Groups of galaxies: relationship between environment and galaxy properties

Héctor J. Martínez1* and Hernán Muriel2

1Grupo de Investigaciones en Astronomía Teórica y Experimental, IATE, Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, X5000BGR Córdoba, Argentina
2Consejo de Investigaciones Científicas y Técnicas (CONICET), Avenida Rivadavia 1917, C1033AAJ Buenos Aires, Argentina

ABSTRACT

We analyse how the properties of galaxies in groups identified in the Sloan Digital Sky Survey depend on the environment. In particular, we study the relationship between galaxy properties and group mass and group-centric distance. Among the galaxy properties we have considered here, we find that the $g-r$ colour is the most predictive parameter for group mass, while the most predictive pair of properties are $g-r$ colour and $r$-band absolute magnitude. Regarding the position inside the systems, the $g-r$ colour is the best tracer of group-centric distance and the most predictive pair of properties are $g-r$ colour and spectral type taken together. These results remain unchanged when a subsample of high-mass groups is analysed. The same happens if the brightest group galaxies are excluded.

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

1 INTRODUCTION

It is well known that galaxy properties correlate with the environment, for example, the morphology–density relation (Dressler 1980), star formation–density relation (Gómez et al. 2003). Nevertheless, the detailed joint distribution of these properties as a function of the galaxy clustering remains unclear. As all the galaxy properties (e.g. morphology, luminosity and colour) are correlated it is not surprising that all properties correlate with environment, but the question that arises is which of the properties are correlated to environment independently of the others. In a recent paper, Blanton et al. (2005) systematically explore the local environment of galaxies in the Sloan Digital Sky Survey (SDSS; York et al. 2000), as a function of their luminosity, surface brightness, colour and Sérsic index. These authors find that colour is the galaxy property most predictive of the local environment for field galaxies. They also analyse pairs of properties taken together, finding that galaxy colour and luminosity jointly comprise the most predictive one.

While clusters of galaxies have been intensively studied over the last decades, detailed studies of galaxy groups and their evolution have only recently begun. The study of the properties of galaxies in intermediate mass systems is particularly important to understand how galaxies evolve and how different physical mechanisms affect them. In particular, galaxy interactions are expected to be more common in groups than in clusters. In groups, velocity dispersions are typically not much larger than that of the member galaxies. It has been argued that the high fraction of early-type galaxies in clusters is mainly the result of galaxy–galaxy interactions within groups (Zabludoff & Mulchaey 1998 2000; Hashimoto & Oemler 2000).

Martínez et al. (2002) showed how the fraction of star-forming galaxies goes down as a function of group mass. Domínguez et al. (2002) found a similar trend with decreasing group-centric distance. It is well known that there are correlations between different galaxy properties. Therefore, the observed trend of increasing fraction of non-star forming galaxies (a spectroscopic property) with group mass, implies a similar relation between the fraction of red galaxies (a photometric property) or the fraction of bulge-dominated galaxies (a morphological property) with group mass. In this work, we address the following questions: ‘which galaxy properties are more tightly correlated with group mass?’ and ‘which galaxy properties are more affected by the position inside a group?’ This paper is organized as follows. In Section 2, we describe the sample of galaxies in groups we use; while the analysis of the dependence of galaxy properties on mass and on the group-centric distance are carried out in Sections 3 and 4, respectively. We summarize our results and discuss them in Section 5.

2 THE SAMPLE OF GALAXIES IN GROUPS

The sample of galaxies in groups used in this paper has been taken from the group catalogue identified by Zandivarez, Martínez & Merchán (2006). This catalogue was constructed from the main galaxy sample (MGS; Strauss et al. 2002) of the Fourth Data Release of the SDSS (DR4; Adelman-McCarthy et al. 2006) following...
the same procedure as in Mercháñ & Zandivarez (2005). It consists of a standard friend-of-friend algorithm for group identification, the application of a procedure to avoid artificial merging of smaller systems in high-density regions and an iterative method to compute reliable group centre positions. The catalogue, in its improved identification version, includes 14004 galaxy groups with at least four members in the area spectroscopically surveyed by DR4, accounting for a total of 85687 galaxies.

We have chosen to work with volume-limited samples of galaxies instead of using flux-limited ones and individual galaxy weights according to their luminosities. We find that the results are more robust in a volume-limited sample. In a magnitude-limited sample, the galaxy population observed in the nearest groups is significantly different than that observed for the most distant ones. Something similar happens with the groups’ parameters. Therefore, observational effects such as seeing that affect certain galaxy parameters can introduce systematic effects in our statistics. In Section 3, we present some tests in order to evaluate the reliability of the results. We have restricted our analysis to galaxies in groups down to $M_r - 5 \log(h) = -18$ and up to a conservative maximum redshift of $z_{\text{max}} = 0.043$, that gives a volume-limited sample according to the selection criteria of the MGS. Another relevant reason to choose a small value for $z_{\text{max}}$ is related to two of the galaxy parameters we are considering in our analysis: the concentration parameter, defined as the ratio of the radii that enclose 90 and 50 per cent of the Petrosian flux and the surface brightness that involves the latter. Seeing affects the determination of those radii, and this becomes more important for more distant galaxies that have smaller angular size. Our sample consists of 6183 $[M_r - 5 \log(h)]$ galaxies in 1691 groups. From this sample, we construct a number of subsamples of galaxies defined by group virial mass and number of members that are detailed in the analysis sections. Throughout this work, we use the virial mass and virial radius of groups computed by Zandivarez et al. (2006). Therefore, when we refer to ‘group mass’, it should be remembered that we are dealing with ‘group virial mass’. The mass distribution for our sample of groups is shown in the lower right-hand panel of Fig. 1.

## 2.1 Galaxy parameters

The SDSS provides several photometric and spectroscopic parameters of the surveyed galaxies. Among the available data for each object in DR4, we have used in our analyses parameters that are related to different physical properties of the galaxies: luminosity, star formation rate, light distribution inside the galaxies and the dominant stellar populations. The galaxy parameters we have focused our study on are as follows.

(i) $r$-band absolute magnitude, $M_r$.

(ii) $g-r$ colour.

(iii) The monoparametric spectral classification based on the eigentemplates expansion of galaxy’s spectrum $e\text{class} = \text{atan}(\text{ecoef } f_2/\text{ecoef } f_1)$. This parameter ranges from about $-0.35$ for early-type galaxies to 0.5 for late-type galaxies. The galaxy spectral classification eigentemplates were created from a sample of about 200000 spectra. The eigenspectra are an early version of those created by Yip et al. (2004).

(iv) $r$-band surface brightness, $\mu_r$, computed inside the radius that encloses 50 per cent of Petrosian flux, $r_{50}$.

(v) $r$-band concentration parameter defined as the ratio between the radii that enclose 90 and 50 per cent of the Petrosian flux, $C = r_{90}/r_{50}$.

Typically, early-type galaxies have $C > 2.5$, while for late-types $C < 2.5$ (Strateva et al. 2001).

We list in Table 1 the parameters cut-offs we have adopted for the present analyses, and in Fig. 1 we show the corresponding distributions for the galaxies in our sample.

| Property | Minimum value | Maximum value |
|----------|--------------|--------------|
| $M_r - 5 \log(h)$ | $-22$ | $-18$ |
| $(g-r)$ | $0.2$ | $0.9$ |
| $\mu_r$ | $19$ | $23$ |
| $e\text{class}$ | $-0.2$ | $0.4$ |
| $C = r_{90}/r_{50}$ | $1.8$ | $3.4$ |

$C = r_{90}/r_{50}$. Typically, early-type galaxies have $C > 2.5$, while for late-types $C < 2.5$ (Strateva et al. 2001).

### 3 Dependence of Galaxy Properties on Group Mass

In order to determine which galaxy properties are more correlated with the mass of the group where the galaxy is located, we have followed here the Blanton et al. (2005) approach. First, we consider the variance of the logarithm of the galaxy’s parent group mass, $\log(M)$:

$$\sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} [\log(M_i) - \bar{\log}(M)]^2,$$

where $\bar{\log}(M)$ is the average logarithm of the group mass.
Hence, \( \sigma_{eclass} \) taken together, closely followed by the pairs, the most predictive pair of properties is \( (\mu_r, g-r) \). The relation between group mass and colour shown in this figure is a special care must be taken regarding the possible presence of brightest group galaxies that may be by far the principal contributor to the group’s total luminosity. This could bias the results for high-mass groups where the brightest group galaxies are expected to be particularly bright. Therefore, we have redone the calculations excluding the brightest object in each group and found that the results hold.

We performed a number of tests to analyse the reliability of our results: restricting the samples by the number of galaxy members in the groups; splitting the samples into two roughly equal number subsamples according to different criteria such as the region in the sky according to their right ascension and into those that have an even (odd) identification number in the Zandivarez et al. (2006) catalogue. The results of these tests are summarized in Table 4. We observe that the ranking of single properties is stable, it is the same for all but for the subsample of high-mass groups with at least eight members, where there is an inversion between

\[
\log(M) = \frac{1}{N_j} \sum_{X_j \in \Delta X/2} \log(M_j)
\]

where \( \log(M) \) is the mean value of \( \log(M) \) for the \( n \) galaxies in the sample. Then, we measure the mean value of \( \log(M) \) as a function of a given galaxy property \( X \). For doing this, we split galaxies into \( m \) bins centred in the values \( X_j \) (\( j = 1, m \)), and compute:

\[
\sigma_X^2 = \frac{1}{n-1} \sum_{j=1}^{m} \sum_{X_j \in \Delta X/2} [\log(M_j) - \log(M)]^2 \leq \sigma^2.
\]

Table 2. Galaxy parameters as group mass indicators. The quantity \( \sigma^2 \) is variance of \( \log(M) \), \( \sigma_X^2 \) is the variance around the mean values of \( \log(M) \) for each parameter \( X \) and \( \sigma_{XY}^2 \) is the variance around the mean relation for the pairs or properties \( X \) and \( Y \). Quoted values are expressed in units of \( 10^{-3} \).

| Property \( X \) | \( \sigma^2_X - \sigma^2 \) | \( M_j \) | \( g-r \) | \( \mu_r \) | \( eclass \) | \( C \) |
|-----------------|-----------------|----------|----------|---------|----------|------|
| \( M_j \)      | –1              | \ldots   | –27      | –6      | –25      | –12  |
| \( g-r \)      | –20             | \ldots   | –27      | –25     | –23      | –22  |
| \( \mu_r \)    | –3              | \ldots   | –6       | –25     | –19      | –25  |
| \( eclass \)   | –16             | –25      | –23      | –19     | –19      |      |
| \( C \)        | –8              | –12      | –22      | –25     | –19      |      |

The only change with respect to the whole sample of groups is in the pairs, the most predictive pair is now \( eclass/M_j \), and the second one is \( g - r/M_j \), but the differences in their \( \sigma_X \) are small. We show in Fig. 2 in solid lines the mean value of \( \log(M) \) as a function of the single properties are shown in dotted lines in Fig. 2.

Table 3. Similar to Table 2 for massive \( \{ \log[M/(h^{-1}M_{\odot})] > 13.5 \} \) groups only. Quoted values are expressed in units of \( 10^{-4} \).

| Property \( Y \) | \( \sigma^2_Y - \sigma^2 \) | \( M_j \) | \( g-r \) | \( \mu_r \) | \( eclass \) | \( C \) |
|-----------------|-----------------|----------|----------|---------|----------|------|
| \( M_j \)      | –9              | \ldots   | –59      | –33     | –60      | –39  |
| \( g-r \)      | –40             | \ldots   | –59      | –50     | –51      | –56  |
| \( \mu_r \)    | –9              | –33      | –50      | –37     | –30      |      |
| \( eclass \)   | –26             | –60      | –51      | –37     | \ldots   | –43  |
| \( C \)        | –17             | –39      | –56      | –30     | –43      |      |

Figure 2. Mean value of \( \log(M) \) as a function of galaxy properties. Continuous lines are the results for the whole sample of groups used in this work, while dotted lines correspond to the \( \log[M/(h^{-1}M_{\odot})] \geq 13.5 \) subsample. Error bars were estimated using the bootstrap resampling technique.

\[
\mu_{XY} = \frac{1}{n} \sum_{X_j \in \Delta X/2} \sum_{Y_j \in \Delta Y/2} \log(M_{ji})
\]

\[
\sigma_{XY}^2 = \frac{1}{n-1} \sum_{j=1}^{m} \sum_{X_j \in \Delta X/2} [\log(M_{ji}) - \log(M)]^2 \leq \sigma^2.
\]
the second and the third most predictive properties. In all cases the single most predictive quantity is the \( g - r \) colour. Regarding the pairs of properties, most subsamples give the same first pair: colour with absolute magnitude. The exceptions are the two high-mass subsamples. It is clear that the second most predictive pair is not stable.

4 DEPENDENCE OF GALAXY PROPERTIES ON GROUP-CENTRIC DISTANCES

As said before, Domínguez et al. (2002) found a trend of the fraction of different galaxy types with the distance to the centre of the groups, with low and non-star forming galaxies being located preferentially towards the centres (see also Weimann et al. 2006). Therefore, similar behaviours are to be expected for other galaxy parameters such as colour or concentration index. In a similar way as we have done in the previous section, we study here which galaxy property, or pair of properties, is most closely related to galaxy distance from the group centre. We have applied here the same statistics as in the previous section, replacing the logarithm of the group mass in equations (1)–(3) by the group-centric distance in units of the group virial radius, \( r_{\text{vir}} \), computed by Zandivarez et al. (2006). We have restricted the sample of groups to those that have at least eight members, to ensure ourselves that determinations of group centre positions are more robust, with this restriction we have 2662 galaxies in 428 groups.

In Fig. 3, we show the mean values of \( r/r_{\text{vir}} \) as a function of the parameters for all groups with at least eight members and for the high-mass subsample. The resulting values for \( \sigma_{X}^{2} - \sigma^{2} \) and \( \sigma_{XY}^{2} - \sigma^{2} \) are quoted in Table 5. The \( g - r \) colour is the single parameter that correlates best with the distance from the group centre, the second place corresponds to surface brightness. Among the pairs of parameters, in the first place is \( g - r \) and \( e\text{class} \). When analysing the high-mass subsample which comprises 1387 galaxies in 166 groups (Table 6 and Fig. 3), we find the same ranking for the single parameters and the same first pair, but a different order in the remaining pairs.

We have performed similar tests as in previous section to evaluate the stability of the results. This is summarized in Table 7. We find that colour is the parameter most correlated with group-centric distance in all subsamples, and in most of them, the surface brightness is the following one. The differences between the single parameter ranking for the different subsamples are among the second to the fourth places that are taken by the quantities \( \mu_{r} \), \( e\text{class} \) and \( C \). But as can be seen in Table 5, their values \( \sigma_{X}^{2} - \sigma^{2} \) do not differ significantly. For the pairs of properties, in most cases the first place corresponds to colour and spectral type, while the second ranked pair is not stable at all.

5 DISCUSSION AND CONCLUSIONS

By using a large sample of galaxies in groups in the SDSS DR4, we have analysed how the properties of galaxies in groups are related to the environment. We find that the \( g - r \) colour is the parameter most dependent on group mass. The pair of properties that is most correlated to group mass are \( g - r \) colour and \( r \)-band absolute magnitude.
Table 6. Similar to Table 5 for massive \{log [M/(h^{-1} M_{\odot})] > 13.5\} groups only. Quoted values are expressed in units of 10^{-3}.

| Property X | Property Y |
|------------|------------|
| $\alpha r^2$ | $\sigma_{r}^2$ | $M_{r}$ | $g - r$ | $\mu_r$ | $\sigma_{mr}^2$ | $eclass$ | $C$ |
| $M_{r}$ | -2 | ... | -118 | -57 | -3 | -21 |
| $g - r$ | -47 | -118 | ... | -64 | -304 | -242 |
| $\mu_r$ | -19 | -57 | -64 | ... | -58 | -151 |
| $eclass$ | -17 | -3 | -304 | -58 | ... | -163 |
| $C$ | -9 | -21 | -242 | -151 | -163 | ... |

Table 7. Galaxy parameters as group-centric distance indicators: tests of stability. First column indicates the subsample (see text), second column lists the ranking of the most predictive single properties, last column lists the first two most predictive pairs of properties.

| Subsample | Single parameter ranking | First two pairs |
|-----------|--------------------------|-----------------|
| All groups | $g - r, \mu_r, eclass, C, M_{r}$ | $g - r, eclass, eclass/\mu_r$ |
| High mass | $g - r, \mu_r, eclass, C, M_{r}$ | $g - r, eclass, g - r/C$ |
| $\alpha < 12^b$ | $g - r, \mu_r, eclass, C, M_{r}$ | $g - r, eclass, g - r/C$ |
| $\alpha \geq 12^b$ | $g - r, eclass, \mu_r, M_{r}$ | $g - r/\mu_r, g - r/C$ |
| Even | $g - r, \mu_r, eclass, C, M_{r}$ | $g - r, eclass, g - r/M_{r}$ |
| Odd | $g - r, eclass, \mu_r, M_{r}$ | $g - r/\mu_r, g - r/C$ |

The results do not change when we consider massive groups \(M > 10^{13.5} h^{-1} M_{\odot}\). Regarding the position inside the systems, again we find that colour is the most predictive property for group-centric distances, while colour and eclass comprise the most predictive pair. The results do not vary when we exclude low-mass systems.

It should be noted that both, the single and the pair of most predictive galaxy properties as a function of the group environment, are nearly the same ones that Blanton et al. (2005) found for field galaxies using the local density. The only difference appears in the pair of properties when the group-centric distance is considered. It should be noted that both, the single and the pair of most predictive galaxy properties as a function of the group environment, are nearly the same ones that Blanton et al. (2005) found for field galaxies using the local density. The only difference appears in the pair of properties when the group-centric distance is considered. Blanton et al. (2005) found that colour and luminosity are the most predictive pair of properties, while according to our results, the pair colour/eclass is the most relevant. The similarity between our results for galaxies in groups and those by Blanton et al. (2005) for field galaxies suggests that the physical process associated with the galaxy formation and evolution are similar for these two environments.

It should be noted that the study of high-mass systems gives similar results to those of the whole sample. This might be indicating that, over an important range of environments, galaxies are affected in a similar way. From field to high-mass groups it is expected the merger rate to vary, nevertheless, it is remarkable that the same galaxy property is the one that correlates best with the environment. It would be interesting to repeat the present analysis for massive clusters of galaxies.

It is also interesting to note that the concentration parameter, closely related to the galaxy morphology, is not good in predicting the group environment. This is particularly surprising considering the well-known effect of morphological segregation in systems of galaxies. This result indicates that the morphological transformations that produce these relations are in a sense a byproduct of the transformations that produce the environmental trends on other properties like colour.

ACKNOWLEDGMENTS

We thank the anonymous referee for helpful comments that improved this paper. This work has been partially supported with grants from Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET), Secretaría de Ciencia y Tecnología de la Universidad de Córdoba and Agencia Nacional de Promoción Científica y Tecnológica, Argentina.

Funding for the SDSS has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max Planck Institut für Astronomie (MPIA), the Max Planck Institut für Astrophysik (MPA), New Mexico State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

REFERENCES

Adelman-McCarthy J. K. et al., 2006, ApJS, 162, 38
Blanton M. R. et al., 2003, AJ, 125, 2348
Blanton M. R., Eisenstein D., Hogg D. W., Schlegel D. J., Brinkmann J., 2005, ApJ, 629, 143
Domínguez M. J., Zandivarez A. A., Martínez H. J., Merchán M. E., Muriel H., Lambas D. G., 2002, MNRAS, 335, 825
Dressler A., 1980, ApJ, 236, 351
Gómez P. L. et al., 2003, ApJ, 584, 210
Hashimoto Y., Oemler A. J., 2000, ApJ, 530, 652
Martínez H. J., Zandivarez A., Domínguez M., Merchán M. E., Lambas D. G., 2002, MNRAS, 333, L31
Merchán M. E., Zandivarez A., 2005, ApJ, 630, 759
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Strateva I. et al., 2001, AJ, 122, 1861
Strauss M. A. et al., 2002, AJ, 121, 1810
Weinmann S. M., van den Bosch F. C., Yang X., Mo H. J., 2006, MNRAS, 366, 2
Yip C. W. et al., 2004, AJ, 128, 585
York D. G. et al., 2000, AJ, 120, 1579
Zabludoff A. I., Mulchaey J. S., 1998, ApJ, 496, 39
Zabludoff A. I., Mulchaey J. S., 2000, ApJ, 539, 136
Zandivarez A., Martínez H. J., Merchán M. E., 2006, ApJ, in press (astro-ph/0602405)

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.