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Global environmental effects versus galaxy interactions

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ABSTRACT

We explore properties of close galaxy pairs and merging systems selected from the Sloan Digital Sky Survey Data Release 4 in different environments with the aim to assess the relative importance of the role of interactions over global environmental processes. For this purpose, we perform a comparative study of galaxies with and without close companions as a function of local density and host halo mass, carefully removing sources of possible biases. We find that at low- and high-local-density environments, colours and concentration indices of close galaxy pairs are very similar to those of isolated galaxies. At intermediate densities, we detect significant differences, indicating that close pairs could have experienced a more rapid transition on to the red sequence than isolated galaxies. The presence of a correlation between concentration index and colours indicates that the physical mechanism responsible for the colour transformation also operates in the transformation of the luminous matter distribution. At fixed local densities, we find a dependence of the red galaxy fraction on dark matter halo mass for galaxies with or without a close companion. This suggests the action of host halo mass related effects. Regardless of dark matter halo mass, we show that the percentage of red galaxies in close pairs and in the control sample are comparable at low- and high-local-density environments. However, at intermediate local densities, the gap in the red fraction between close pairs and the control galaxies increases from ∼10 per cent in low-mass haloes up to ∼50 per cent in the most massive ones. Interestingly, we also detect that 50 per cent of merging systems populate the intermediate local environments, with a large fraction of them being extremely red and bulge dominated. Our findings suggest that in intermediate-density environments galaxies are efficiently pre-processed by close encounters and mergers before entering higher local density regions.

Key words: galaxies: evolution – galaxies: general – galaxies: interactions.

1 INTRODUCTION

Several observational and theoretical works have gathered evidence to determine that the environment where galaxies reside plays a fundamental role in shaping their properties. However, although the transformation of blue, late-type and star-forming field galaxies into red, early-type and passive cluster galaxies has been well established (Oemler 1974; Dressler 1980; Lewis et al. 2002; Gomez et al. 2003; Baldry et al. 2004; Balogh et al. 2004; O'Mill, Padilla & Lambas 2008), there is no consensus on the mechanisms responsible for this transformation. Many explanations have been proposed including: (i) *ram pressure stripping* of cold interstellar gas of galaxies falling at high velocities into the intracluster medium, which produces a fast truncation of the SF (Gunn & Gott 1972); (ii) *starvation* or *strangulation*, which are also stripping gas processes of the hot diffuse component of satellite galaxies, which affects the SF on longer time-scales (Larson, Tinsley & Caldwell 1980); (iii) *harassment*, the cumulative effect of several rapid encounters with other cluster members, which leads to substantial changes in the galaxy morphology (Moore, Lake & Katz 1998); (iv) *mergers* and *interactions* of galaxies which can trigger an intense burst of SF, rapidly consuming the cold gas and forming spheroidal systems (Toomre & Toomre 1972; Kauffmann, White & Guiderdoni 1993). These explanations, however, are still under discussion.

van den Bosch et al. (2008) and Weinmann et al. (2009) analyse the role of satellite quenching for the build up of the red galaxy sequence. They find that the environmental processes which shut

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down the star formation (SF) activity in satellite galaxies are equally efficient in host haloes of all masses. This rules against mechanisms that are thought to operate only in very massive haloes, such as ram pressure or harassment. They suggest that the process responsible for quenching the SF in satellites should last a time-scale of a few Gyr, suggesting starvation as the satellite-specific transformation mechanism. They also claim that an additional mechanism is also required because quenching alone cannot explain the morphological transformations in the build up of the red sequence.

Alternatively, attempts have been made to remove the problem from clusters entirely by proposing a pre-processing of disc blue galaxies to red earlier type systems at moderate environments (Balogh et al. 2004; Mihos 2004; Moss 2006; Patel et al. 2009). Recently, many authors have investigated the dependence of galaxy properties on environment at intermediate densities (i.e. galaxy groups in the outskirt of clusters, infall populations) suggesting different mechanisms to account for them. Patel et al. (2009) find that galaxies at cluster-centric radii larger than 3 Mpc show an enhanced red galaxy fraction, indicating that intermediate-density regions and groups in the outskirts of clusters are locations where the local environment influences the transition of galaxies on to the red sequence, as opposed to mechanisms that operate on cluster scales (e.g. ram pressure stripping, harassment). In the same direction, Moss (2006) provides evidence stating that the cluster giant S0 population can be explained as the outcome of minor mergers with the infalling population integrated over the past $\sim$10 Gyr.

Analysis of the SF at intermediate environments show that the current SFR of a galaxy falling along a supercluster filament is likely to undergo a sudden enhancement before the galaxy reaches the virial radius of the cluster (Porter et al. 2008). These authors suggest that the main process responsible for this rapid burst are close interactions with other galaxies in the same filament, if the interactions occur before the gas reservoir of the galaxy gets stripped off due to the interaction with the intracluster medium.

On the other hand, Gallazzi et al. (2008) explore the amount of obscured SF as a function of environments in the A901/902 supercluster. The SF hidden among red galaxies is detected by using SF indicators that are not affected by dust attenuation. Otherwise, they could be missed or mistakenly classified as post-starburst on the basis of their weak emission lines obtained via optical, dust-sensitive SFR indicators. Combining the near ultraviolet (UV)/optical data with infrared (IR) photometry, they find that $\sim$60 per cent of red star-forming galaxies have IR-to-UV luminosity ratios which indicate high dust obscuration. Interestingly, most of them populate intermediate-density regions. In agreement with this result, Wolf, Gray & Meisenheimer (2005) have also identified an excess of dusty red galaxies with young stellar populations in the infalling region of the same cluster. More evidence of dust-obscured SF at intermediate regions is provided by Miller & Owen (2002). They find that up to $\sim$20 per cent of the galaxies in 20 nearby Abell clusters have dust-obscured SF and are preferentially located at intermediate-density regions, with respect to normal star-forming galaxies or active galactic nuclei (AGN). In addition, Poggianti et al. (2008) report that dusty starburst candidates present a very different environmental dependence than post-starburst galaxies. They find that the spectra of dusty starburst candidates are numerous in all environments at intermediate redshifts, particularly among galaxy groups. This favours the hypothesis of dusty starbursts triggered by mergers, expected to be common in groups.

Motivated by these findings, we revise the role of mergers and galaxy interactions in driving galaxy evolution at different density environments by using the Sloan Digital Sky Survey (SDSS) Data Release 4 (DR4) data. In a hierarchical clustering universe, as Mihos (2004) noted, galaxy clusters would form not by accreting individual galaxies from the field, but rather through the infall of less massive groups moving along the filaments. Such infalling groups provide locations with much lower velocity dispersions than the cluster medium, thus permitting strong slow encounters more normally associated with the field. In agreement, Moss (2006) shows that $\sim$50–70 per cent of the infall population are found to be in merging systems and slow galaxy–galaxy encounters. Hence, we will focus our analysis on close encounters and merger candidates in order to disentangle their role at such intermediate-density regions.

This kind of study requires to isolate the effects of galaxy interactions by comparing galaxies in pairs with isolated galaxies in a control sample (CS). In order to build a suitable CS, we made a thoughtful analysis of possible bias effects in the selection of isolated galaxies considering a previous theoretical analysis of Perez, Tissera & Blaizot (2009, hereafter P09), who showed that the set of constrains used to define a CS might introduces significant biases. This technical issue is extensively discussed in the Appendix of this paper, where we compare the performance of different CS definitions.

This paper is organized as follows. In Section 2, we describe the SDSS DR4 Galaxy pair and CS catalogues. In Section 3, we study the role of close galaxy interactions and mergers at different densities analysing effects of local (3.1) and global (3.2) environments, characterized, respectively, by the local density parameter, computed using the fifth brighter neighbours, and by the host halo masses. Finally, in Section 4 we summarize our results.

2 GALAXY PAIR AND CONTROL SAMPLE CATALOGUES

The analysis of this paper is based on the SDSS DR4 photometric and spectroscopic galaxy catalogue, for which there are estimations of gas-phase oxygen abundances, stellar masses and metallicities provided by Tremonti et al. (2004) and Gallazzi et al. (2005). SF rate estimates for galaxies are obtained as described in Brinchmann et al. (2004). The SDSS DR4 galaxy sample is essentially a magnitude-limited spectroscopic sample with $r_{\rm lim} < 17.77$ covering a redshift range $0 < z < 0.25$. We considered a shorter redshift range, $0.01 < z < 0.1$, in order to avoid strong incompleteness at larger distances (Alonso et al. 2006). We also excluded from our sample AGN, which could affect our interpretation of results due to contributions from their emission-line spectral features.

We characterized the local environment of galaxies defining a projected density parameter, Σ. This parameter is calculated by using the projected distance to the fifth nearest neighbour, $\Sigma = 5/(\pi d_5^2)$. Following Balogh et al. (2004), neighbours have been chosen to have luminosities brighter than $M_r < -20.5$ and radial velocity differences lower than 1000 km s^{-1}. In the case of pairs, we also estimated the local density by using the sixth nearest neighbour, in order to assess possible biases in the definition of the local density for galaxy pairs. However, we find that our results are insensitive to the definition of Σ by using either the fifth or the sixth nearest neighbour.

We use the SDSS DR4 galaxy group catalogue from Zapata et al. (2009) to assign a host halo mass ($M_{\rm vir}$) to each individual galaxy in our sample. This group catalogue is complete above masses of $10^{13}\,h^{-1}\,{\rm M}_{\odot}$, out to the limit redshift of our galaxy sample, $z = 0.1$. The mass assignment is done by searching for the closest group, in terms of its virial radius $r_{\rm vir}$, to each galaxy; if a group is found within 1.5 $r_{\rm vir}$ in projection and with a velocity difference,

$\Delta v < 1000\,\mathrm{km\,s^{-1}}$ the galaxy is assigned the group mass as its host halo mass. Galaxies which do not satisfy these conditions for any group mass are assumed to be hosted by haloes below the mass completeness limit of $10^{13}\,h^{-1}\,\mathrm{M_{\odot}}$.[1]

Following Alonso et al. (2006, and references therein), we build a Galaxy pair catalogue (GPC) requiring members to have relative projected separations $r_{\mathrm{p}} < 100\,\mathrm{kpc}\,h^{-1}$ and relative radial velocities $\Delta V < 350\,\mathrm{km\,s^{-1}}$. In order to properly assess the significance of the results obtained from the GPC, we use a CS constructed by selecting galaxies without a near companion within the threshold used to define galaxy pairs. This CS is carefully defined by imposing several constraints on its members in order to avoid bias effects as discussed by P09. Particularly, we build the CS by selecting isolated galaxies which match one-to-one redshifts, stellar masses, local densities and host halo masses of each galaxy in pairs. We refer the reader to the Appendix for a more detailed technical description of the construction of this robust 'unbiased' CS which hereafter will be called the CS4. We also define a close galaxy pair sample restricting the projected relative separation to $r_{\mathrm{p}} < 20\,\mathrm{kpc}\,h^{-1}$ (see the Appendix for more details).

3 GLOBAL ENVIRONMENTAL EFFECTS VERSUS GALAXY INTERACTIONS

Studies of galaxy properties and their dependence on environment are key to understand the role of mechanisms driving the evolution of galaxies. In this section, we analyse close galaxy interactions and mergers as possible environmental processes leading to evolutionary transformations. In order to assess how efficient galaxy interactions are with respect to other environmental mechanisms, we analyse the properties of close galaxy pairs in different environments characterized by their local galaxy density and by their host dark matter halo masses.

3.1 Galaxy interactions

The analysis of the colour distributions of galaxies by Baldry et al. (2004, also Balogh et al. 2004) showed that these distributions could be well fitted by a double Gaussian over a wide range of absolute magnitudes and local densities. The negligible variation of the blue and red peak locations of this bimodal distribution with local galaxy density at fixed luminosities suggests that the process responsible for the transformation from blue to red colours needs to be very fast and efficient in order to overcome the effects of environment. In Fig. 1, we show the $u - r$ colour distributions of close galaxy pairs in comparison to their isolated counterparts in CS4. The analysis was performed for the three different local-density environments defined in Table 1. We find that at low- and high-density environments (upper and lower panel, respectively), the colour distributions of close pairs are more similar to those of CS4 than at intermediate local densities. As expected, low-density environments are mostly populated by blue galaxies whereas high densities are populated by red galaxies. Interestingly, at intermediate environments (middle panel), the close pair and the CS4 colour distributions exhibit significant differences, with pairs having a larger fraction of red members. This might indicate that close pairs could have experienced a more efficient transition from blue to red colours, while isolated galaxies in CS4 experience a more inefficient transformation.

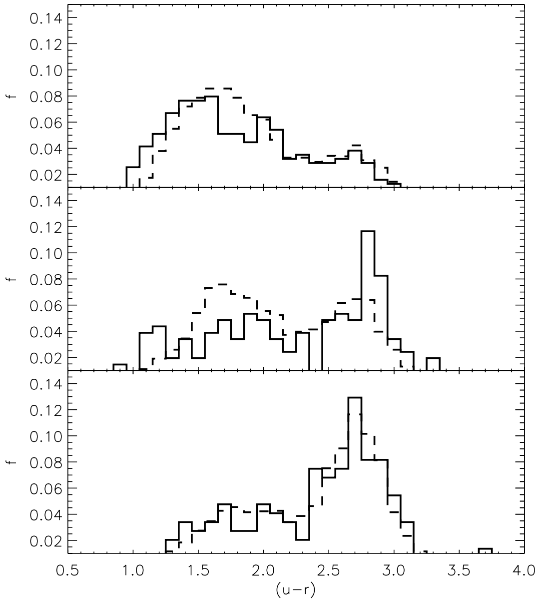

Figure 1. Colour distributions of close galaxy pairs (solid lines) and of CS4 (dashed lines), at low (upper panel), intermediate (middle panel) and high (lower panel) density environments.

Table 1. Ranges of local-density environments (Σ) and halo masses (M_{vir}) considered in this paper.

Environment	Σ ($\mathrm{Mpc^{-2}}\,h^{-2}$)	Halo mass	M_{vir} ($10^{10}\,\mathrm{M_{\odot}}\,h^{-1}$)
Low	$\log \Sigma < -0.57$	Small	$M_{\mathrm{vir}} < 13$
Intermediate	$-0.57 < \log \Sigma < 0.05$	Medium	$13 < M_{\mathrm{vir}} < 13.5$
High	$\log \Sigma > 0.05$	Large	$M_{\mathrm{vir}} > 13.5$

Note. Left-hand column: ranges of local-density environments (low, intermediate and high). Right-hand column: ranges of dark matter halo sizes (small, medium and large).

It is remarkable that the more significant disagreement in their colours is observed at both the blue and red tails, with a clear excess of extremely blue and red systems in close pairs (see also Alonso et al. 2006). The blue excess of close galaxy pairs is expected to be tidally induced, associated to the enhanced SF already shown in Fig. 3 (e.g. Lambas et al. 2003; Nikolic, Cullen & Alexander 2004). The extremely red close pairs could be accounted for by dusty, obscured star-forming systems, as suggested by observations which indicate an intrinsic reddening associated to the near-IR emission of hot dust present in tidally triggered star-forming regions (Geller et al. 2006; Lin et al. 2007). Interestingly, there are observational indications of an excess of the red, obscured star-forming galaxies at intermediate densities (Wolf et al. 2005; Gallazzi et al. 2008; Poggianti et al. 2008). These evidences may support the idea of a connection between the excess of red close galaxy pairs at intermediate densities and a tidally induced dusty SF. However, there are other plausible interpretations. Red galaxies in pairs could be systems dominated by old stellar populations which had their gas reservoir stripped as they entered higher density regions so that interactions are now unable to trigger new SF events. This possibility

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[1] This assumption may encounter problems near the survey boundaries where galaxies may be part of a group just outside the angular mask. Taking a conservative width of $1.5\,h^{-1}$ Mpc for the boundary and assuming that the percentage of galaxies falling below the completeness limit is the same as that of the total sample, $\simeq$17 per cent, the estimated number of boundary galaxies with masses above $10^{13}\,h^{-1}\,\mathrm{M_{\odot}}$ is only $\simeq 1500$.

will be tested in the following sections when we analyse the dependence on environment since this should affect both galaxies in pairs and in isolation. Alternatively, isolated galaxies could also include merger remnants with blue colours as a consequence of the recently triggered SF activity while close galaxy pairs could be just starting to interact and, hence, reflect only the colour of the underlying stellar population. Unfortunately, we cannot address this possibility using the currently available data.

Even when the morphological classification of interacting systems is difficult to perform, especially in the case of mergers and close galaxy pairs with tidal distortions, one can consider the concentration index, *C*, defined by the ratio of the Petrosian 90–50 per cent *r*-band light radii, as a global indicator of the structural luminosity distribution in these galaxies. Bearing this in mind, we explore the concentration index distributions of close galaxy pairs in comparison with those of CS4 at the same three different local-density environments of Fig. 1. In order to highlight the result of Fig. 2, we plot a dotted vertical line indicating the critical concentration index value of $C = 2.5$ adopted to segregate concentrated, bulge-like ($C > 2.5$) galaxies from more extended, disc-like ($C < 2.5$) systems. The concentration index distributions of close pairs approximately match those of CS4 at low- and high-density environments, following the expected morphology–density relation (Dressler 1980; Gomez et al. 2003), with a larger fraction of disc (bulge) dominated systems populating the low (high) density environments. Again, it is at intermediate-density regions where we find a significant difference, indicating that most of the members of pairs tend to be bulge-dominated systems.

The similar trends found for colours and concentration index as a function of environment (Figs 1 and 2) suggest a common physical mechanism responsible for both the galaxy colour and the concentration index.

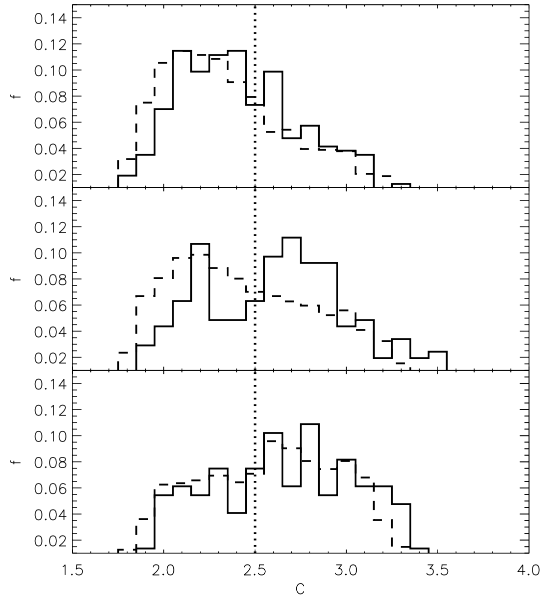

Figure 2. Concentration index ($C = r90/r50$) distributions of close galaxy pairs (solid lines) and of CS4 (dashed lines), for low (upper panel), intermediate (middle panel) and high (lower panel) density environments. Vertical dotted lines represent the critical concentration index value ($C = 2.5$) adopted to segregate bulge ($C > 2.5$) from disc ($C < 2.5$) dominated structures.

3.2 Global environmental effects

Up to this point, we have only analysed the role of close galaxy interactions at different local-density environments. However, many other environmental processes (e.g. ram pressure stripping, starvation, harassment, etc.) may collaborate to produce the trend found at intermediate densities. In order to isolate the effect of galaxy interactions from other environmental processes, we have also investigated galaxy properties taking into account the masses of their dark matter host haloes. For this purpose, we resorted to the dark matter halo catalogues of Zapata et al. (2009) which identified groups in the SDSS DR4 (with a minimum number of 10 members) by using dynamical criteria as explained in details by the authors. Then, we assigned each galaxy in our catalogue to one of these groups by using the criteria explained in Section 2. Galaxies which did not satisfy them are considered to inhabit haloes with masses lower than $10^{13}\, h^{-1}\, \mathrm{M}_{\odot}$.

Fig. 3 shows the red fraction $[(u - r) > 2.5]$ of close galaxy pairs and of those galaxies in the CS4 as a function of the local galaxy density parameter (Σ). The analysis was performed for three different halo mass ranges described in Table 1: small, medium and large mass haloes. We studied galaxies in both GP4 and CS4 which reside in the same local-density regions and in haloes of similar mass, and hence any possible signal should be presumably ascribed to galaxy interactions. From this figure, we can see that the underlying trend is consistent with the expected increase of the red fraction with local galaxy density for both galaxies in pairs and without a companion, which might be associated with the action of host halo mass dependent processes. Interestingly, at intermediate local densities (shaded regions), regardless of halo mass, the red fraction of galaxies in close pairs (square symbols) comfortably exceeds that of isolated galaxies in the CS4 (solid lines), suggesting that the mechanism which drives the evolution of galaxies in close pairs at intermediate-local-density regions is not regulated by host halo mass dependent processes alone.

To quantify these results, we also calculated the percentages of red galaxies in close pairs and in the CS4 for the three different bins of local-density environments and halo masses defined in Table 1. We find that, independent of their halo masses, at low- and high-local-density environments the percentages of red systems in close pairs are very similar to those found in the CS4 (Columns 1 and 3 of Table 2). Computing the difference of percentage between the close pairs and the CS4 for these two columns, we get a maximum value of ∼8 per cent, with an increase of ≈10 per cent from low- to high-mass haloes for both galaxies in pairs and in the CS. However, at intermediate densities (Column 2), the gap between the red fraction of close pairs and CS4 increases remarkably from 7.7 per cent in low-mass haloes to 45.6 per cent in high-mass haloes.

We have also analysed the role of mergers in different environments. The merging galaxy sample considered in this paper was extracted from the close galaxy pair sample by selecting objects with morphological disturbances and strong signals of interactions, as explained by Alonso et al. (2007). First, we analyse the cummulative distribution of merging systems and close galaxy pairs in different local-density environments in comparison with galaxies in the CS4 (Fig. 4). As can be seen, the number of close galaxy pairs (thin line) and merging systems (open symbols) increases more rapidly than the CS4 (thick line), particularly at intermediate-density environments (delimited by the vertical dashed lines in the figure). This result agrees with previous works indicating that merging systems and galaxy–galaxy encounters are frequent in intermediate-density regions (e.g. Moss 2006). As the figure shows, we find

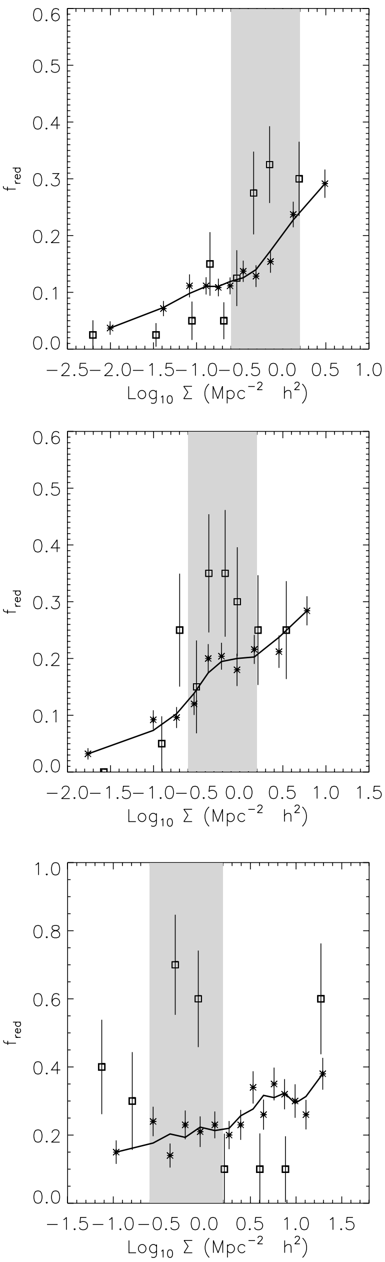

Figure 3. Fraction of red systems [$(u - r) > 2.5$] in close galaxy pairs (open squares) and in the CS4 (asterisks) as a function of the local-density parameter, Σ. Error bars represent bootstrap errors and solid lines smoothed functions of the CS4 trends. Shaded areas remark the intermediate-local-density environments. Samples were divided in three different bins of halo masses, from top to bottom panels: small, medium and large haloes (See Table 1 for descriptions).

~30 per cent of close galaxy pairs and 50 per cent for merging systems at intermediate-local-density environments. In Fig. 5, we show colours and concentration indices of close galaxy pairs (blue dots) and merging systems (green asterisks), at the same local-density bins previously considered. A large fraction of merging systems populating the sequence of extremely red and bulge-dominated galaxies can be found at intermediate local densities (middle panel). Particularly, 26 per cent of merging galaxies at intermediate densities are in the red [$(u - r) > 2.8$] tail, a percentage which rises to 50 per cent by adding the blue [$(u - r) < 1.5$] tail.

Table 2. Percentages of red galaxies, $(u - r) > 2.5$, at low-, intermediate- and high-local-density environments, hosted by small, medium and large halo masses (see Table 1 for descriptions). These percentage are provided for close galaxy pairs (CP) and for the CS4.

$M_{\rm vir} \setminus \Sigma$	Low (per cent)	Intermediate (per cent)	High (per cent)	Samples 4
Small	16.9	37.5	66.1	CP
	18.9	29.8	57.9	CS4
Medium	17.8	50.7	42.0	CP
	20.8	36.7	48.2	CS4
Large	33.3	85.7	56.1	CP
	32.8	40.1	60.9	CS4

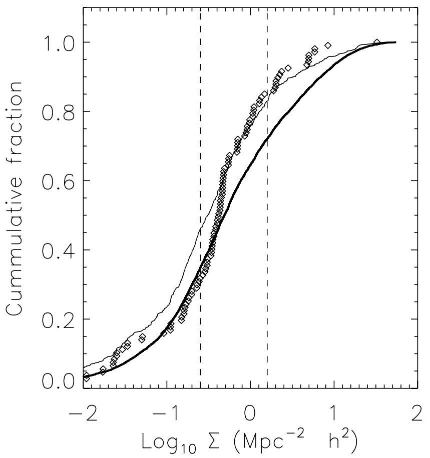

Figure 4. Cummulative fraction of galaxies in close pairs (thin line), merging systems (open symbols) and CS4 (thick line) as a function of local-density parameter. Vertical dashed lines indicate the intermediate-local-density regions (see Table 1).

These results could be interpreted within the theoretical work of Kapferer et al. (2008) if we assume that dust obscuration is hiding much of the enhanced SF activity triggered by interactions. Kapferer et al. (2008) find that the global SFR of interacting systems is largely enhanced in the presence of a moderate ram pressure, in comparison to the same interaction without the presence of an ambient medium. They use hydrodynamical simulations to model interacting galaxies moving through a hot, thin medium. This model mimics an average low ram pressure in the outskirts of galaxy cluster where systems interact at low velocities, resembling galaxy interactions occurring within groups, falling along cluster filaments. Combining this prediction with the observational results that show an increment of red dusty star-forming systems at intermediate environments (Gallazzi et al. 2008), we might suggest that at intermediate-density regions, where galaxy interactions are more frequent, low ram pressure stripping from the diffuse intragroup medium could collaborate to enhance the effect of galaxy interactions, rising the fraction of red star-forming galaxies in close pairs up to almost 50 per cent over that found in the CS4.

Nevertheless, we should warn about the fact that the large excess of red galaxy fractions in close pairs at intermediate local densities and within large haloes could be overestimated. Large haloes tend to have larger differences between the central and satellite galaxy luminosities than smaller ones. Consequently, some galaxies could be mistakenly classified as CSs although they could have a near companion, faint enough to be undetected by the SDSS.

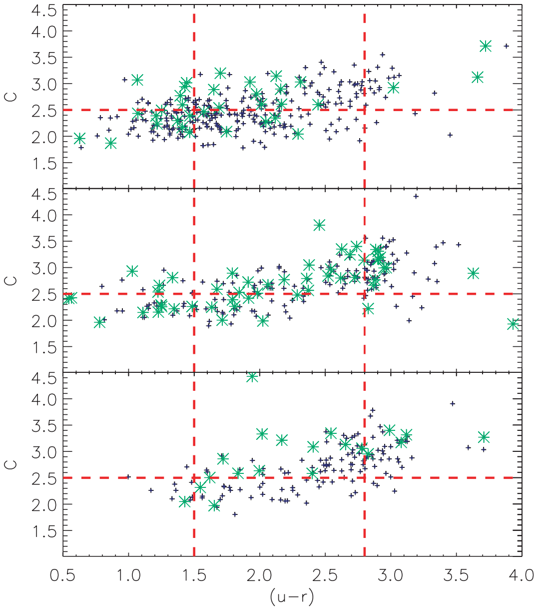

Figure 5. Scatter plot of colour and concentration index for close galaxy pairs (blue small dots) and merging systems (green asterisks) at low (upper panel), intermediate (middle panel) and high (lower panel) density environments (see Table 1). Red horizontal lines (at $C = 2.5$) separate disc from bulge-dominated systems, and vertical ones indicate the blue $[(u - r) < 1.5]$ and red $[(u - r) > 2.8]$ tails in the colour distributions.

4 SUMMARY

Recently, many authors have proposed that intermediate-density regions (i.e. galaxy groups in the outskirt of clusters, infalling populations) are the locations where the local environment influences the transition of galaxies on to the red sequence, as opposed to mechanisms that operate on cluster scales. In this paper, we use the SDSS DR4 data to explore the role of mergers and interactions as environmental processes driving evolutionary transformations of galaxies. We analyse properties of galaxy pairs and merging systems in different local-density environments and with different host halo masses, comparing these properties with those of isolated galaxies in an unbiased CS.

We build a GPC from SDSS DR4 data, by requiring its members to have relative projected separations: $r_{\rm p} < 100\,{\rm kpc}\,h^{-1}$ and relative radial velocities: $\Delta V < 350\,{\rm km\,s^{-1}}$. For comparison, and in order to isolate the effects of galaxy interactions, we have considered previous theoretical findings (P09) and build an 'unbiased' CS imposing constrains on redshift, stellar mass, local density and halo mass, to match those of galaxies in the pair catalogue. The analysis of biases in the selections of the SDSS CS shows that, contrary to semi-analytical simulations, the local-density environment is responsible for introducing the largest bias effect, giving the dark matter halo mass a less significant role in the CS definition than previously reported (Barton et al. 2007; P09). Even when the dynamical method to estimate halo masses is still crude, this finding might be an indication of an unsuitable treatment of satellite galaxies in the SAMs.

In order to assess the efficiency of galaxy interactions in comparison to other environmental mechanisms, we analyse the properties of close galaxy pairs in different local environments and residing in host haloes of different masses, in comparison to isolated galaxies in the 'unbiased' CS in similar environments. We have characterized the local environment by means of the local galaxy projected density, computed with the fifth nearest bright neighbour, and via constraints on their host DM halo masses.

Our results can be summarized as follows.

(i) We analyse the colour distributions of close galaxy pairs in comparison to those of the CS at low, intermediate and high local densities. We find that, at low- and high-density environments, the colour distributions of close pairs are similar to those of the CS. An opposite effect is found at intermediate densities, where their colour distributions exhibit significant differences, indicating that close pairs could have experienced a more rapid transition from blue to red colours, while the isolated galaxies in the CS undertake a more inefficient transformation. The significant disagreement in their colour distributions is detected in both colour tails, with a clear excess of extremely blue and red systems in close pairs. We speculate that these excesses might be likely associated with the enhancement of obscured (e.g. Gallazzi et al. 2008) and unobscured (e.g. Alonso et al. 2006) SF activity tidally induced by close interactions. Other explanations are possible as well, as is discussed in Section 3.1

(ii) In consistence with our analysis on colours, the distributions of concentration indices of close galaxy pairs and galaxies in the CSs show that they are similar at low- and high-local-density environments, following the expected morphology–density relation. Again, it is at intermediate-local-density regions where we find important differences, indicating that most of the galaxies in pairs have more concentrated luminosity distributions. The correlation found between concentration indices and colours suggests that the physical mechanism responsible for the colour properties could also operate in the transformation of the internal luminous matter distribution of galaxies.

(iii) We find that ∼50 per cent of the merging systems visually identified in our close GPC inhabit intermediate local densities. We detect that, at this intermediate densities, a large fraction of mergers are red and bulge dominated. Particularly, 26 per cent of these mergers are in the red $[(u - r) > 2.8]$ tail while 24 per cent are located at the blue $[(u - r) < 1.5]$ extreme.

(iv) We have also investigated galaxy interactions at different halo masses in order to isolate the effects coming from this environmental indicator. For low- and high-local densities, we detect an increase in the red fraction for increasing dark matter halo mass as expected, and with similar levels for galaxies in pairs and in the CS. However, at intermediate local densities and regardless of halo mass, we find that the red fraction of systems in close pairs largely exceeds that of isolated systems in the CS, up to ∼50 per cent for the largest haloes. Under the hypothesis that the red colours are produced by obscured SF due to dust stirring, triggered by the interaction, our results would be consistent with those of Gallazzi et al. (2008) who actually found an excess of obscured SF at intermediate local densities. From a theoretical point of view, the larger excess at intermediate local densities could be interpreted by the findings of Kapferer et al. (2008) who claimed that the global SF rate of interacting systems is largely enhanced by a moderate ram pressure stripping, in comparison to the same interaction without the presence of an ambient medium.

We conclude that mergers and galaxy interactions are important processes in the regulation of galaxy properties, particularly at intermediate-local-density environments where these interactions seem to be more frequent. Although we detect the action of the host DM halo in the steady increase of the red fraction as a function of halo mass, we also unveil a distinctive behaviour for galaxies in pairs at intermediate-density environments. These regions could be considered as the locations where galaxies are pre-processed by mergers and close encounters that transform their colours and luminosity distributions. Finally, we suggest that our findings could also help to improve the modelling used in SAMs, particularly regarding the tidal effects of galaxy–galaxy interactions in a previous stage before merging, which are currently not included in most semi-analytic schemes.

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APPENDIX A: BUILDING A CONTROL SAMPLE FOR A GALAXY PAIR CATALOGUE

The effect of galaxy interactions has been largely studied in optical and IR surveys (Lambas et al. 2003; Alonso et al. 2004; Nikolic et al. 2004; De Propis et al. 2005; Alonso et al. 2006; Kewley, Geller & Barton 2005; Lin et al. 2007; Michel-Dansac et al. 2008; Park & Choi 2009) and also using numerical simulations (Barnes & Hernquist 1996; Mihos & Hernquist 1996; Larson & Tinsley 1978; Perez et al. 2006a,b). These results conclude that mergers and close interactions could actually modify the SF, morphology, colours and metallicities of galaxy pairs. In all these cases, people have attempted to isolate the effects of galaxy interactions by comparing galaxies in pairs with isolated galaxies. However, different authors have proposed different ways to build these CSs. By using SDSS DR4 mock galaxy catalogues, built up from the SAM of De Lucia & Blazoit (2007), Perez et al. (P09) show that the set of constrains used to define a CS might introduce biases which could affect the interpretation of results. The fact that the physics of galaxy interactions are not included in the SAM allows the authors to attribute differences between the mock control and pair samples solely to selection biases. Particularly, they find that a CS defined by only applying redshift and luminosity requirements exhibits different stellar masses, morphologies, halo masses and local projected density distributions than those of galaxies in pairs. They also show that these biases are diminished by $\approx$70 per cent after imposing constrains on redshifts, stellar masses and local densities, and are completely removed when halo masses are also considered (also see Barton et al. 2007). However, P09 note that the contribution of the halo mass bias could be probably exacerbated by the recipes adopted in SAMs to model satellite galaxies. Based on these previous theoretical findings, we analyse possible bias selection in the construction of the observational CS, in order to isolate signals of galaxy interactions in a more robust way.

A1 Analysis of biases in the selection of the SDSS-CS

After selecting the galaxy pair members, according to the criteria defined in Section 2, we are able to build an isolated galaxy sample (IGS) with the remaining galaxies without a near companion. In a first attempt to build a CS, we follow recent observational works (Lambas et al. 2003; Alonso et al. 2006; Michel-Dansac et al. 2008) and define a CS by selecting galaxies from the IGS which match one to one the redshift and *r*-band magnitude of each galaxy in pairs, hereafter called SDSS-CS1. However, according to P09 this SDSS-CS1 is supposed to be affected by several bias selection effects.

In this section, we apply the tests devised by P09 to the SDSS-CS1, excluding the morphological selection, which we will not consider in our work since in the case of merging systems or close galaxy pairs with tidal features it is rather difficult to objectively define their morphology.

In Fig. A1, we perform a comparative analysis of stellar masses, halo masses and local projected density (Σ) distributions for SDSS DR4 galaxy pairs (solid lines) and for the SDSS-CS1 (dashed lines). The most significant differences between control and pair properties are observed for the distributions of local-density environment. In agreement with theoretical findings by P09, galaxy pairs tend to inhabit higher density regions than galaxies in the SDSS-CS1.

Consistently with P09, we find that galaxy pairs exhibit slightly larger stellar masses than their isolated counterparts in the SDSS-CS1. However, observations show that pair and control halo mass distributions are similar, in contradiction to P09 who reported that in the SAM the halo mass is the main factor contributing to bias the mock-CS1. As a matter of fact, P09 found that mock galaxy pairs are hosted by larger dark matter haloes than galaxies in the mock CS1. However, they warned that this effect could be overestimated in the SAM due to the environmental treatment of the starvation of hot gas in satellite galaxies (Weinmann et al. 2006; Kang & van den Bosch 2008; P09). Thus, the fact that SDSS galaxies with and without a near companion have similar halo mass distributions (Fig. A1) could be considered as an indication of the exacerbated environmental modelling of satellite galaxies in the SAM. However, we remind the reader that the dynamical estimates of halo masses used in this paper could also be introducing potential sources of errors due to the uncertainties introduced by velocity dispersions (Eke et al. 2004; Padilla et al. 2004).

The observational results shown in Fig. A1 indicate that even when the local-density environment is the most significant bias in the SDSS-CS1, we should also take into account both stellar and halo masses in order to properly select the SDSS CS.

A2 Treatment of selection effects

In order to remove the bias introduced by the differences in stellar masses, we define a CS using stellar masses instead of magnitudes as a constrain. Thus, the SDSS-CS2 is built up by selecting galaxies from the IGS so that the distributions of redshifts and stellar masses match those of galaxies in pairs. Ellison et al. (2008) also build a CS using a similar approach to our SDSS-CS2 in order to study close galaxy pairs in the SDSS. Additionally, we build a SDSS-CS3 imposing constrains on redshift, stellar mass and halo mass. Finally, we define the SDSS-CS4 populated by IGS galaxies matching the galaxy pair redshift, stellar mass, local-density environment and halo masses; the SDSS-CS4 should not be affected by selection biases according to the results by P09.

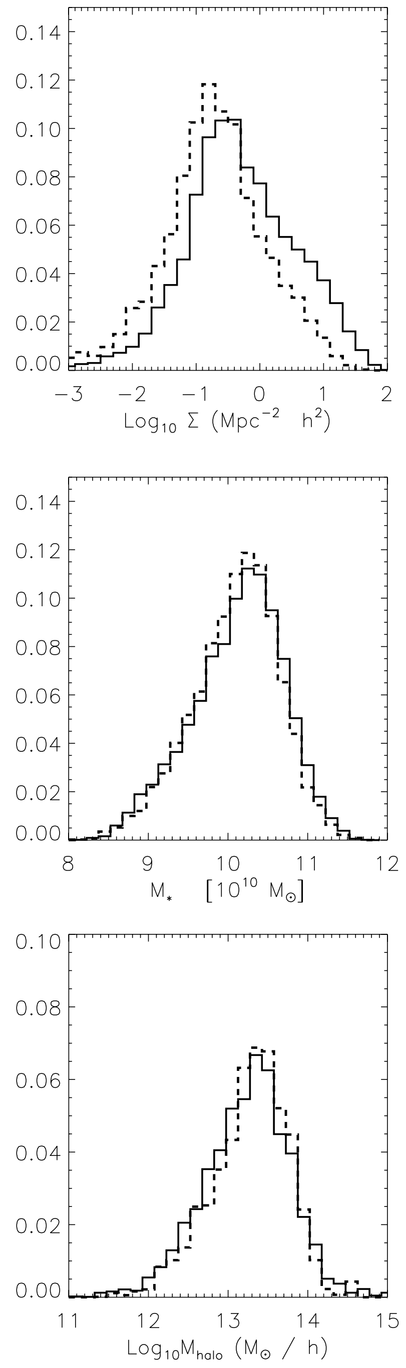

Figure A1. Distributions of local-density parameter (Σ) (upper panel), stellar masses (middle panel) and dark matter halo masses (lower panel), for SDSS galaxies in pairs (solid lines) and in the SDSS-CS1 (dashed lines).

After this CS building process, we have to remark that in order to construct the more suitable and 'unbiased' SDSS-CS4, we remove around 8 per cent of the galaxies in pairs from the original GPC sample to account for the lack of counterparts in the IGS with identical stellar masses, local-density environments and halo masses.

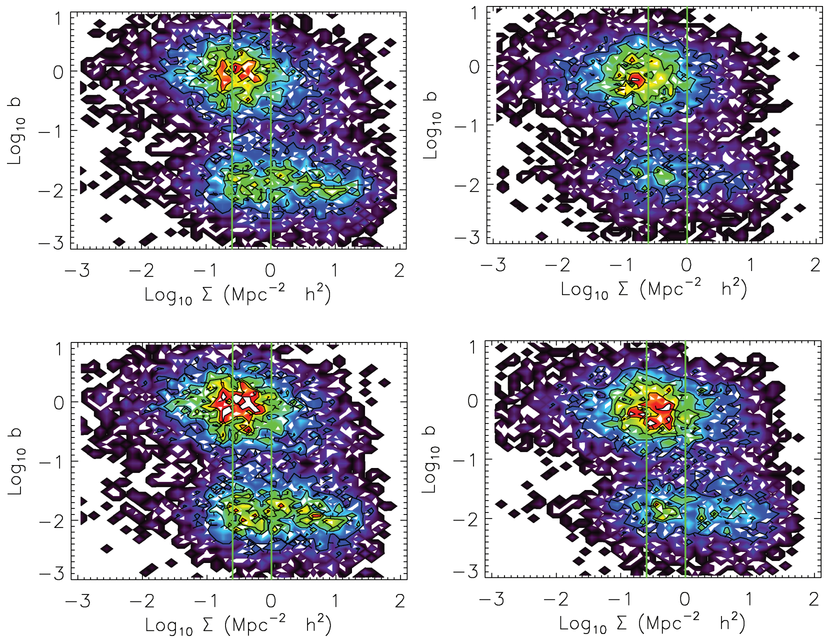

Figure A2. Contour plots of the stellar birth rate (*b*) and local-density (Σ) parameters, for galaxy pairs (left-hand panels) and CSs (right-hand panels). Upper (lower) panels show the biased samples 2 (unbiased samples 4), see the text for more details. The sequence from red to dark blue colours indicates a decrease in the galaxy number density. Green lines divide low-, intermediate- and high-density environments (see Table 1).

Most of the removed galaxies in pairs reside in high-density regions where galaxies satisfying our isolation requirements are less common (Fig. A1).

A3 Isolating the effect of interactions

We have shown that the set of constrains used to define the SDSS-CS1 introduces biases which could affect the interpretation of the results found for galaxy pairs. In this section, we revise some previous observational analysis of galaxy pairs from the SDSS-CS1 (Lambas et al. 2003; Alonso et al. 2006; Michel-Dansac et al. 2008) to evaluate how their results would be modified considering the different CSs defined in the previous section.

In order to test the performance of each CS, we study their colours, metallicities and SF activity, comparing them to those of galaxies in pairs. Particularly, we analyse the dependence of the SF activity on the environment, as well as $u - r$ colour distributions for the SDSS-CS1, SDSS-CS2 and SDSS-CS3, finding similar results for all these CS (see P09 for a discussion on the mass–metallicity relation). The most significant change is detected when analysing the properties of SDSS-CS4, indicating that the local-density environment is responsible for introducing an important bias effect (see the upper panel of Fig. 1). Using results from a SAM, P09 showed that the halo mass is the parameter with the largest contribution towards biasing a CS. However, they could not separate this latter bias effect from the modelling bias associated to the treatment of satellites. The analysis of SDSS CSs shows a less significant role of the dark matter mass in the CS definition than previously reported (Barton et al. 2007; P09), and contributes to show the exacerbated environmental modelling of satellite galaxies in the SAM (Weinmann et al. 2006; Kang & van den Bosch 2008).

A3.1 Comparative analysis of galaxy pairs, SDSS-CS2 and SDSS-CS4

Since bias effects are removed only after defining the SDSS- CS4, from this point on we will only show the results for samples SDSS-CS2 and the ‘unbiased’ case. Note that we have chosen the SDSS-CS2 instead of the SDSS-CS1, since they behave similarly and, on the other hand, the stellar mass is a more fundamental quantity than the luminosity of a galaxy (Brinchmann & Ellis 2000; Kauffmann et al. 2003; Panter, Heavens & Jimenez 2004).

We first analyse the SF activity in different density environments. Particularly, we estimate the SF history of systems by defining the stellar birthrate parameter, $b = 0.5\, t_{\rm H}({\rm SFR}/M_*)$, where $t_{\rm H}$ is the Hubble time and ${\rm SFR}/M_*$ is the present SF rate normalized to the total stellar mass (Brinchmann et al. 2004). In Fig. A2, we show the contour plots of the stellar birthrate parameter as a function of the local-density estimator (Σ) for galaxy pairs (left-hand panels) and CSs (right-hand panels). The upper plots show the result for galaxies with and without a near companion using the ‘biased’ CS2[2] definition. Lower panels show the ‘unbiased’ results obtained by comparing galaxies in pairs with those in the CS4. Note, that in order to define the ‘unbiased’ CS4, we remove a small fraction of galaxies in pairs, thus the galaxy pair samples also change from the top to the bottom panels. In order to clarify the discussion, from this point on we will refer to the galaxy pair samples as GP2 (upper-left panel) and GP4 (lower-left panel), respectively. The green lines in the plots divide the three different environmental regions discussed throughout this paper (see Table 1 for description).

As we can appreciate in the top panels of Fig. A2, the biased samples show that while galaxies with a near companion (top-left panel) have a clearer bimodal distribution in the SF–environment relation (i.e. a large fraction of passive SF galaxies populating high-density regions), isolated galaxies (top-right panel) are more consistent with a unimodal SF distribution shifted to high values of the stellar birthrate parameter. These significant differences between galaxies in GP2 and in CS2, however, cannot be only attributed to galaxy interactions, but also to a biased selection of these

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[2] For simplicity, hereafter from this point on we have suppressed the SDSS prefix in sample names.

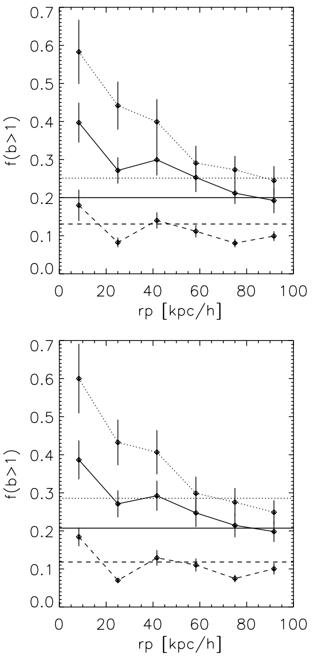

Figure A3. Fraction of strong star-forming galaxies ($b > 1$ where b has been normalized to the mean b of the corresponding CS) in the GP catalogue as a function of their relative projected separation, $r_{\rm p}$, at high (dashed lines), intermediate (solid lines) and low (dotted lines) density environments (see Table 1). Horizontal lines represent the fractions associated to each CS estimated with respect to their mean SF activity. In the upper panel, we show the result for GP2 and CS2, and in the lower one for GP4 and CS4.

samples. Indeed, we can see that the SF–environment relation of the ‘unbiased’ CS4 (bottom-right panel) significantly changes with respect to that of CS2 (top-right panel), resembling more closely that of its pair counterpart, GP4 (bottom-left panel). This means that after correcting for the biases the differences between the SF–environment distributions of galaxies with and without a near companion are partially reduced. However, discrepancies still remain even when GP4 is compared to the unbiased CS4, suggesting a real effect coming from galaxy interactions. We find that, at high densities, the GP4 has a larger fraction of low star-forming systems than the CS4 while at intermediate- and low-density environments it has larger fractions of strong star-forming galaxies.

Alonso et al. (2006) have previously analysed the efficiency of galaxy interactions in driving the SF, and how the environment can modify this efficiency. They show that, at low- and intermediate-density regions, close galaxy interactions are more effective at triggering important SF activity than galaxies without a near companion. We revised their estimates using samples 2 (CS2 and GP2) and samples 4 (CS4 and GP4) for the purpose of assessing possible bias effects. Fig. A3 shows the fraction of strong SF galaxy pairs as a function of their relative projected separations, $r_{\rm p}$. This fraction is defined by systems with SF activity larger than the mean b of their corresponding CS so that they have $b > 1$. The analysis was performed at high (dashed lines), intermediate (solid lines) and low (dotted lines) density environments (see Table 1). Horizontal lines represent the mean value of the fraction associated to the corresponding CS in each environment. We reproduce the findings of Alonso et al. (2006) where the only significant change is detected in low-density regions, where we find that galaxy pairs are required to be closer than in GP2 (within 1σ) in order to exhibit an enhanced SF activity. This is a consequence of an increment of the SF activity in the CS4 with respect to that measured in the CS2 at low densities, indicated by the increase of the fraction of $b > 1$ galaxies from 0.25 to 0.29 [see also Fig. A2 (right-hand panels)].

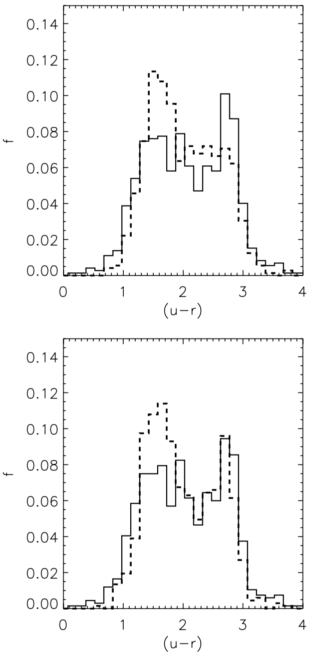

Figure A4. Colour distributions of close galaxy pairs (solid lines) and CSs (dashed lines). The upper panel shows both pair and control galaxies of samples 2 and lower panel the same for samples 4.

Given that galaxy pairs closer than a critical relative projected separation are more efficient at forming stars than their isolated counterparts, we will concentrate our analysis on studying the properties of close galaxy pairs from this point on. The lower panel of Fig. A3 shows that regardless of environment systems with $r_{\rm p} < 20\,{\rm kpc}\,h^{-1}$ have a statistically significant enhancement in their SF activity. Thus, we select close galaxy pairs by using this threshold on the relative projected separation.

We also analyse the colour distributions of close galaxy pairs in comparison with the two CS. In Fig. A4, we can see that even though the differences at the red peak are reduced after removing the bias effects in the selection of the CS4 the excess of close galaxy pairs in both red and blue tails with respect to the CS4 still persists, supporting the claim that these trends are actually produced by galaxy interactions and not introduced by a biased selection. This result confirms previous observational works of Alonso et al.(2006) who reported an excess of blue galaxies in close pairs with respect to that found in their CS, associated with a larger fraction of actively star-forming galaxies. They also find a larger fraction of red galaxies in close pairs with respect to those systems without a near companion, an effect that might indicate that dust, stirred up during encounters, could affect colours, partially obscuring the tidally induced SF (Gallazzi et al. 2008). Other possible interpretation of this trend is that many galaxies in pairs have been very efficient at forming stars during the early stages of their evolution, so that at present they exhibit red colours.

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