The evolution of the bi-modal colour distribution of galaxies in SDSS groups

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ABSTRACT

We analyse $u - r$ colour distributions for several samples of galaxies in groups drawn from the Fourth Data Release of the Sloan Digital Sky Survey. For all luminosity ranges and environments considered the colour distributions are well described by the sum of two Gaussian functions. We find that the fraction of galaxies in the red sequence is an increasing function of group virial mass. We also study the evolution of the galaxy colour distributions at low redshift, $z \leq 0.18$ in the field and in groups for galaxies brighter than $M_r - 5 \log(h) = -20$, finding significant evidence of recent evolution in the population of galaxies in groups. The fraction of red galaxies monotonically increases with decreasing redshift, this effect implies a much stronger evolution of galaxies in groups than in the field.

Key words: galaxies: fundamental parameters – galaxies: clusters: general – galaxies: evolution

1 INTRODUCTION

The galaxy population in the local universe consists broadly of two classes of objects, early and late types, distinguishable by their morphology, broadband colour and star formation rate (e.g., Strateva et al. 2001; Brinchmann et al. 2004; Balogh et al. 2004b; Kauffmann et al. 2004). The properties of early-type galaxies are almost independent of the environment (Dressler et al. 1997; Bernardi et al. 2003) and there is evidence that the properties of late-types are insensitive to the environment too (Biviano et al. 1990; Zandivarez et al. 2006). There is also conclusive evidence that this bi-modality exists at least out to $z \sim 1$, and that the fractions of early and late types are different compared to $z = 0$ (Bell et al. 2004; Tanaka et al. 2005). More recently, Driver et al. (2006) and Allen et al. (2006) conclude that galaxy bi-modality reflects the two-component nature of galaxies (bulge-disc) rather than two distinct galaxy populations.

There are several physical processes related to environment that can be responsible of the observed bi-modality by transforming galaxies from late to early types and by truncating their SFRs. Some of them are typical of cluster environment, such as ram pressure (Gunn & Gott 1972), galaxy harassment (Moore et al. 1996) and interactions with the cluster potential (Byrd & Valtonen 1990). Some other processes such as galaxy mergers and interactions should be more common in groups of galaxies where the relative velocities of the galaxies are lower. Another process that increases

the fraction of red galaxies in groups or clusters is strangulation (Balogh et al. 2000), that consists in the removal of the hot gas reservoir of in-falling galaxies so their star formation halts after their cold gas is consumed.

In the last years, with the advent of large galaxy redshift surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Two-degree Field Galaxy Redshift Survey (Colless et al. 2001), several authors have studied the relation between different galaxy properties and the environment (e.g., Lewis et al. 2002; Domínguez et al. 2002; Gómez et al. 2003; Goto et al. 2004; Tanaka et al. 2004; Balogh et al. 2004a,b). In particular, Balogh et al. (2004b) found that, at fixed luminosity the fraction of red galaxies is a strong function of projected galaxy density. Baldry et al. (2004) and Balogh et al. (2004b) have proposed a scenario where mergers are driving the bi-modality, with a red population resulting from merger processes, and a blue population that form stars at a rate determined by their internal physical properties. In this scenario, to preserve the Gaussian nature of the colour distributions the environmentally triggered transformations from blue to red colours should occur in a short timescale, or at high redshift.

Most studies have parametrised environment with the projected density of galaxies brighter than a given luminosity threshold, measured typically using the area containing the 5-10th nearest neighbour. As pointed out by Weinmann et al. (2006), the physical meaning of this projected density depends on the environment, while it measures local density in clusters, in low density regions a more global density estimate is derived by this measurement. There are few studies that have investigated how galaxy

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properties correlate with halo mass using large group catalogues. Martínez et al. (2002) found that the fraction of early type galaxies increases continuously from the lowest to the highest mass groups in the Merchán & Zandivarez (2002) catalogue constructed from the 100K release of 2dFGRS. Yang et al. (2005b) confirmed this result using an independent group catalogue based in the final release of 2dFGRS. However, Tanaka et al. (2004) found no dependence of SFR and morphology on group velocity dispersion, σ, when analysing galaxies in groups identified in the first data release of SDSS. Consistently with this, Balogh et al. (2004b) found no trend of the fraction of red galaxies with σ in clusters. Some of the most recent works on the subject agree that galaxy properties and halo mass are indeed correlated. Weinmann et al. (2006) analyse the dependence of colour, star formation and morphology on halo mass in a group catalogue constructed from the second data release of SDSS using the algorithm by Yang et al. (2005a). By splitting galaxies into early, intermediate and late-types according to their colour and specific star formation rate, they find that at fixed luminosity, the fraction of early type galaxies is a smooth increasing function of halo mass. Martínez & Muriel (2006) have shown that colour is the galaxy property that correlates best with group mass using the group catalogue by Zandivarez et al. (2006) constructed from the fourth data release of SDSS (DR4; Adelman-McCarthy et al. 2006).

For a better understanding of the impact of group environment on galaxy evolution, it is important to trace their redshift evolution. In clusters of galaxies, a strong evolution in the fraction of blue galaxies was originally detected by Butcher & Oemler (1978) and later by other authors (e.g. Butcher & Oemler 1984; Rakos & Schombert 1995; Margoniner & de Carvalho 2000; Margoniner et al. 2001; De Propris et al. 2003). Evolution of the fraction of galaxies of different morphological types has also been found in clusters (e.g Dressler et al. 1997; Andreon, Davoust, & Heim 1997; Couch et al. 1998; Fasano et al. 2000). Evolution in groups was reported by Allington-Smith et al. (1993). They compared a sample of groups photometrically selected in the vicinity of bright radio galaxies at low ($z \leq 0.25$) and intermediate ($0.25 \leq z \leq 0.5$) redshift and report evolution of the blue galaxy fraction analogous to that observed in clusters. However, field contamination is a significant limitation of photometric data, and it is not clear how the radio selection might bias the sample of groups. Robust evidence of the evolution of galaxies in groups was found by Wilman et al. (2005) by comparing an intermediate redshift sample at $0.3 \leq z \leq 0.55$ from the CNOC2 survey (Carlberg et al. 2001) with local groups ($0.05 \leq z \leq 0.1$) in the 2PIGG catalogue (Eke et al. 2004). The authors found that the fraction of passive galaxies is a strong function of environment and luminosity and declines strongly with redshift. Their results provide indications of the effect of different mechanisms acting in high and intermediate density regions.

Making use of the large amount of galaxy data made publicly available by the Sloan Digital Sky Survey team in their Fourth Data Release, we study in this paper how the bi-modality in the $u - r$ colour distribution of galaxies varies from field galaxies to group galaxies of different masses and seek for possible evolution in the nearby universe $z \leq 0.18$. This paper is organised as follows: in section 2 we describe the sample of galaxies in groups we use; in section 3 we analyse the dependence on group virial mass of the $u - r$ colour distribution for several luminosity defined subsamples of galaxies, its evolution at low redshift is analysed in section 4. We summarise our results and discuss their implications in section 5.

2   THE SAMPLES

The samples of galaxies used in this paper are included in the Main Galaxy Sample (MGS; Strauss et al. 2002) of DR4. The sample of galaxies in groups was constructed by Zandivarez et al. (2006). They identified groups of galaxies in the MGS of DR4 using the same technique as Merchán & Zandivarez (2005). The technique consists in a standard friend-of-friend algorithm for group identification together with a procedure to avoid the artificial merging of smaller systems in high density regions and an iterative method to compute reliable group centre positions. The resulting group sample includes 14004 galaxy groups with at least 4 members in the area spectroscopically surveyed by DR4, accounting for a total of 85728 galaxies. Our sample of field galaxies consists of those MGS DR4 galaxies that were not identified as belonging to groups by Zandivarez et al. (2006). Thus, our field sample includes some galaxies that belong to small groups that were undetected given the characteristics of the group finding procedure.

Galaxy magnitudes were corrected for Galactic extinction following Schlegel et al. (1998), absolute magnitudes were computed assuming $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 100 \ h \ \mathrm{km \, s^{-1} \, Mpc^{-1}}$ and $K-$corrected using the method of Blanton et al. (2003) (KCORRECT version 4.1). All magnitudes are in the AB system. For the purpose of this work we use both Petrosian and Model magnitudes. Since the MGS is defined using Petrosian magnitudes, we use them to define volume-limited subsamples of galaxies. For analysing $u - r$ colours of galaxies we use Model magnitudes instead, since aperture photometry may include non-negligible Poisson and background subtraction uncertainties in the $u-$band.

3   DEPENDENCE OF THE COLOUR DISTRIBUTION ON GROUP MASS

The colour distribution of galaxies at a given luminosity is well described by the sum of two Gaussian distributions (e.g., Balogh et al. 2004b; Baldry et al. 2004) representing the blue and the red sequences. According to Balogh et al. (2004b), at fixed luminosity, the mean colours of both populations are nearly independent of the galaxy surface density. In contrast, the fraction of galaxies in the red population strongly correlates with surface density but not with cluster velocity dispersion. This seems to be difficult to reconcile with the results by Martínez et al. (2002), Yang et al. (2005b) and Weinmann et al. (2006). In order to study in detail the evidence for differences in galaxy evolution in the group group environment and shed light on the processes governing this evolution, in this section we explore the colour bi-modality of galaxies in groups of different virial masses and compare it to the corresponding colour distribution of field galaxies.

For studying the $u-r$ colour distribution of galaxies in groups and in the field, we restrict our samples to $z \leq 0.055$. This choice guarantees a volume limited sample of galaxies down to $M_r - 5\log(h) = -19.0$. We then divide the galaxies into 5 luminosity bins:

- $L_1 : -19.5 \leq M_r - 5\log(h) \leq -19.0$;
- $L_2 : -20.0 \leq M_r - 5\log(h) \leq -19.5$;
- $L_3 : -20.5 \leq M_r - 5\log(h) \leq -20.0$;
- $L_4 : -21.5 \leq M_r - 5\log(h) \leq -20.5$; and
- $L_5 : M_r - 5\log(h) \leq -21.5$.

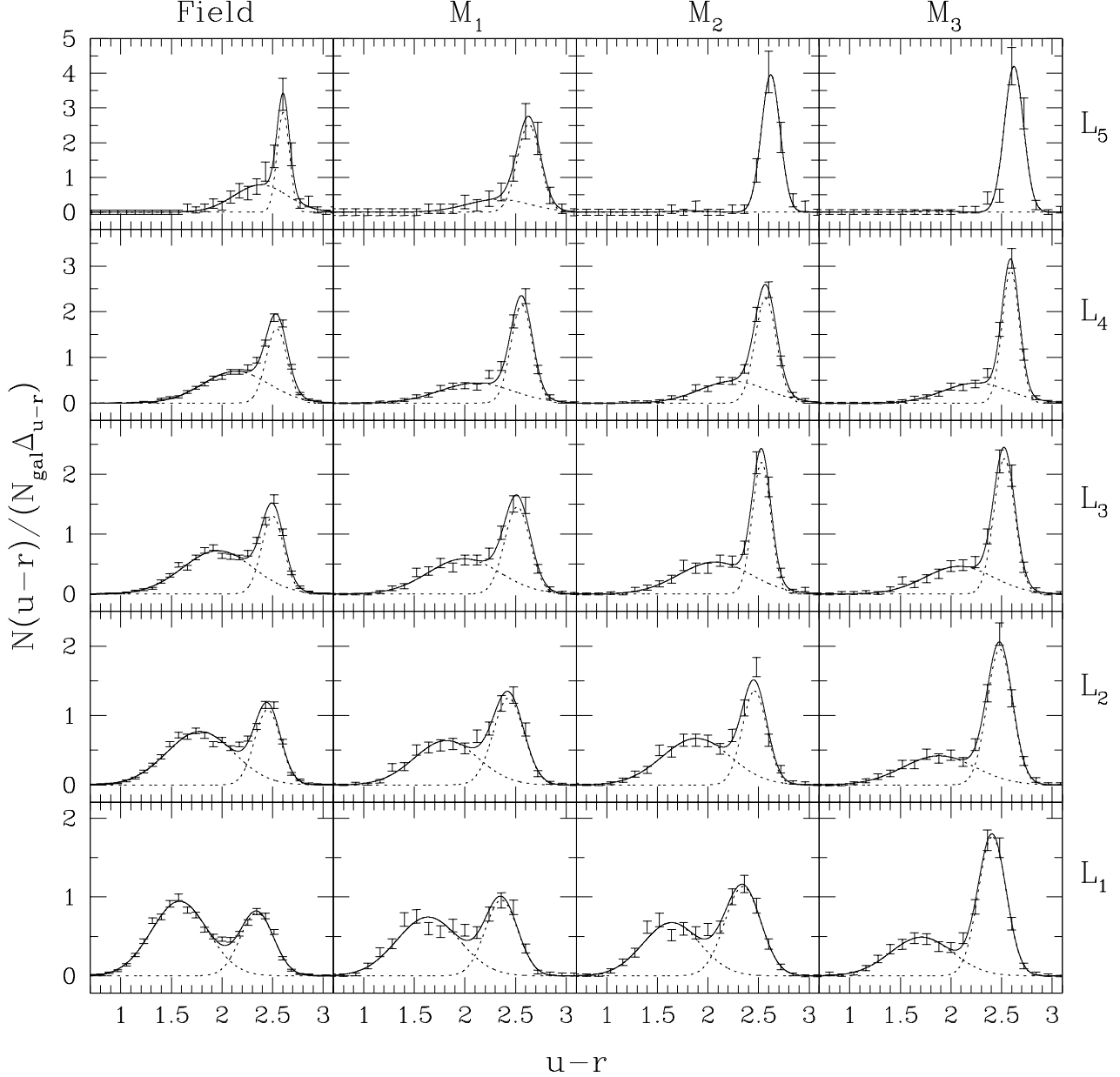In order to characterise the dependence of the distributions on

Figure 1. The $u - r$ model colour distributions for different subsamples of galaxies at $z \leq 0.055$. Each panel shows the colour distribution for the indicated environment (top axis) and luminosity (right axis). Error-bars were computed assuming Poissonian statistics. We show in solid line the best-fitting function that results from the sum of the two Gaussian functions shown in dotted lines.

group mass, we divide each luminosity-defined subsample of galaxies in groups into 3 mass bins according to the parent group virial mass:

- M_1 : $11.0 \leq \log(Mh/M_\odot) \leq 13.0$;
- M_2 : $13.0 \leq \log(Mh/M_\odot) \leq 13.5$ and
- M_3 : $13.5 \leq \log(Mh/M_\odot) \leq 15.0$

For each subsample, we have computed the $u-r$ colour distribution and fitted with the sum of two Gaussian functions:

$$\frac{N(u-r)}{N_{\text{gal}}\Delta_{u-r}} = A_b \exp\left(-\frac{((u-r) - c_b)^2}{\sigma_b^2}\right) + \qquad (1)$$

$$A_r \exp\left(-\frac{((u-r) - c_r)^2}{\sigma_r^2}\right),$$

where the sub-indexes b and r stand for 'blue' and 'red' sequences, N_{gal} is the number of galaxies in the subsample, and Δ_{u-r} is the colour bin's width. The fitting procedure consists in a standard Levenberg-Marquardt method that estimates the 6 best-fitting parameters in equation 1.

The colour distribution for each subsample and its corresponding best-fitting two-Gaussian function are shown in Figure 1. We confirm previous findings that a two-Gaussian model is a good parametrisation of the observed colour distribution in all cases. Clearly, the colour distribution depends on both luminosity and en-
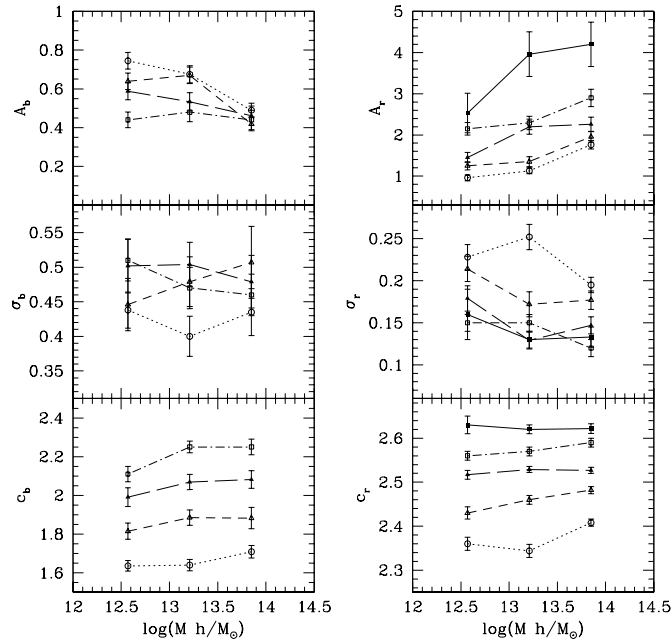
Figure 2. The double Gaussian best-fitting parameters of Figure 1 as a function of group mass for each luminosity defined subsample of galaxies. The x-axis values are the median of the group masses for each mass bin. Left column shows in its three panels the values for the Gaussian function that represents the blue population, while right column displays the corresponding values for the red population. In both columns, top panels show the amplitudes A_b and A_r, middle panels the widths σ_b and σ_r, and bottom panels the colours c_b and c_r. Open circles and dotted lines correspond to L_1 galaxies, open triangles and short dashed lines to L_2 galaxies, filled triangles and long dashed lines to L_3 galaxies, open squares and dot-long dashed lines to L_4, galaxies and filled squares and continuous lines to L_5 galaxies. Notice the lack of blue population galaxies in the highest luminosity bin.

vironment. It is noticeable that the peak of the red galaxy population becomes more prominent in groups of increasing mass and for brighter galaxies. Another feature that varies among the different subsamples, is the amplitude and position of the blue peak. It differs significantly between field and groups. This peak weakens with mass and reddens from fainter to brighter galaxies and from low to high group mass.

In Figure 2 we show the best-fitting parameters corresponding to these distributions as a function of group virial mass. Notice that we do not show the parameters corresponding to the blue sequence for L_5 galaxies since this sequence is absent in groups of masses M_2 and M_3, as can be seen in Figure 1. The parameters' trends become clearer in this figure. As a function of group mass and for all luminosities considered here, we find that:

• the amplitude of the blue sequence, A_b, decreases, the width σ_b is broadly consistent with no variation, and the mean colour, c_b, reddens;

• on the other hand, the amplitude of the red sequence, A_r, strongly increases, σ_r decreases, and the mean colour c_r reddens, except for L_5 galaxies in which case it is consistent with no variation with mass.

In Figure 3 we show the fraction of galaxies in the red sequence as a function of group virial mass, for $L_{1...4}$ galaxies. As pointed
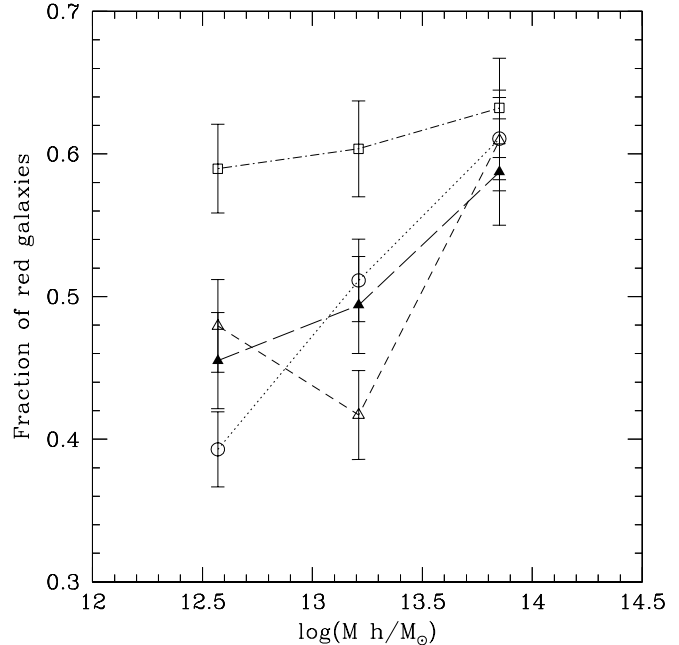

Figure 3. Fraction of galaxies in the red distribution as a function of group mass Open circles and dotted lines correspond to L_1 galaxies, open triangles and short dashed lines to L_2 galaxies, filled triangles and long dashed lines to L_3 galaxies, and open squares and dot-long dashed lines to L_4, galaxies.

out above, the colour distribution of L_5 galaxies is consistent with no blue sequence for the higher mass bins. Clearly, the fraction of red galaxies is a growing function of group mass for the remaining luminosities. Over the whole range of masses considered here, the fraction of galaxies in the red sequence grows by 22% for L_1, 13% for L_2, 13% for L_3, and 4% for L_4 galaxies.

Our findings are in qualitative agreement with the results by Martínez et al. (2002), Weinmann et al. (2006), and Martínez & Muriel (2006). On the other hand, they disagree with the results by Balogh et al. (2004b) and Tanaka et al. (2004), although these authors consider velocity dispersion instead of mass. However, unlike Weinmann et al. (2006), we do find a dependence of the mean colour of both sequences with mass. This could be due to the fact that we use $u - r$ colour, instead of $g - r$, and u-band flux is a much better indicator of star formation than $g-$band flux. Also, different ways of splitting galaxies into early and late types could make the difference between Weinmann et al. (2006) results and ours. The observed dependence of the mean colour of each sequence on group mass agrees with Balogh et al. (2004b) results, who find similar changes with local density, particularly for the blue sequence.

We have repeated our analysis by fixing the Gaussian widths given their lack of strong variation with mass. The results are essentially the same, indicating the robustness of our conclusions.

4   EVOLUTION OF THE COLOUR DISTRIBUTION

In this section we explore the presence of evolution of galaxy colours at low redshift and its dependence on environment. We restrict our samples to those luminosities that allow the construction of volume-limited subsamples of galaxies with a number of objects

large enough that allow splitting into at least 3 bins in redshift, that, in turn, contain enough objects for a good statistics. We restrict our analysis to the low redshift evolution of the colour of galaxies brighter than $M_r - 5\log(h) = -20$, that is, L_3, L_4 and L_5 galaxies. For each of these subsamples, we have computed the colour distributions within different redshift limits: $z \leq 0.09$ for L_3 galaxies, $z \leq 0.12$ for L_4, and $z \leq 0.18$ for the L_5 subsample. That is, we investigate the evolution of $L_{3,4,5}$ galaxies in the last 1.4, 1.9 and $2.6h^{-1}$ Gyr, respectively. In order to have robust statistics we only use two mass subsamples: the low mass subsample comprising galaxies in groups with virial masses $M_{\rm vir} \leq 10^{13.5}\ h^{-1}\ M_\odot$, and a high mass subsample including those galaxies in groups with $M_{\rm vir} > 10^{13.5}\ h^{-1}\ M_\odot$. These two mass bins correspond approximately to dividing the sample at the peak of the group virial mass distribution.

We find in all cases that the two-Gaussian model is a good description of the colour distribution. We show the best-fitting parameters as a function of redshift for galaxies in the field, in groups and in the high mass subsample in Figures 4 and 5. Along with the trends found for luminosity and group mass in the previous subsection, there appear here some interesting trends as a function of redshift. Regarding the blue sequence (Figure 4), the most significant change is that in massive groups the amplitude increases with redshift. The trends for σ_b are noisy and in most cases consistent with no evolution with the exception of L_5 galaxies, for which the sequence gets broader with increasing redshift. The mean colour c_b evolves with z for L_3 and L_4 galaxies, being bluer in the past. The evolution with redshift is much stronger for the red sequence (Figure 5). The amplitude of the red sequence is a decreasing function of redshift, much more prominent in galaxy groups than in the field. In all cases the red sequence gets broader with redshift, and its mean colour gets slightly bluer.

The colour distribution of galaxies in groups significantly differs from that corresponding to field galaxies for all redshifts considered. It should be taken into account that an important fraction of red galaxies in field samples are actually galaxies belonging to small groups that might have not been identified by Zandivarez et al. (2006) because some of the other group members are fainter than the limiting apparent magnitude of the SDSS spectroscopic survey. Therefore, the actual differences between field and group should be even more significant for the higher redshift bins. We have tested the stability of our results by restricting the groups to a subsample with at least 6 members. The analysis of this subsample gives essentially the same results than that of the total group sample indicating the lack of low number statistic biases as well as possible dependences on the number of members.

In Figure 6 we show the fraction of galaxies in the red sequence as a function of redshift. It is clear that in groups these fractions increase with cosmic time even when we are considering a small redshift range. We also notice the remarkable different behaviour of field and massive group galaxies. While the former show almost no changes, group galaxies exhibit a very significant decrease of the red population towards higher redshifts. This result is in agreement with Wilman et al. (2005) comparison of nearby groups from the 2PIGG catalogue, at $z \sim 0.1$, with groups at $0.3 \leq z \leq 0.55$ from the CNOC2 survey. It is worth emphasising that in this work we have found statistically significant evolution in the recent ($< 2.6h^{-1}$Gyr) past, made possible by the improved statistics of the larger number of galaxies in DR4.
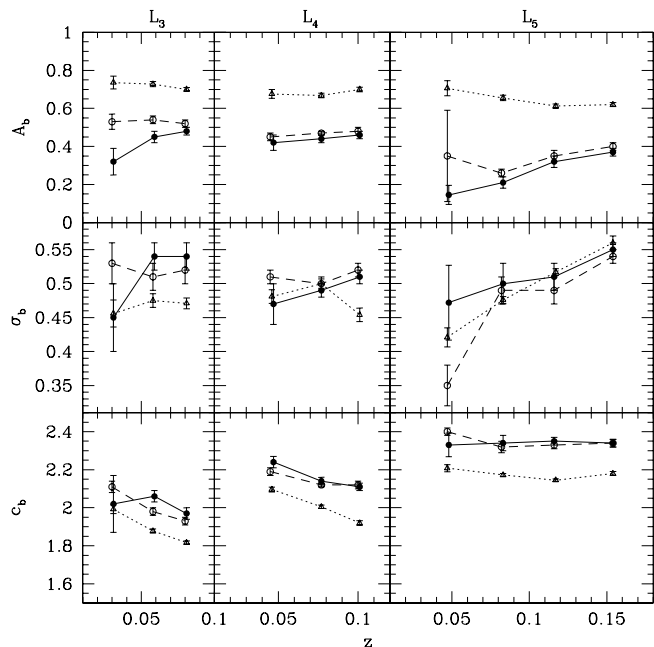

Figure 4. Best-fitting parameters for the blue population as a function of redshift for our luminosity samples L_3, L_4 and L_5 (see labels on top axis), in the field (open triangles and dotted lines), all groups (open circles and dashed line) and high mass groups (filled circles and continuous line). The three top panels show the amplitude A_b, middle panels the Gaussian width σ_b, and the bottom panels show the mean colour c_b.
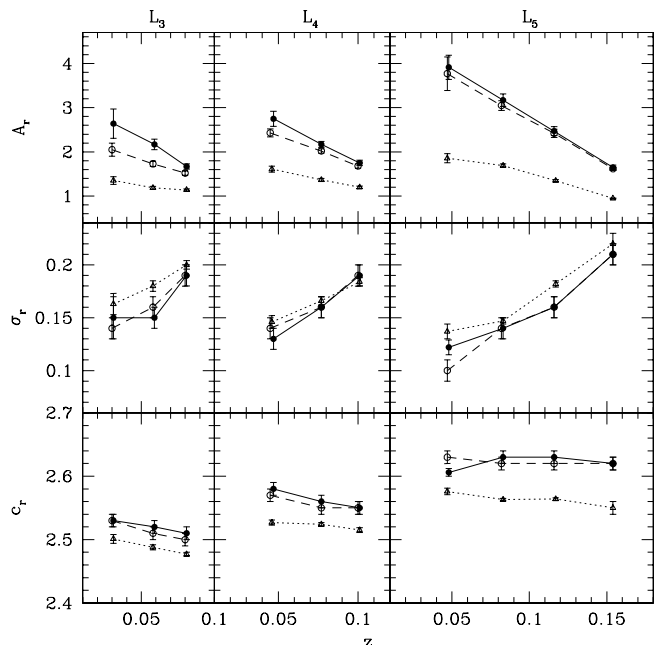

Figure 5. Best-fitting parameters for the red population as a function of redshift for our luminosity samples L_3, L_4 and L_5 (see labels on top axis), in the field (open triangles and dotted lines), all groups (open circles and dashed line) and high mass groups (filled circles and continuous line). The three top panels show the amplitude A_r, middle panels the Gaussian width σ_r, and the bottom panels show the mean colour c_r.
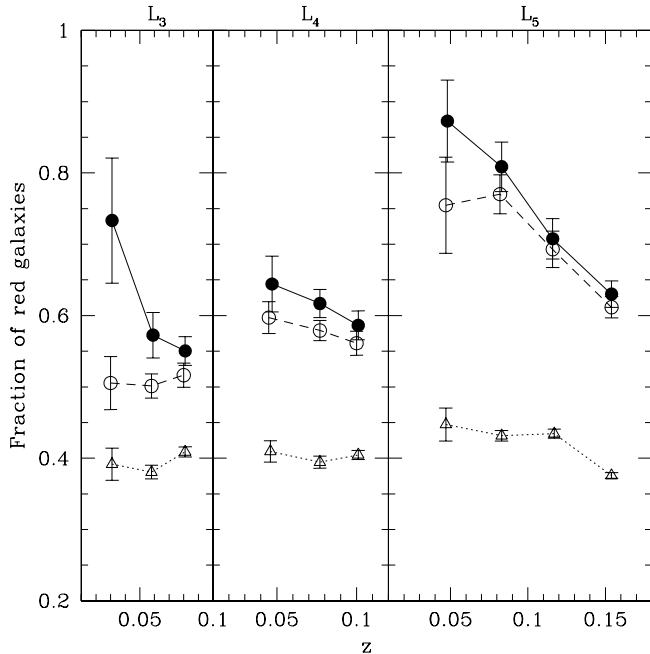
Figure 6. Fraction of galaxies in the red sequence as a function of redshift. Open triangles and dotted lines: field galaxies; open circles and dashed lines: group galaxies; filled circles and continuous lines: galaxies in high mass groups.

5 SUMMARY AND CONCLUSIONS

We have used one of the largest sample of groups available, identified in the SDSS DR4 by Zandivarez et al. (2006) to study the colour distribution of galaxies in groups, its dependence on luminosity and group mass, and its evolution at low, $z \leq 0.18$, redshift.

We have found that, for all subsamples of galaxies in groups analysed, the $u - r$ model colour distribution is well fitted by the sum of two Gaussian distributions that can be used to divide the galaxies into a blue and a red population. The colour distributions strongly depend on galaxy luminosity and on parent group virial mass. We have also found that the fraction of galaxies in the red sequence is a function of group mass

For galaxies brighter than $M_r - 5 \log(h) \leq -20$, we have studied the evolution of the colour distribution at low, $z \leq 0.18$, redshift, finding significant evidence of an increase on the fraction of red galaxies with cosmic time in groups in the last $\sim 2.6h^{-1}$ Gyr. This effect is stronger for groups more massive than $M > 10^{13.5}h^{-1}M_{\odot}$, in stark contrast to the lack of evolution observed in field galaxies over the same period. Our results are consistent with the idea that the global evolution of galaxies (for example the observed decline of the SFR since $z \sim 1$; e.g., Cowie et al. 1996) takes place primarily in high density, dynamically evolved regions such as groups and clusters.

We have presented evidence that the processes that transform galaxies from late to early types have been more effective in groups of increasing mass than in the field, and that they have been efficiently acting on galaxies in the last $\sim 2.6h^{-1}$ Gyr. These findings could be used to constrain semi-analytic of galaxy formation, providing important clues to the mechanisms driving the observed colour evolution. As derived from our work the $u - r$ colour distribution is well described by the sum of two Gaussian functions for the range of galaxy luminosities and host group mass analysed

within the redshift range explored. To preserve this form, processes that transform galaxies should occur in short timescales, as discussed by Balogh et al. (2004b) (see also Baldry et al. 2004). In these studies, the authors propose that the main process driving this evolution is merging. Groups are probably the best environment for mergers given the high density and the relatively low galaxy velocity dispersion. The results by Zandivarez et al. (2006), give additional support to this idea by showing that the characteristic luminosity of galaxies in groups is an increasing function of halo mass and that this behaviour is due to changes in the characteristic luminosity of galaxies in the red sequence.

We conclude that there has been a significant difference in galaxy colour evolution in groups in the last ~ 3Gyr. The observed evolution is stronger in the more massive galaxy groups, where the relative fraction the most luminous galaxies ($M_r - 5 \log(h) \leq -21.5$) in the red sequence increases from $\sim 60\%$ to 90%, compared to a roughly constant fraction of 40% in the field.

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