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Galaxy triplets in Sloan Digital Sky Survey Data Release 7 – II. A connection with compact groups?

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ABSTRACT

We analyse a sample of 71 triplets of luminous galaxies derived from the work of O'Mill et al. We compare the properties of triplets and their members with those of control samples of compact groups, the 10 brightest members of rich clusters and galaxies in pairs. The triplets are restricted to have members with spectroscopic redshifts in the range $0.01 \leq z \leq 0.14$ and absolute r-band luminosities brighter than $M_r = -20.5$. For these member galaxies, we analyse the stellar mass content, the star formation rates, the $D_n(4000)$ parameter and $(M_g - M_r)$ colour index. Since galaxies in triplets may finally merge in a single system, we analyse different global properties of these systems. We calculate the probability that the properties of galaxies in triplets are strongly correlated. We also study total star formation activity and global colours, and define the triplet compactness as a measure of the percentage of the system total area that is filled by the light of member galaxies. We concentrate in the comparison of our results with those of compact groups to assess how the triplets are a natural extension of these compact systems. Our analysis suggests that triplet galaxy members behave similarly to compact group members and galaxies in rich clusters. We also find that systems comprising three blue, star-forming, young stellar population galaxies (blue triplets) are most probably real systems and not a chance configuration of interloping galaxies. The same holds for triplets composed of three red, non-star-forming galaxies, showing the correlation of galaxy properties in these systems. From the analysis of the triplet as a whole, we conclude that, at a given total stellar mass content, triplets show a total star formation activity and global colours similar to compact groups. However, blue triplets show a high total star formation activity with a lower stellar mass content. From an analysis of the compactness parameter of the systems we find that light is even more concentrated in triplets than in compact groups. We propose that triplets composed of three luminous galaxies, should not be considered as an analogous of galaxy pairs with a third extra member, but rather they are a natural extension of compact groups.

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

1 INTRODUCTION

It is well known that several properties of galaxies depend on environment. Pioneering work by Dressler (1980) shows that galaxy morphology depends on local galaxy density: late-type galaxies prefer low-density environments, while dense environments tend to be populated by early-type galaxies. There is also a strong correlation between galaxy star formation rates (SFRs) and environment: galaxies in high-density environments present a decrease in SFRs compared to field galaxies (Gómez et al. 2003; Baldry et al. 2004; Balogh et al. 2004; Mateus & Sodré 2004). The effect of local

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environment on galaxy colours has been studied by O'Mill, Padilla & Lambas (2008). These authors find that at $z = 0$ faint galaxies show a clear increase in the fraction of red galaxy as the local density increases. On the other hand, bright galaxies present a constant red galaxy fraction.

There are several known processes that influence galaxy properties. The hot intracluster gas is the main responsible for stripping the gas of galaxies in the core of clusters. Mechanisms such as ram-pressure stripping (Gunn & Gott 1972) and the strangulation or starvation scenarios (Larson, Tinsley & Caldwell 1980) lead to a decrease in the SFR of cluster galaxies. Tidal interactions of galaxy pairs and mergers affect the morphology of galaxies and can convert spiral galaxies into elliptical and S0s (Toomre & Toomre 1972). These processes can also trigger star formation, depending on the gas reservoir of the galaxies (Yee & Ellingson 1995; Kennicutt 1998). In the extremely dense environments of compact groups, galaxies are separated only by a few galaxy radii from each other and with a low relative velocities, an ideal scenario for interactions and mergers (Mamon 1992).

Several studies have analysed the properties of galaxies in different systems, such as pairs, compact groups, groups with four or more members and clusters. Nevertheless, there are few works addressing the properties of galaxies in triple systems. Hernández-Toledo et al. (2011) performed *BVRI* surface photometry of a sample of 54 galaxies selected from the catalogue of isolated triplets of galaxies in the Northern hemisphere (Karachentseva, Karachentsev & Shcherbanovskii 1979) and investigate the properties of 34 galaxies in 13 triplets. These authors found that these systems are spiral dominated and a fraction of 56 per cent of the triplets present morphological signatures associated with interactions. They also found a fraction of 35 per cent of bars, that can rise up to 66 per cent in the late-type spirals, and a fraction of 20 per cent of rings, hosted preferentially in late-type components. Based on these results the authors suggest that triple systems are essentially different from Hickson compact groups and more representative of the field. However, the results of this work are based mainly in observations of a low number of systems. For this reason, these authors also highlight the relevance of building a complete sample of local isolated triplet of galaxies that allows a significant statistical analysis.

O'Mill et al. (2012, hereafter Paper I) constructed a sample of isolated triplets of galaxies brighter than $M_r = -20.5$ and complete up to $z = 0.4$ from the Data Release 7 of Sloan Digital Sky Survey (SDSS-DR7; Abazajian et al. 2009). The aim of this paper is to analyse the properties of a sample of spectroscopic galaxies derived from this triplet catalogue and compare them with the properties of galaxies in different systems such as pairs, compact groups and clusters. The proximity and low relative velocities of galaxy members in triplets present an ideal scenario for galaxy interactions and mergers, placing these systems in a state of ongoing collapse. For these reasons in this paper we will also investigate the properties of the system as a whole.

This paper is organized as follows. In Section 2 we describe the triplet and galaxy system samples used in this work. In this section we also build control samples in order to avoid biases in the comparison of properties of galaxies in different systems. In Section 3 we analyse the specific star formation rate (SFR/M_*), the strength of the 4000 Å break, $D_n(4000)$, which is a spectral indicator of the stellar population mean age, and $(M_g - M_r)$ colour index of galaxies in the different systems under analysis. We study all these properties as a function of the stellar mass content in order to avoid biases due to differences in this parameter. In Section 4, we analyse the triplet as a system. We use bootstrap techniques in order to assess the probability that the configurations of galaxies in triple systems are correlated or, on the contrary, can be explained by a random sampling. We also investigate how the total stellar mass of the system affect the properties of galaxies in triplets and analyse global properties as total SFR and global $(M_g - M_r)$ colour index of the system as a whole. We also analyse the compactness of the triplets by defining a parameter S that is a measure of the percentage of the system total area that is filled by the light of member galaxies. In this section we also compare the properties of triple systems with the global properties of compact groups. Finally, in Section 6 we discuss our main results.

Throughout this paper we adopt a cosmological model characterized by the parameters $\Omega_\mathrm{m} = 0.25$, $\Omega_\Lambda = 0.75$ and $H_0 = 70\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2 SAMPLES

In this work we analyse several samples of galaxy systems derived from the SDSS-DR7 (Abazajian et al. 2009). SDSS (York et al. 2000) has mapped more than one-quarter of the entire sky, performing photometry and spectroscopy for galaxies, quasars and stars. SDSS-DR7 is the seventh major data release, corresponding to the completion of the survey SDSS-II. It comprises 11663 deg^2 of imaging data, with an increment of ∼2000 deg^2, over the previous data release, mostly in regions of low Galactic latitude. SDSS-DR7 provides imaging data for 357 million distinct objects in five bands, *ugriz*, as well as spectroscopy over $\simeq\pi$ sr in the North Galactic Cap and 250 deg^2 in the South Galactic Cap. The average wavelengths corresponding to the five broad-bands are 3551, 4686, 6165, 7481 and 8931 Å (Fukugita et al. 1996; Hogg et al. 2001; Smith et al. 2002). For details regarding the SDSS camera see Gunn et al. (1998); for astrometric calibrations see Pier et al. (2003). The survey has spectroscopy over 9380 deg^2; the spectroscopy is now complete over a large contiguous area of the Northern Galactic Cap, closing the gap that was present in previous data releases.

2.1 Galaxy triplets sample

In Paper I we analysed spectroscopic and photometric data extracted from SDSS-DR7 in order to build a catalogue of isolated triplets of galaxies. The spectroscopic data were derived from the Main Galaxy Sample [MGS; Strauss et al. (2002)]. k-corrections for this sample were calculated bandshifted to $z = 0.1$, using the software K-CORRECT_V4.2 of Blanton & Roweis (2007). The photometric data were derived from the photometric catalogue constructed by O'Mill et al. (2011),[1] which contains photometric redshift and k-correction for the photometric data of the SDSS-DR7. For both data sets, k-corrected absolute magnitudes were calculated from Petrosian apparent magnitudes converted to the AB system. The final catalogue comprises 1092 isolated triplets of galaxies with absolute r-band magnitude brighter than $M_r = -20.5$ in the redshift range $0.01 \le z \le 0.4$. A full description of the algorithm developed to build this catalogue can be found in Paper I.

One of the aims of this paper is to analyse different properties of galaxies in triplets by including information extracted from their spectra. For this reason we have considered only triple systems composed of three spectroscopic galaxies that are close in projected separation $r_\mathrm{p} < 200\,h^{-1}$ kpc and with a radial velocity difference $\Delta V_\mathrm{spec} < 700\,\mathrm{km\,s^{-1}}$. Because of completeness in the spectroscopy,

[1] http://www.starlight.ufsc.br/index.php?section=1

we have restricted our analysis to the redshift range $0.01 \leq z_{\rm spec} \leq 0.14$.

In order to select isolated systems, we implement two of the isolation criteria described in Paper 1:

(i) $N_{0.5} = 3$;
(ii) $N_1 \leq 4$.

Here, $N_{0.5}$ and N_1 are the number of galaxies brighter than $M_r = -20.5$ within 0.5 and 1 h^{-1} Mpc, respectively, from the triplet centre considering the same restrictions on ΔV used to identify triplet members.

In the same way that Paper I, we calculated the distance of each triplet to the closest neighbour group/cluster, dc, using two catalogues: Zapata et al. (2009), updated to the SDSS-DR7, for $z \leq 0.1$, and for the redshift range $0.1 \leq z \leq 0.14$, the Gaussian Mixture Brightest Cluster Galaxy (GMBCG) catalogue of clusters (Hao et al. 2010) that includes photometric redshift information. For each triplet system candidate we computed the projected distance to the closest neighbour cluster considering a radial velocity restriction $\Delta V < 1000\,{\rm km\,s^{-1}}$ when spectroscopic information is available, and $\Delta V < 7000\,{\rm km\,s^{-1}}$ when photometric redshifts are involved.

We acknowledge that the systems obtained by these conditions are consistent with a minimum distance to a rich cluster of $dc \geq 3\,h^{-1}$ Mpc, similar to the restriction $dc \geq 5\,h^{-1}$ Mpc given in Paper I.

Under these considerations, the final sample of galaxy triplets contain 71 isolated systems with 213 spectroscopic galaxies brighter than $M_r = -20.5$ in the redshift range $0.01 \leq z \leq 0.14$.

2.2 Comparison samples

The aim of this work is to analyse the spectroscopic properties of galaxies in triplets and compare them with the properties of galaxies belonging to different galaxy systems. Here we consider samples of galaxies in compact groups, clusters and galaxy pairs.

2.2.1 Compact groups

McConnachie et al. (2009) identified compact groups of galaxies, using the photometric data of the SDSS-DR6, through the implementation of the 'Hickson criteria':

(i) $N(\Delta m = 3) \geq 4$;
(ii) $\theta_N \geq 3\,\theta_{\rm G}$;
(iii) $\mu_{\rm e} \leq 26.0\,{\rm mag\,arcsec^{-2}}$.

Here $N(\Delta m = 3)$ is the number of galaxies in the magnitude interval $[r_1, r_1 + 3]$, where r_1 is the r-band magnitude of the brightest galaxy in the group. $\mu_{\rm e}$ is the effective surface brightness of the system calculated by distributing the flux of the member galaxies over $\theta_{\rm G}$, where $\theta_{\rm G}$ is the angular diameter of the smallest circle encompassing the geometric centres of the galaxies in the group. Finally, θ_N is defined as the angular diameter of the largest concentric circle that contains no other (external) galaxies within this magnitude range or brighter.

McConnachie et al. (2009) build two catalogues: Catalogue A comprising galaxies in compact groups with Petrosian r-band magnitude in the range $14.5 \leq r \leq 18.0$ and Catalogue B including galaxies in the broader magnitude range $14.5 \leq r \leq 21.0$. Because of independent visual inspection by the authors of all galaxy members in Catalogue A, the contamination due to gross photometric errors is negligible. This sample includes compact groups that have $\Delta v \leq 1000\,{\rm km\,s^{-1}}$, where Δv is a measure of the maximum line-of-sight velocity difference between group members for groups with more than two members with spectroscopic redshift information. Catalogue B includes many more groups than Catalogue A but has the disadvantage of a larger contamination due to poor photometric classification.

We will use Catalogue A as a comparison sample for this work. Nevertheless, this catalogue was constructed from the sixth release of the SDSS, therefore, we have added to this catalogue spectroscopic redshift information from SDSS-DR7, and in what follows we will use systems in Catalogue A that have all their galaxies with spectroscopic measurements.

We have cross-correlated our triplet sample with this compact group catalogue in order to exclude common systems. We found five coincidences of our triplets with the compact groups sample. From these common systems, four consist on three triplet galaxies plus one galaxy with $\Delta v > 1000\,{\rm km\,s^{-1}}$. The remained common system is comprised by the three triplet galaxies and one galaxy fainter than $M_r = -20.5$. We have therefore removed these five compact groups from the original sample.

2.2.2 10 first ranked cluster galaxies

This sample was derived from the catalogue of galaxy groups of Zapata et al. (2009) updated to the SDSS-DR7. These authors implement a friends-of-friends algorithm with varying linking lengths $D_{12} = D_0 R$ and $V_{12} = V_0 R$, in the direction perpendicular and parallel to the line-of-sight, respectively, where $D_0 = 0.24\,h^{-1}$ Mpc and $V_0 = 450\,{\rm km\,s^{-1}}$. The spatial scaling R takes into account the variation in the space density of galaxies in a flux-limited sample. From this catalogue, we selected a sample of clusters of galaxies considering systems with virial masses $M_{vir} > 10^{14}\,h^{-1}\,{\rm M_{\odot}}$ and more than 10 galaxy members. The galaxies belonging to these systems were ranked in r-band luminosity. Then we compiled a sample selecting the 10 first ranked cluster galaxies (10FRCGs) of each system, excluding the most luminous galaxy, since these galaxies usually have very distinctive properties.

2.2.3 Pairs

The sample of galaxy pairs analysed in this work was obtained by Lambas et al. (2012). These authors construct a galaxy pair catalogue selecting galaxies in the SDSS-DR7, with relative projected separations $r_{\rm p} < 25\,h^{-1}$ kpc and relative radial velocities difference $\Delta V < 350\,{\rm km\,s^{-1}}$. Previous studies of the team found that these limits are adequate to define galaxy pairs with enhanced star formation activity (Lambas et al. 2003; Alonso et al. 2006). In this work we have excluded from these sample, galaxy pairs that resides in groups, according to Alonso et al. (2012). These authors analysed in detail the properties of galaxy interactions in high-density environments, identifying pairs that reside in groups by cross-correlating the total galaxy pair catalogue of Lambas et al. (2012) with the group catalogue constructed by Zapata et al. (2009), updated to the SDSS-DR7.

In order to compare the properties of galaxies in different systems, we cross-correlate all the galaxy samples described above, with the derived galaxy properties from the MPA-JHU emission line analysis for the SDSS-DR7.[2] From this catalogue we extract several galaxy

[2] Available at http://www.mpa-garching.mpg.de/SDSS/DR7/

Table 1. Name and number of galaxies in the triplet and control samples.

Name	Number of galaxies
Triplets	213
cgs	230
Pairs	472
10FRCGs	2089

properties: as a spectral indicator of the stellar population mean age, we will use the strength of the 4000 Å break, $D_n(4000)$, defined as the ratio of the average flux densities in the narrow continuum bands 3850–3950 and 4000–4100 Å (Balogh et al. 1999). We also use the SFR and specific star formation rates (SFR/M_*) according to Brinchmann et al. (2004) and total stellar masses (M_*) calculated from photometry (Kauffmann et al. 2003).

2.3 Control samples

When comparing properties of galaxies that belong to different samples it is important to consider differences in the galaxy redshift distribution. For this reason, we construct control samples using a Monte Carlo algorithm to randomly select galaxies that matched the galaxy triplet redshift distribution, for the different systems samples analysed in this work. The distribution of M_r of triplet galaxies is truncated by definition at $M_r = -20.5$ (Paper I). In order to avoid biases due to less luminous galaxies, we restrict our analysis to galaxies brighter than $M_r = -20.5$.

We performed a Kolmogorov–Smirnov (KS) test between the redshift distribution of the control samples and the redshift distribution of triplet galaxies. From this test we obtain a p value that represents the probability that a value of the KS statistic will be equal or more extreme than the observed value, if the null hypothesis holds. In all cases we obtained $p > 0.05$ for the null hypothesis that the samples were drawn from the same distribution. Table 1 summarizes the name and number of objects in the triplet galaxy sample and in the control samples analysed in this work.

Fig. 1 shows the distribution of redshift, absolute r-band magnitude (M_r) and log $M_*/\mathrm{M}_\odot$ for the sample of triplet galaxies and for the *cgs*, pairs and 10FRCGs control samples. From this figure it can be appreciated that all the samples present a similar redshift distribution. The restriction $M_r > -20.5$ is reflected on the log $M_*/\mathrm{M}_\odot$ distribution. Although all the samples cover a similar log $M_*/\mathrm{M}_\odot$ range, compared to triplet galaxies, galaxies in pair presents a shift towards the less massive tail of the distribution and 10FRCGs show an increment in the relative number of massive galaxies with respect to the triplet sample. Nevertheless, the distribution of log $M_*/\mathrm{M}_\odot$ for galaxies in *cgs* is almost equal to the distribution of triplet galaxies. In order to avoid biases due to differences in M_* we restrict our analysis to the range covered by the sample of galaxies in triplets ($10^{10} \leq M_* \leq 10^{11.5}\,\mathrm{M}_\odot$).

3 ANALYSIS OF THE PROPERTIES OF GALAXIES IN TRIPLETS

The aim of this section is to compare the properties of individual galaxies in triplets with galaxies in compact groups, pairs and clusters. These galaxies reside in environments with diverse local and global densities; therefore, their main properties can be affected by different processes related to environment and evolution.

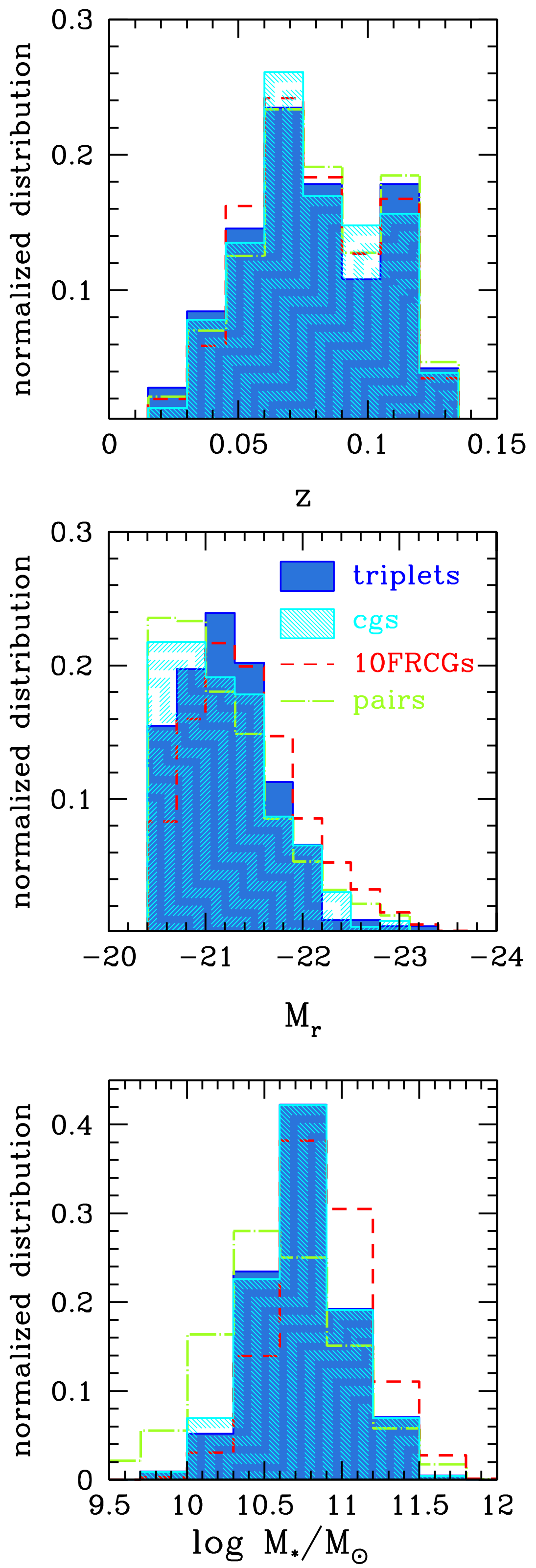

Figure 1. Distribution of redshift z (top panel), absolute r-band magnitude M_r (middle panel) and log $M_*/\mathrm{M}_\odot$ (bottom panel) for the galaxy samples analysed in this section (key in the figure). (A colour version of this figure is available in the online journal.)

Galaxies in clusters usually present early morphological types, low SFRs and red colours compared with galaxies in other systems. The preferred scenario for their formation invokes a set of mechanisms that remove the gas from spiral galaxies in the cluster environment, such as *ram-pressure stripping* of disc gas (Gunn & Gott 1972) and *strangulation* or *starvation* scenarios (Larson et al. 1980).

Galaxy pair interactions play an important role in the establishment of galaxy properties. Different observational and theoretical analysis have shown that interactions in close pair of galaxies provide powerful mechanisms to trigger star formation activity (Yee & Ellingson 1995; Kennicutt 1998), and the efficiency of the starbursts depends on the particular internal characteristics of the galaxies and of their gas reservoir (Toomre & Toomre 1972; Barnes & Hernquist 1992, 1996; Mihos & Hernquist 1996). In a recent work, Lambas et al. (2012) found that, at a given total stellar mass, pairs with galaxies of similar luminosity are significantly more efficient (a factor of ≈2) in forming new stars, with respect to both minor pairs (formed by two galaxies with a large relative luminosity ratio) or a control sample of non-interacting galaxies, showing that the characteristics of the interactions and the ratio of luminosity of galaxy pair members are important parameters in setting galaxy properties.

Compact group galaxies are predominately ‘red and dead’ (Brasseur et al. 2009). These galaxies reside in high local density environments, but the velocity dispersion of compact groups is lower than those of clusters (Hickson et al. 1992). This is an ideal scenario for investigating galaxy interactions that can affect properties such as galaxy morphology and SFR. More than 50 per cent of compact group galaxies are early type (Hickson, Kindl & Huchra 1988; Palumbo et al. 1995). Using high angular resolution observations obtained with the Very Large Array (VLA), Verdes-Montenegro et al. (2001) found that compact groups as a whole are H I deficient and that individual galaxies show a larger degree of deficiency than the groups globally (24 per cent of the expected H I). In most cases this could be a consequence of efficient gas stripping from individual galaxies going into the group environment. Although interactions between galaxies can enhance star formation, galaxies in compact groups present SFRs similar to those in a control sample of isolated, not strongly interacting galaxies, matched in *J* band total galaxy luminosity (Tzanavaris et al. 2010). In agreement with these results, Brasseur et al. (2009) found, using simulations, that most compact group galaxies are red and gas deficient, with a low specific SFR.

In order to investigate whether the galaxies in triplets resemble the galaxies in compact groups, or if these galaxies are similar to galaxies in other systems, we compute mean values of log SFR/M_*, $D_n(4000)$ index and $(M_g - M_r)$ colour, for the triplets, and for the *cgs*, pairs and 10FRCGs control samples as a function of stellar mass (Fig. 2).

In general, galaxies in the sample of pairs present mean values that correspond to star-forming blue galaxies with young stellar populations. In contrast, galaxies in triplets present a behaviour similar to *cgs* and 10FRCGs: lower SFR/M_*, redder colours and present higher values of the $D_n(4000)$ index.

In the lower stellar mass intervals in Fig. 2 it can be appreciated that galaxies step towards higher SFR/M_*, lower $D_n(4000)$ index and bluer colours. In the first stellar mass bin the mean values of the properties of galaxies in different systems are similar. For the three higher M_* bins in Fig. 2 there is almost no difference between the mean values of the properties of galaxies in the systems under analysis.

The distributions of log SFR/M_*, $D_n(4000)$ and $(M_g - M_r)$ colour for the galaxies in the samples analysed in different M_* bins are shown in Fig. 3 (log SFR/M_* (top), $D_n(4000)$ index (middle) and $(M_g - M_r)$ colour (bottom). We notice that the distribution of galaxies in the first M_* bin is unimodal corresponding to high star formation (log SFR/$M_* > -10.5$), blue colours ($(M_g - M_r) < 0.75$) and populations with low $D_n(4000)$ index ($D_n(4000) < 1.6$). For the two following stellar mass bins galaxies present a bimodal distribution with a considerable fraction of low star-forming, old stellar population, red galaxies. In particular, for the second M_* interval, the distribution of galaxies in triplets has a slight tendency to resemble the distribution of galaxies in pairs, while the distribution of galaxies in *cgs* is more similar to those of galaxies the in 10FRCGs sample.

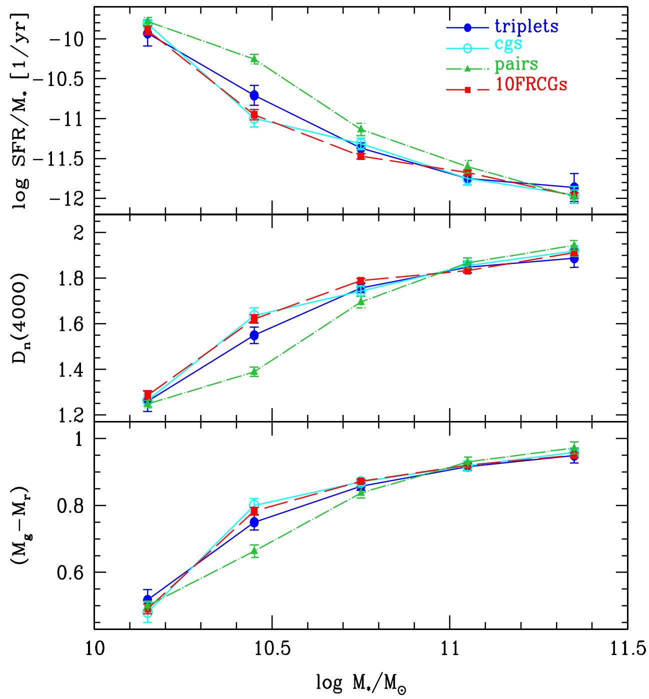

Figure 2. Mean values of log SFR/M_* (top), $D_n(4000)$ index (middle) and $(M_g - M_r)$ colour (bottom), as a function of log $M_*/\mathrm{M}_\odot$ bins, for the galaxy samples analysed in this section (key in the figure). Error bars were calculated using bootstrapping techniques. (A colour version of this figure is available in the online journal.)

When considering galaxies with stellar masses above log $M_*/\mathrm{M}_\odot = 10.9$, there are almost no differences between the distributions of the samples analysed, corresponding to a dominant population of galaxies with low SFR, high $D_n(4000)$ and red colours. This is in agreement with the results of Kauffmann et al. (2003), who suggest that at stellar masses above $3 \times 10^{10}\,\mathrm{M}_\odot$ there is an increment in the fraction of old stellar population, bulge-like, low star-forming galaxies.

From the analysis of Figs 2 and 3 we conclude that galaxies in triplets show SFRs, colours and stellar populations that behave similarly to galaxies in compact groups and clusters. In contrast, pair galaxy members present systematically higher star formation activity indicators.

4 ANALYSIS OF THE TRIPLET SYSTEMS

4.1 Resampling

Brasseur et al. (2009) suggest that the majority of galaxies in compact groups that are blue, gas rich and/or have high SFRs are

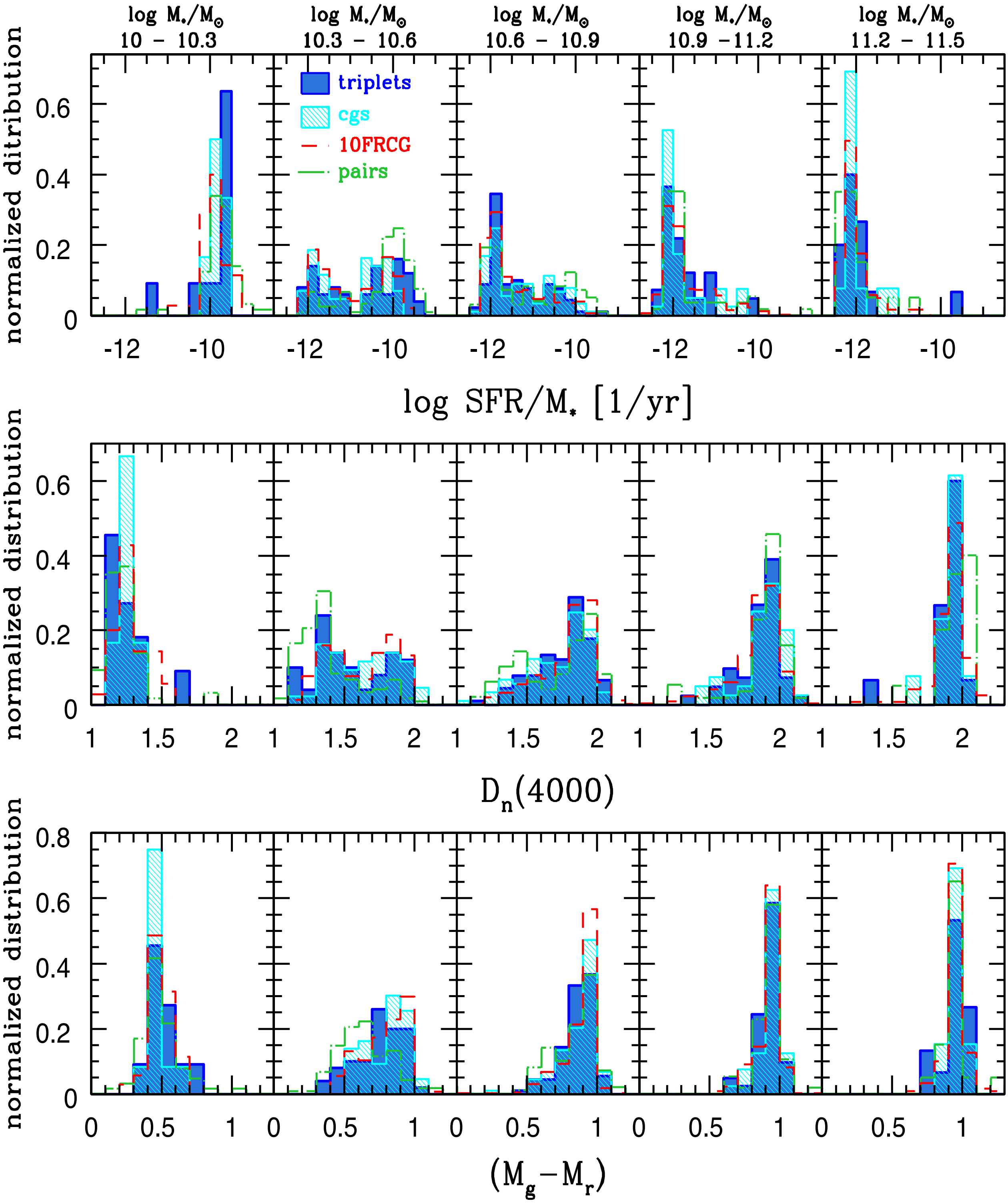

Figure 3. Distribution of log SFR/M_* (top), D_n(4000) index (middle) and ($M_g - M_r$) colour (bottom) in log M_*/M$_\odot$ bins for the galaxy samples analysed in this section (key in the figure). The mean values of the distributions in each stellar mass bin are representative of the mean values of Fig. 2. (A colour version of this figure is available in the online journal.)

interlopers. The results obtained in the previous section suggest that there is a population of blue, active star-forming galaxies, mainly comprised by low stellar mass objects in all the system samples analysed in this work.

In Paper I we used a mock catalogue to analyse the completeness and contamination of the algorithm developed for the identification of triplet of galaxies, and found a high level of completeness (∼80 per cent) and low contamination (∼5 per cent). Nevertheless, in order to assess the probability that blue galaxies in the triplet sample could be contaminated by interloping galaxies, we have attempted to determine whether the configurations of galaxies in the sample of triple systems are correlated or, on the contrary, can be explained by random configurations.

For this purpose we consider blue and red triplet members ($(M_g - M_r) \leq 0.75$ and $(M_g - M_r) > 0.75$, respectively), star-forming and non-star-forming galaxies ($\log \mathrm{SFR}/M_* \geq -10.75$ and $\log \mathrm{SFR}/M_* < -10.75$) and galaxies dominated by young and old stellar populations ($D_n(4000) \leq 1.6$ and $D_n(4000) > 1.6$, respectively).

Next, we compute the number of systems that satisfy independently the following combinations of galaxy properties:

(i) (1a): three blue galaxies;
(ii) (1b): three star-forming galaxies;
(iii) (1c): three young stellar population galaxies;
(iv) (2a): three red galaxies;
(v) (2b): three non-star-forming galaxies;
(vi) (2c): three old stellar population galaxies.

We found six triples with combination (1a), hereafter blue triplets. These blue triplets also satisfy combinations (1b) and (1c). There are 36 triplets with combination (2a), hereafter red triplets. Out of these red systems, 32 belong to combination (2b) and 29 to (2c).

In order to assess the probability that the actual number of triplets satisfying a given combination of member properties could be obtained from a random sampling, we use a bootstrap technique. Thus, we generate 1000 random triplet catalogues by a random reassignment of the galaxies from the total sample, and for each realization we calculate the number of random triplets that satisfy the different combinations described above. This procedure allows us to obtain the expected number of systems that would have these combinations by chance, and therefore assess the correlation of triplet member properties.

Fig. 4 shows the distribution of the number of systems that satisfy the combinations of galaxy properties described above from the random triplet sample. If the combination of galaxy properties of the real triplet sample were at random, the most probable number of systems verifying the combinations (1a) is 1 and for (1b) and (1c) is 2. For the combination (2a) the mean of the distribution is 30 and for (2b) and (2c) is 23.

We calculate the probability that the number of triplets satisfying each combination can be derived by a random sampling as $p = N_{\mathrm{rec}}/N_{\mathrm{t}}$, where N_{rec} is the number of times that the actual value is obtained in $N_{\mathrm{t}} = 1000$ trials.

We find that the probability of random occurrence of six systems satisfying combinations (1a) is 0.1 per cent; for the combination (1b) 1.1 per cent and for (1c) 1.4 per cent. The probability of

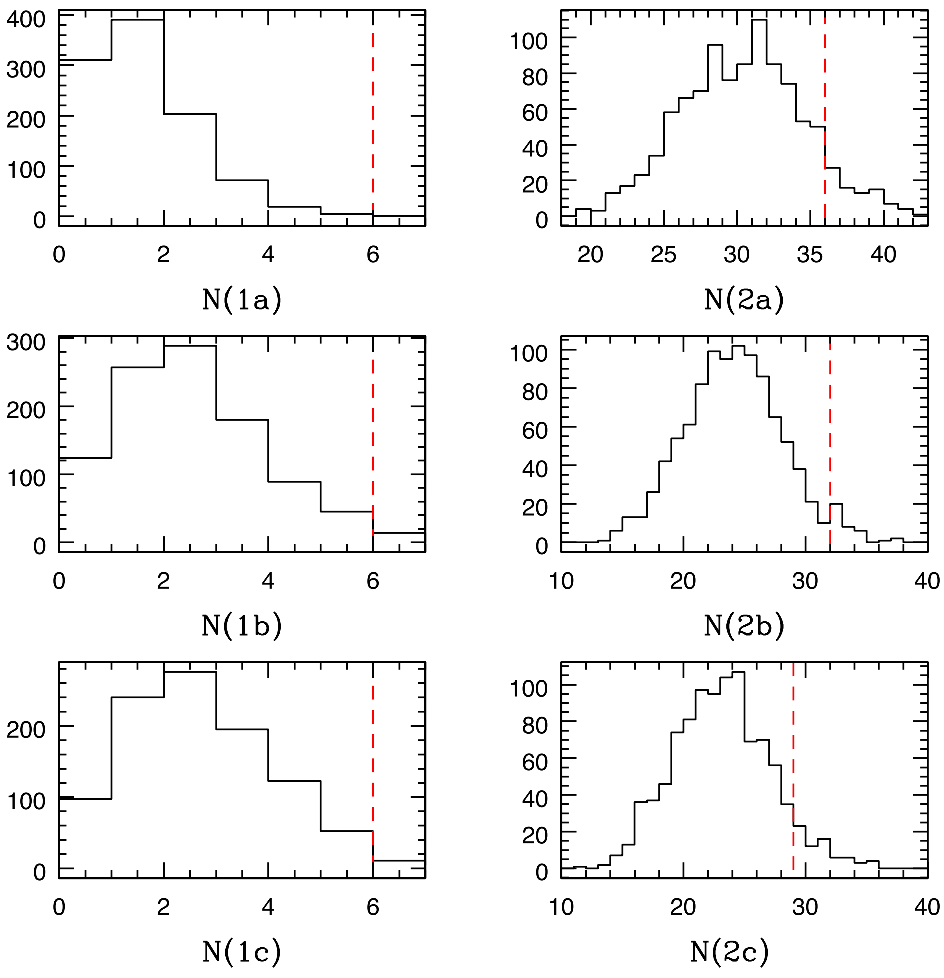

Figure 4. Distribution of the number of systems that verify combinations (1a) (left-hand upper panel), (1b) (left-hand middle panel), (1c) (left-hand bottom panel), (2a) (right-hand upper panel), (2b) (right-hand middle panel) and (2c) (right-hand bottom panel) for 1000 triplet random samples. Vertical dashed red lines correspond to the actual values for the real triplet sample.

Table 2. Combination name, actual number of triples satisfying each combination and the probability p of these combinations computed using bootstrap resampling techniques.

Combination	Number of triplets	Probability
(1a)	6	0.1 per cent
(1b)	6	1.1 per cent
(1c)	6	1.4 per cent
(2a)	36	2.7 per cent
(2b)	32	2.3 per cent
(2c)	29	2 per cent

random occurrence of 36 systems satisfying combination (2a) is 2.7 per cent, that of 32 systems for combination (2b) is 2.3 per cent and for 29 systems with combination (2c) is 2 per cent. In Table 2 we summarize these numbers.

The results obtained from this analysis indicate that both blue triplets and red triplets have such a combination of galaxies that cannot be explained by a random reassignment of the galaxies. In particular, we conclude that systems comprising blue, star-forming, young stellar population galaxies have a high probability of being real systems and not a mere configuration of interloping galaxies. In support of this result, Hernández-Toledo et al. (2011) found that galaxy triplets are spiral rich systems populated mostly by late-type spirals with an excess of ~0.6 mag in the global blue luminosity in comparison to field galaxies.

4.2 Total stellar mass of the triplets and its influence on member properties

In the previous section we found that the galaxy configurations of triplets cannot be explained by a random sampling of the triplet galaxies. In particular there are six blue triplets that are comprised by blue, young stellar population and star-forming galaxies. In this section we investigate the dependence of triplet members properties on the total stellar mass of the system considering separately blue and red triplets and by comparison to the results from compact groups. This joint analysis of our results and those for compact groups is based on their similar stellar mass range, a fact that does not hold for pairs nor for clusters.

For the samples of triplets and compact groups described in Sections 2.1 and 2.2.1, we calculate the redshift of each system as the mean redshift of their member galaxies. We restrict our analysis to the redshift range of triplets and perform a KS test to the redshift distributions of triplets and compact groups. The value obtained for p is greater than 0.05 so we cannot reject the null hypothesis that the redshift of triplets and compact groups is drawn from the same distribution. The samples of triplets and compact groups used in this section comprise 71 and 163 systems, respectively, and we show in Fig. 5 the distributions of redshift and log Total $M_*/\mathrm{M}_\odot$ for these samples. It can be appreciated that compact groups have a higher stellar mass content than triplets. This is somewhat expected since triplets consist of three bright galaxies while compact groups are composed of more than four members. In our study, we have considered the total stellar mass range spanned by the triplet sample ($10.6 < \log$ Total $M_*/\mathrm{M}_\odot < 11.8$) and analyse the properties of galaxies as a function the total stellar mass content of the system.

The contours shown in Fig. 6 represent the properties of compact groups members and the points correspond to galaxies in triplets. We have considered separately blue triplets (light-blue filled triangles) and red triplets (red filled squares), as well as triplets that do not

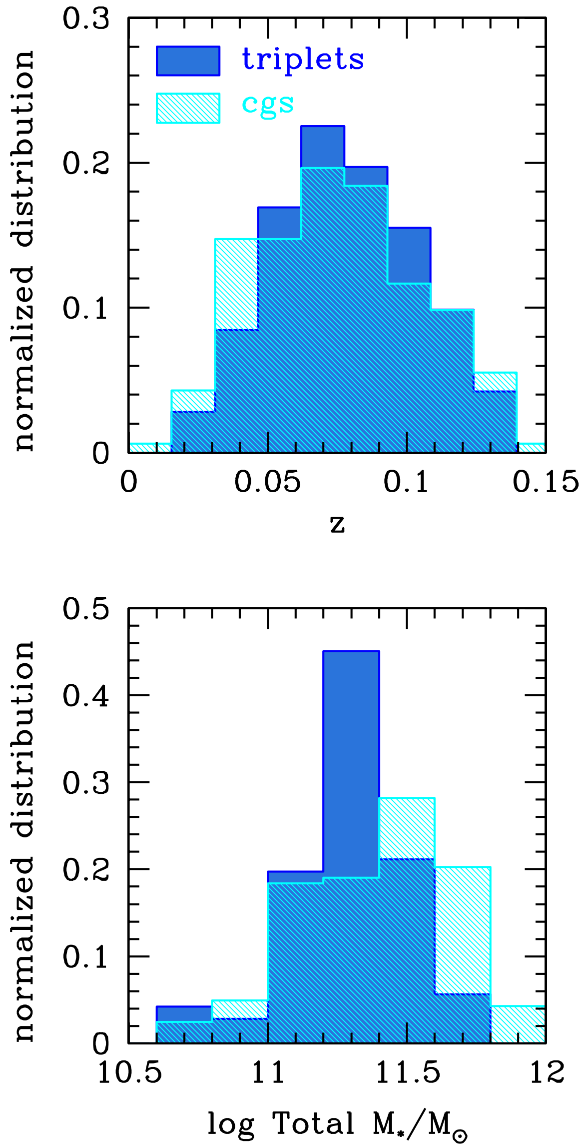

Figure 5. Distribution of redshift (top) and log Total $M_*/\mathrm{M}_\odot$ (bottom) for triplets and compact groups. KS test gives a $p > 0.05$ for the null hypothesis that the redshift of triplets and compact groups was drawn from the same distribution. (A colour version of this figure is available in the online journal.)

fulfil these categories (blue dots). The top, middle and bottom panel of this figure correspond to the SFR/M_*, the ($M_g - M_r$) colour index and the concentration index C,[3] respectively, as a function of the total stellar mass content. The C parameter is a suitable indicator of galaxy morphological type bimodality: early-type galaxies have $C > 2.6$ while later-type galaxies have typically $C < 2.6$ (Strateva et al. 2001).

It can be appreciated, as expected, that the compact groups tend to have a tail towards larger total stellar masses. Nevertheless, triplets and compact groups members present a similar behaviour. From this figure, we can also observe that blue triplets correspond to low total stellar mass systems. Galaxies in these triplets also show a higher star formation activity and lower values of the concentration index, C, corresponding to disc objects. On the other hand, galaxies

[3] $C = r_{90}/r_{50}$, where r_{90} and r_{50} are the radii containing 90 and 50 per cent of the Petrosian galaxy light.

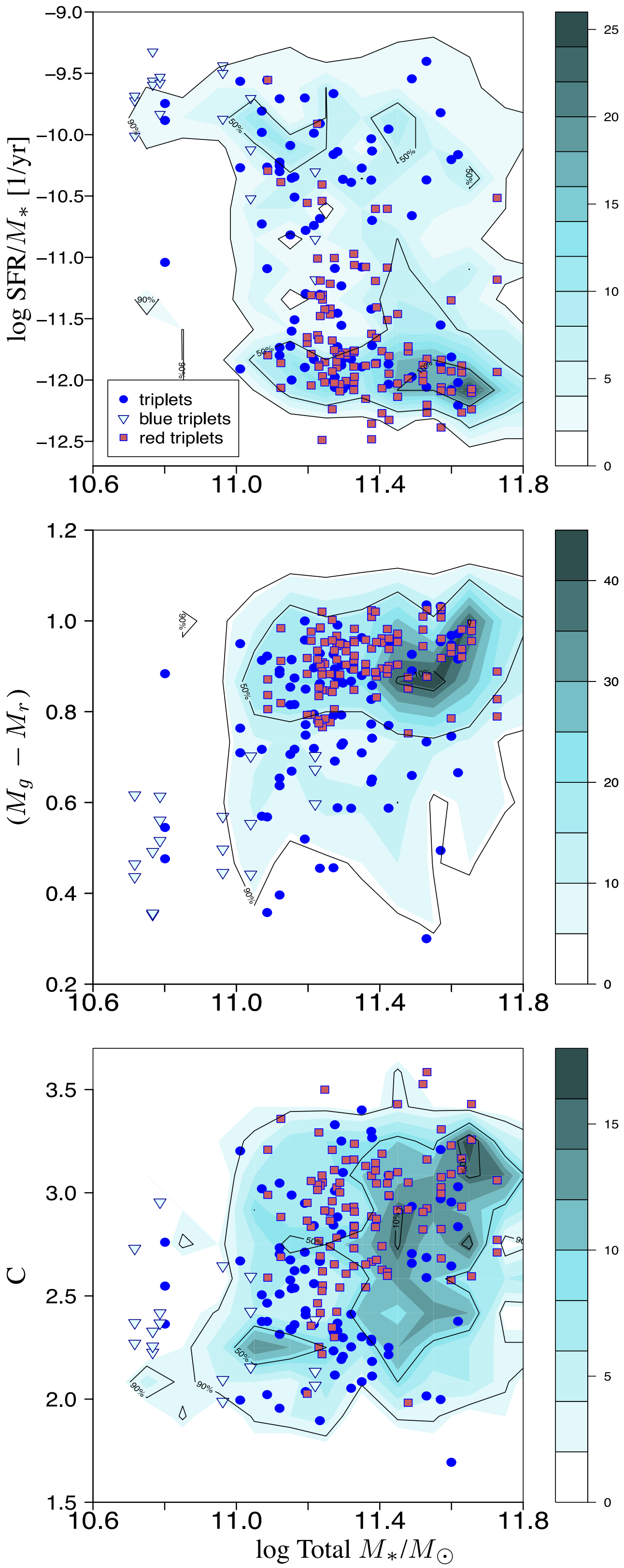

Figure 6. SFR/M_* (top), ($M_g - M_r$) colour index (middle) and concentration index C (bottom) as a function of total stellar mass. Filled contours represent compact group galaxies, in black contours we have plotted the levels comprising the 10, 50 and 90 per cent of the galaxies in this sample. The points correspond to triplet galaxies where we show blue and red triplets as defined in Section 4 (key in the figure). (A colour version of this figure is available in the online journal.)

in red triplets prefer higher total stellar mass systems and tend to be ellipticals with a low star formation efficiency.

4.3 Global properties of triplets

The dynamic of galaxy systems suggests that interactions are common in compact systems such as triplets and compact groups (Hernández-Toledo et al. 2011). Diaferio, Geller & Ramella (1994) performed dissipationless *N*-body simulations finding that compact configurations are continually replaced by new systems because within a single rich collapsing group, compact groups of galaxies form continuously. From the observational point of view, Väisänen et al. (2008) combined near-infrared imaging and optical spectroscopy with archival *Hubble Space Telescope* imaging and *Spitzer* imaging and spectroscopy, revealing that the luminous infrared galaxy (LIRG) IRAS 19115−2124 is actually a triple system where the LIRG phenomenon is dominated by the smallest of the components.

Since galaxies in triplets and compact groups may finally end in a single system, in this section we analyse different global properties of triplets of galaxies by considering the system as a whole. We will also perform the same analysis on compact groups in order to compare the results obtained for these systems. For this purpose we used the samples of triplets and compact groups defined in the previous section.

With the aim to complement the previous analysis, we also explore the dependence of the total SFR and total colour as a function of the total stellar mass of the systems. To measure the level of compactness of the systems, we have defined a geometric criteria in order to guarantee that the systems under analysis are not limited by the selection criterion commonly used in determining the system compactness. Radii of compact groups are defined by the Hickson criteria as the smallest circle that contains the geometric centres of compact group members. In order to define a homogeneous compactness criterion for triplets and compact groups we calculate the triplets minimum enclosing circle using the code of Hearn & Vijay (1982). Then we define the compactness S as

$$S = \frac{\sum_{i=1}^{N} r_{90}^2}{r_{\rm max}^2},$$

where r_{90} is the radius enclosing 90 per cent of the Petrosian flux of the galaxy in the r band, $r_{\rm max}$ is the minimum enclosing circle that contains the geometric centres of the galaxies in the system and N is the total number of members of the system. By definition, this quantity is a measure of the percentage of the system total area that is filled by the light of member galaxies.

Left-hand panels in Fig. 7 show the properties of the systems as a whole, as a function of the total stellar mass content. Here again, the contours represent the compact groups, and the points correspond to the triplets. Right-hand panels in this figure show the distribution of the total SFR, global ($M_g - M_r$) colour and compactness S for both samples.

As it was observed for individual galaxies, it can be seen that the blue triplets have a high total star formation activity and tend to be less massive systems. Red triplets are more massive objects and show a lower total SFR. From this figure it can also be appreciated that there is a correlation between the total SFR and total stellar mass for the triplets, while compact groups present an approximately constant trend. This is reflected in the total SFR distribution (right-hand upper panel): triplets are clearly bimodal, while the compact groups distribution is more consistent with a single population.

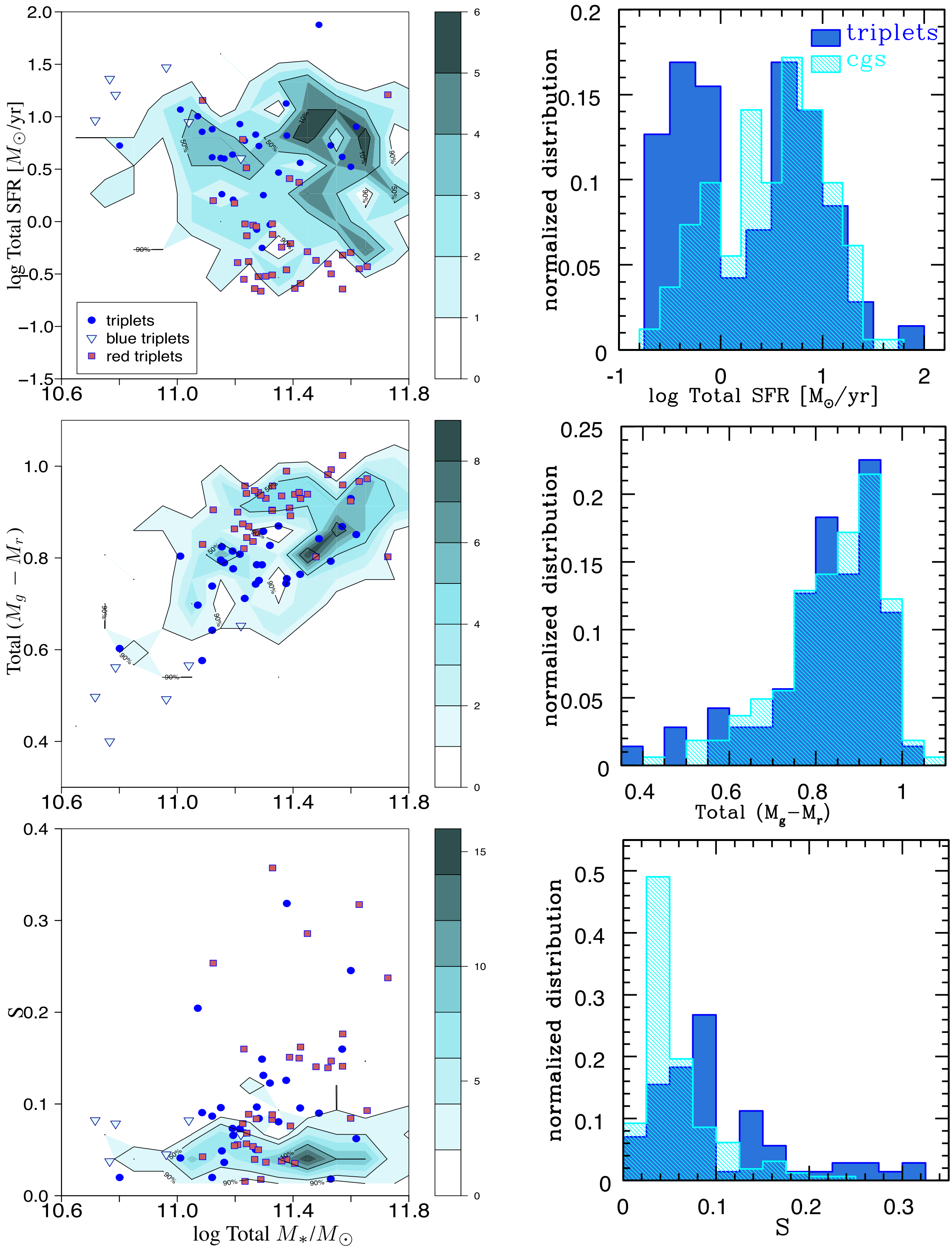

Figure 7. Left: total SFR (top), total $(M_g - M_r)$ colour index (middle) and compactness S (bottom) as a function of total stellar mass. Filled contours represent compact groups, in black contours we have plotted the levels comprising the 10, 50 and 90 per cent of the systems in this sample. The points indicate triplets, we have discriminated between blue and red triplets as defined in Section 4 (key in the figure). Right: total SFR (top), total $(M_g - M_r)$ colour index (middle) and compactness S (bottom) distribution for triplets and compact groups (see key in the figure). (A colour version of this figure is available in the online journal.)

Regarding total colour, there is a positive correlation with total stellar mass in both samples. As expected by its definition, blue triplets are located in the blue, low-mass tail of the distribution.

In the left-hand bottom panel of Fig. 7, we show the S parameter as a function of the total stellar mass. As can be appreciated, the compactness S of triplets increases towards high total stellar masses, and blue triplets tend to have less compact configurations. On the other hand, compact groups show a nearly constant trend. Besides, as seen in the right-hand bottom panel, it can be appreciated that the light in triplet systems is even more concentrated than in compact groups.

5 RESULTS AND DISCUSSIONS

We have studied 71 galaxy triplets in the redshift range $0.01 \leq z \leq 0.14$ with galaxy members brighter than $M_r < -20.5$. Our study also includes a comparative analysis of galaxies in compact groups, the 10 brightest members of rich clusters and pair galaxies. We also analyse the stellar mass content, the sSFRs, the spectral $D_n(4000)$ index and the $(M_g - M_r)$ colour index of member galaxies.

Galaxies in triplets show SFRs, colours and stellar populations comparable to those of galaxies in compact groups and clusters. This contrasts with pair galaxy members, which have systematically higher star formation activity indicators. Thus, we conclude that triplets cannot be considered as an extension of galaxy pairs with a third extra member.

With the aim of determining whether the configurations of galaxies in the sample of triple systems are strongly correlated or, on the contrary, can be explained by a random sampling, we generate 1000 random triplet catalogues by a random reassignment of the galaxies from the real sample. From this analysis we conclude that systems comprising three blue, star-forming, young stellar population galaxies (blue triplets) are most probably real systems and not a chance configuration of interloping galaxies. The same holds for triplets composed of three red, non-star-forming galaxies showing the correlation of galaxy properties in these systems.

Since triplets and compact group members may finally merge into a single system we have computed global parameters to provide a fair comparison of these systems as a whole. We have analysed different properties, such as total SFRs and total global colours, finding that, in general, triplets and compact groups exhibit a similar behaviour. Nevertheless we find that blue triplets, located in the less massive tail of the total stellar mass distribution, show an efficient total star formation activity with respect to compact groups which present low efficiency in forming new star generations, in the same total stellar mass range. In contrast, both high stellar mass red triplets and compact groups in the same stellar mass region show low total star formation activity.

In order to provide a compactness parameter of the triplets that can be suitably compared to the other systems, we have defined a parameter S as the sum of the areas comprising 90 per cent of the light of galaxies divided into the system minimal enclosing circle area. This quantity is a measure of the percentage of the system total area that is filled by the light of member galaxies. The distribution of this compactness parameter shows, surprisingly, that light is even more concentrated in triplets than in compact groups.

The results obtained in this work suggest that triplets composed of three luminous galaxies, have member with properties more similar to compact group members than to galaxies in pairs and that the behaviour of triplets as a whole is similar to compact groups. Based on the results presented in this work, we argue that triplets are a natural extension of compact groups to systems with lower number of galaxies.

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