Lupton, R. H., Nichol, R. C., Szalay, A. S. 2004, ApJ, 600, 681
Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., Ellingson, E. 1999, ApJ, 527, 54
Balogh, M. L., Morris, S. L. 2000, MNRAS, 318, 703
Balogh, M. L., Navarro, J. F., Morris, S. L. 2000, ApJ, 540, 113
Balogh, M. L., Couch, W. J., Smail, I., Bower, R. G., Glazebrook, K. 2002, MNRAS, 335, 10
Balogh, M. L., Baldry, I. K., Nichol, R., Miller, C., Bower, R., Glazebrook, K. 2004a, ApJL, 615, L101
Balogh, M. L. et al. 2004b, MNRAS, 348, 1355
Beers, T. C., Flynn, K., Gebhardt, K. 1990, AJ, 100, 32
Bower, R. G. 1991, MNRAS, 248, 332
Bower, R. G., Balogh, M. L. 2004, in Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, ed. J. S. Mulchaey, A. Dressler, A. Oemler (Cambridge: Cambridge Univ. Press) (astro-ph/030642)
Butcher, H., Oemler, A.,Jr. 1978, ApJ, 219, 18
Butcher, H., Oemler, A.,Jr. 1984, ApJ, 285, 426 (BO84)
Carlberg, R. G., Yee, H. K. C., Ellingson, E. 1997, ApJ, 478, 462
Carlberg, R. G., Yee, H. K. C., Ellingson, E., Abraham, R., Gravel, P., Morris, S., Prichet, C. J. 1996, ApJ, 462, 32
Coleman, C. D., Wu, C.-C., Weedman, D. W. 1980, ApJS, 43, 393
Colless, M. et al. 2001, MNRAS, 328, 1039
Colless, M. et al. 2003 (astro-ph/0306581)
Couch, W. J., Balogh, M. L., Bower, R. G., Smail, I., Glazebrook, K., Taylor, M. 2001, ApJ, 549, 820
Couch, W. J., Newell, E. B. 1984, ApJS, 56, 143
Diaferio, A., Kauffmann, G., Balogh, M. L., White, S. D. M., Schade, D., Ellingson, E. 2001, MNRAS, 323, 999
Drake, N., Merrifield, M. R., Sakelliou, I., Pinkley, J. C. 2000, MNRAS, 314, 768
Dressler, A., Gunn, J. E. 1992, ApJS, 78, 1
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., Sharples, R. M. 1999, ApJS, 122, 51
Duc, P.-A. et al. 2002, A&A, 382, 60
Eggen, O., Lynden-Bell, D., Sandage, A. 1962, ApJ, 136, 748
Eke, V. R. et al. 2004, MNRAS, 348, 866
Ellingson, E., Lin, H., Yee, H. K. C., Calrlberg, R. G. 2001, ApJ, 547, 609
Finn, R. A., Zaritsky, D., McCarthy, D. W., Jr. 2004, ApJ, 601, 141
Fujita, Y., Nagashima, M. 1999, ApJ, 516, 619
Fukugita, M., Shimasaku, K., Ichikawa, T. 1995, PASP, 107, 945
Gioia, I. M., Luppino, G. A. 1994, ApJS, 94, 583
Gunn, J. E., Gott, J. R., III 1972, ApJ, 176, 1
Hopkins, A. M. 2004, ApJ, 615, 209
Hopkins, A. M. et al. 2003, ApJ, 599, 971
Kauffmann, G. 1996, MNRAS, 281, 487
Kauffmann, G. et al. 2003, MNRAS, 341, 54
Kauffmann, G., White, S. D. M., Heckman, T. M., Ménard, B., Brinchmann, J., Charlot, S., Tremonti, C., Brinkmann, J. 2004, MNRAS, 353, 713
Kennicutt, R. C. 1992, ApJS, 79, 255
Kodama, T., Arimoto, N. 1997, A&A, 320, 41
Kodama, T., Balogh, M. L., Smail, I., Bower, R. G., Nakata, F. 2004, MNRAS, 354, 1103
Kodama, T., Bower, R. G. 2001, MNRAS, 321, 18
Larson, R. B., Tinsley, B. M., Caldwell, C. N. 1980, ApJ, 237, 692
Lilly, S. J., Le Fèvre, O., Hammer, F., Crampton, D., 1996, ApJ, 460, L1
Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., Fruchter, A. 1996, MNRAS, 283, 1388
Madau, P., Pozzetti, L., Dickinson, M. 1998, ApJ, 498, 106
Martini P., Kelson D., Mulchaey J.S., Athey A. 2004, in Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, ed. J. S. Mulchaey, A. Dressler, A. Oemler (Cambridge: Cambridge Univ. Press) (astro-ph/030642)
Margoniner, V. E., de Carvalho, R. R., Gal, R. R., Djorgovski, S. D. 2001, ApJ, L143
Moore, B., Katz, N., Lake, G., Dressler, A., Oemler, A., Jr. 1996, Nature, 379, 613
Moore, B., Lake, G., Quinn, T., Stadel, J. 1999, MNRAS, 304, 465
Okamoto, T., Nagashima, M. 2003, ApJ, 587, 500
Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, A. J., Butcher, H., Ellis, R. S., Oemler, A., Jr. 1999, ApJ, 518, 576
Postman, M., Lubin, L. M., Oke, J. B. 1998, AJ, 116, 560
Postman, M., Lubin, L. M., Oke, J. B. 2001, AJ, 122, 1125
Quilis, V., Moore, B., Bower, R. G. 2000, Science, 288, 1617
Stoughton, C. et al. 2002, AJ, 123, 485
Thuan, T. X., Gunn, J. E. 1976, PASP, 88, 543
van Dokkum, P. G., Franx, M., Fabricant, D., Illingworth, G. D., Kelson, D. D. 2000, ApJ, 541, 95
Wilman, D. J., Balogh, M. L., Bower, R. G., Mulchaey, J. S., Oemler, A., Jr., Carlberg, R. G., Eke, V. R., Lewis, I. J., Morris, S. L, Whitaker, R. J. 2004, MNRAS, submitted
Yee, H. K. C., Elingson, R., Carlberg, R. G. 1996, ApJS, 102, 269
York, D. G. et al. 2000, AJ, 120, 1579