Segregation Effects According to the Evolutionary Stage of Galaxy Groups

A.L.B. Ribeiro1⋆ P.A.A. Lopes2 and M. Trevisan3

1 Laboratório de Astrofísica Teórica e Observacional, Universidade Estadual de Santa Cruz – 45650-000, Ilhéus-BA, Brazil
2 Observatório do Valongo, Universidade Federal do Rio de Janeiro, Brazil
3 Instituto Astronômico e Geofísico- USP, São Paulo-SP, Brazil

Accepted 2010 September 20. Received 2010 July 19

ABSTRACT
We study segregation phenomena in 57 groups selected from the 2PIGG catalog of galaxy groups. The sample corresponds to those systems located in areas of at least 80% redshift coverage out to 10 times the radius of the groups. The dynamical state of the galaxy systems was determined after studying their velocity distributions. We have used the Anderson-Darling test to distinguish relaxed and non-relaxed systems. This analysis indicates that 84% of groups have galaxy velocities consistent with the normal distribution, while 16% of them have more complex underlying distributions. Properties of the member galaxies are investigated taking into account this classification. Our results indicate that galaxies in Gaussian groups are significantly more evolved than galaxies in non-relaxed systems out to distances of \( \sim 4R_{200} \), presenting significantly redder (B-R) colors. We also find evidence that galaxies with \( M_R \leq -21.5 \) in Gaussian groups are closer to the condition of energy equipartition.

Key words: galaxies – groups.

1 INTRODUCTION
Groups of galaxies contain about half of all galaxies in the Universe (e.g., Huchra & Geller 1982; Geller & Huchra 1983; Nolthenius & White 1987; Ramella et al. 1989). They represent the link between galaxies and large-scale structures and play an important role to galaxy formation and evolution. One of the most important questions about galaxy systems is related to segregation phenomena. The study of segregation effects is important to understand how system environment is transforming galaxies at the present epoch. Evidence for different loci in position and velocity spaces according to luminosity, spectral type and color of galaxies suggests ongoing evolution of clusters through the process of mergers, dynamical friction and secondary infall (e.g. Adami, Biviano & Mazure 1998, Biviano et al. 1999). Segregation has also been observed in galaxy groups (e.g. Mahdavi et al. 1999, Carlberg et al. 2001), suggesting a continuum of segregation properties of galaxies from low-to-high mass systems (Girardi et al. 2003). However, the dynamical state of galaxy groups is not taken into account in these studies. Differences in segregation phenomena may emerge if one divides groups according to their evolutionary stage. Recently, Hou et al. (2009) have examined three goodness-of-fit tests (Anderson-Darling, Kolmogorov and \( \chi^2 \) tests) to find which statistical tool is best able to distinguish between relaxed and non-relaxed galaxy groups. Using Monte Carlo simulations and a sample of groups selected from the CNOC2, they found that the Anderson-Darling (AD) test is far more reliable at detecting real departures from normality. Their results show that Gaussian and non-Gaussian groups present distinct velocity dispersion profiles, suggesting that discrimination of groups according to their velocity distributions may be a promising way to access the dynamics of galaxy systems. Extending up this kind of analysis to the outermost edge of groups one can probe the regions where they might not be in dynamical equilibrium. In this letter, we look for segregation effects in galaxy groups selected from the 2PIGG catalog (Eke et al. 2004), using 2dF data out to \( 4R_{200} \), and taking into account the evolutionary stage of the groups resulting from the AD test.

2 DATA AND METHODOLOGY
2.1 2PIGG sample
We use a subset of the 2PIGG catalog, corresponding to groups located in areas of at least 80% redshift coverage in 2dF data out to 10 times the radius of the systems, roughly estimated from the projected harmonic mean (Eke et al. 2004). The idea of working with such large areas is to probe the effect of secondary infall onto groups. Members and in-
terlopers were redefined after the identification of gaps in the redshift distribution according to the technique described by Lopes et al. (2009). Before selecting group members and rejecting interlopers we refine the spectroscopic redshift of each group and identify its velocity limits. For this purpose, we employ the gap-technique described in Katgert et al. (1996) and Olsen et al. (2005) to identify gaps in the redshift distribution. A variable gap, called density gap (Adami et al. 1998), is considered. To determine the group redshift, only galaxies within 0.50 h \(^{-1}\) Mpc are considered. Details about this procedure are found in Lopes et al. (2009); see also Ribeiro et al. (2009) for applications of this technique to 2dF galaxy groups. With the new redshift and velocity limits, we apply an algorithm for interloper rejection to define the final list of group members. We use the “shifting gapper” technique (Fadda et al. 1996), which consists of the application of the gap-technique to radial bins from the group center. We consider a bin size of 0.42 h \(^{-1}\) Mpc (0.60 Mpc for h = 0.7) or larger to ensure that at least 15 galaxies are selected. Galaxies not associated with the main body of the group are discarded. This procedure is repeated until the number of group members is stable and no further galaxies are eliminated as intruders. In the present work, we have sampled galaxies out to 10 times the hamonic mean radius of the systems, including galaxies whose distances to the centers can reach ~8 Mpc. To avoid contamination of nearby structures, we select galaxies within the maximum radius \(R_{\text{max}} = 4.0 \text{ Mpc} \) (see La Barbera et al. 2010). After applying the shifting gapper procedure we have a list of group members and we call \(R_A\) the aperture equivalent to the radial offset of the most distant member (normally close to \(R_{\text{max}}\)). We estimate the velocity dispersion (\(\sigma\)) within \(R_A\) and then the physical radius (\(R_{200}\)) of each group. Finally, a virial analysis is perfomed for mass estimation (\(M_{200}\)). Further details regarding the interloper removal and estimation of global properties (\(\sigma\), physical radius and mass) are found in Lopes et al. (2009).

2.2 Classifying groups

The first step in our analysis is to apply the AD test (see Hou et al. 2009 for a good description of the test) to the velocity distributions of galaxies in groups. This is done for different distances, producing the following ratios of non-Gaussian groups: 6% (\(R \leq 1 R_{200}\)), 9% (\(R \leq 2 R_{200}\)), and 16% (\(R \leq 3 R_{200}\) and \(R \leq 4 R_{200}\)). Approximately 90% of all galaxies in our sample have distances \(\leq 4 R_{200}\). This is the natural cutoff in space we have made in this work. Some properties of galaxy groups are presented in Table 1. We have classified groups according to the AD test (at 0.05 significance level) done at \(R \leq 4 R_{200}\) , encompassing all groups with evidence for normality deviations. Properties of non-Gaussian (NG) groups in Table 1 were computed twice, with and without a correction based on iterative removal of galaxies whose absence in the sample cause the groups become Gaussian, following a procedure similar to Perea, del Olmo & Moles (1990). The corrected properties are just those the system would have if it was made only with galaxies consistent with the normal velocity distribution. This correction allows one to honestly compare typical properties of G and NG groups. Not doing that, NG groups could have their properties overestimated by a factor of \(\sim 1.5\), taking all members within \(4 R_{200}\). After this procedure, we see in Table 1 that G and corrected NG groups have similar properties.

2.3 Composite groups

A suitable way to investigate galaxies in multiple galaxy systems is to combine them in stacked objects (Biviano et al. 1992). Thus, we built two composite groups, Gaussian–G (composed of 48 systems) and non-Gaussian–NG (composed of 9 systems). Galaxies in these composite groups have distances to group centers normalized by \(R_{200}\) and their velocities refers to the group median velocities and are scaled by the group velocity dispersions

\[
u_i = \frac{\nu_i - \langle \nu_j \rangle}{\sigma_j}
\]

where \(i\) and \(j\) are, respectively, the galaxy and the group indices. Velocity dispersions of the composite groups refer to the dimensionless quantity \(u_i\). Absolute magnitudes, \(M_R\), are obtained from Super-COSMOS R band, a 2dF photometric information. Cosmology is defined by \(\Omega_m = 0.3, \Omega_{\Lambda} = 0.7,\) and \(H_0 = 100 \text{ h km s}^{-1} \text{Mpc}^{-1}\). Distance-dependent quantities are calculated using \(h = 0.7\). All figures presented in the next section correspond to cumulative data in \(R/R_{200}\) or \(M_R\). Error-bars in our analysis are obtained from a bootstrap technique with 1000 resamplings.

3 SEGREGATION ANALYSIS

Segregation analysis is a powerful tool to evaluate galaxy evolution in galaxy systems (e.g. Goto, 2005). We probe segregation phenomena out to \(4 R_{200}\), looking for differences in galaxies with respect to the dynamical state of the groups. First, we test the presence of luminosity segregation in the velocity space by computing the normalized velocity dispersion, \(\sigma_u\), of the stacked G and NG groups. In Figure 1, we plot \(\sigma_u\) of the composite groups as a function of the absolute magnitude in the R band. We clearly see that, at \(M_R \leq -21.5\), the velocity dispersions decreases towards brighter absolute magnitudes. On the other hand, for fainter absolute magnitudes, the velocity dispersions are approximately constant. More interestingly, although the result is similar for both stacked groups, for the NG group we see a steeper correlation in the bright end than that we see for the G group. If one assumes a constant galaxy mass-to-light ratio, energy equipartition implies \(\sigma_u \propto 10^{0.2 M_R}\) (e.g. Adami, Biviano & Mazure, 1998). The regression lines between \(\log \sigma_u\) and \(M_R\) have slopes 0.18±0.05 and 0.38±0.03, for G and NG groups, respectively. That is, the brightest galaxies are moving more slowly than other group galaxies. Such a segregation in the velocity space may be interpreted as evidence that these galaxies have reached energy equipartition, as a consequence of dynamical friction (e.g. Capelato et al. 1981). In fact, the slope we found for galaxies in the

| Type      | \(R_{200} \) (Mpc) | \(M_{200} \) (\(10^{14} M_\odot\)) | \(\sigma \) (km/s) | \(N_{200}\) | \(N_T\) |
|-----------|-------------------|---------------------------|-----------------|-----------|-------|
| G         | 0.94 ± 0.31       | 0.88 ± 0.79               | 223 ± 89        | 10 ± 4    | 24 ± 11 |
| NG        | 1.32 ± 0.27       | 1.41 ± 0.83               | 363 ± 99        | 12 ± 5    | 40 ± 12 |
| NG_r      | 0.97 ± 0.23       | 0.95 ± 0.95               | 257 ± 76        | 10 ± 4    | 31 ± 10 |

Table 1. Mean properties of groups
G group is consistent with this interpretation. However, the steeper relation between $\sigma_u$ and $M_R$ probably indicates a departure from equipartition state for galaxies in the NG group. We also should note that, for $M_R \geq -21.5$, velocity dispersions are larger in the NG group. Therefore, although fainter galaxies both in G and NG groups seem to lie in the velocity equipartition state generated by violent relaxation, these galaxies in the NG group have more kinetic energy. A complementary view of this scenario follows from what is seen in Figure 2. Note that the velocity dispersion profiles show declining and rising trends, for G and NG groups, respectively. They approximately cross each other at $2.5 R_{200}$ and then separate more and more for larger radii. This is consistent with the results of Hou et al. (2009), for the CNOC2 galaxy groups sample. Rising profiles are generally interpreted as a possible signature of mergers (Menci & Fusco-Femiano, 1996), which suggests a current intense phase of environmental influence on galaxies in the inner parts of non-Gaussian groups. Looking for a counterpart of these effects in color, we plot in Figure 3 the color profiles for the G and NG groups. They clearly reveal a stronger reddening towards the center for galaxies in the G group. Also, note that the profiles turn flat approximately at $3 R_{200}$, but galaxies are still redder in Gaussian groups out to $4 R_{200}$. This result indicates that non-Gaussian groups contain less evolved galaxies at the present epoch even in the outskirts. In fact, galaxies in the NG group are fainter than those in the G group for all radii, with luminosities presenting rising profiles in both cases (see Figure 4). Spearman tests indicate significant increasing trends up to $1 R_{200}$ and $2.3 R_{200}$ for the G and NG stacked systems, respectively.

4 DISCUSSION

We have studied segregation effects in 57 galaxy groups selected from the 2PIGG catalog (Eke et al. 2004) using 2dF data out to $4 R_{200}$. This means we probe galaxy distribution near to the turnaround radius, thus probably taking into account all members in the infall pattern around

---

**Figure 1.** Composite groups velocity dispersion as a function of the absolute magnitude in the R band. Filled circles denote galaxies in G groups, while open circles denote galaxies in NG groups. Dashed lines indicate the regression fits for galaxies with $M_R \leq -21.5$.

**Figure 2.** Composite groups velocity dispersion as a function of the normalized radial distances to the group centers. Filled circles denote galaxies in G groups, while open circles denote galaxies in NG groups.

**Figure 3.** B-R color of galaxies in the composite groups as a function of the normalized radial distances to the group centers. Filled circles denote galaxies in G groups, while open circles denote galaxies in NG groups.
expected for systems undergoing a phase of mass accretion. We also thank S. Rembold for interesting discussions. ALBR thanks the support of CNPq, grants 201322/2007-2 and 471254/2008-8. PAAL thanks the support of FAPERJ, process 110.237/2010. MT thanks the support of FAPESP, process 2008/50198-3.

REFERENCES

Adami C., Biviano, A. & Mazure, A., 1998, A&A, 331, 439
Adami C., Mazure, A., Biviano, A., Katgert, P. & Rhee, G., 1998, A&A, 331, 493
Biviano, A., Girardi, M., Giuricin, G., Mardirossian, F. & Mezzetti, M., 1992, ApJ, 396, 35
Biviano, A., Katgert, P., Thomas, T. & Adami, C., 2002, A&A, 387, 8
Capelato, H., Gerbal, D. & Mathez, G., Mazure, A., Roland, J. & Salvador-Solé, E., 1981, A&A, 96, 235
Carlberg, R., Yee, H.K.C., Morris, S.L., et. al., 2001, ApJ, 563, 736
Cupani, G., Mezzetti, M. & Mardirossian, F., 2008, MNRAS, 390, 645
Eke, V.R. et al. (2dfGRS Team), 2004, MNRAS, 348, 866
Fadda D., Girardi M., Giuricin G., et al., 1996, ApJ, 473, 670
Geller, M.J. and Huchra, J.P., 1983, ApJS, 52, 61
Girardi, M., Rigoni, E., Mardirossian, F. & Mezzetti, M., 2003, A&A, 406, 403
Goto, T., 2005, MNRAS, 359, 1415
Hou, A., Parker, L., Harris, W. & Wilman, D.J., 2009, ApJ, 702, 1199
Huchra, J.P. and Geller, M.J., 1982, ApJ, 257, 423
Katgert P., Mazure A., Perea J. et al. 1996, A&A, 310, 8
La Barbera, F., Lopes, P.A.A., de Carvalho, R.R., de la Rosa, I.G. & Berlind, A.A., 2010, MNRAS, in press (arXiv:1003.1119)
Lopes P.A.A., de Carvalho R.R., Kohli-Moreira J.L., Jones C., 2009, MNRAS, 392, 135
Mahdavi, A., Geller, M.J., Böhringer, H., Kurtz, M.J. & Ramella, M., 1999, ApJ, 518, 69

Acknowledgments

We thank the referee for very useful suggestions. We also thank S. Rembold for interesting discussions. ALBR thanks the support of CNPq, grants 201322/2007-2 and 471254/2008-8. PAAL thanks the support of FAPERJ, process 110.237/2010. MT thanks the support of FAPESP, process 2008/50198-3.

Figure 4. Absolute magnitude in R band as a function of the normalized radial distances to the group centers. Filled circles denote galaxies in G groups, while open circles denote galaxies in NG groups.

the groups (e.g. Rines & Diaferio 2006; Cupani, Mezzetti & Mardirossian 2008). Instead of focusing our analysis on choosing specific galaxy types to study segregation, we have used the dynamical state of galaxy systems to test for different levels of environmental influence on galaxies. The theoretical expectation is that the underlying velocity distribution is normal for systems in dynamical equilibrium. Using the AD test, we divided the sample in Gaussian and non-Gaussian groups. These were used to build the composite G and NG groups. Some general results we found were expected: segregation in velocity space (galaxies brighter than $M_R = 21.5$ are moving more slowly than other group galaxies); and color and luminosity gradients towards the center of the groups. However, important differences emerge when we compare the behaviour of galaxies in G and NG groups. For instance, color gradient and overall reddening are stronger in the case of the G group out to large distances, showing a significant raise of more evolved galaxies from non-relaxed to relaxed systems (Figure 3). This is consistent with the luminosity profiles, indicating that galaxies in the G group are significantly brighter than those in the NG group (Figure 4). On the other hand, the rising velocity dispersion profile for galaxies in the NG group indicate that, though less evolved now, galaxies in non-Gaussian systems may be undergoing a more intense phase of interactions in their inner parts at the present epoch (Figure 2). These results are in agreement with the work of Popesso et al. (2007), in which Abell clusters with an abnormally low X-ray luminosity for their mass have a higher fraction of blue galaxies, and are characterized by leptokurtic (more centrally concentrated than a Gaussian) velocity distribution of their member galaxies in the outskirts ($1.5 < R/R_{200} < 3.5$), as expected for systems undergoing a phase of mass accretion. This also fairly agrees with Osmond & Ponman (2004) who have found that groups with an abnormally low velocity dispersion relative to their X-ray properties have a higher fraction of spirals and could be dynamically unrelaxed. The low velocity dispersions are probably consequence of the interactions in the inner part of the groups. Since they only considered the central group regions and the brightest galaxies, our analysis suggests that they may have found unrelaxed systems, but could have underestimated the global velocity dispersions of these groups (see Table 1 and Figure 2).

Taken together, these facts point out a scenario where young systems have galaxies bluer and fainter up to large radii ($\sim 4R_{200}$), possessing lower velocity dispersions in the inner parts (and higher velocity dispersions in the outer parts) in comparison to more evolved systems. This latter result is also related to the segregation detected in the velocity space. Galaxies brighter than $M_R = 21.5$ are moving more slowly than other group galaxies, but the relation $\sigma_u - M_R$ is steeper for non-Gaussian groups, indicating a departure from the energy equipartition expectation $\sigma_u \propto 10^{0.25M_R}$ (see Figure 1). Our work suggests that the slope of the relation $\sigma_u - M_R$ could be used to determine the evolutionary stage of galaxy groups.
Menci, N. & Fusco-Femiano, R., 1996, ApJ, 472, 46
Nolthenius, R. and White, S.D.M., 1987, MNRAS, 225, 505
Olsen L.F. et al. 2005, A&A, 435, 781
Osmond, J. & Ponman, T., 2004, MNRAS, 350, 1511
Perea, J., del Olmo, A. & Moles, M., 1990, A&A, 237, 319
Popesso, P., Biviano, A., Böringer, H. & Romaniello, M., 2007, A&A, 461, 397
Ramella, M., Geller, M. & Huchra, J.P., 1989, ApJ, 344, 57
Ribeiro, A.L.B., Trevisan, M., Lopes, P.A.A & Schilling, A.C., 2009, A&A, 505, 521
Rines, K. & Diaferio, A., 2006, AJ, 132, 1275

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