Comparing galaxy populations in compact and loose groups of galaxies III. Effects of environment on star formation

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ABSTRACT

Aims. This paper is part of a series in which we perform a systematic comparison of the galaxy properties inhabiting compact groups, loose groups and the field. In this paper we focus our study to the age and the star formation in galaxies.

Methods. For galaxies in selected samples of compact groups, loose groups and field, we compare the distributions of the following parameters: D (4000) as an age indicator, and the specific star formation rate as indicator of ongoing star formation. We analyse the dependence of these parameters on galaxy type, stellar mass and, for group galaxies, their dependence on the dynamic state of the system. We also analyse the fraction of old, and of high star forming galaxies as a function of galaxy stellar mass in the environments we probe.

Results. Galaxies in compact groups have, on average, older stellar populations than their loose group or field counterparts. Early-type galaxies in compact groups formed their stars and depleted their gas content more rapidly than in the other environments. We have found evidence of two populations of late-type galaxies in dynamically old compact groups: one with normal specific star formation rates and another with markedly reduced star formation.

Conclusions. Processes that transform galaxies from star forming to quiescent act upon galaxies faster and more effectively in compact groups. The unique characteristics of compact groups make them an extreme environment for galaxies, where the transition to quiescence occurs rapidly.

Key words. Galaxies: groups: general – galaxies: fundamental parameters – galaxies: evolution

1. Introduction

One of the major challenges of the modern astrophysics is to determine when and where stars form. The well known morphology-density relation [Dressler 1978, Dressler 1980] clearly indicates that the environment plays a fundamental role in the evolution of galaxies. Moreover, it has been suggested by Kauffmann et al. (2003a) that the galaxy property most sensitive to environment is the star formation rate by unit mass (specific star formation rate, SSFR). These authors found that galaxies with low stellar masses, show a decrease of the SSFR by more than a factor of 10 from low to high density. This decrease is less marked for high-mass galaxies. Models of galaxy formation tend to reproduce the dependence of the star formation rate, SFR, with the local density, nevertheless, they fail to reproduce the fraction of quiescent galaxies. Hirschmann et al. (2014) found that models slightly under-estimate the quiescent fraction of central galaxies and significantly over-estimate that of satellite galaxies.

Although the local density can be a suitable way of representing the environment, similar values of local density can be found in regions with different physical conditions for both, the dynamics of galaxies and the intergalactic medium. A good example of this situation are compact groups (CGs) and the core of rich clusters of galaxies. These two environments may have similar local density but very different velocity dispersion and gas temperature. On the other hand, similar velocity dispersion can be found in environments with very different local density, as is the case of CGs and loose groups (LGs). Therefore, the comparative study of the galaxy properties in different types of systems of galaxies has become a powerful tool to understand the effects of the environment in galaxy evolution. These analyses have been benefited by the large-scale galaxy surveys, such as the Sloan Digital Sky Survey (SDSS, York et al. 2000) that have allowed the identification of thousands of groups, CGs and clusters of galaxies.

In Coenda et al. (2012) (hereafter paper I) and Martínez et al. (2013) (hereafter paper II) we performed a detailed comparison between the properties of galaxies in compact and loose groups. In paper I, we found that the fraction of red and early-type galaxies is larger in CGs. Our results suggest that galaxies in CGs are, on average, systematically smaller in size, more concentrated, and have higher surface brightness than galaxies in the field or in LGs. In Paper II we compared the properties of the brightest group galaxy (BCGs) and found that BCGs in CGs are brighter, more massive, larger, redder and more frequently classified as elliptical. We concluded that galaxies inhabiting CGs have undergone a major transformation compared to galaxies that inhabit LGs.

Traces of the different paths in the evolution of galaxies can be found in terms of differences in the ages of the stellar populations. Proctor et al. (2004) and Mendes de Oliveira et al. (2005) compared the ages of galaxies in CGs and in other dense environments and found that galaxies in CGs tend to be older. The high density and low velocity dispersion in the CG environment set up the ideal conditions for gravitational interactions and, eventually, a favourable scenario for the truncation of the star formation. de la Rosa et al. (2007) found evidences of star
show lower SSFR values, while late-type spirals peak at higher values compared with their counterparts in isolation and support the scenario where galaxies in CGs have evolved more rapidly than isolated galaxies.

It has been suggested that the large scale structure can also affect the evolution of galaxies. Scudder et al. (2012) compared the galaxy properties in a sample of CGs that they further split by the large scale environment into isolated and embedded subsamples. They found that the SFR of star forming galaxies in CGs are significantly different between isolated and embedded systems, being higher in the first environment.

The galaxy properties in LGs have been extensively studied and it has been shown that the group environment is also efficient in quenching the star formation (e.g. Martínez et al. 2002; Bai et al. 2010; Wetzel et al. 2011; McGee et al. 2011; Rasmussen et al. 2012; Wetzel et al. 2013). Wetzel et al. 2013 studied the quenching timescale of satellite galaxies and found that the SFR in groups evolve unaffected for 2-4 Gyrs after the infall, and then, the star formation quenches rapidly. Similar timescales have been estimated by McGee et al. (2011).

It becomes clear that both loose and compact groups are efficient in quenching the star formation in galaxies, nevertheless it is not yet clear how the compactness differences moderate or increase the quenching process. As it was done in Papers I and II we propose a systematic comparison between the properties of galaxies in compact and loose groups and field galaxies. In this paper we focus on the star formation rate and the age of galaxies. For this purpose we use the MPA-JHU DR7 release of spectra measurements (http://www.mpa-garching.mpg.de/SDSS/DR7/). Using line fluxes, continuum indexes, line widths, etc. the MPA-JHU catalogue provides stellar masses (Kauffmann et al. 2003a), star formation rate (Brinchmann et al. 2004) and gas-phase metallicity (Tremonti et al. 2004) for the the Main Galaxy Sample (MGS, Strauss et al. 2002) of the Seventh Data Release of the SDSS (DR7, Abazajian et al. 2009). This paper is organised as follows: in section 2 we describe the samples of groups and galaxies used; in section 3 we perform comparative studies of the galaxy populations in CGs, LGs and the field; finally, our results are summarised and discussed in section 4. Throughout the paper, a flat cosmological model is assumed, with parameters $\Omega_0 = 0.3$, $\Omega_m = 0.7$, and a Hubble’s constant $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$. All magnitudes were corrected for Galactic extinction using the maps by Schlegel et al. (1998) and are in the AB system. Absolute magnitudes and galaxy colours were $K$–corrected using the method of Blanton et al. (2003) (KCORRECT version 4.1).

2. The samples

2.1. The sample of compact and loose groups

The samples of compact and loose groups of galaxies used in this paper have been constructed from the same group catalogues used in Paper I and following the same selection criteria.

The sample of compact groups is drawn from catalogue A of McConnachie et al. (2009), who used the original selection criteria of Hickson (1982) to identify compact groups in the sixth data release of the SDSS (Adelman-McCarthy et al. 2008). The catalogue A has 2,297 groups, adding up to 9,713 galaxies, down to a Petrosian magnitude of $r = 18$, and has spectroscopic information for 4,131 galaxies (43% completeness). In this work, we select all groups in the A catalogue within the redshift range $0.06 \leq z \leq 0.18$, which have spectroscopic redshift for at least one member galaxy that have a coun-
Fig. 2. Distributions of \( D_n(4000) \) parameter in our samples. Left panels include early-type galaxies according to their concentration parameter, while right panels include late-type galaxies in our samples. Panels (a) and (b) show all galaxies in the samples, panels (c) and (d) galaxies in groups with \( ETF \geq 70\% \), while panels (f) and (g) galaxies in groups with \( ETF < 70\% \). All distributions have been normalised to have the same area. Below each panel we show the residuals between the CGs and the other distributions. The bin size is 0.14. Based on KS tests, we find there is no pair of them drawn from the same underlying distribution. Line types as in Fig. 1.

The authors computed group virial masses from the virial radius of the systems and the velocity dispersion of member galaxies (Limber & Mathews 1960; Beers et al. 1990). The sample of ZM11 comprises 15961 groups with more than 4 members, adding up to 103342 galaxies. As in Paper I, we split the sample of loose groups into two subsamples of low, \( \log(M_{vir}/M_\odot h^{-1}) \leq 13.2 \), and high, \( \log(M_{vir}/M_\odot h^{-1}) \geq 13.6 \) virial mass. This choice excludes about 30% of the groups in ZM11, those of intermediate virial mass, that is within 0.2 dex of the median virial mass of the ZM11 catalogue at \( \log(M_{vir}/M_\odot h^{-1}) \sim 13.4 \). Analogously to Paper I, in order to perform a fair comparison between the galaxies of CGs and LGs, we use a Monte Carlo algorithm to randomly select groups from these two subsamples. These new subsamples of low and high mass LGs have similar redshift distributions to that of the CGs. Our final subsamples of low and high mass LGs include 2319 and 2352 systems, adding up to 6996 and 7055 galaxies, respectively.

The samples of groups and galaxies used in this study are not exactly the same as in Paper I because here we restrict our analyses to galaxies which have data from the MPA-JHU DR7. This means that not all the galaxies we used in Paper I are included now, which in turn, implies that about 9% of the compact groups in Paper I are now ruled out since they have not a single galaxy with MPA-JHU DR7 data. The exclusion of these compact groups determines minor changes in the loose group samples which are bound to have redshift distributions similar to that of the compact groups.

We refer the reader to Paper I for further details.

2.2. The galaxy sample

The MPA-JHU data contains the derived galaxy properties from the emission line analysis for the DR7 of the SDSS. The catalogue provides stellar masses based on fits to the photometry following Kauffmann et al. (2003a) and Salim et al. (2007), star formation rates based on Brinchmann et al. (2004) and gas phase metallicity following Tremonti et al. (2004). The MPA-JHU data is based on a re-analysis of the spectra in order to take more care in the extraction of emission line fluxes than is done in the general purpose SDSS pipeline. The MPA-JHU also provides the index \( D_n(4000) \) based on the denition from Balogh et al. (1998). The \( D_n(4000) \) index is a good indicator of the stellar population age. For composite galaxies (up to 40 per cent of their H\(_\alpha\) luminosity come from AGN), the MPA-JHU data use the \( D_n(4000) \) to estimate the SSFR. The parameters considered in our analysis are the stellar mass, the \( D_n(4000) \) index and the SSFR. Average uncertainties in these quantities are: 0.13 dex, 0.5 and 0.5 dex, respectively.

As in Paper I, we compare the properties of galaxies in CGs and LGs with the properties of field galaxies. We consider as field galaxies to all DR7 MGS galaxies that were not identified as belonging to LGs by ZM11 groups or to CGs by McConnachie et al. (2009), and have apparent magnitudes \( 14.5 \leq r \leq 17.77 \). For an adequate comparison with our samples of galaxies in groups, we use the same Monte Carlo algorithm of the previous subsection to construct a sample of field galaxies that has a similar redshift distribution as that of galaxies in our CG sample. This field sample includes 200102 galaxies.
3. Comparing properties of galaxies: stellar mass, Specific Star Formation Rate and $D_n(4000)$

Analogously to Paper I, we classify galaxies into early and late types according to their concentration index. Typically, early-type galaxies have $C \geq 2.5$, while for late-types $C < 2.5$ (Strateva et al. 2001). In this paper we compare properties of galaxies in samples drawn from an apparent magnitude limited catalogue. Given a quantity bin, galaxies in it will have a range of absolute magnitudes and therefore a range of volume over which they could be detected in SDSS. In order to compensate for this, hereafter we weight galaxy properties by using the $1/V_{\text{max}}$ method (Schmidt 1968), determining the maximum volume $V_{\text{max}}$ for which each galaxy could have been found.

We compare the normalised distributions of the stellar mass of galaxies in CGs and LGs and no differences are found, while field galaxies are slightly less massive than galaxies in other environments. We do not attempt to analyse the distributions of the metallicity because only ~12% of galaxies in CGs have measured metallicity.

3.1. Environment vs. $D_n(4000)$

Fig. 1 compares the normalised distributions of the $D_n(4000)$ index for galaxies in CGs with LG and field galaxies. Below each panel of Fig. 1 we show the residuals between the distributions, i.e., for the property $X$, the difference $\Delta F(X) = f_{\text{CG}}(X) - f(X)$, where $f_{\text{CG}}(X)$ and $f(X)$ are the fractions of galaxies in the bin centred on $X$ in the CGs and in the other sample, respectively. Kolmogorov-Smirnov tests (KS) confirm that, among the distributions shown, there is no pair of them drawn from the same underlying distribution. As can be seen from Fig. 1 the stellar populations in galaxies in CGs tend to be older than in field or LG galaxies. We find no difference between low or high mass LGs. CGs contain an excess of galaxies with $D_n(4000) \geq 1.75$ and a deficit with $D_n(4000) \leq 1.75$. The stellar populations in field galaxies are the youngest. Our results agree with the comparison of CGs and field galaxies by Proctor et al. (2004), Mendes de Oliveira et al. (2005) and de la Rosa et al. (2007).

We compare in Fig. 2 the normalised distributions of the $D_n(4000)$ index of late (right panels) and early-type galaxies (left panels). In this figure, we also analyse separately groups with a large ($\geq 70\%$) fraction of early-type galaxies (ETF) (central panels), and groups with a lower ETF (bottom panels). As pointed out by Bitsakis et al. (2010), if a group is dominated by early-type galaxies, it is more likely to be dynamically old, because interactions and mergers have had to occur in order to produce those galaxies. Conversely, groups not dominated by early-types, could be considered as dynamically young since some of their galaxies may have been gravitationally interacting for the first time. Thus, we use the ETF as an indication of group age. In the computation of the ETF we use all galaxies available in the CG catalogue, not only those that have spectroscopic data. In all panels of Fig. 2 it is clear that both, early and late-type galaxies in CGs tend to have older stellar populations than in the other environments. The most significant result from this figure is that when we consider groups with large ETF: on the one hand, the stellar populations in early-type galaxies in both CGs and LGs have similar ages (panel c), on the other hand, the stellar populations in late-type galaxies in CGs are on average much older than in LGs (panel d). This is in agreement with previous findings as Bitsakis et al. (2010, 2011).

Given that galaxy properties strongly depend on stellar mass (Kauffmann et al. 2003), we explore the dependence of the $D_n(4000)$ on stellar mass. Fig. 3 shows in its left panel the fraction of galaxies with $D_n(4000) \geq 1.6$ as a function of stellar mass, and in its central and right panels, the corresponding fractions for early and late-type galaxies, respectively. We use the criteria of Tinker et al. (2011) to separate between galaxies with old and young stellar populations. In particular, galaxies with $D_n(4000) \geq 1.6$ have old stellar populations. This criteria has been used by other authors (Geha et al. 2012, Krause et al. 2013). Over the whole range of stellar mass the fraction of galaxies with old stellar populations increases with mass and is larger.
moving from the field to massive LGs. Galaxies in CGs, however, show differences. For stellar masses below \( \log(M_\star/M_\odot) \sim 10.5 \), their stellar populations are the oldest irrespective of their type. On the other hand, for higher stellar masses, the CG environment cannot be distinguished from LGs whether we consider all galaxies or just the early-types. The fraction of late-types with old stellar populations is consistent with field values, or it is marginally smaller, for masses \( \log(M_\star/M_\odot) \gtrsim 10.8 \). This could be an indication that an important fraction of massive late-type galaxies in CGs have undergone important episodes of relatively recent star formation.

3.2. Environment vs. SSFR

Fig. 4 shows the distributions of the SSFR for our different samples of galaxies. SSFR values show a clear bimodality, more markedly on LGs, but still present in the field and in CGs. Clearly, the population of field galaxies is dominated by galaxies with \( \log(\text{SSFR}/\text{yr}^{-1}) > -11 \), and the opposite is seen in CGs. LGs show an intermediate behaviour and a more clear bimodality (e.g. Wetzel et al. 2011).

In Fig. 4 we split the galaxy samples into early and late-types and also distinguish whether the galaxies inhabit groups with \( \text{ETF} \geq 70\% \) or lesser. As expected, the bimodality seen in Fig. 4 can be explained in terms of early and late-type galaxies. It is also clear that both, early and late-types in CGs have lower values of SSFR compared to LG and even lower when compared to field galaxies. Of particular interest is panel (d): here we find a marked bimodality in the SSFR of late-type galaxies in CGs with \( \text{ETF} \geq 70\% \), i.e., two populations of late-type galaxies similar in numbers, one with ‘normal’ star formation and another with quenched star formation, both of them inhabiting old CGs. A bimodality in the distribution of the SSFR in CGs galaxies has been reported previously by Johnson et al. (2007), Tzanavaris et al. 2010, Walker et al. (2012), Bitsakis et al. (2010, 2011).

We further explore the SSFR of galaxies in Fig. 6 where we show the fraction of galaxies with high SSFR (\( \log(\text{SSFR}/\text{yr}^{-1}) \gtrsim -11 \)) as a function of stellar mass. Field and LG galaxies have smooth, featureless, decreasing trends with stellar mass, over the whole mass range. At fixed mass, the fraction of star forming galaxies is larger in the field, followed by low mass LGs and high mass LGs. Regarding CGs, for masses below \( \log(M_\star/M_\odot) \sim 10.5 \), the fraction of star forming galaxies is lower than in the other environments (left panel). This is also
true for late-type galaxies (right panel). For higher masses, CGs are not distinguishable from LGs, considering the whole population or just the early-types (central panel). This is not the case, however, of the fraction of star forming late-types. It is consistent with, though even marginally higher than, the field value. All trends observed in this figure are in agreement with Fig. 3.

In the light of Figs. 5 (panel (d)) and 6 we further explore the SSFR of late-type galaxies in Fig. 7. In this figure we split galaxies not only as whether they are in large ETF groups but also distinguishing galaxies with \( \log(M_*/M_\odot) \geq 10.5 \) or lower. The strong gap in the SSFR is seen only in CGs, it is clearly present in galaxies inhabiting large ETF groups for both stellar mass ranges. The gap is particularly strong for massive late type galaxies. This further suggests that the high-density, low-velocity dispersion environment of CGs has accelerated the transition of galaxies from star forming to quiescent. Similar results have been reported by [Tzanavaris et al. (2010)] and [Plauchu-Frayn et al. (2012)].

4. Conclusions and Discussion

We study the specific star formation rate and ages of galaxies in compact groups, loose groups and in the field in the redshift range \( 0.06 < z < 0.18 \). We select samples of galaxies in CGs drawn from [McConnachie et al. (2009)] and in LGs taken from ZM11. We construct two samples of LG: low \( \log(M_*/M_\odot) \leq 13.2 \) and high \( \log(M_*/M_\odot) \geq 13.6 \) virial mass, both samples bound to have similar redshift distribution as the CG sample. Similarly, our sample of field galaxies was drawn to reproduce the redshift distribution of CGs. Galaxy properties used in our work were taken from the MGS sample of the SDSS DR7 and the MPA-JHU DR7 release. The final samples have 748, 2319, 2352 of compact, low-mass, high-mass loose groups respectively. The corresponding number of member galaxies are: 978, 6996 and 7055. The field sample comprises 200102 galaxies.

We classify galaxies into early and late-types according to their concentration index. Following [Bitsakis et al. (2011)], we distinguish groups of galaxies as dynamically old or dynamically young. A group is classified as dynamically old if more than 70% of its galaxies are early-types, or as dynamically young if otherwise. We find that the stellar populations in galaxies in CGs are, on average, older than in LGs or in the field. This agrees with [Proctor et al. (2004), Mendes de Oliveira et al. (2005), de la Rosa et al. (2007)] and [Plauchu-Frayn et al. (2012)]. The stellar populations in late-type galaxies in CGs are on average, much older than in LGs. This is in agreement with [Bitsakis et al. (2010, 2011)]. For stellar masses \( \log(M_*/M_\odot) \leq 10.5 \), both, the stellar populations of early and late-types in CGs are older than in the other environments. For higher stellar masses, in early-types in CGs the stellar populations have ages similar to their LGs counterparts, and in late-types in CGs are of similar age to field galaxies, or even younger.

The distribution of SSFR is clearly bimodal, more markedly in LGs but still present in CGs and in the field. This bimodality has been reported in LGs by [Wetzel et al. (2011)] and by [Johnson et al. (2007), Tzanavaris et al. (2010), Bitsakis et al. (2010, 2011) and Walker et al. (2012)] in CGs. The bimodal distribution can be explained in terms of two galaxy populations: early and late-types.

Early and late-type galaxies in CGs have, on average, lower SSFR values than in LGs and the field. For \( \log(M_*/M_\odot) \leq 10.5 \), CGs have the lowest fraction of star forming galaxies irrespective of galaxy type. For higher masses, the fraction of star forming early-types in CGs is comparable to LGs, and the fraction of star forming late-types in CGs is consistent with, or even higher than, the field. The distribution of SSFR for late-type galaxies in CGs shows a bimodality, with a strong gap for groups dynamically old. No such gap is found in any of the other environments.

Our findings suggest that, compared to the other environments, early-type galaxies in CGs have formed their stars and depleted their gas content more rapidly. This is an indication that these galaxies have had more frequent mergers and multiple past interactions, which is something expected within an environment characterised by its high density and its low velocity dispersion.

For late-type galaxies in dynamically old CGs, we have found evidence of two populations of galaxies regarding their SSFR. One population of late-types have 'normal' SSFR and they are forming stars, while the other population shows lower values of SSFR. Star forming late-types in CGs may be recent acquisitions. By falling into CGs, these galaxies increase their
star formation and rapidly consume their gas. Further gas depletion and subsequent star formation quenching may be accounted for through merger events.

It is well known that groups of galaxies play a central role in accelerating galaxy evolution by enhancing star formation process and leading a transition to quiescence. The results of this series of papers, point out to the fact that compact groups are clearly more efficient than loose groups in transforming galaxies. It is clear that the unique characteristics of compact groups, namely, their high spatial density and low velocity dispersion, makes them one of the most extreme environments for galaxies, an environment where the transition from star forming to quiescence takes place in particularly short time scales.

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Fig. 6. Fraction of star forming galaxies according to their star formation rate (log(SFR)$\geq -11$) as a function of the stellar mass. Vertical error-bars are obtained by using the bootstrap resampling technique. Left panel considers the whole samples of galaxies, central panel the early-type galaxies, while right panel late-types. The binsizes in stellar mass are 0.5 dex for LGs, 0.4 dex for CGs and 0.3 dex for the field. Abscissas are the medians of the mass within each bin. Bins with lesser than 10 galaxies were excluded. Symbols and lines types as in Fig. 4.