A CORRELATION BETWEEN LIGHT CONCENTRATION AND CLUSTER LOCAL DENSITY FOR ELLIPTICAL GALAXIES

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ABSTRACT

Using photometric and redshift data for the Virgo and Coma Clusters, we present evidence for a correlation between the light concentration of elliptical galaxies (including dwarf ellipticals) and the local three-dimensional (i.e., nonprojected) density of the clusters: more concentrated ellipticals are located in denser regions. The null hypothesis (i.e., the absence of any relation) is rejected at a significance level of better than 99.9%. In order to explain the observed relation, a power law relating the galaxy light concentration and the cluster three-dimensional density is proposed. We study how the projection effects affect the form and dispersion of the data points in the light concentration–projected density diagram. The agreement between our model and the observed data suggests that there is a paucity of dwarf elliptical galaxies in the cluster central regions.

Subject headings: galaxies: clusters: general — galaxies: fundamental parameters — galaxies: interactions — galaxies: photometry — galaxies: structure

1. INTRODUCTION

Analyzing the Abell cluster 2443, Trujillo et al. (2001a, hereafter T01a) showed evidence for a correlation between galaxy light concentration and local cluster surface density for elliptical galaxies: more centrally concentrated ellipticals appear to populate denser regions. If this relation is shown to hold for other clusters, it means that the qualitative morphology density relation noted by previous authors (e.g., Dressler 1980; Dressler et al. 1997; Fasano et al. 2000) can be placed on a more quantitative basis; that is, the detailed structure of the individual galaxies (beyond the broad elliptical/spiral distinction) is related to their immediate environment/density.

That the structural properties of ellipticals are related to the properties of their parent clusters was noted early on by Strom & Strom (1978). The characteristic sizes of galaxies decrease by a factor of 1.5 in the denser regions. This effect was explained by tidal disruption and high-speed impulse encounters. However, as we discussed in T01a, this mechanism does not seem to be the correct explanation for the correlation presented in our previous paper. Since mergers tend to increase the concentration of galaxies (White 1983; Barnes 1990, 1992) and bulges (Aguerri, Balcells, & Peletier 2001), we proposed this mechanism as a possibly more viable explanation.

By understanding how the properties of galaxies relate to those of their parent clusters, we can hope to learn about the formation and evolution of both. In this Letter the connection between galaxy light concentration and cluster density is examined and confirmed for the Virgo and Coma Clusters. We pay special attention to the effects of projection on this relation and show how its shape and its scatter can be easily explained.

2. GALAXY DATA AND MEASUREMENTS

The data for the Coma cluster were taken from a quantitative morphological analysis of the galaxies placed in the central region of this cluster, covering an area of 0.28 deg² (see details in C. M. Gutiérrez et al. 2002, in preparation). The images were obtained on 2000 April 25 and 27 using the Wide Field Camera at the 2.5 m Isaac Newton Telescope at the Observatorio del Roque de los Muchachos on La Palma. The pixel scale is 0′′.333 pixel⁻¹, and the seeing was 1′′.1. The field was observed through the R filter for a total integration time of 3900 s. B−R color information for the observed galaxies was obtained from the Coma Cluster galaxies catalog presented in Godwin, Metcalfe, & Peach (1983). This catalog is complete down to $m_B = 20$.

Briefly, the structural parameters of the elliptical galaxies were obtained by fitting a two-dimensional Sérsic model $r^{1/n}$ (Sérsic 1968) to the observed galaxies. Both the ellipticity shapes of the galaxies and the effects of seeing on the images were taken into account when fitting the model (details of the parameter-recovering method are explained in T01a). We used a Moffat function with $β = 2.5$ to describe the point-spread function. The parameters were estimated with an error of less than 10% down to $R = 17$ ($m_B = 19$), which we assume as our limiting magnitude for an accurate morphological structure analysis. Assuming $H_0 = 75$ km s⁻¹ Mpc⁻¹ (which we do throughout) and a redshift for Coma of $z = 0.023$, this implies an absolute limiting magnitude of $M_B = −15.84$ and an observed field covering the inner 500 kpc.

We then computed the concentration index of the best-fitting $r^{1/n}$ models using a new index presented in Trujillo, Graham, & Caon (2001b) and further developed in Graham, Trujillo, & Caon (2001). This index measures the light concentration within a profile’s half-light radius ($r_h$): it is the ratio of flux inside some fraction $α$ of the half-light radius to the total flux inside the half-light radius. For an $r^{1/n}$ model, this index can be analytically defined as

$$C_n(α) = \frac{γ(2n, b_α α^{1/n})}{γ(2n, b_α)},$$

(1)

where $n$ is the shape parameter of the $r^{1/n}$ model and $b_α$ is derived numerically from the expression $Γ(2n) = 2Γ(2n, b_α)$, with $Γ(α)$ and $γ(α, x)$, respectively, the gamma function and the incomplete gamma function (Abramowitz & Stegun 1964). The parameter $α$ can be any value between 0 and 1 and defines what level of concentration is being measured. We used a value of $α = 0.3$.

We computed the local cluster surface density around each galaxy in our sample in the following way. Using the position information from the catalog by Godwin et al. (1983), we com-
uted the distance to the 10th nearest neighbor, \( r_{10} \), and derived the density as \( \rho_{\text{proj}} = 10/(\pi r_{\text{cc}}^2) \). In order to avoid contamination from field galaxies and to assure uniform completeness on the whole area, we selected from that catalog only those galaxies with \( m_B \leq 20 \) (\( M_B < -14.84 \)) and satisfying the redshift condition 4000 km \( s^{-1} < cz < 10,000 \) km \( s^{-1} \) (a 3 \( \sigma \) interval around the mean cluster redshift). The redshift information was obtained from M. Colless (2001, private communication) from the data used in Edwards et al. (2002). For those galaxies lacking velocity data, we use the color constraint \( 1 < B-R < 2 \) (see, e.g., Mobasher et al. 2001).

The same calculations were carried out for the Virgo Cluster. The concentration indexes were computed from the best-fitting S{\`e}rsic \( n \)-values published in Caon, Capaccioli, & D’Onofrio (1993) and Binggeli & Jerjen (1998); only galaxies classified as elliptical galaxies or dwarf elliptical (dE) galaxies brighter than \( m_B = 15.45 \) were used. The projected densities were computed using the galaxies listed in the Virgo Cluster Catalog (Binggeli, Sandage, & Tammann 1985), from which we selected only those with confirmed membership and brighter than \( m_B = 16.45 \). The cutoff magnitudes used in Virgo correspond to the same limiting absolute magnitudes used for Coma (assuming a Coma-Virgo distance modulus of 3.50 mag from D’Onofrio et al. 1997).

3. A \( C_r(\xi) \)-LOCAL DENSITY POWER-LAW RELATION

The relation between galaxy light concentration and local cluster surface density is shown in Figure 1. Solid points represent those elliptical galaxies with \( M_B < -17.5 \) (22 from Virgo and 15 from Coma), whereas dwarf galaxies are denoted by open points (21 from Virgo and 42 from Coma). Since \( C_r(\xi) \), as defined in equation (1), is a monotonic function of the global shape parameter \( n \) (Trujillo et al. 2001b), the local density—\( C_r(\xi) \)—relation implies a relation between the local density and \( n \) as well. The strength of these correlations are of course equal. We prefer to maintain the discussion in terms of the concentration parameter because it has a more tangible meaning than the index \( n \).

A point we want to emphasize is the “triangular” form of the shape observed between the galaxy light concentration and the cluster projected density. This kind of relation is what one would expect in case a relation between galaxy light concentration and cluster three-dimensional density is assumed. To understand this, we note that projection effects will tend to mix both more and less concentrated galaxies at higher projected densities, but at lower projected densities only galaxies with low concentrations will be seen; i.e., no high-concentration objects will appear in low-density environments.

To illustrate this, we study what the shape and scatter in the correlation look like by constructing three-dimensional simulated spherical clusters. For simplicity, we use the generalized King model density profile for the three-dimensional galaxy distribution:

\[
\rho(r) = \frac{2^{\beta+1/2}}{[1 + (r/r_c)^2]^{\beta+1/2}},
\]

where \( r_c \) is the core radius and \( \beta \) is a parameter that models the “tail” of the profile. The extension of the tail decreases with increasing \( \beta \). This model has a flat (core) behavior at \( r < r_c \).

Each galaxy in the realization has associated a galaxy light concentration as a function of the cluster three-dimensional density as follows:

\[
C_r \left[ \frac{\rho(r)}{\rho(r_c)} \right] = C_{r,\text{max}} \times \left[ \frac{1}{M} \rho(r) \right]^\beta,
\]

where \( C_{r,\text{max}} \) and \( M \) are the maximum values of the concentration and the cluster density, respectively. The maximum value of \( C_r \) is reached at the center \( r = 0 \). Based on the highest values of the concentration that we observe in our measurements, we set \( C_{r,\text{max}} = 0.7 \). On the other hand, \( M = 2^{\beta+1/2} \) for the King model.

In our models we assume that the distribution of the artificial galaxies that are used to evaluate the local density (i.e., the deeper sample) is described also by the King model. To calibrate the density of this deep sample we have imposed on the model that \( \log \rho_{\text{proj}}(0) = 3 \) [where \( \rho_{\text{proj}}(0) \) is the projected density at the center of the cluster]. This value is close to the highest density that we observe in our observational data (see Fig. 1).

Following equation (3), each point (\( \rho_{\text{proj}}, C_r \)) in Figure 1 can be understood (one-to-one) in terms of the pair (\( R, r \)), where \( R \) is the three-dimensional radial distance and \( r \) is the projected two-dimensional radial distance associated to this point in the cluster model.

The comparison between the simulated model point distribution and the observed point distribution is done by using the generalization of the Kolmogorov-Smirnov (K-S) test to two-dimensional distributions (Fasano & Franceschini 1987). The two-dimensional K-S statistic used \( (D) \) is defined as the maximum difference (ranging over both data points and quadrants) of the corresponding fractions between the data and the model. In order to match the observed point distribution intervals (see Fig. 1), we restrict the above comparison to the 0.18 < \( C_r < 0.70 \) and 1.4 < \( \log \rho_{\text{proj}} < 3 \) intervals.

The cluster simulations—described in the Appendix—are repeated 1000 times so as to build a distribution function \( DF \) for the quantity \( D_{\text{max}} \) (the largest difference of \( D \) for each cluster simulation). Finally, we repeat the process, this time using our observed data points, to obtain \( D_{\text{max, obs}} \).

Following standard statistical methods, we evaluate the probability associated with the measured value of \( D_{\text{max, obs}} \) by cal-

![Fig. 1.—Light concentration index is plotted vs. the projected surface density. Filled symbols correspond to bright elliptical galaxies (\( M_B < -17.5 \)) in the Coma Cluster (triangles) and Virgo Cluster (circles). Open symbols are dwarf galaxies in Coma (triangles) and Virgo (circles). Overplotted on the observed points is a simulated cluster realization of 1000 points (small dots) following equation (3), with \( \beta = 1.3 \) and \( \delta = 0.2 \) (see text for details).](image-url)
calculating the fractional area under the $DF$ curve where the frequency is equal to or less than that of $D_{\text{max, obs}}$.

In Figure 2 we plot the isocontours of confidence level 68% and 95% associated with our models. To illustrate how well one of the “acceptable” models can reproduce the shape of the data distribution, a realization of the model $\beta = 1.3$ and $\delta = 0.2$ (using 1000 points) is overplotted on the observed distribution in the log $\rho_{\mu} - C_{\mu}$ diagram in Figure 1. It clearly shows that the shape and the dispersion present in Figure 1 are just the product of the projection effects, even when starting from perfectly noiseless three-dimensional relations, such as the one in equation (3).

In looking at Figure 1, note that the toy galaxies crowd near the diagonal (in particular the upper right corner), while most of the real galaxies (in particular dE galaxies) are located in the bottom part of the plot. To explain this different distribution we must note first that when constructing the artificial clusters, we ignore the actual luminosity function of elliptical and dE galaxies in the cluster (i.e., artificial galaxies are placed in the clusters taking into account only the density profile).

It is clear that any improved version of the present models (out of the scope of this Letter) would have to take into account the fact that the dE galaxies are more abundant than elliptical galaxies. Moreover, as the dE galaxies are also less concentrated objects than the elliptical galaxies (see, e.g., the luminosity-concentration diagram in Fig. 8 of Graham et al. 2001), one can expect that in observed galaxy distributions, as in the one presented in Figure 1, most of the galaxies are found in the bottom part of the plot.

The distribution of artificial galaxies is also a function of the assumed symmetry used to describe the cluster (in our case spherical symmetry). The diagonal line in Figure 1 is populated by the artificial galaxies that lie over the plane perpendicular to the line of sight passing through the cluster center. The fact that the structure of real clusters departs significantly from the spherical symmetry of our simple model accounts for the differences between the observed and simulated distributions.

To evaluate the null hypothesis (i.e., the absence of any relation between the galaxy light concentration and the cluster density), we have constructed three-dimensional clusters where each galaxy has a concentration index independent of the density and randomly distributed in the interval $0 < C_{\mu} < 0.7$. The null hypothesis is rejected at a confidence level of more than 99.99%. This is the main result of this Letter: whatever the exact form of the relation between galaxy light concentration and cluster density may be, it is clear that such a relation exists. Also, we have checked the consistency of our data by making an internal comparison (based on a two-dimensional K-S test) between the distribution of Virgo and Coma galaxies. The hypothesis that the two samples come from the same parent population turns out to be acceptable (rejection probability $\sim$0.3).

4. DISCUSSION

A discussion of the mechanisms that may be acting to generate the above correlation was presented in T01a. There, we explained that a mechanism based on mergers is favored over other scenarios based on tidal friction and high-speed impulse encounters. In any case, in the center of galaxy clusters, different mechanisms may be operating to reshape the form of the galaxies, and no single mechanism is expected to account for the whole range of observed properties.

From the model we have proposed to analyze the distribution of galaxies in Figure 1, it follows that dE galaxies do not populate the central region of the clusters. Using equations (2) and (3), it is easy to determine the radial distance to the center of the cluster once the galaxy concentration is known. Assuming that the maximum galaxy light concentration of dE galaxies is 0.4 (see Fig. 1) and that the acceptable models are in the ranges $1.2 < \beta < 1.8$ and $0.15 < \delta < 0.35$ (see Fig. 2), dE galaxies are removed from the center of the clusters out to a radius of $\sim1r_c - 3r_c$.

Other authors (Secker, Harris, & Plummer 1997; Gregg & West 1998; Adami et al. 2001; Andreon 2002) have found independent evidence supporting this result. This would be an indication that in the denser cluster environments, the dE galaxies (which are only weakly gravitationally bound) can be destroyed by tidal disruption. For the King model, we can make a direct comparison between our results and the cluster evolutionary model proposed by Merritt (1984), in which tidal forces in the cluster center disrupt the galaxies. The minimum size that a galaxy must have in order not to be tidally disrupted is $\sim15 h^{-1}$ kpc. The maximum of the tidal disruption forces is reached at $r \sim r_c$. Thus, this scenario predicts that dE galaxies are easily destroyed while the larger and more massive elliptical galaxies are able to survive in the center of the cluster. Our results are in good agreement with this.

Another important result that follows from the kind of law suggested in equation (3) is the possibility of making a three-dimensional reconstruction of the elliptical galaxies in the cluster. If the spherical assumption for the density profile of the cluster is good enough, then by measuring the galaxy light concentration of each elliptical galaxy it will be possible to determine its three-dimensional radial distance. Of course, this kind of reconstruction is a priori possible for any law that relates a galaxy property (concentration, size, color, etc.) with the cluster environment density.

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APPENDIX

THE CLUSTER SIMULATIONS

We carried out cluster simulations as follows:

1. We populate each cluster realization with the same number of artificial galaxies as the observed ones (99), having radial distances in accord with the density law in equation (2), and we assign to them the concentration index given by equation (3). The data points are then projected on the \( \log p_{proj} - C_p \) diagram.

2. For each point \((x, y)\) in the diagram, we compute the fractional number of data points in the four quadrants \( f_1(x > x_o, y > y_o), f_2(x < x_o, y > y_o), \) and \( f_3(x > x_o, y < y_o) \).

3. We then compute, for the same points, the expected fractions given by our density model, which can be determined analytically using the following expressions:

\[
f_\ast = F(r^{+}) - \frac{\int_{0}^{\ast} \cos \left[ \arcsin \left( \frac{R^+}{u} \right) \right] \rho(u)u^2 \, du}{\int_{0}^{\ast} \rho(u)u^2 \, du}, \quad (A1)
\]

\[
f_\ast + f_1 = F(r^+), \quad (A2)
\]

\[
f_\ast + f_2 = 1 - F(r^+), \quad (A3)
\]

\[
f_\ast = 1 - F(r^+) - \frac{\int_{0}^{\ast} \cos \left[ \arcsin \left( \frac{R^+}{u} \right) \right] \rho(u)u^2 \, du}{\int_{0}^{\ast} \rho(u)u^2 \, du}, \quad (A4)
\]

where \((R^+, r^+)\) are the values of projected and three-dimensional radial distances, respectively, associated to the observed point \([\log p_{proj}(i), C_p(i)]\), and \( F(r) \) is the cumulative distribution function defined (for a radial symmetric model) as

\[
F(r) = \frac{\int_{0}^{\ast} \rho(u)u^2 \, du}{\int_{0}^{\ast} \rho(u)u^2 \, du}, \quad (A5)
\]

with \( \rho(u) \) given by equation (2). For the King model proposed above, \( F(r) \) can be derived analytically when \( 1 < \beta < 2 \):

\[
F(r) = \frac{4}{3\pi} \left[ \frac{r}{r_c} \right]^3 \frac{\Gamma(1/2 + \beta) \cdot \Gamma[3/2, \beta + 1/2, 5/2, - (r/r_c)^2]}{\Gamma(\beta - 1)}, \quad (A6)
\]

where \( \Gamma \) is the hypergeometric function (Abramowitz & Stegun 1964, p. 556).

4. For each point \((x, y)\) we find the maximum difference between the observed and expected fractions in the four quadrants. This is repeated for all data points, so as to obtain the largest difference \( D_{\text{max}} \) for each cluster simulation.

\[1\) In our case \([\log p_{proj}(i), C_p(i)]\).

\[2\) By construction, \( f_1 + f_2 + f_3 + f_4 = 1 \).

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