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THE SHAPE OF GALAXY STRUCTURES

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ABSTRACT

An analysis is presented for a statistically complete sample of 547 galaxy structures with $z \leqslant 0.16$, each containing at least 10 objects. The sample was divided according to structure richness, representing 10 richness classes, with the distribution of ellipticities differing among individual classes. Mean ellipticity varies from 0.34 to 0.18, less well populated structures being more elongated that richer ones. Statistics indicate that structures with at least 50 members originate from the same population. The mean redshift of a structure class is a function of richness, with less well populated classes exhibiting greater mean redshifts than richer galaxy clusters. Further analysis reveals a dependence of the ellipticity-redshift correlation on structure richness. Among rich galaxy clusters there is an anti-correlation between the parameters, the strongest correlation occurring for the most poorly populated galaxy classes.

Key words: galaxies: clusters: general – galaxies: evolution – large-scale structure of universe

1. INTRODUCTION

The shape of galaxy structures can reflect conditions prevailing at the moment the structure originated. Detailed information on this parameter, as well as the factors influencing the observed shape, is therefore crucial for better understanding the formation of large-scale structures in the universe. It is commonly believed that large-scale structures are formed by gravitational collapse. Such structures are apparently not spherically symmetric, nor do their shapes result from rotation (e.g., Dressler 1981). Yet it is anticipated that some information about the original density perturbations leading to structure formation can be gleaned from studying the actual shapes of such structures.

We previously noted the weak dynamical evolution of low-redshift galaxy structures (Biernacka et al. 2009), which conformed with several claims, both observational and theoretical, that the recent virialization of galaxy structures is observable. The present study investigates, from an observational basis in which structures and their parameters are obtained in the same manner, the influence of structure richness on parameters connected with the shape of galaxy groups and clusters. We use a statistically complete sample of 547 structures containing at least 10 members within the structure area (Panko & Flin 2006).

The present study is organized as follows. Section 2 presents the observational data and method of analysis, while Section 3 describes the result of our investigations. We tested: (1) the influence of structure richness on the characteristics of ellipticity distributions in groups and clusters; (2) the dependence of the relation between redshift z and structure ellipticity e on richness; and (3) the ellipticity evolution rate de/dz as a function of structure richness. Our conclusions are presented in Section 4 at the end of the paper.

2. OBSERVATIONAL DATA AND METHOD OF ANALYSIS

2.1. The Catalog of Galaxy Structures

The Muenster Red Sky Survey (Ungruhe et al. 2003, hereafter MRSS) is a galaxy catalog resulting from scans of 217 ESO plates. It contains about 5.5 million galaxies located in the southern sky covering an area of 5000 deg^2, complete to $r_F = 18\overset{\text{m}}{.}3$. The two-dimensional Voronoi tessellation technique (Ramella et al. 1999, 2001) was applied to the MRSS, producing a statistically complete catalog of galaxy structures (Panko & Flin 2006, hereafter PF Cat). Each structure listed in PF Cat contains at least 10 galaxies within the structure area, and parameters for each structure were calculated within magnitude limits of m_3, $m_3 + 3^m$, where m_3 is the magnitude of the third brightest galaxy in the region considered. The ellipticity of each structure was defined as $e = 1 - \frac{b}{a}$, where a and b are the major and minor semiaxes of an ellipse that best fits the two-dimensional distribution, calculated using the standard covariance ellipse method (Carter & Metcalfe 1980).

Structure redshifts, z, were determined using a relationship between m_{10} and z, where m_{10} is the magnitude of the tenth brightest galaxy in the region (Postman et al. 1985). From the identification of PF structures with comparable groups in the ACO (Abell et al. 1989), there were 466 structures in common, with the ACO clusters having measured redshifts. Structures were considered to be identical when the distance between structure centers was less than $0.3r$, where r is the equivalent radius for the PF structure. A comparison was also made between objects taken from the PF Cat and the APM (Dalton et al. 1997), which also has measured redshifts. A separate comparison was carried out using a $0.5r$ criterion for structure coincidence, in conjunction with a deeper version ($r_F = 19\overset{\text{m}}{.}3$) of the PF Catalog. Such comparisons facilitated the derivation of a tight $m_{10} - z$ relation that permitted estimates of redshift to be made for all 6188 PF structures. The resulting $m_{10} - z$ relation is displayed in Figure 1, where the differences among the four investigated relations are small. Subsequent analysis of galaxy structures was made using the relation in final form:

$$\log z = -3.771 + 0.1660 \cdot m_{10} \tag{1}$$

which implies that the PF Cat contains structures with z up to 0.18.

From the 6188 identified galaxy structures we extracted 547 ones with $m_3 \leqslant 15\overset{\text{m}}{.}3$, which give the brightness of the dimmest galaxy in structures within the survey completeness limit $18\overset{\text{m}}{.}3$. This ensures statistical completeness of the investigated sample.

These 547 structures were subsequently divided into five samples of different structure richness. The least well populated class contained only 10 to 30 galaxies, somewhat richer class

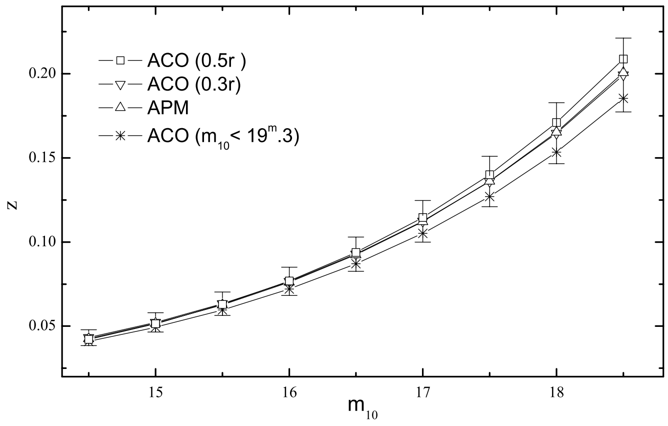

Figure 1. Calculated $m_{10} - z$ relations according to comparisons made of structures identified in the PF Cat with those for ACO and APM clusters.

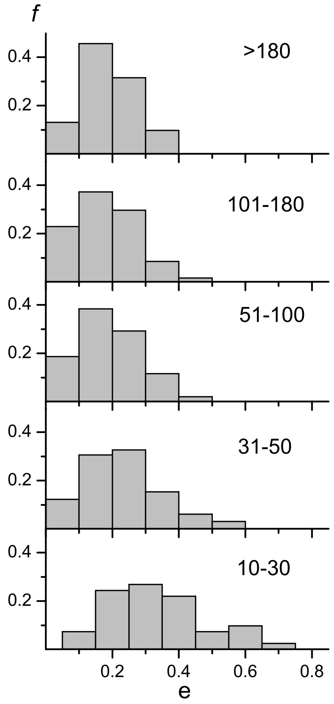

Figure 2. Frequency distributions of structure ellipticities in five classes with richness identified in the upper right portion of each section.

between 31 and 50 galaxies, then 51 and 100 objects, the second-last class containing between 101 and 180 members. The richest class contains more than 180 individual galaxies. Background galaxies were included in the analysis. The influence of group richness was analyzed according to the ellipticity and mean redshift of each structure, as well as relative to an ellipticity–distance relation.

2.2. Results

Our initial investigation involved a study of the relationship between the ellipticity and richness of individual structures. Histograms were constructed to represent the distribution of derived ellipticity for the 10 richness classes. The resulting distributions appeared to be different, as seen in Figure 2. The mean ellipticities and their standard deviations are: 0.34 ± 0.14, 0.23 ± 0.12, 0.19 ± 0.09, 0.18 ± 0.09, and 0.18 ± 0.08, progressing from the most poorly populated to the richest samples, respectively. The mean value of ellipticity depends on structure richness, with poorly populated groups tending to be more elongated than more richly populated ones.

Table 1
The Similarity of Ellipticity Distributions in the Group Richness Classes According to λ

Sample	31–50	51–100	101–180	>180
10–30	1.704	2.477	2.546	2.462
31–50		1.312	1.451	1.367
51–100			0.310	0.300
101–180				0.725

Table 2
The Mean Redshifts z in Different Richness Groups

Sample	z_{mean}	SD	The number of structures in sample
10–30	0.113	0.022	41
31–50	0.097	0.014	98
51–100	0.085	0.013	198
101–180	0.072	0.010	118
>180	0.065	0.010	92

A Kolmogorov–Smirnov test was used to establish whether or not the distributions are drawn from the same parent population. The Kolmogorov–Smirnov statistics resulting from a comparison of each distribution with all remaining ones are presented in Table 1. The critical values of λ for the statistical comparison are as follows: $\lambda_\alpha = 1.36$ corresponds to a significance level of $\alpha = 0.05$, and $\lambda_\alpha = 1.63$ to a significance level of $\alpha = 0.01$.

Based upon the statistical analysis, it can be concluded that the ellipticity distributions for structure classes containing more than 50 galaxies originate from the same parent population, whereas less populated structures constitute different populations.

The mean redshift for each structure class was also investigated, with the results of the statistical analysis summarized in Table 2. In the table, Column 1 divides the sample according to richness class, Column 2 lists the mean redshift for that group, and Column 3 is the standard deviation of the mean. The last column contains the number of structures falling into each corresponding bin. The difference between the values of redshift z in extreme bins is greater than 2σ. A systematic decrease of z with structure richness is evident. Figure 3 presents the relationship between redshift and richness for five richness groups.

Figure 4 represents the dependence of group richness with redshift. The correlation coefficient from a linear fit is $R_1 = -0.880$, while for a quadratic fit it is $R_2 = 0.970$ and for an exponential one $R_e = 0.996$. These values confirm the statistical significance of the redshift–richness relation. Uncertainties in the data do not allow us to distinguish between the two types of nonlinear fits. However, the observed dependence deviates markedly from a simple linear correlation.

The existence of an ellipticity–redshift relation seems to be well established. The influence of structure richness on the relation was studied by dividing 547 structures into five samples according to the number of galaxies counted in a structure. Poorly populated galaxy groups with 10 to 30 members constituted the first sample, while the second and third samples embodied structures containing 31–50 and 51–100 members, respectively. The last samples included rich clusters with 100–180 galaxies and more than 180 member galaxies, respectively. Such a division was motivated by the similarity of ellipticity histograms described previously and our willingness to consider the richest clusters separately. Figure 5 illustrates the dependence between

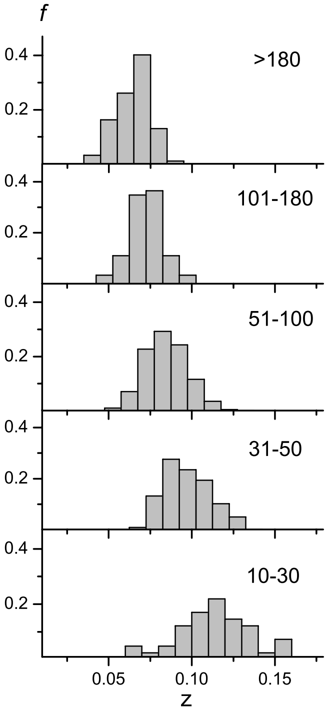

Figure 3. Frequency distribution of structure redshifts for samples containing different numbers of galaxies in the structure.

structure ellipticity and redshift for five investigated samples, along with the linear relation that was fitted to the parameters. An analysis was also made of the cluster ellipticity evolution rate de/dz using our five samples (see Figure 6).

The value of de/dz changes dramatically from one sample to another. Values of de/dz with their standard deviations are: 2.55 ± 0.94, 1.52 ± 0.89, -0.39 ± 0.52, -1.02 ± 0.85, and -0.24 ± 0.83 from the most poorly populated to richest samples, respectively. The ellipticity evolution rate de/dz was also calculated for a somewhat different division into five samples. Although the resulting numbers differed from the above values, they followed closely the relation between de/dz and z presented in Figure 6 for groups with less then 100 member galaxies.

3. CONCLUSIONS

A statistically complete set of data covering a large part of the southern sky was examined in order to identify in uniform fashion a variety of classes of richly populated and poorly populated aggregates of galaxies, each containing at least 10 members. A total of 547 such structures were investigated. The approach followed permitted us to identify several samples rich enough to permit meaningful statistical investigation. The covariance ellipse method used to describe the shapes of the resulting structures proved to be a practical tool (Biernacka 2007; Kim et al. 2002). It was found that structure richness has important and statistically significant correlations with several parameters connected to group and cluster shape.

Statistical analysis indicates that structures containing more than 50 members appear to originate from the same parent population, in other words their structure ellipticity distributions are essentially identical. In agreement with earlier works (Struble & Ftaclas 1994; Plionis 2004), it is found that the more poorly populated structures are more elongated than richly populated ones. It is suggested that such a result may reflect variations in the initial conditions during structure formation (Biernacka et al. 2008). Small elongated groups appear to have formed along pre-existing filaments, and later become more spherical in shape as a result of hierarchical clustering. Such a conclusion is supported by the discovery that, in the sample of 547 structures investigated here, the mean redshifts for galaxy groups are larger than the mean redshifts for richer clusters.

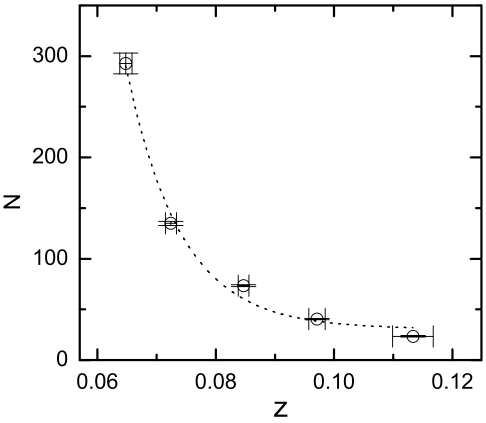

Figure 4. Dependence of group richness on redshift z. Error bars correspond to $\alpha = 0.95$ confidence intervals.

The $e-z$ relation depends upon richness as well, with the dependence being similar to the rate of evolution of ellipticity de/dz as a function of redshift z. For poorly populated groups, both the ellipticity and the ellipticity evolution rate de/dz differ at a 3σ level from results found for other, more richly populated, samples. The sample containing galaxy aggregations containing between 10 and 30 members displays a significant correlation with redshift, while the three remaining samples for richer groups exhibit either a weak correlation or an anti-correlation.

Recently, Plionis et al. (2009) investigated a sample of 150 ACO clusters with $z < 0.14$ containing at least 20 members. Their sample does not contain merging and interacting clusters, or clusters with dynamical substructures. They found that the direction of evolution is different for clusters of different richness. While their values of de/dz differ from the present results, the directions of the trends are identical. The differences that do exist can be attributed to the analysis of totally different samples, with different richness classes for the subsamples and different redshift limits.

It has proven to be difficult to compare the present results with numerical simulations. A very extensive numerical study (Hopkins et al. 2005) in the framework of ΛCDM cosmology examines cluster ellipticities to redshift $z = 3$. The present study investigates low-redshift clusters, making a simple comparison impossible. The numerical simulations indicate that cluster mean ellipticity should increase with redshift as well as cluster mass. The present results agree with the first prediction, but conflict with the second. As pointed out above, however, the redshift coverage of our galaxy samples is very small in comparison with that of existing numerical simulations, and the simulations considered cluster masses of clusters greater than $2 \times 10^{13}\, h^{-1}\, M_\odot$, which corresponds only to the richest of our samples. A natural extension of the present study to investigate a larger sample of galaxy groups and clusters over a much larger redshift range would therefore be very useful.

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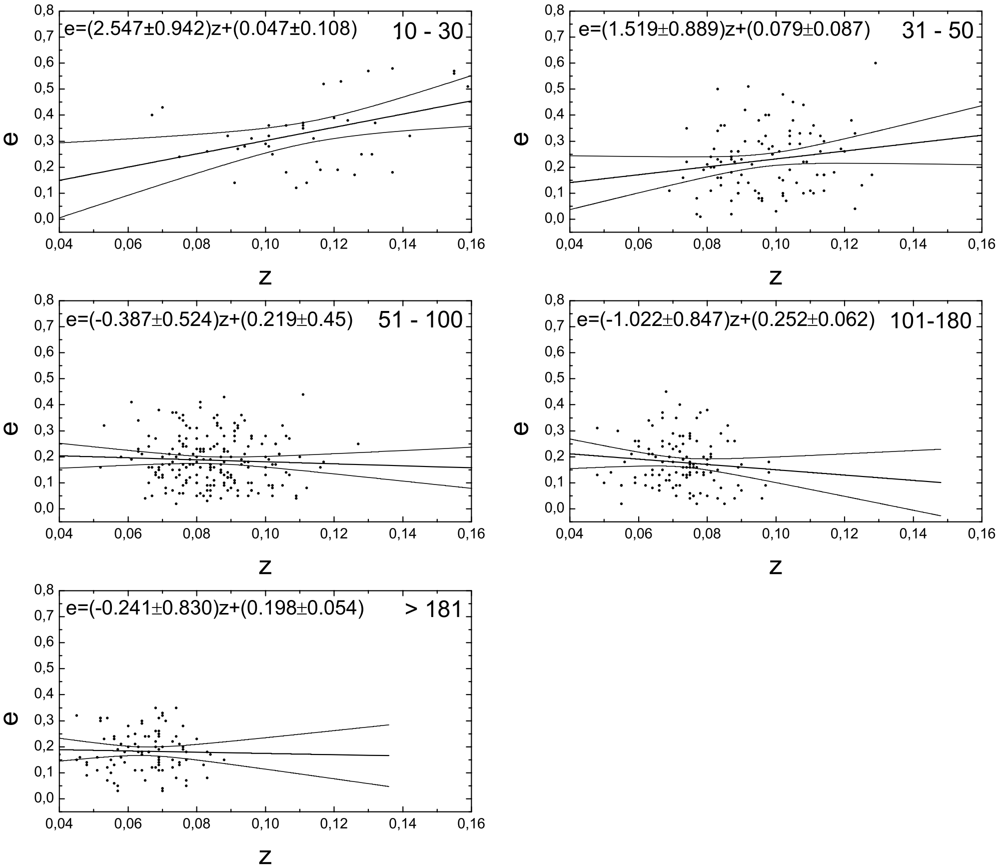

Figure 5. Ellipticity–redshift relation for galaxy group samples, with the galaxy populations of each structure noted in the upper right-hand corners. The fitted linear relations together with their $\alpha = 0.95$ confidence intervals are also plotted.

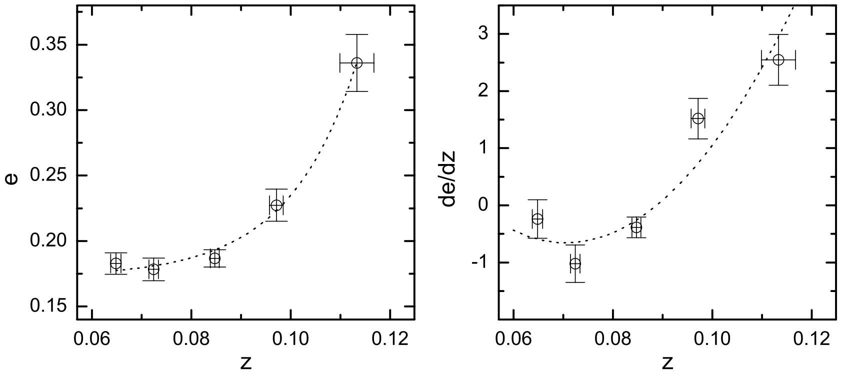

Figure 6. Cluster ellipticity e (left panel) and cluster ellipticity evolution rate de/dz (right panel) vs. redshift for five samples of different richness. Error bars correspond to $\alpha = 0.95$ confidence intervals.

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