

Effects of galaxy interactions in different environments

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ABSTRACT

We analyse star formation rates derived from photometric and spectroscopic data of galaxies in pairs in different environments using the 2dF Galaxy Redshift Survey (2dFGRS) and the Sloan Digital Sky Survey (SDSS). The two samples comprise several thousand pairs, suitable to explore into detail the dependence of star formation activity in pairs on orbital parameters and global environment. We use the projected galaxy density derived from the fifth brightest neighbour of each galaxy, with a convenient luminosity threshold to characterise environment in both surveys in a consistent way. Star formation activity is derived through the η parameter in 2dFGRS and through the star formation rate normalised to the total mass in stars, SFR/M^* , given by Brinchmann et al. (2004) in the second data release SDSS-DR2. For both galaxy pair catalogs, the star formation birth rate parameter is a strong function of the global environment and orbital parameters. Our analysis on SDSS pairs confirms previous results found with the 2dFGRS where suitable thresholds for the star formation activity induced by interactions are estimated at a projected distance $r_p = 100 h^{-1}$ kpc and a relative velocity $\Delta V = 350 \text{ km s}^{-1}$. We observe that galaxy interactions are more effective at triggering important star formation activity in low and moderate density environments with respect to the control sample of galaxies without a close companion. Although close pairs have a larger fraction of actively star-forming galaxies, they also exhibit a greater fraction of red galaxies with respect to those systems without a close companion, an effect that may indicate that dust stirred up during encounters could affect colours and, partially, obscure tidally-induced star formation.

Key words: cosmology: theory - galaxies: formation - galaxies: evolution - galaxies: abundances.

1 INTRODUCTION

The current cosmological paradigm for structure formation postulates that galaxies formed by hierarchical aggregation. In this scenario, galaxy interactions and mergers play a principal role being a possible efficient mechanism to modify the mass distribution and trigger star formation activity. It was Toomre & Toomre (1972) who first showed that tidal interactions can transform spiral and irregular galaxies into bulge ellipticals and S0s. Later on, more sophisticated numerical simulations (e.g. Barnes & Hernquist 1996; Mihos & Hernquist 1996) showed that the gas component might experience torques produced by the companion with a subsequent increase of gas density which triggers star-bursts during the orbital decay phase of the accreting satellite. Tidally induced gas inflows fuel such starbursts. Cosmological hydrodynamical

simulations confirmed these results within a hierarchical scenario (Tissera 2000; Tissera et al. 2001).

Several observational works showed that mergers and interactions of galaxies affect star formation activity in galaxies in the Local Universe (e.g., Larson & Tinsley 1978; Donzelli & Pastoriza 1997; Barton, Geller & Kenyon 2000; Petrosian 2002) and finding clear signs that the number of interacting systems increased with redshift (see for instance Le Fèvre et al. 2000). However, it is still unknown the impact of mergers and interactions on the life of galaxies and consequently, the level of agreement with the predictions of hierarchical clusterings.

The study of galaxies in pairs provides useful insights in the nature of interactions. Kennicutt et al. (1987) analysis of close pairs yield a general trend for enhanced star formation and nuclear activity although with a wide dispersion

about the mean. Zepf & Koo (1989) studied close pairs of faint galaxies, separated by less than 4.5 arcsec, finding that although the colours of some galaxies correspond to recent episodes of star formation the overall colour distribution was very similar to that of field galaxies. Yee & Ellingson (1995) and Patton et al. (1997) found no significant differences between the mean properties of isolated galaxies and galaxies in pairs, although those which appear to be undergoing interactions or mergers had strong emission lines and blue rest-frame colours.

Barton et al. (2000) first showed the existence of a clear correlation between the relative and velocity separations and star formation activity in galaxy pairs in the field. Recently, Lambas et al. (2003, hereafter Paper I) studied an order of magnitude larger pair catalog statistically confirming the effects of interactions on the star formation activity of galaxies, based on a comparative analysis of the properties of isolated galaxies and galaxies in pairs selected from the 2dFGRS public release data. More recently, Alonso et al. (2004, hereafter Paper II) extended these investigations to high density environments: groups and clusters. Results from Paper II indicated that pairs in groups were systematically redder and with a lower present-day star formation activity than other galaxy members, except for galaxy pairs with relative separation $r_p < 15 h^{-1}$ kpc which showed significantly higher star formation activity in comparison to galaxy members without a close companion.

Regarding the dependence of star formation activity on environment, Martínez et al. (2002) and Domínguez et al. (2002) analysed the relative fractions of passively star-forming galaxies in high density regions corresponding to groups of galaxies extracted from the 2dFGRS. A similar analysis carried out by Gomes et al. (2003) and Balogh et al. (2004) in the SDSS and 2dFGRS surveys, also gave a clear indication of a strong dependence of star formation on environment which tend to decrease with increasing density. Balogh et al. (2004) found that, at fixed galaxy luminosity, the fraction of the red galaxies was a strong function of local density, increasing up to ~ 70 per cent of the population in the highest density environments. Similar trends were obtained by Hogg et al. (2003), who showed that the red galaxies, regardless of luminosity, are found in overdense regions. Kauffmann et al. (2004) used a complete sample of galaxies from SDSS, to study the structure and star formation activity as a function of local density and stellar mass, finding that the star formation activity was the galaxy property most sensitive to environment with an strongest dependence for smallest stellar mass systems. These authors also claimed that mergers could lead to this dependence, although environment driven processes such as tidal stripping, which could remove gas from galaxies quenching their star formation activity might be important in high density regions principally for low stellar mass systems.

These works extended the pioneer studies by Dressler (1980) who analysed the morphology-density relation showing that the star formation activity resided preferentially in disc galaxies in lower density regions. Different physical processes may play a role in driving the morphology-density relation among which mergers and interactions stands out in a hierarchical universe. Even for systems in the field or in groups, the cumulative effects of many weaker encounters (Richstone 1976; Moore et al. 1996) or few merger events

could have imprinted important features in their astrophysical properties.

In this paper we focus on the statistical study of the effects of the presence of a close companion on colours and star formation activity of galaxies in different environments. For this aim, we use the sample of pairs obtained from the 2dFGRS in Paper II and construct a pair catalog from the SDSS-DR2 which we have added star formation rates and stellar masses estimated by Brinchmann et al. (2004). This paper is structured as follows: Section 2 describes how catalogs are built up and possible incompleteness and selection effects. Section 3 discusses the dependence of star formation on orbital parameters and environments. Section 4 deals with colour distributions as a function of environment. And in Section 5 we summarize the main findings.

2 OBSERVATIONAL DATA AND GALAXY PAIR CATALOGS

In this Section we describe the selection procedure of galaxy pairs from both SDSS and 2dFGRS surveys. We also discuss possible aperture effects in both pair catalogs and incompleteness problems of SDSS pairs. Regarding the star formation activity, colours and local density, we include a description of these parameters.

2.1 Pairs from the SDSS survey

The SDSS (Abazajian et al. 2004) is a photometric and spectroscopy survey that will cover approximately one-quarter of the celestial sphere and collect spectra of more than one million objects. The imaging portion of the second release SDSS comprises 3324 square degrees of sky imaged in five wavebands (u , g , r , i and z) containing photometric parameters of 53 million objects. The main galaxy sample is essentially a magnitude limited spectroscopic sample (Petrosian magnitude) $r_{lim} < 17.77$, most of galaxies span a redshift range $0 < z < 0.25$ with a median redshift of 0.1 (Strauss et al. 2002). Within the survey area, DR2 includes spectroscopic data which cover 2627 square degrees with 186240 spectra of galaxies, quasars, stars and calibrating blank sky patched. The spectra are obtained from 3 diameter fibers (7 square degree area) projected on the sky and the spectrographs produce data covering 3800-9200 Å. The spectral resolution at $\lambda \sim 5000$ Å is ~ 2.5 Å and redshift uncertainties result approximately in 30 km s^{-1} .

We have estimated the stellar birth rate parameter, $b = (1 - R)t_H(SFR/M_*)$, where t_H is the Hubble time, R is the fraction of the total stellar mass initially formed that is return to the interstellar medium over the lifetime of the galaxy, and SFR/M_* is the present star formation rate normalised to the total mass in stars given by Brinchmann et al. (2004). We use the mean value $R = 0.5$ estimated for galaxies by Brinchmann et al. (2004).

We have considered a redshift range $0.01 < z < 0.1$ in order to avoid strong incompleteness at larger distances as well as significant contributions from peculiar velocities at low redshifts. In order to find suitable limits in projected distance r_p and relative velocity ΔV to identify galaxy pairs with star formation enhancement in SDSS we followed the

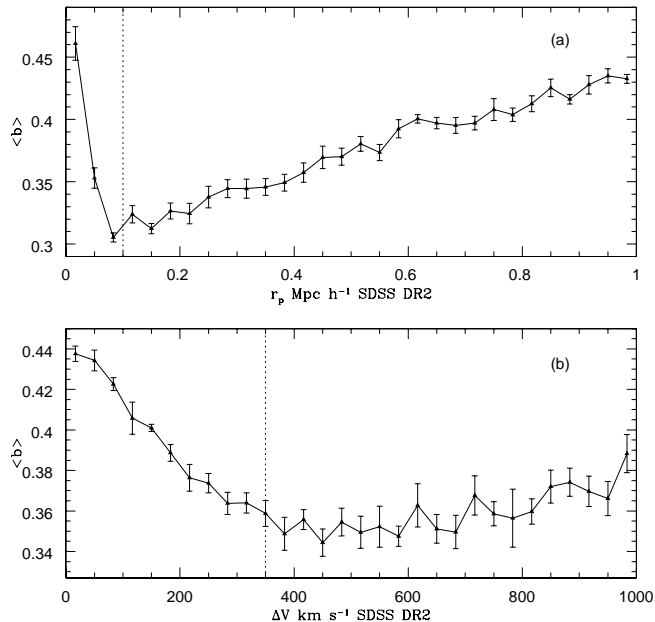


Figure 1. Mean birthrate parameter b as a function of projected separation r_p (a) and relative velocity ΔV (b) for SDSS-DR2 neighbours. The dotted vertical lines depict the projected separation and relative velocity thresholds used for the identification of galaxy pairs. Error bars here and in all figures of the paper correspond to uncertainties derived from the Bootstrap resampling technique.

procedure described in Paper I and Paper II. We firstly analyse neighbours in concentric spheres within $r_p < 1 h^{-1}$ Mpc and $\Delta V < 1000 \text{ km s}^{-1}$, centered at a given galaxy. For these neighbours, we show in Fig.1 the mean birthrate parameter $\langle b \rangle$ as a function of projected separation, r_p , and relative velocity, ΔV . As it can be appreciated from this figure, there is a clear trend for the closest neighbours to have higher star formation activity. We find a significant enhancement of $\langle b \rangle$ in galaxies with $r_p < 100 h^{-1}$ kpc and $\Delta V < 350 \text{ km s}^{-1}$ (vertical lines) with respect to the mean stellar birth rate parameter value of total SDSS-DR2 survey, $\langle b \rangle = 0.35$. By imposing these thresholds, a SDSS-DR2 galaxy pair catalog of 7674 galaxy pairs was built up which include information on the star formation activity of all its members.

These thresholds are similar to those inferred from the 2dFGRS catalog confirming that these limits are reliable to select pair galaxies with statistically enhanced star formation activity. Even more, this good agreement between 2dFGRS and SDSS provides confidence on previous results and stimulates new analysis on the nature of star formation activity triggered by interactions.

Contamination by active galactic nuclei (AGN) could contribute to the emission spectral features affecting our interpretation of star formation activity. In order to analyse this effect, we cross-correlated the AGNs catalog constructed by Brinchmann et al. (2004) with our SDSS-DR2 pair catalog. We found that $\approx 17\%$ of galaxies in our total pair sample were classified as AGNs. Extracting these AGNs sources, the final SDSS-DR2 galaxy pair catalog comprises 6405 pairs.

2.2 Pairs from the 2dFGRS

The 2dFGRS is one of the largest present-day spectroscopic survey. It includes spectra for 245591 objects with determined redshifts for 221414 galaxies brighter than a limit magnitude in $b_j = 19.45$. The survey covers an area of approximately 1500 square degrees in three regions: NGP strip, SGP strip and 100 random fields. The strip in the North Galactic Hemisphere has 70000 galaxies and cover $75^\circ \times 7.5^\circ$. There are approximately 140000 galaxies in the $75^\circ \times 15^\circ$ South Galactic Hemisphere strip centered on the South Galactic Pole. The 100 random fields scattered over the entire southern region of the APM galaxy survey outside of the main survey strip comprise 40000 galaxies.

In this paper, we selected pair galaxies following the lines discussed in Paper I and Paper II. The pair selection was re-done so that pairs could be identified in all environments from voids to rich clusters. We adopted the thresholds $r_p = 100 h^{-1}$ kpc and $\Delta V = 350 \text{ km s}^{-1}$, according to our previous works. The final pair catalog in the 2dFGRS comprises 6067 galaxy pairs. We have considered a redshift range $0.01 < z < 0.10$, but note, that in this case, AGNs have not been extracted.

The 2dFGRS provides a spectroscopic classification of the star formation activity of galaxies by the η parameter obtained from a principal component analysis. In Paper I we deduced a linear correlation between b and spectral-type index η which allowed the estimation of the b parameters for these galaxies. However, in order to estimate a birth rate parameter for galaxies in the 2dFGRS which could be compared to that obtained for SDSS-DR2, we use pair galaxies in common in both catalogs to correlate the b parameter derived by the SFR/M^* in SDSS with the η index in 2dFGRS. We find that $b(SFR/M^*)$ and η define a linear correlation of the form $b(\eta) = ((0.25 \times \eta) + 1.06) - 0.35$ (see Fig.2a), except for the lowest η values. However, for the analysis we carry out in this paper, this underestimation of b for galaxies with very extreme η values does not affect our results. In all our analysis, we have therefore adopted this $b(\eta)$ relation for 2dFGRS galaxies.

2.3 Aperture and Incompleteness Effects

We discuss the possible presence of systematics that could bias our star formation rates and pair definition, namely *aperture* and *incompleteness*. Fiber angular sizes are $2''$ and $3''$ for 2dFGRS and SDSS while incompleteness is expected to affect more strongly the SDSS. Here we evaluate incompleteness effects for the SDSS by combining the photometric and spectroscopic catalogs.

2.3.1 Possible Aperture Effects:

Aperture effects is an important concern because these surveys have observed all galaxies through a fixed $2''$ (2dFGRS) or $3''$ (SDSS) size fibers, smaller than the average angular size of galaxies. This can lead to minimize the effects of star formation in large disc galaxies. Possible effects of aperture bias have been discussed in some detail by several authors (Baldry et al. 2002; Gomez, et al. 2003; Balogh et al. 2004; Kauffmann et al. 2004; Brinchmann et al. 2004).

Balogh et al. (2004) analysed the aperture effects in

different environments finding that there was no significant trend of galaxy size with local density. Therefore, the effect of aperture bias depends mainly on the spatial distribution of star formation across the galaxy with a lack of strong environment biases. From galaxies in SDSS, Brinchmann et al. (2004) found that there are still strong aperture effects in SFR/M^* for galaxies with $\log M^* > 10.5$. This is expected since these galaxies often have prominent bulges, in which the specific SFR is expected to be low. This would affect the star formation rate of the most massive galaxies in our sample, but not the intermediate and low mass systems, which dominate our statistics of interacting pairs ($\sim 70\%$).

From these analysis we conclude that this potential bias is not likely to have a large effect on our analysis of star formation in pair galaxies in different environments.

2.3.2 Incompleteness Effects

In order to assess the effects of incompleteness, we built up a subsample of pairs free from incompleteness effects by cross-correlating the spectroscopic and the photometric surveys. We explored the fields in the photometric SDSS survey around each spectroscopic pair restricted to $m_r = 17.5^1$, searching for those galaxy pairs without any extra galaxy companion in the photometric survey within a projected distance of $100 h^{-1}$ kpc at the same limiting magnitude. By doing so, we obtain a subsample of pairs that is free from spectroscopic incompleteness bias and is, therefore, appropriate to test the results for the samples analysed in the paper against incompleteness effects of the spectroscopic survey. By comparison between both pair samples (clean and contaminated), we estimated that the spectroscopic catalog has an incompleteness of $\approx 9.5\%$. Although this is not a large fraction, we have examined the possible effects in our analysis in Section 3 where we conclude that there is not a serious bias in our results.

2.4 Control Samples

In order to unveil the effects of interactions in different environments we constructed control samples for the 2dFGRS and SDSS pair catalogs defined by galaxies without a close companion within the adopted separation and velocity thresholds. By using a Monte Carlo algorithm, for each galaxy pair, we selected two other galaxies without a spectroscopic companion within $r_p < 100 h^{-1}$ kpc and $\Delta V < 350$ km s $^{-1}$. Moreover, these galaxies were also required to match the observed redshift and luminosity distributions of the corresponding pair sample. In this way they will also share incompleteness effects and any other selection bias which may depend on redshift and luminosity. We did not impose other restriction since the purpose of the control sample is to take into account any possible redshift and luminosity bias while allowing a confrontation of other physical parameters such as colours and star formation activity as a function of redshift.

In Fig.2 (panels *b* and *c*) we show the redshift distributions for SDSS and 2dFGRS pair samples (solid lines) and

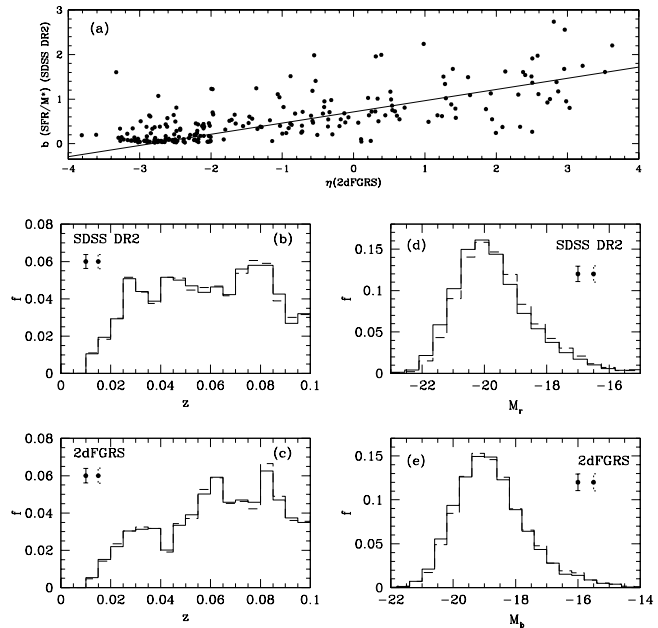


Figure 2. Panel a: $b(SFR/M^*)$ versus η for pair galaxies in common from both catalogs. The solid line represent the linear correlation of the form $b(\eta) = ((0.25 * \eta) + 1.06) - 0.35$. Panels (b) and (c) show the redshift distributions and panels (d) and (e) the M_r and M_{b_j} distributions in SDSS and 2dFGRS catalogs, respectively. The solid lines correspond to galaxies in pairs and dashed lines correspond to galaxies in the control samples. Error bars denote the mean Poisson errors.

their corresponding control catalogs (dashed lines). Similarly, panels *d* and *e* show the M_r and M_{b_j} distributions from SDSS and 2dFGRS. It can be appreciated that luminosities and redshift for both pairs and control samples are similarly behaved in SDSS and 2dFGRS surveys with very small Poisson errors.

2.5 Characterizing environment in 2dFGRS and SDSS surveys

The characterization of the local environment of galaxies is attained by defining a projected local density parameter, Σ . This parameter is calculated through the projected distance d to the 5th nearest neighbour, $\Sigma = 5/(\pi d^2)$. Neighbours have been chosen to have luminosities above a certain threshold and with a radial velocity difference lesser than 1000 km s $^{-1}$. In a similar way as Balogh et al. (2004), we imposed the condition $M_r < -20.5$ to select neighbours in SDSS. For the 2dFGRS catalog we estimated a corresponding magnitude limit of $M_b = -19.3$ by requiring that galaxy pairs in the common region with the SDSS had a similar density parameter Σ in both catalogs. This behaviour is illustrated in Fig.3(a,b), where we show the distribution of the derived values of Σ for both pair catalogs.

We explored if the results obtained in their paper could depend on our particular choice of local density estimator. For that purpose, we also used the local densities given by Kauffmann et al. (2004). These authors estimated the local density by counting galaxies within cylinders of 2 Mpc in

¹ With this magnitude restriction we are considering ≈ 70 per cent of the total sample

Table 1. Local Density Ranges

Environment	Σ Ranges ($Mpc^{-2} h^{-2}$)	d ($Mpc h^{-1}$)
Low	$\log(\Sigma) < -0.57$	2.4
Medium	$-0.57 < \log(\Sigma) < 0.05$	$2.4 < d < 1.2$
High	$\log(\Sigma) > 0.05$	1.2

d : averaged distance to the 5th nearest neighbour (see Section 3 for details).

projected radius and $\pm 500 \text{ km s}^{-1}$ in depth, in a complete sample of galaxies from SDSS. We found a good correlation signal between both density estimators indicating that either of these two definitions are adequate to characterize the environment of galaxies. Also, this comparison has proven that incompleteness effects in our sample are not significantly affecting our Σ estimations. The results discussed in the following sections have been checked to be robust against the particular definition of local environment. Hence we claim, that it is environment, and not a particular way of characterizing it, that determines the observed trends found in our work. In order to analyse in to more detail the dependence of star formation on environment, in Fig.3(c,d) we show the histograms corresponding to the birth rate parameter, $\log(b)$, obtained from SFR/M^* for pairs in the SDSS and from η for pairs the 2dFGRS surveys, as a function of local density. We also define three environment classes: low, medium and high, by selecting three suitable ranges of Σ values in order to have equal number of galaxies in each class. These density thresholds are shown in Table 1. In order to assess the significance of Σ thresholds, we have computed this parameter for galaxies in 2dF galaxy groups of Merchán & Zandivarez (2002), finding $\log \Sigma$ values in the range 0.04 to 2.02 in consistency with our present definition of high density environment ($\log \Sigma > 0.05$).

In Fig.3 (c,d) we plot the distribution of birth rate parameter for both galaxy pair catalogs segregated in the three defined environment classes. As it can be clearly appreciated, strong star-forming galaxies tend to avoid high density regions. From this figure, the reader can judge how similarly the star formation activity as a function of the local density behaves for the both pair catalogs. We claim that this agreement is good enough to provide a suitable joint analysis of the two data sets.

3 DEPENDENCE OF STAR FORMATION ON ORBITAL PARAMETERS AND ENVIRONMENT

In Paper I and Paper II we analysed the star formation activity in pairs in two well-segregated environments: field and groups, finding that galaxies in close pairs always exhibited enhanced star formation with respect to galaxies without a close companion. It is interesting to further investigate the effects of environment with a larger sample where environment now can be characterized as a more continuous variable from very low density regions to very high ones. Moreover, the possibility of working with two different catalogs will allow us to challenge the robustness of the results.

We first explored the dependence of the relation be-

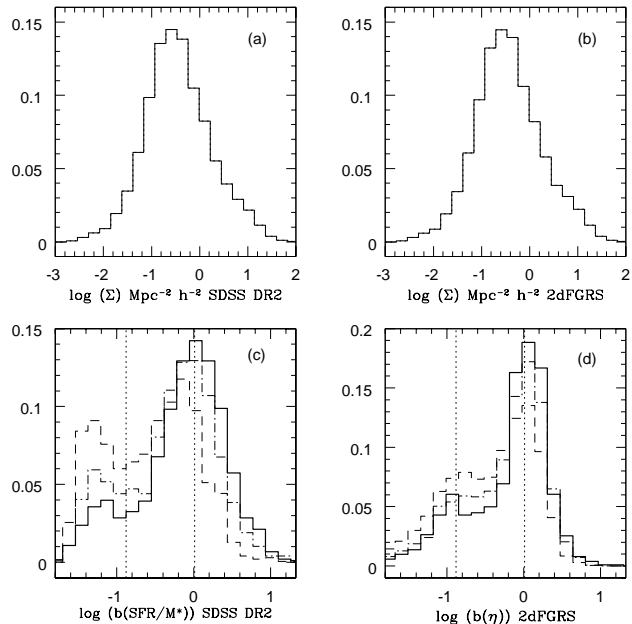


Figure 3. Distribution of $\log(\Sigma)$ for galaxy pairs in the SDSS (a) and 2dFGRS (b) surveys. Distribution of $\log(b(SFR/M^*))$ and $\log(b(\eta))$ for pair galaxies in SDSS (a) and 2dFGRS (b) catalogs in different environments: $\log \Sigma > 0.05$ (dashed lines), $-0.57 < \log \Sigma < 0.05$ (dot-dashed lines) and $\log \Sigma < -0.57$ (thick solid lines).

tween the star formation activity and the orbital parameters on environment found in Paper I and II. For this purpose we calculated the fraction of strong star-forming galaxies as a function of the orbital parameters in pairs and in the control samples in both surveys. We adopted the value $b > 1.03$ for both SDSS and 2dFGRS pair samples since this value define the high star formation peak in Fig.3 for the three defined environmental classes. The results are displayed in Fig.4 from where we notice a clear increase of the star formation activity for smaller r_p values, a tendency that is more significant in low density environments. A similar behaviour is observed for the dependence on relative velocity, ΔV , where again star formation is enhanced with respect to the corresponding fraction of the control sample for smaller relative velocities and it is clearly over the value of the control samples only in low density environments. Our results are consistent with those derived in close galaxy pairs by Nikolic et al. (2004), who find the specific star-formation rate to decrease at large relative velocity although this effect is small compare to that observed with relative separation, r_p .

Therefore, from the analysis of Fig.4, we deduce that galaxy pairs with $r_p \approx 50 h^{-1} \text{ kpc}$ and $\Delta V \approx 200 \text{ km s}^{-1}$ have a statistically significant enhancement of star formation activity, regardless of environment. Hence, we define a close pair subsample formed by those systems within such limits.

In order to study into more detail how the fraction of actively star-forming galaxy in close pairs varies with environment, we have computed the fraction of strong star-forming galaxies as a function of projected local density parameter, Σ . The correlation with Σ is illustrated in Fig.5. from where

we can see a strong dependence of the star formation activity on local density for the close pair samples and their corresponding control ones. It is clear that close pairs show enhanced star formation activity compared to galaxies in the control sample for densities lower than $\log \Sigma \simeq -1.0$. For $\log \Sigma > 0$, pairs show a lower star formation activity than galaxies without a close companion, a fact already discussed in Paper II. The transition area is within $\log \Sigma \simeq -1$ and $\log \Sigma \simeq 0$, where the fraction of strong star-forming systems seems to be independent of the presence of a close neighbour. This density range can be associated with that of loose group environments.

As discussed in Paper II (see also Pérez et al. 2005 for a comprehensive analysis of interlopers), interlopers can affect more strongly higher density regions but, the probability to have interlopers is smaller as we take closer pairs. Moreover, contamination by loose galaxies in the field would tend to increase the mean star formation toward that of the control sample. Hence, it is unlikely that the behaviour found in Fig.5 can be caused by interlopers.

As mentioned in subsection 2.3.2, in the case of the SDSS survey, incompleteness in the spectroscopic sample could introduce possible systematic bias in our results. In spite of the low fraction of contamination ($< 10\%$) we have studied the star formation activity for the clean and contaminated subsamples ($m_r \leq 17.5$) from SDSS catalog defined previously. We calculated the fraction of strong star-forming galaxies ($b > 1.03$) as a function of projected distance and relative velocity, in the three different density environments (Table 1). The results are shown in Fig.6 where it can be seen that the trends are very similar in both samples within the quoted uncertainties. This test indicates that incompleteness in the spectroscopic SDSS survey is not a serious concern for our analysis.

Given the strong dependence of star formation activity on morphological type, we have tested in SDSS if the effects of interactions obtained, depend on the concentration parameter C (ie. is the ratio of Petrosian 90 %- 50% r-band light radii) and on stellar mass M^* given by Kauffmann et al. (2004). Galaxies with a bulge (disc) dominated morphology have $C > 2.5$ ($C < 2.5$) values, so we have analysed the fraction of star-forming galaxies in the pair sample as a function of projected separation for these two concentration-type galaxies separately. The results are shown in Fig.7 where it can be appreciated the increase of star formation activity at small separations for both disc and bulge dominated galaxies. Of course, disc-dominated galaxies have in general a much larger fraction of star-forming galaxies than bulge-dominated systems. But, regarding the comparison of pair to control samples, the two types of objects behave in a similar fashion under the presence of a close companion. Similarly, galaxies with small mass in stars are more likely to be strong star-forming systems than galaxies with large stellar masses. However, the trend of increasing star formation activity for close relative separation is observed in a similar fashion for both large and low stellar mass systems.

Hence the fact that we detect lower star formation activity in pairs in the denser regions with respect to galaxies without a close companion in the same kind of environment suggests that galaxy pairs as bound systems could be more evolved than their surrounding loose galaxies. In fact when the local density increases, the fraction of strong star-

forming galaxies decreases gradually supporting the fact that, as the probability of mergers and interactions increased with density, so does the level of evolution of those systems that have remained as pairs in these environments.

A comprehensive analysis of these environmental effects requires also a study of extremely low star-forming systems. We calculate the fraction of galaxies with low star formation activity in pairs and in the control samples as those with $b < 0.13$ in both SDSS and 2dFGRS surveys as a function of projected galaxy separation between pair members, r_p , and relative velocity, ΔV , for the same three different environments used in Fig.4. This $b = 0.13$ value corresponds to approximately the low SFR peak for the SDSS and the 2dFGRS distributions as it can be seen in Fig.3.

From Fig.8, we can notice a clear increase of the low star-forming galaxy fraction in pair with larger r_p and ΔV values, a trend that is more significant in high density environments. As we mentioned before, the effects of spurious pairs should be higher for larger relative projected separations and in higher density regions. Hence, part of the trend could, in principle, reflect the effects of interlopers. However, on one hand, for close pairs these effects are not that significant as mentioned before and, on the other, the incorporation of interlopers should push the average of pairs toward that of the control sample while we are actually getting a lower value for close neighbours.

In Fig.9 we show the fraction of galaxies with low star-forming activity as a function of the projected local density parameter in close pairs and in the corresponding control samples. From this figure, it can be appreciated the expected dependence on local density for galaxies with and without a close companion so that the fraction of low star-forming systems increases with increasing density. However, we also found an increase of low star-forming galaxies in very low density regions. For close pairs there is a clear excess of low star-forming galaxies in all environments.

4 COLOURS OF GALAXIES IN PAIRS

In this section, we make use of the galaxy colour information in SDSS-DR2 using Petrosian magnitudes for each object to further study galaxies in pairs. We calculate the colours with K and extinction corrections following Blanton (2003).

Fig. 10 shows the $u-r$ colour distributions for galaxies in close pairs (solid lines) and in the control sample (dashed lines) for the three environmental classes previously defined. From this figure it can be appreciated that close pairs have distributions with an excess of both red and blue galaxy colours with respect to those of the corresponding control sample. This behaviour is more significant in low density environments. Error bars correspond to Poisson deviations in each colour bin. A more detailed look yields that, regardless of environment, galaxies in pairs populate more densely the colour ranges $u-r < 1.4$ (dotted line), corresponding to blue, young stellar populations, and the regions with $u-r > 3$ (dot-dashed line) dominated by the more extreme red stellar population, than those of the control samples. A similar analysis for $g-r$ colours yields a comparable trend with the blue and the red extreme defined by $g-r < 0.4$ and $g-r > 0.95$, respectively. These values are adopted as colour thresholds to define the extreme red and blue populations.

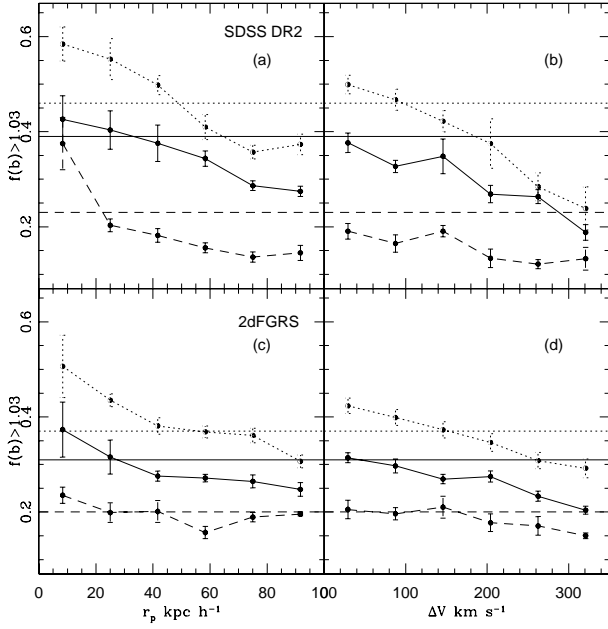


Figure 4. Fraction of strong star-forming galaxies (with $b > 1.03$) in the SDSS (upper panel) and 2dFGRS (lower panel) pair catalogs as a function of the projected distance r_p (a, c) and relative velocity ΔV (b, d) for the three different environmental classes: $\log \Sigma > 0.05$ (dashed lines), $-0.57 < \log \Sigma < 0.05$ (solid lines) and $\log \Sigma < -0.57$ (dotted lines). The horizontal lines show the corresponding fractions of the control samples.

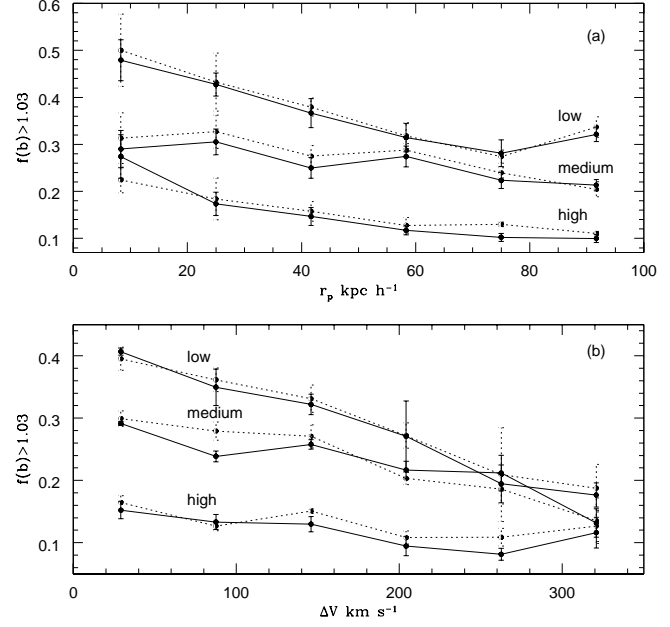


Figure 6. Fraction of galaxies in pairs restricted to $m_r \leq 17.5$ with $b > 1.03$ for the total (solid lines), and clean (dotted lines) samples in SDSS, as a function of r_p (a), and ΔV (b), for high ($\log \Sigma > 0.05$), medium ($-0.57 < \log \Sigma < 0.05$) and low ($\log \Sigma < -0.57$) density environments.

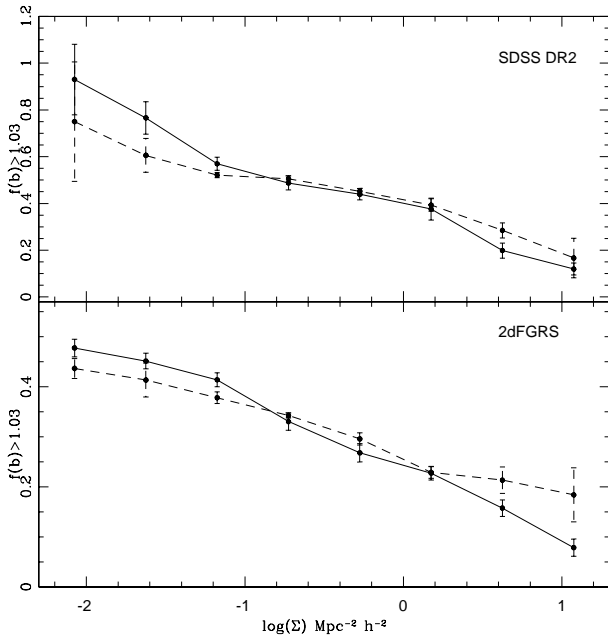


Figure 5. Fraction of strong star-forming galaxies (with $b > 1.03$) as a function of $\log \Sigma$ in close pairs: $r_p < 50 h^{-1} \text{kpc}$ $\Delta V < 200 \text{ km s}^{-1}$ (solid lines) and in the control samples (dashed lines) in SDSS (upper panel) and 2dFGRS (lower panel) surveys.

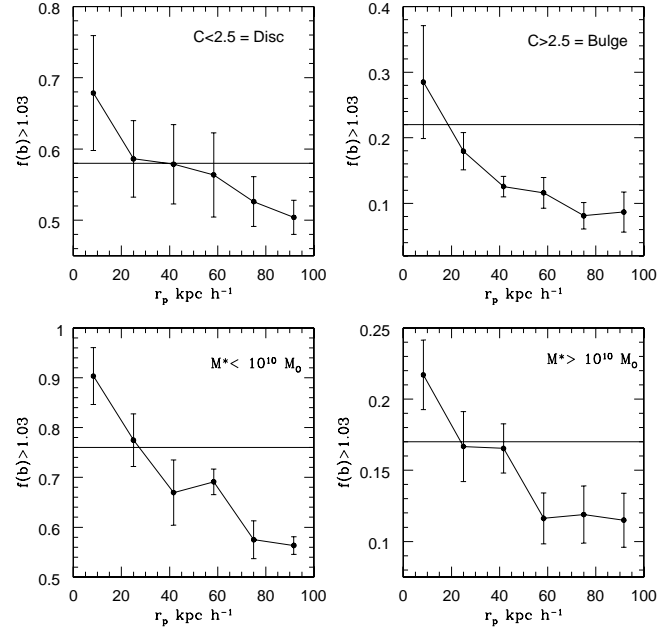


Figure 7. Upper panels: Fraction of galaxies with $b > 1.03$ in the SDSS pair catalog as a function of r_p for large $C > 2.5$ or low $C < 2.5$ concentration index values corresponding to bulge or disc dominated morphologies, respectively. Lower panels: Same as in upper panels for subsamples with low and high mass in stars ($M^* < 10^{10} M_\odot$ and $M^* > 10^{10} M_\odot$). The horizontal lines in the four panels correspond to the fractions of the control samples.

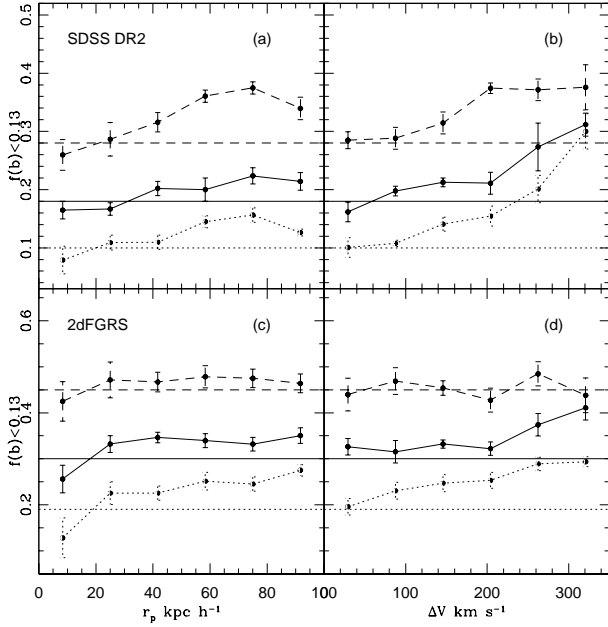


Figure 8. Fraction of low star-forming galaxies (with $b < 0.13$) as a function of projected distance, r_p (a, c), and relative velocity, ΔV (b, d), for three different environmental classes: $\log \Sigma > 0.05$ (dashed lines), $-0.57 < \log \Sigma < 0.05$ (solid lines) and $\log \Sigma < -0.57$ (dotted lines), in the SDSS (upper panel) and 2dFGRS (lower panel) surveys. The horizontal lines show the fractions of the corresponding control samples.

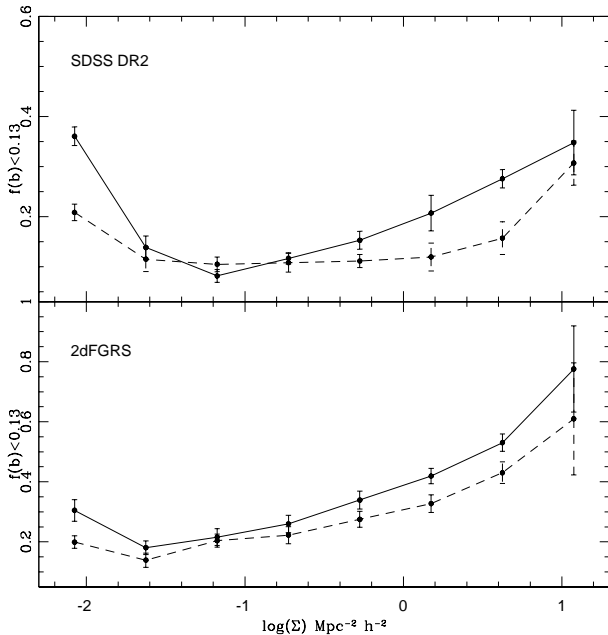


Figure 9. Fraction of low star-forming galaxies (with $b < 0.13$) as a function of $\log \Sigma$ in close pairs: $r_p < 50 h^{-1} \text{ kpc}$, $\Delta V < 200 \text{ km s}^{-1}$ (solid lines) and in the control samples (dashed lines) in SDSS (upper panel) and 2dFGRS (lower panel) surveys.

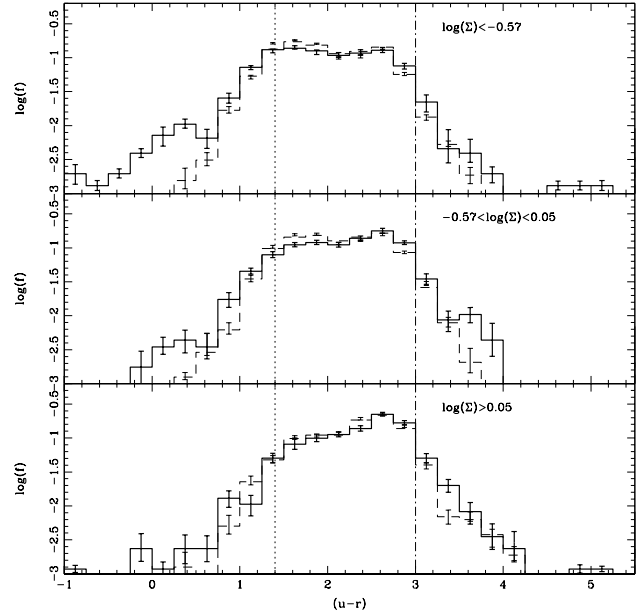


Figure 10. Distribution of $u-r$ colours for galaxies in close pairs ($r_p < 50 h^{-1} \text{ kpc}$, $\Delta V < 200 \text{ km s}^{-1}$) (solid line) and in the corresponding control samples (dashed lines), for the three different environmental classes defined in Section 2.5. The vertical lines correspond to the adopted blue (dotted) and red (dot-dashed) limits. Error bars correspond to Poisson standard errors.

4.1 The extreme blue and red galaxies

Following the analysis of Section 3, we also computed the fraction of galaxies with extreme blue and red colour indexes as a function of projected separation and relative velocity, for the same three environmental classes. We use the colour thresholds determined in the previous section: $u-r < 1.4$ and $g-r < 0.4$.

Fig.11 shows an increase of the fraction of extreme blue galaxies for small r_p and ΔV . This behaviour indicates that galaxies in close pairs have an excess of young stellar populations with respect to that of the control sample. This excess is similar for the three environments (approximately a factor 1.5) although, high density regions, systems have to be closer to reach this excess. The relative separation thresholds vary from $\approx 50 h^{-1} \text{ kpc}$ to $\approx 20 h^{-1} \text{ kpc}$ from low to high density regions. This behaviour is consistent to that found for the star formation activity as it can be appreciated from Fig.4.

In Fig.12 we have plotted the fraction of extreme blue galaxies as a function of projected local density parameter, Σ , for systems in both close pairs and control samples. As expected, the global trend with Σ is complementary to that found in Fig.5 so that the fraction of extreme blue galaxies in close pairs is higher in low density regions in comparison to the corresponding ones of the control sample. This relation inverses for high densities where we find that this fraction is larger in control sample. The transition area occurs in a density range consistent with that found for the fraction of strong star-forming pairs.

We have also explore the dependence of the fraction of

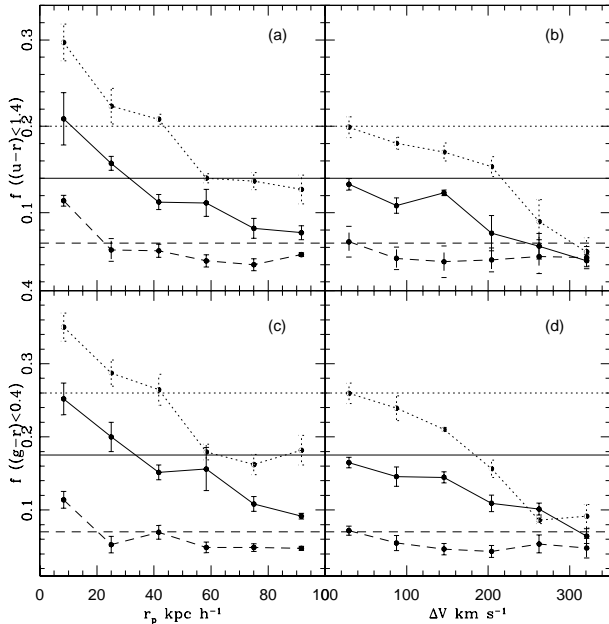


Figure 11. Fraction of galaxies with $(u - r) < 1.4$ and $(g - r) < 0.4$ as a function of projected distance, r_p (a,c) and relative velocity, ΔV (b,d), for the three different environmental classes defined in Fig.4. The horizontal lines show to the fractions of the corresponding control samples.

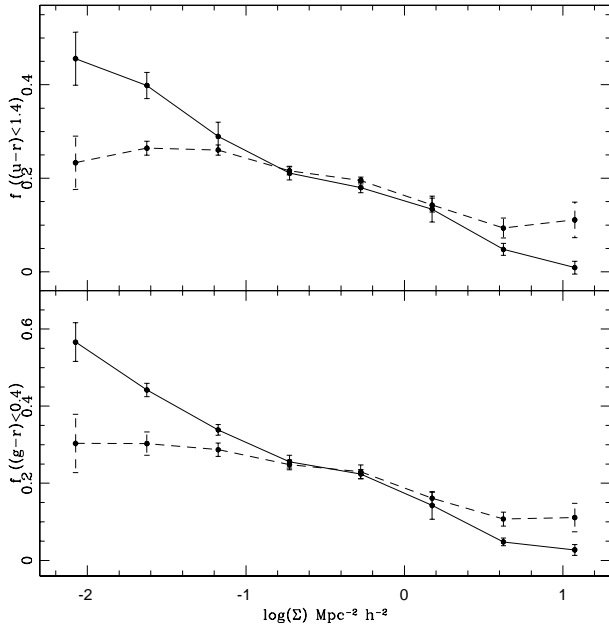


Figure 12. Fraction of galaxies with $u - r < 1.4$ (a) and $g - r < 0.4$ (b) as a function of projected local density, Σ , for close pairs (solid lines) and control sample (dashed lines).

extreme red galaxies on projected separation and relative velocity. Fig.13 shows an equivalent set of plots to that of the extreme blue fraction displayed in Fig.11, for the same range of Σ values. Note, that the fraction of red galaxies in the control samples are almost independent of environment and their bootstrap errors are ≈ 0.005 . For galaxies in pairs there is an increase of this fraction for small r_p and ΔV values, indicating that close pairs have an excess of red objects regardless of the environment. The bootstrap error bars for the fractions of the pair and control samples indicate that the signal is statistically meaningful at more than 3σ -level.

One possible interpretation of this trend is that many galaxies in pairs have been very efficient in forming stars at early stages of their evolution so that, currently, they exhibit red colours. However, from Fig.8 we can appreciate that the fractions of low star-forming galaxies decrease for smaller relative separation for all environments, while the strong star-forming fractions increase (Fig.4). The behaviour of colours and star formation activity suggests that there is an important fraction of galaxies in very close pairs ($r_p < 20 h^{-1}$ kpc) which tend to be redder than the rest of the galaxies but have enhanced star formation activity with respect to the control sample. The red colours of these star-forming galaxies in close pairs could be due to obscuration as the result of dust stirred up during the encounter which could also hide part of the star formation activity.

In order to further understand the dependence on environment of the fraction of galaxies with red colour indexes in close pairs and in galaxies without a close companion, we have analysed the fraction of extreme red galaxies in close pairs as a function of the local density parameter, Σ . The results are shown in Fig.14 from where it can be appreciated that there is an excess of extreme red galaxies in close pairs compared to that of the control sample in all kind of environment. This trend tends to be stronger in high density environments, consistent with the results of low star-forming galaxies discussed in Section 3.

We also notice that at, extremely low density environments, galaxies regardless of the presence of a companion, also show a larger fraction of red objects in comparison with those of transition density region. This feature is consistent with the change in the slope of the relation between the fraction of low star-forming galaxies and Σ detected for $\log \Sigma \leq -1.2$ (Fig.9). We argue that these trends can be interpreted as the result of the growth of small scale overdensities in global underdense regions, where the subsequent infall of gas and as a consequence, the star formation activity is likely to have been strongly reduced at later times. Hence generally, galaxies would be less efficiently fed by gas infall in this regions, and on top of that, galaxies in pairs would be more efficient at consuming this gas, producing a larger fraction of red and low star-forming systems.

Previous studies of the colour distribution of galaxies showed an important dependence of the fraction of red galaxies with environment and luminosity (Kauffmann et al. 2004; Balogh et al. 2004; Baldry et al. 2003). In particular, Balogh et al. (2004) claimed that the colour distribution is bimodal with only the relative fraction of galaxies in the red and blue peaks varying with local density and luminosity. These authors interpreted their results resorting to a rapid change of galaxy colours due to mergers and interactions. Our results support to these findings given the strongest de-

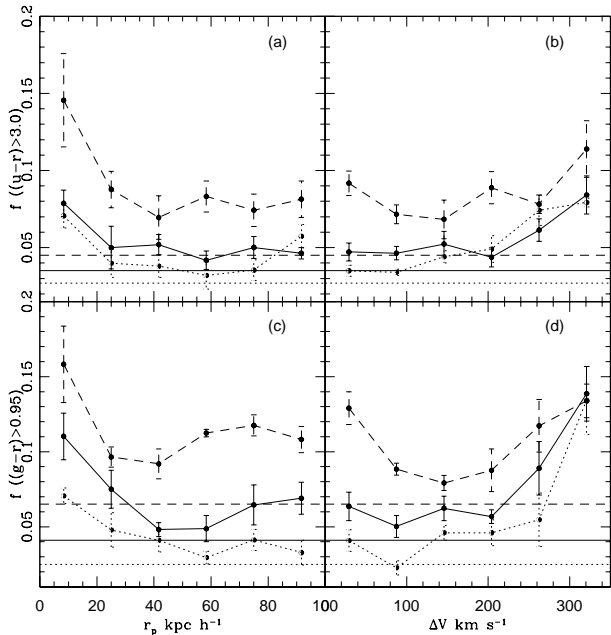


Figure 13. Fraction of galaxies with $(u - r) > 3.0$ and $(g - r) > 0.95$ as a function of projected distance r_p (a,c) and relative velocity ΔV (b,d) for the three different environmental classes defined in Fig.8. The horizontal lines show the fractions of the corresponding control samples.

pendence of the star formation activity and colours of galaxies in pairs on environment with respect to galaxies without a close companion. A detail discussion on the bimodal colour distribution of galaxies in pairs will be presented in a forthcoming paper.

5 CONCLUSIONS

We have carried out a detailed analysis of photometric and spectroscopic properties of galaxies in pairs at different environments. The galaxy pair catalogs derived from the 2dFGRS and SDSS-DR2 galaxy surveys available comprise 6067 and 6405 pairs, respectively. In order to characterize environment, we have used a projected galaxy density derived from the fifth bright nearest neighbour of each galaxy. We have adopted $M_r < -20.5$ in SDSS and $b_j < -19.3$ in 2dFGRS so that the derived projected densities of both surveys are nearly consistent with each other. In agreement with previous works our analysis indicates that, globally, star formation activity obtained from 2dFGRS and SDSS are strong functions of both global environment and orbital parameters. Our analysis on SDSS pairs confirms previous results found from the 2dFGRS that the projected distance $r_p < 100 h^{-1}$ kpc and relative velocity $\Delta V < 350$ km s^{-1} are suitable thresholds for the presence of a companion to be correlated with effects on the star formation activity of galaxies.

The SDSS galaxy pair catalog has been cleaned of AGNs. Conversely, the 2dFGRS may suffer for some contamination by AGNs which can affect the relation. This could explain in part some of the small differences found in the

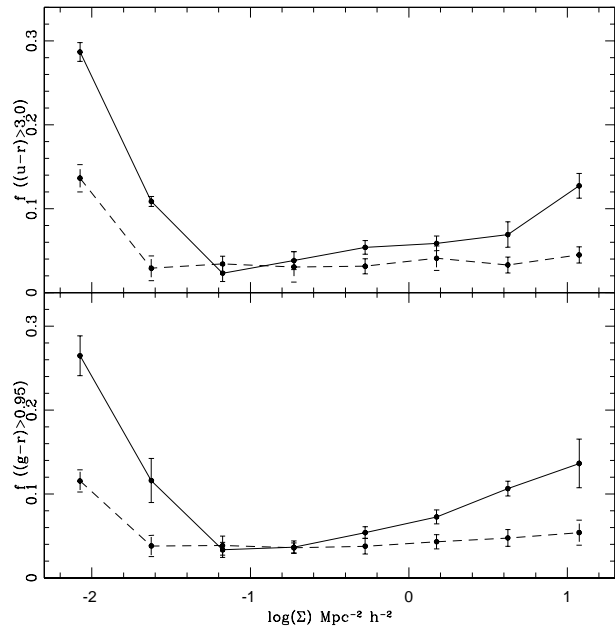


Figure 14. Fraction of galaxies with $u - r > 3.0$ (a) and $g - r > 0.95$ (b) as a function of projected local density, Σ , in close pairs (solid lines) and in the control sample (dashed lines).

results from both catalogs. Note, nevertheless, that trends are very similar.

Our results found can be summarized as follows:

- There is an increase of star formation in pairs for smaller projected separations and relative velocities in all environments. However, in high density regions galaxies have to be closer to statistically show an enhancement respect to galaxies without a close companion.
- The dependence of the fractions of extremely blue and actively star-forming galaxies in close pairs on local density show a different behaviour respect to the equivalent fraction of galaxies without a close companion. In low density environment, blue and star-forming galaxies tend to be in pairs. In high density regions, galaxies without a close companion have a higher contribution to the blue and actively star-forming systems. The transition local densities correspond to group environments.
- Extremely red and low star-forming galaxies in pairs outnumber those without a close companion in all environments. The fraction of red and low star-forming galaxies without a close companion shows an increase in the lowest density regions analysed. The corresponding fraction of galaxies in pairs increases in both the low and the high density ends. In low density environments, this effect is more pronounced for pair galaxies owing to the combined effects of the expected lack of gas infall in such regions and the high efficiency of galaxies in pair to use the available gas for new stars at early stages of their evolution.
- For very close projected distances ($r_p < 25 h^{-1}$ kpc), there is a statistical significant decrease of low star-forming pairs in all environments together with an important increase of extremely red galaxies in pairs. This finding suggests that dust stirred-up during the encounter may be af-

fecting colours and probably also obscuring part of the star formation activity.

These results show that galaxy-galaxy interactions are an important mechanism for triggering star formation regardless of environment, although at high density systems have to be closer to react to the presence of a companion. We also found that, in low density environments, extremely blue and star-forming galaxies tend to be in pairs, conversely to the situation in high density regions where more violent activity is found in galaxies without a close companion expect for very close pairs. This relation has an equivalent behaviour to that of the morphology-density relation which shows that, in the local universe, actively star-forming systems tend to be located in low density regions, with a transition area corresponding to group environments. Conversely, the red and low star-forming extreme is dominated by galaxies in pairs in all environments (except for very close pairs). We argue that this trend unveils the ubiquitous effects of interactions also in previous stages of evolution which exhausted the gas reservoir in close systems. Since these analyses are based on close pairs, contamination by interlopers is expected not to be significant. Dust, however, may be have some effect in very close pairs, although their role is still difficult to quantify statistically until an equivalent catalog can be constructed in adequate wavelengths.

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