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Bimodality in the U−R colour as a probe for cluster galaxy evolution at intermediate redshifts*

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ABSTRACT

We have performed deep U- and R-band imaging of three rich galaxy clusters at intermediate redshifts, CL 0024+1654 ($z = 0.39$), MS 1621.5+2640 ($z = 0.43$) and CL 0016+1609 ($z = 0.55$), using the Nordic Optical Telescope. For each of these clusters, and for MS 1008−1224 ($z = 0.30$) using public data, we constructed U−R vs. R colour magnitude diagrams (CMDs), which we use as a new probe for cluster galaxy evolution timescales. The CMDs are distinctly bimodal, with a population of red (U−R > 3) and blue (U−R < 2) galaxies separated by a 'gap', a region of low number density in the CMD. Using a phenomenological galaxy formation model, we produce mock U−R CMDs in order to interpret the observational results. Our analysis suggests that the U−R CMD provides useful constraints on models of galaxy formation and evolution, due to the (observed frame) U-band sensitivity to star formation activity, especially for the redshift range probed. We make a first attempt at modifying galaxy formation models to better match the observational data presented, mostly through the modelling of physical processes that regulate star formation, including a global star formation threshold as well as completely truncating star formation within galaxy clusters due to processes like ram-pressure stripping.

Key words: galaxies: evolution

1 INTRODUCTION

The colour of a galaxy is a measure of the current mix of its stellar populations, as determined by its formation and merger history (e.g. Kodama & Bower 2001). The colour-magnitude diagram (CMD) is therefore a useful diagnostic to study the evolution of galaxies, as examplified by studies of the cluster red sequence. The aim of this paper is to study the distribution of all galaxies within the CMD in order to learn what their position within the diagram can tell us about their past and present evolutionary properties.

The variations in colour due to differences in stellar population mix are largest when the range of colours of the constituent single stellar populations are largest. In this paper we show that for galaxies at intermediate redshifts the U−R colour is an optimal choice for discriminating between evolved and actively star forming galaxies; at $z \approx 0.4$ the U-band filter passes photons from a local minimum in the spectral energy distribution (SED) of many typical galaxies, while the R-band filter measures the SED around a local maximum (as illustrated in Fig. 8).

For several clusters at intermediate redshifts, observed as part of a gravitational lensing programme (Rögnvaldsson et al. 2001; Dye et al. 2002), we found a bimodality in the

* Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias, and on observations collected at the European Southern Observatory, Paranal, Chile (VLT-UT1 and VLT-UT2 Science Verification Program).

U−R colour distribution, or alternatively put, a depletion in the number of galaxies with U−R between 2 and 3. This lead us to consider further the U−R CMD, in which this depletion shows up as a 'gap' between two fairly distinct populations of galaxies: cluster ellipticals, which form a clear red sequence near U−R ≈ 4, and actively star forming galaxies, which populate the region around U−R ≈ 1 − 2. Thus, the position of cluster galaxies within a CMD can be used to assess the evolutionary state of their constituent stellar populations, and, for example, whether any star formation occured in their recent history.

Our practical aim is to study whether U−R CMDs are a good probe of cluster galaxy evolution, as well as to determine how U−R CMDs reflect known cluster characteristics and their evolution. On the basis of template spectra for 'standard' galaxies, the gap in the U−R CMD is likely to move *and* change size with redshift, but should certainly exist at most redshifts. However, it is expected to be most distinct from redshift 0.3 onwards, so we selected clusters in the redshift range $0.3 < z < 0.6$ in order to study the significance of the gap. We do not push beyond $z \approx 0.6$ where observing in the U-band becomes prohibitively expensive, and redshifts are harder to get. We selected four clusters in this redshift range for which a statistically significant number of cluster member redshifts are known. For three of these we obtained observational data ourselves, while for the fourth literature data was used. This dataset will establish an evolutionary sequence in redshift.

The lay-out of this paper is as follows: in Section 2 we describe the observational dataset and the resulting U−R CMDs. In Section 3 we discuss the origin of the depletion in the U−R CMD by looking at stellar population models, while in Section 4 galaxy formation models are used to produce mock CMDs in order to interpret the observations. Finally, the results are summarized and discussed in Section 5.

2 OBSERVED U−R COLOUR MAGNITUDE DIAGRAMMES

2.1 Overview of observational data

The observational data discussed in this paper were taken as part of a gravitational lensing programme, in which the depletion in number counts towards rich clusters is measured (Rögnvaldsson et al. 2001; Dye et al. 2002). In short, deep U and R band observations of three clusters were obtained using the ALFOSC camera on the Nordic Optical Telescope (NOT). With its highly UV sensitive thinned LORAL chip, the ALFOSC camera is ideally suited for U-band observations which are normally extremely challenging from the ground.

We selected those lensing clusters for which a significant number of galaxy redshifts within the field of view are known, and which have a significant spread in cluster redshift. The CNOC survey (e.g. Carlberg et al. 1996) was most complete in this respect, and all our target clusters are part of that survey. The sample is listed in Table 1, including two fields, which we included in our analysis to contrast the U−R CMDs for galaxy clusters with that of field galaxies.

In the following we provide more details on each of the clusters and the two blank fields. All magnitudes are for the AB system, whereas the magnitudes calculated for the theoretical models adopt $H_0 = 70$ km s^{-1} Mpc^{-1}.

2.1.1 MS 1008 ($z = 0.30$)

MS 1008 was observed as part of the FORS/ISAAC and FORS2 Science Verification Programmes of the VLT at ESO, known as the Cluster Deep Field. This data is public, with 3 hours of R band and 6 hours of U band data (see `www.eso.org/science/ut1sv/` for the R band observations, and `www.eso.org/science/ut2sv/` for the U band observations, which also provided the completeness limit in the U band listed in Table 1). The cluster was selected for this programme because published data indicates a large mass/velocity dispersion at intermediate redshift, which is corroborated by the existence of gravitational arcs. Mayen & Soucail (2000) used it to study lens magnification, and quoted the completeness limit in R listed in Table 1, whereas Athreya et al. (2002) performed a weak lensing analysis using the same dataset.

The cluster was also selected because it is part of the Einstein Medium Sensitivity Survey (EMSS, Gioia & Luppino 1994) and part of the CNOC survey (Carlberg et al. 1996; Yee et al. 1998), which includes 47 redshifts within the FORS field of view, including 34 cluster members.

2.1.2 CL 0024 ($z = 0.39$)

The first NOT run resulted in a total integration time of 2hr20m in U and 20m in R, i.e. half a night (01/10/97), with moderate to bad seeing (1.1"-2") and high humidity. However, this data was of insufficient quality to be used in the final analysis. The second run was much more succesful: we were able to integrate for 10hr25m in U and 2hr40m in R. More details about the data acquisition and reduction are provided by Rognvaldsson et al. (2001) and Dye et al. (2002).

CL 0024 has been a focus of gravitational lensing studies and a considerable amount of published information is available, including ground-based photometry (g, r and i) and spectroscopy (Dressler et al. 1985; Dressler & Gunn 1992), and HST imaging (F450W and F814W; Smail et al. 1997). In addition, Czoske and collaborators have kindly made their redshift measurements of this cluster (Czoske et al. 2001) available to us, so that a total of 163 redshifts are available within the ALFOSC field of view, including 138 probable cluster members.

2.1.3 MS 1621 ($z = 0.43$)

For this cluster we obtained almost 8 hours of data. The total integration time was 5h45m in U and 2h in R, taken on three nights (24/5/98, 25/5/98, and 29/6/98). Photometric calibration was done using M92 standard stars. The seeing was good to moderate, 0.8" - 1.5". Redshifts have been obtained from the CNOC study (Ellingson et al. 1998), but only 54 redshifts lie within the ALFOSC field of view, including 35 cluster members.

2.1.4 CL 0016 ($z = 0.55$)

This cluster is one of the most extensively studied medium redshift clusters, with ground-based photometry in g, r,

Table 1. Overview of the observational data

Cluster ID	z	integration time U	integration time R	known redshifts	limiting mag. U	limiting mag. R	telescope / instrument
MS 1008−1224	0.301	4h10m	1h30m	47	25.8	26	VLT / FORS(2)
CL 0024+1654	0.393	10h25m	2h40m	163	25.7	25.8	NOT / ALFOSC
MS 1621.5+2640	0.426	5h45m	2h	54	25.2	25.1	NOT / ALFOSC
CL 0016+1609	0.545	4h30m	1h30m	186	24.6	24.5	NOT / ALFOSC
CFRS−14 field	-	2h30m	1h25m	-	24.5	24.1	NOT / ALFOSC
ELAIS−N2 field	-	3h15m	2h10m	-	26.5	26	WHT / PFIP

Overview of all observational data considered in this paper. All sets except the cluster MS 1008−1224 (obtained from the VLT/FORS2 archive) and the ELAIS−N2 (observed with the William Herschel Telescope) field have been taken at the Nordic Optical Telescope with the same filters.

V, R, I (Ellingson et al. 1998, LeFèvre et al. 1994), spectroscopy (Dressler and Gunn 1992; Belloni and Röser 1996) and HST imaging with morphological analysis (Smail et al. 1997; Wirth, Koo & Kron 1994). It has also been observed in the B-band by Clowe et al. (2000).

Due to bad weather we only obtained 2 hours of U band data and 20 mins of R band data at our first attempt, but got 6 hours of data at our second run on 16/10/2001. The 2 hours worth of data from the first run were not of sufficient quality, unfortunately, so we had to discard those data.

2.1.5 CFRS−14 field

In order to help interpret the U−R CMDs for galaxy clusters, a reference CMD for 'field' galaxies is very useful. This is provided by the field sample used for the galaxy-galaxy lensing survey of Jaunsen & Hjorth (1999), which they observed with the same telescope, filters, and instruments as we did.

2.1.6 ELAIS−N2 field

We also consider another field sample, which is much bigger and deeper, but has not been obtained with the NOT, nor with exactly the same filters. The U-band data has been taken at the William Herschel Telescope by Rob Ivison, using the PFIP prime focus camera with two 2k×4k CCDs, with the high-throughput liquid U filter. The R-band data was taken by Chris Willott using the same instrument at the same telescope (see Roche et al. 2002 and González-Solares et al. 2005 for details).

2.2 The observed U−R Colour-Magnitude Diagrammes

For each of the four clusters and the two field samples (all listed in Table 1), we present the U−R CMDs in Fig. 1. All galaxies plotted are those for which we obtained reliable colours, and which are brighter than the limiting magnitude listed in Table 1. We can clearly see a sparsely populated region between U−R $\approx$ 2 and U−R $\approx$ 3, which we designate as a gap, even though it is not completely empty. This gap separates the the cluster red-sequence from star forming galaxies with U−R $<$ 2, thus producing a distinct bimodality in the colour distribution. Only for CL 0016 is the dataset too incomplete to see either the gap or the cluster red-sequence. This gap is somewhat less distinct for the field populations, for which it is known that most of these galaxies have U−R $\approx 1-2$ (Hogg et al. 1997), with the redder galaxies likely to be residing in groups and poor clusters that can never be avoided in any field sample.

The clusters were selected on the basis of their redshifts and the availability of sufficient spectroscopic redshifts for their cluster members. These were taken from the literature, and a matching of galaxy positions provides us with U−R CMDs for cluster members only. These are shown in Fig. 2 for those clusters for which we have enough data, being MS 1008, CL 0024, and MS 1621. The 'gap' is visible, even though our samples are still relatively small. It is best observed for CL 0024, which has the largest number of redshifts available.

In comparing the diagrammes for galaxies with confirmed redshifts to the full sample CMDs shown in Fig. 1, the first thing to notice is that the brightest and bluest galaxies typically are not cluster members: they are interloper star-forming field galaxies. The brightest cluster galaxies are invariably red.

2.3 The redshift dependence of the U−R colour for template galaxies

The redshift dependence of the U−R colour is illustrated in Figure 3, where U−R is plotted as a function of redshift for several 'standard' galaxies, using the Coleman, Wu & Weedman (1980) templates. Overplotted are our data for all four clusters, separated into cluster (plus symbols) and field (star symbols) galaxies according to their redshifts. The difference in U−R colour for these galaxies is rapidly increasing from $z = 0.2$ onwards, reaching a maximal difference at $z = 0.5$, and then gently sloping off beyond that. Thus, the U−R colour difference between early- and late-type galaxies is around 3 magnitudes at intermediate redshifts ($0.4 < z < 0.6$), allowing relatively large observational errors in the colour determination while maintaining the power to separate out different galaxy types.

A problem with the use of template spectra for galaxies which are abundant at the present epoch is that at $z = 0.5$ the universe is two thirds of its present age, which inevitably

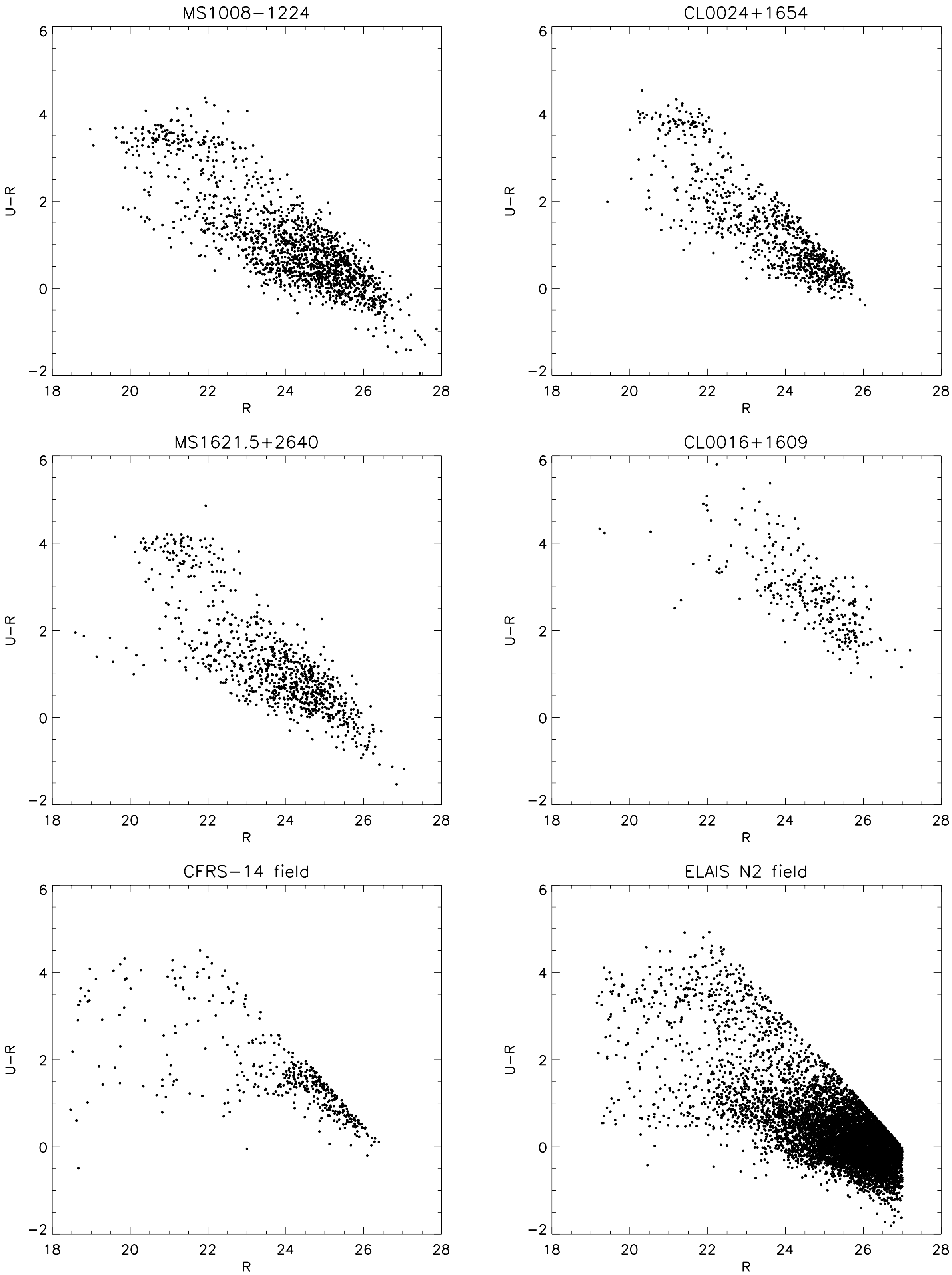

Figure 1. Observed U−R colour-magnitude relation for the clusters MS 1008 (at $z = 0.30$), CL 0024 (at $z = 0.39$), MS 1621 (at $z = 0.43$), and CL 0016 (at $z = 0.55$), plus the same relations for two field samples, the CFRS−14h and ELAIS−N2 fields.

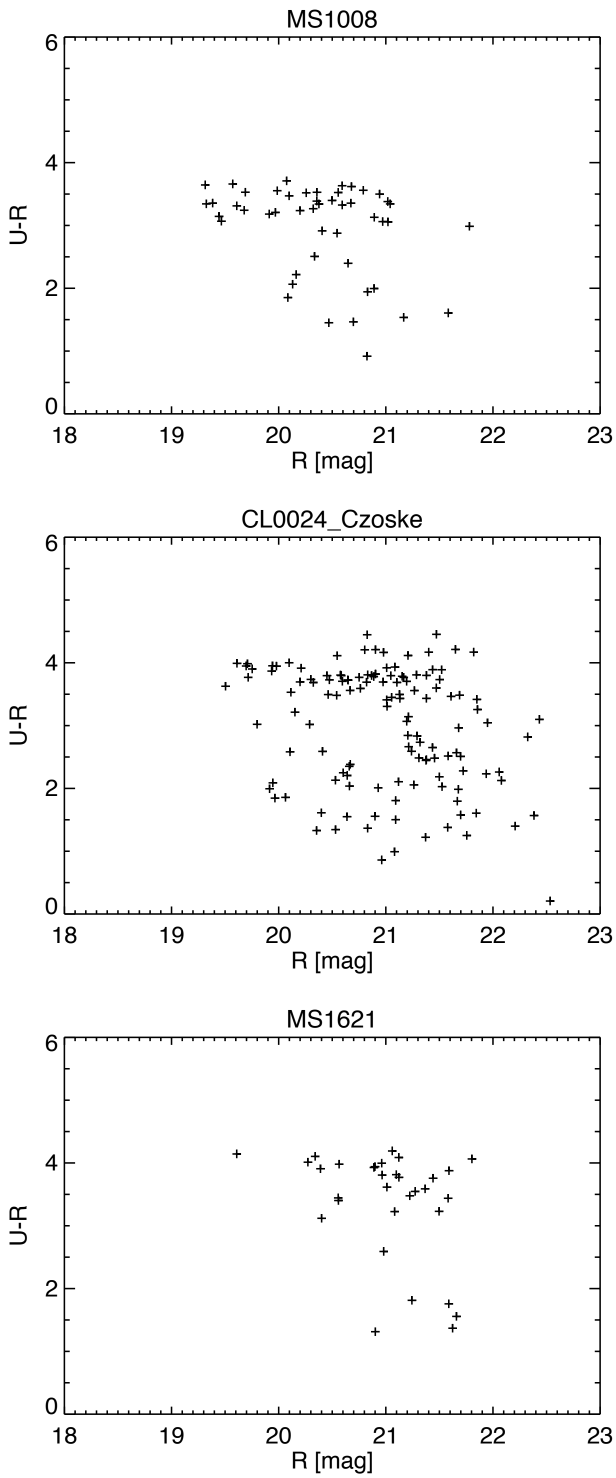

Figure 2. Observed U−R colour-magnitude relation for *confirmed cluster members only* for MS 1008 ($z = 0.30$), CL 0024 ($z = 0.39$), and MS 1621 ($z = 0.43$).

means that its galaxy population is probably different at that epoch. Also, the merging of galaxies and the formation of clusters is more abundant at intermediate redshifts, resulting in a larger fraction of galaxies other than the 'standard' galaxies plotted in Fig. 3, like irregular, starburst, and post-starburst galaxies. These can be either bluer (due to significantly enhanced star formation) or redder (due to excessive dust reddening) than the standard ones, so that the total range in U−R colour for a $z = 0.5$ galaxy cluster can be considerable.

2.4 Probability density functions

Instead of examining the U−R CMD in its entirety, it is instructive to look at the U−R colour distribution itself. These distributions are plotted as normalized probability density functions (PDFs) in Fig. 4 for both the confirmed clusters galaxies as well as for the interloper field galaxies found in the same image (solid line). Clearly, most cluster galaxies are, on average, much redder than the interloping field galaxies. The U−R $\approx 1-2$ colours of the latter are in good agreement with the U−R colours found for faint galaxies by Hogg et al. (1997), who quote a mean value of U−R = 1.2 for 25<R<26. However, each of the clusters does contain a number of blue galaxies as well, which are likely to be accreted by the cluster at that time.

3 INTERPRETATION OF THE U−R CMD

3.1 Stellar population synthesis models

In order to understand the observed 'gap' in the U−R CMD, we first look at the building blocks of the luminous parts of galaxies: stellar populations. To predict the SEDs and photometric properties of galaxies we have used the 1999 version of the extensive library of synthetic stellar population models computed by Bruzual & Charlot (1993), which take into account the chemical evolution by linking the star formation rate dM_*/dt and metallicity Z. We assume that the initial mass function (IMF) is universal and is given by a Salpeter IMF.

3.2 U−R colour as a function of redshift for single stellar populations

The redshift of the galaxy determines which part of the full SED is observed through the U and R band filters. The U−R colour at a given redshift therefore depends on the shape of the SED. This is demonstrated in Fig. 5, where full SEDs are shown for some simple but fundamentally different stellar populations: starbursts (solid lines), which have a short exponentially decaying star formation timescale $t_* = 0.1$ Gyr, and a quiescent star forming population (dashed lines), whose star formation rate decays very slowly ($t_* = 10$ Gyr). We show SEDs for two different ages (0.1 and 10 Gyr) in both cases. At the bottom of the plot the transmission curves of the U and R band filters for a stellar population at $z = 0$ (dotted lines) and at $z = 0.4$ (solid lines) are shown.

Clearly, the observed frame U band luminosity is very sensitive to the part of the SED that most strongly evolves with time for a stellar population for a passively evolving stellar population, like a post-starburst population. The implication for the U−R colour as a function of redshift is demonstrated in Fig. 6, by comparing colour evolution at $z = 0.3$ and $z = 0.55$ for a range of single stellar populations. This shows that for short star formation timescales (starbursts with $t_* = 0.1$ Gyr in this example), the U−R colour at $z = 0.4$ rapidly evolves from U−R ≈ 0 to U−R=3

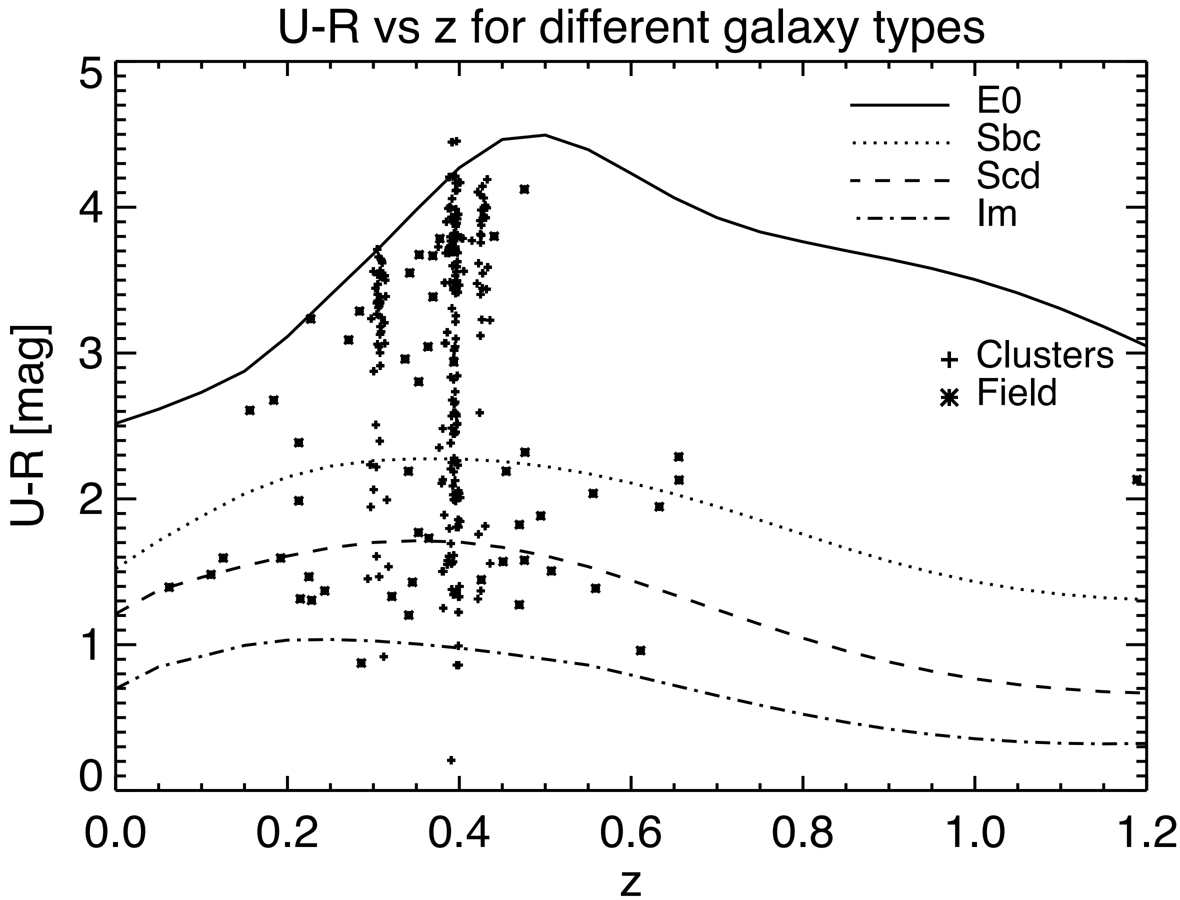

Figure 3. Redshift dependence of the U−R colour observed towards MS 1008 ($z = 0.30$), CL 0024 ($z = 0.39$), MS 1621 ($z = 0.43$) and CL 0016 ($z = 0.55$). Confirmed cluster members are plotted using the + symbol, whereas field galaxies (interlopers) are plotted as crosses. The curves depict colours of 'standard' galaxies, using the templates of Coleman, Wu & Weedman (1980).

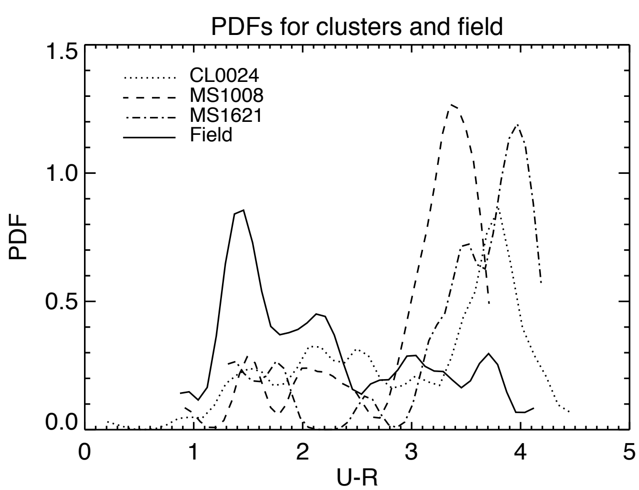

Figure 4. Observed U−R probability density functions (normalized to unity) for MS 1008 (dashed line, at $z = 0.30$), CL 0024 (dotted line, at $z = 0.39$) and MS 1621 (dot-dashed line, at $z = 0.43$), for all galaxies with know redshifts. The solid line shows the distribution for all interloping field galaxies found in the same observed images of the three clusters.

over a period of 1 Gyr, and then evolves slowly to U−R > 4 for the next 10 Gyr. This behaviour is quite different for quiescent star formation that occurs in disks, for which the U−R colour evolves more gently, and even after 10 Gyr is still near or below U−R=2.

This behaviour must form the basis for the production of a 'gap' in the U−R CMD ($z = 0.4$), in the sense that galaxies that are still actively forming stars, expected to be mainly spirals, populate the CMD below the U−R gap, while galaxies that reside above the U−R gap stopped forming stars more than about a Gyr ago (probably mostly ellipticals or dusty starburst galaxies) and now form the cluster red-sequence. This is either because star formation activity was truncated due to specific cluster processes like ram-pressure stripping of the star-forming gas, or because merger activity in the cluster infall region is enhanced such that much of the cold gas reservoir of the infalling galaxy is used up in bursts of star formation. In both cases galaxies falling into the cluster have undergone a rapid change in colour, going from blue infalling spirals to red cluster early-type galaxies in a short time, but where and when this happens is unclear. The gap region itself corresponds to the evolutionary phase of a galaxy in which star formation activity has just been decreased significantly, so few galaxies should populate the gap region.

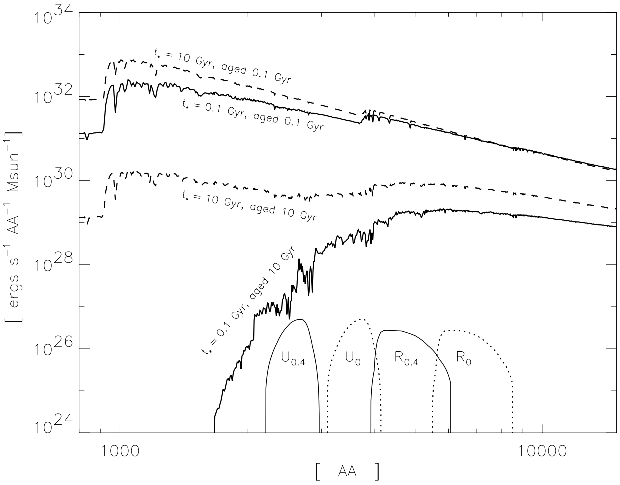

Figure 5. Rest frame spectra of four single stellar populations, two starbursting ones (solid lines, with $t_* = 0.1$ Gyr) and two quiescent ones (dashed lines, with $t_* = 10$ Gyr), for two different ages (0.1 and 10 Gyr). The transmission curves of the U and R band filters for a galaxy at $z = 0$ (dotted lines) and at $z = 0.4$ (solid lines) are shown as well.

4 THE U−R COLOUR-MAGNITUDE DIAGRAMME FOR PHENOMENOLOGICAL GALAXY FORMATION MODELS

Most observed and simulated galaxies consist of a mix of simple stellar population models like the ones shown in Fig. 5. Many recipes exist to construct galaxies with the right mix and variation of stellar populations, mostly within the framework of hierarchical galaxy formation. Because the position of a galaxy in the U−R CMD is quite sensitive to the relative importance of young (actively star forming) populations and old populations, the U−R CMD for clusters is quite sensitive to the parameters of such hierarchical galaxy formation recipes, especially those parameters relating to the starburst strength, as driven by galaxy mergers, and the implementation of physical processes operating in clusters. A good knowledge of the U−R CMD both in the cluster and in the infall region is therefore important in order to constrain these parameters. The phenomenological galaxy formation model of van Kampen, Jimenez & Peacock (1999) is used as a basis model. This paper employs an improved version of this model for a ΛCDM cosmology, with $\Omega_\Lambda = 0.7$, $\Omega_{\rm m} = 0.3$, $h_0 = 0.7$, and $\sigma_8 = 0.93$.

We generated a model for a rich cluster with properties similar to the clusters observed, and placed it at two different redshifts to construct a U−R CMD: $z = 0.3$ and $z = 0.45$, which are the redshifts for which we have the best observational datasets. For the basic model, the resulting CMDs are shown in the top panels of Figs. 7a and 7b respectively, for these two redshifts. Because the basic model does not simulate the effects of the cluster environment on the member galaxies, they are expected to look the same as for a simulated field population of galaxies. Furthermore, the basic model has no 'star formation threshold', meaning that there will always be star formation if there is still cold gas left in the galaxy. This explains why there is no 'cluster red-sequence', and there are far too many blue galaxies in the cluster.

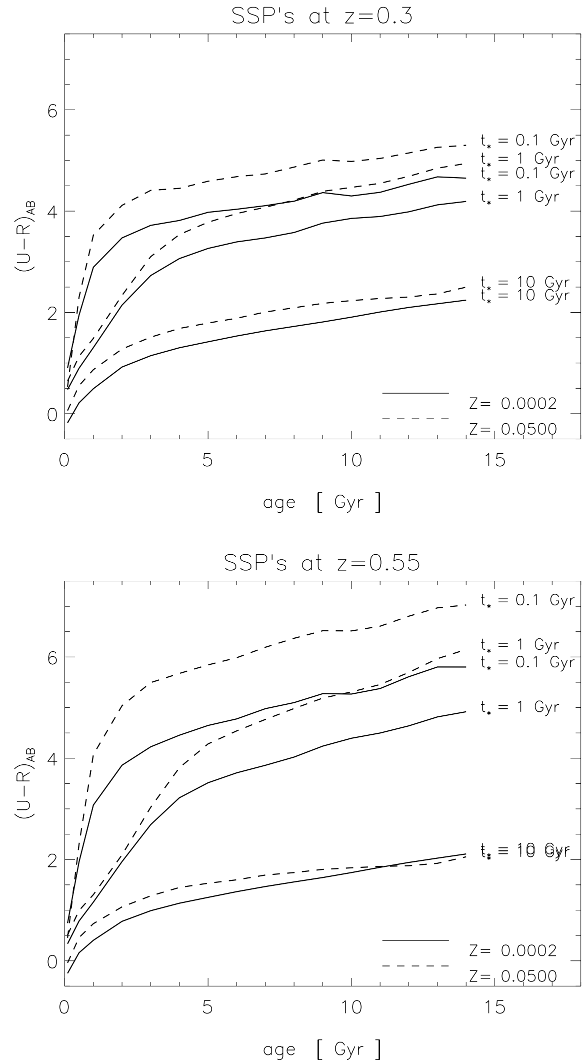

Figure 6. The time evolution of the U−R colour of single stellar populations (SSPs) observed at $z = 0.3$ (top panel) and $z = 0.55$ (bottom panel). Solid lines are for SSPs with primordial metallicity (initially, as the metallicity does evolve with time), whereas dashed lines are for 2.5 times solar metallicity.

For this reason, the overall population is too blue, and we devised an improved model (Rimes & van Kampen 2005, in preparation) in which we use the observed threshold for star formation in galactic disks (Kennicutt 1999; Martin & Kennicutt 2001). This observed fact states that if the surface density of gas in the disk of a spiral galaxies is below a threshold value, star formation is almost completely switched off. This is almost always the case in the outer regions of the gas disk, but as stars form in the rest of the disk, its surface mass density goes down and will hit the threshold after some time. Thus, star formation slowly dies down, and the galaxy will slowly redden as a result.

The U−R CMD for the model with the Kennicutt (1999) threshold implemented are shown in the middle panels of Figs. 7a and 7b, again for the same cluster at redshifts 0.3 and 0.45 respectively. It is clearly seen that a significant fraction of galaxies has moved towards the red

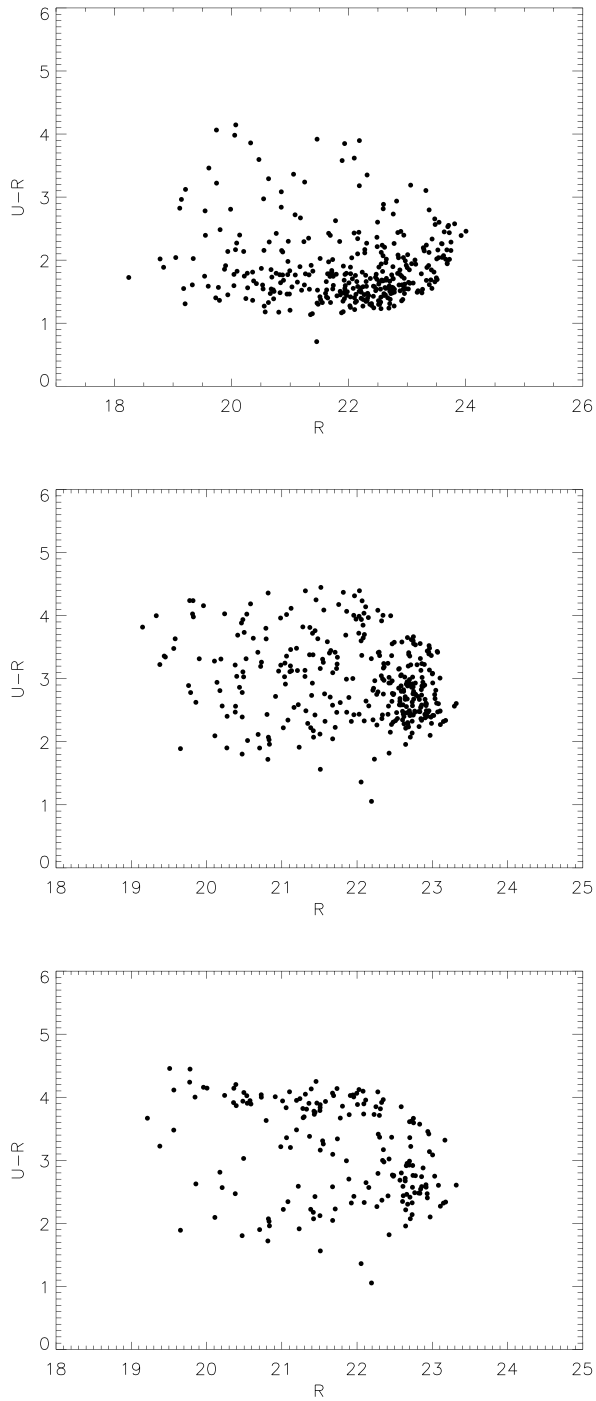

Figure 7a. Simulated data for a galaxy cluster at $z = 0.3$ with no star formation threshold or stripping (top panel), with star formation threshold only (middle panel), and with both a star formation threshold and stripping (bottom panel).

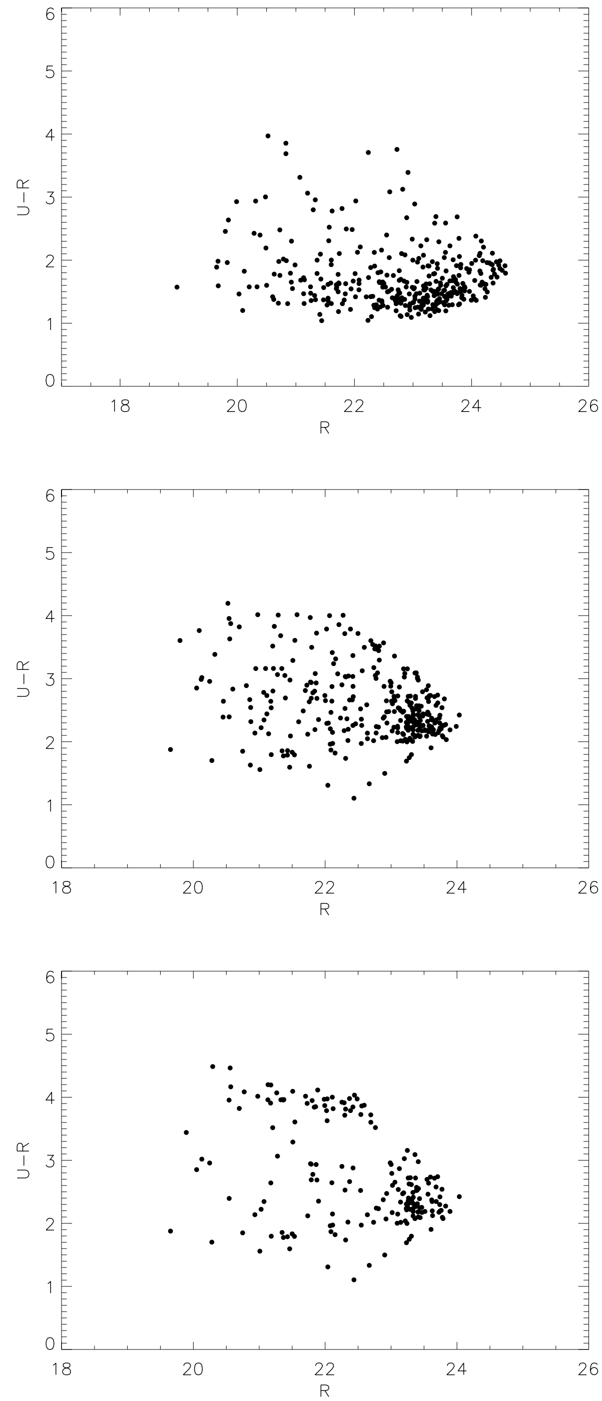

Figure 7b. Simulated data for a galaxy cluster at $z = 0.45$ with no star formation threshold or stripping (top panel), with star formation threshold only (middle panel), and with both a star formation threshold and stripping (bottom panel).

colour of U−R ≈ 4, but a cluster red-sequence is still not observed. In fact, we see a field population which matches well with the observed field populations in the CFRS−14h and ELAIS−N2 fields (bottom panels of Fig. 1). Thus, the model is lacking the ability to simulate cluster galaxies, as not all environmental processes have been taken into account. The hot gas reservoir of a galaxy falling into a cluster is removed, but the cold gas reservoir is left in place. We now turn towards a model where the effect of the cluster on the star-forming cold gas reservoir is taken into account.

4.1 Galaxy cluster physics

The galaxy formation model of van Kampen et al. (1999) does not include processes like ram-pressure stripping which can truncate star formation by taking away the complete cold gas disk. However, because we employ an N-body simulation technique in which galaxy haloes are formed and tracked, we know for each galaxy where it resides at all times. This allows us to incorporate some cluster physics, which for the purpose of this paper is kept fairly simplistic, as the main purpose here is to see to what extent the inclusion of cluster physics changes the U−R CMD, before embarking on a more detailed modelling effort.

During the N-body run, the local density is calculated for each particle, including the 'halo particles' (see van Kampen et al. 1999 for details on the numerical method). Thus, we can simply check which halo lives in a high-density environment like a galaxy cluster, and trigger cold gas stripping if this density crosses a specific threshold. We obtained the smoothed density field through Gaussian smoothing with a filter size of $0.25h^{-1}$Mpc, and set the threshold to be at an overdensity of 100 (with respect to the mean density of the universe at the redshift of the cluster). This number is somewhat arbitrary, but the main aim here is to see whether this process brings visible changes to the CMD, and can reproduce the observed gap. Thus, any galaxy that comes within this isodensity surface looses all its gas, and has its star formation truncated. We intentionally introduce this to see what the maximum effect of stripping is on the U−R CMD, as this is the mechanism that will most quickly redden a galaxy (if extreme dust extinction is excluded).

The result is shown in the bottom panels of Figs. 7a and 7b, for the same clusters at the same redshifts again. We clearly see that we now have a cluster red-sequence, and a gap at the same place as in the observations. Thus, stripping processes seem to explain the observations fairly well, although it is not clear whether this explanation is unique.

4.2 Evolution with redshift

A useful guide to what will happen to the U−R colour of a particular galaxy for different galaxy formation models is a closer inspection of the two main types of galaxies: those with U−R $\approx 1-2$, which have significant ongoing star formation (like a burst), and those that are almost 'dormant', like post-starburst galaxies. In Fig. 8 the spectra are plotted of the reddest (top panel) and bluest (bottom panel) of the brightest galaxies in the CMDs shown in Fig. 7. The consequence for the U−R colour of the redshift of these galaxies is demonstrated by blueshifting the filters over the rest frame spectra.

The reddest galaxies have the bluest colours at around $z \approx 0.4$, unless star formation ceases (almost) completely, as for a post-starburst galaxy. In that case the bluest colours are found when the U-band shifts to the flat part of the UV spectrum. The same applies roughly to the bluest galaxies, unless they are actually starbursting, in which case their redshift is not too important.

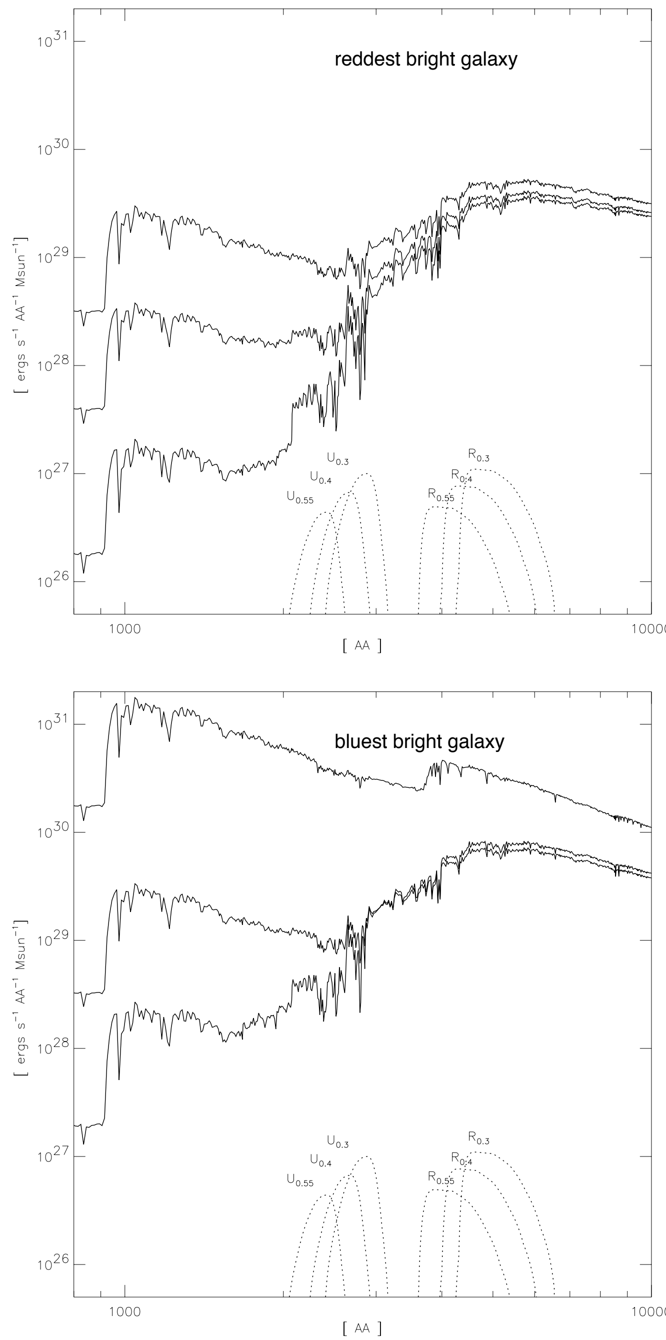

Figure 8. Rest frame spectra of the reddest (top panel) and bluest (bottom panel) of the brightest galaxies from the U−R CMDs shown in Fig. 7a (a cluster at $z = 0.3$), for the three different galaxy formation models. The top lines corresponds to the top panels of Figs. 7a and 7b, and the same applies to the middle and bottom lines. The transmission curves of the U and R band filters at various redshifts (dotted lines) are shown as well.

5 CONCLUSIONS AND DISCUSSION

We have considered the U−R colour-magnitude-diagram for galaxy clusters at intermediate redshifts as a new probe for galaxy formation and evolution, and as a possible test for galaxy formation models. Observed U−R CMDs are presented for four clusters in the redshift range $0.3 < z < 0.55$. The CMDs show a clear number depletion between red, (mostly) 'dormant' galaxies with U−R ≈ 4, and blue actively star forming galaxies with U−R $\approx 1-2$. This 'gap' grows with redshift over the redshift range considered, unless a significant fraction of galaxies does not redden quickly in or around clusters at higher redshift. This might be the case if processes like ram-pressure stripping are not yet significant at higher redshifts, for example, or when the removal of interlopers is harder and therefore fills the gap with field galaxies. The two field samples we considered show a less distinct bimodality, but it is visible nonetheless.

This behaviour can only be explained if blue galaxies can redden quickly enough so as not to 'linger' too long in the gap region $2 < \mathrm{U-R} < 3$. This means that the physical mechanism(s) responsible must act quickly enough to achieve this, pointing towards processes which strip the star forming cold gas reservoir from galaxies altogether, truncating their star formation activity. The galaxy formation models we presented show that we need to include processes like ram-pressure stripping to match the observations, as galaxies need to redden more quickly than those evolving through quiescent star formation towards the Kennicutt (1999) threshold, which produces a more evenly distributed U−R colour distribution without the observed bimodality.

The bimodality is more pronounced in galaxy clusters than in the field, even though it is observed in the latter as well. This makes sense if stripping processes are the driving force in producing bimodality, as these are expected to be most efficient in high-density regions. The presence of a visible gap in the field sample CMDs suggests that these processes are also operating in regions of intermediate densities like groups.

In concluding, we find that both our observational results as well as galaxy formation models indicate that U−R CMDs for clusters have the potential to be a powerful method for constraining galaxy evolutionary processes in and around clusters. Both the observations as well as the models require improvement to do this quantitatively, but we have shown qualitatively that the U−R CMD can do this at intermediate redshifts. This also implies that there will be a redshifted counterpart to the U−R CMD at higher redshifts, which is worth exploring in more detail.

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REFERENCES

Athreya R.M., Mellier Y., van Waerbeke L., Pelló R., Fort B., Dantel-Fort M., 2002, A&A, 384, 743
Belloni P., Röser H.-J., 1996, A&AS, 118, 65
Bruzual A.G., Charlot S., 1993, ApJ, 405, 538
Carlberg R., Yee H. K. C., Ellingson E., Abraham R., Gravel P., Morris S., Pritchet C. J., 1996, ApJ, 462, 32
Clowe D., Luppino G.A., Kaiser N., Gioia I.M., 2000, ApJ, 539, 540
Coleman G.D., Wu C.-C., Weedman D.W., 1980, ApJS, 43, 393
Czoske O., Kneib J.-P., Soucail G., Bridges T.J., Mellier Y., Cuillandre J.-C., 2001, A&A, 372, 391
Dressler A., Gunn J.E., 1992, ApJS, 78, 1
Dressler A., Gunn J.E., Schneider D.P., 1985, ApJ, 294, 70
Dye S., Taylor A.N., Greve T.R., Rögnvaldsson Ö.E., van Kampen E., Jakobsson P., Sigmundsson V.S., Gudmundsson E.H., Hjorth J., 2002, A&A, 386, 12
Gladders M.D., López-Cruz O., Yee H.K.C., Kodama T., 1998, ApJ, 501, 571
Ellingson E., Yee H.K.C., Abraham R.G., Morris S.L., Carlberg R.G., 1998, ApJS, 116, 247
Gioia I.M., Luppino G., 1994, ApJS, 94, 583
Gioia I.M., Shaya E.J., Le Fevre O., Falco E.E., Luppino G.A., Hammer F., 1998, ApJ, 497, 573
González-Solanes E.A., Perez-Fournon I., Rowan-Robinson M., Oliver S., Vaccari M., Lari C., Irwin M., McMahon R.G., Hodgkin S., Ciliegi P., Serjeant S., Willott C.J., 2005, MNRAS, 358, 333 ;
Hoffman Y., Ribak E., 1991, ApJ, 380, L5
Hogg D.W., Pahre M.A., McCarthy J.K., Cohen J.G., Blandford R., Smail I., Soifer B.T., 1997, MNRAS, 288, 404
Jaunsen A.O., Hjorth J., 1999, in Karttunen H., Piirola V., eds., 'Astrophysics with the NOT', University of Turku, Tuorla Observatory, p. 101
Kennicutt 1989, ApJ, 344, 685
Kodama T., Bower R.G., 2001, MNRAS, 321, 18
Le Fèvre O., Hammer F., Angonin M.C., Gioia I.M., Luppino G.A., 1994, ApJ, 422, L5
Martin C.L., Kennicutt R.C., 2001, ApJ, 555, 301
Mayen C., Soucail G., 2000, A&A, 361, 415
Roche N.D., Almaini O., Dunlop J., Ivison R.J., Willott C.J., 2002, MNRAS, 337, 1282
Rögnaldsson O., Greve T.R., Hjorth J., Gudmundsson E.H., Sigmundsson V.S., Jakobsson P., Jaunsen A.O., Christensen L.L., van Kampen E., Taylor A.N., 2001, MNRAS, 322, 131
Smail I., Dressler A., Couch W.J., Ellis R.S., Oemler A., Butcher H., Sharples R.M., 1997, ApJS, 110, 213
van Kampen E., 1995, MNRAS, 273,295
van Kampen E., Jimenez R., Peacock J.A., 1999, MNRAS, 310, 43
Williams R.E., Blacker B., Dickinson M., Dixon W.V.D., Ferguson H.C., Fruchter A.S., Giavalisco M., Gilliland R.L., Heyer I., Katsanis R., Levay Z., Lucas R.A., McElroy D.B., Petro L., Postman M., Adorf H.M., Hook R., 1996, AJ, 112, 1335
Wirth G.D., Koo D.C., Kron, R.G., 1994, ApJ, 435, L105
Yee H.K.C., Ellingson E., Carlberg R.G., 1996, ApJS, 102,269
Yee H.K.C., Ellingson E., Morris S.L., Abraham R.G., Carlberg R.G., 1998, ApJS, 116, 211