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Investigation of the dwarf galaxy population in Hickson Compact Groups

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Hickson Compact Groups (HCGs) are excellent laboratories for the study of the influence of the environment on galaxies. We used dwarf galaxies as tracers and identified them in the outer regions of HCGs with the intention to investigate if the groups are physically bound systems or chance configurations of individual galaxies. In order to establish the dwarf galaxy content of such groups, we observed a sample of five HCGs (16, 19, 30, 31, 42) with the WFI ($0.^\circ 54 \times 0.^\circ 57$) at the ESO/MPIA 2.2 m telescope at La Silla and found more than 2000 new dwarf galaxy candidates in each group. In order to determine the group membership of dwarf elliptical (dE) galaxies we used the red sequence of the Color Magnitude Diagram and additionally morphology, radial light profile, and the surface brightness of the candidate galaxies.

From this analysis it is possible to draw the conclusion that the CGs of our sample are not chance configurations but physically bound systems where dE galaxies have evolved due to the influence of their surroundings. The density distribution of these galaxies decreases from the center to the boundaries of our mosaic data. In all of our HCGs the dwarf galaxy members extend far beyond the density centers of catalogued CGs. Using velocity information of a subsample we calculated the radius of the zero–velocity–surface which is in the order of 2 Mpc indicating sizes similar to galaxy clusters. The determined Luminosity Function (LF) of HCGs matches with the predicted LF of Cold Dark Matter models of dense environments.

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1. Introduction

The analysis of the spatial distribution of galaxies shows, that these are not homogeneously distributed, but except isolated field galaxies they also form galaxy clusters and groups. Galaxy clusters consist of approximately 1000 member galaxies. Galaxy groups are distinguished between Loose Groups (LGs) and Compact Groups (CGs). LGs are composed of around 100 galaxies. These are distributed over a large area with galaxy separations of some 10 galaxy radii. And finally CGs: the smallest systems, containing galaxies.

Hickson [10] was the first, who introduced quantitative selection criteria for CGs. The groups he investigated were then called Hickson Compact Groups (HCGs). The criteria characterise the group membership of galaxies in projection. After the velocities of all member galaxies were known, 1/10 of the 100 HCGs had to be excluded, because they included galaxies with velocities far beyond the average galaxy velocity of the group. With time other catalogues with CGs followed like e.g. the Southern Compact Groups (SCGs; [20]) or the Redshift Selected Compact Groups (RSCGs; [2]). Up to now hundreds of CGs are known, but the nature of CGs is so far unknown. The proximity in projection and the proximity in redshift space argue for physical associations. These are necessary, but not sufficient criteria for a bound system. In the literature arguments exist, which point to a random configuration of galaxies as well as to CGs being physically bound systems (for more information see [14]). The literature results are still controversial and give no clear statements concerning the nature of CGs. The subject of this work was the determination of the nature of CGs using dwarf galaxies (dgs). This is possible, because dgs are the most common type of galaxies. Dwarf irregular galaxies (dIrr) are mainly found in regions of low galaxy density, like e.g. in the outer areas of galaxy clusters or in the field [25]. Dwarf elliptical galaxies (dEs) are mainly found in regions of high galaxy density, like e.g. in the centers of galaxy clusters or as companions of large galaxies [5]. The environment strongly influences the evolution of dgs, thus they are a good indicator for their surrounding. Therefore the question can be answered depending on the number of dE and dIrr galaxies found, if these systems are physically bound systems or chance configurations of individual galaxies. For this reason we determined the whole galaxy population of a sample of five HCGs.

2. Data and Datareduction

We have compiled a set of the five nearest HCGs (16, 19, 30, 31 and 42) using the ESO/La Silla 2.2 m telescope in combination with the Wide Field Imager (WFI). The WFI is an array CCD camera, consisting of $8 \times (2046 \times 4098\,\mathrm{pixels})$ chips with a pixel scale of 0.238 arcsec per $15\,\mu$m pixel acquirering a large field of view $(0.54^\circ \times 0.57^\circ)$ [1]. In order to cover the gaps between the individual CCD images, the HCGs were observed while splitting the integration time into four exposures and an additional spatial offset among the sub exposures. The data were obtained in Johnson–Cousin B and R broad band filters (B/99, Rc162). The exposure times for the B band images amount to 5400 s and to 2700 s in the R band. With this a surface brightness limit of $27\,\mathrm{mag/arcsec^2}$ in the B band and $26\,\mathrm{mag/arcsec^2}$ in the R band were reached. Further standard stars from the Landolt sample [15] were observed for calibration purposes.

The data were reduced using IRAF (Image Reduction and Analysis Facility), and specially MS-

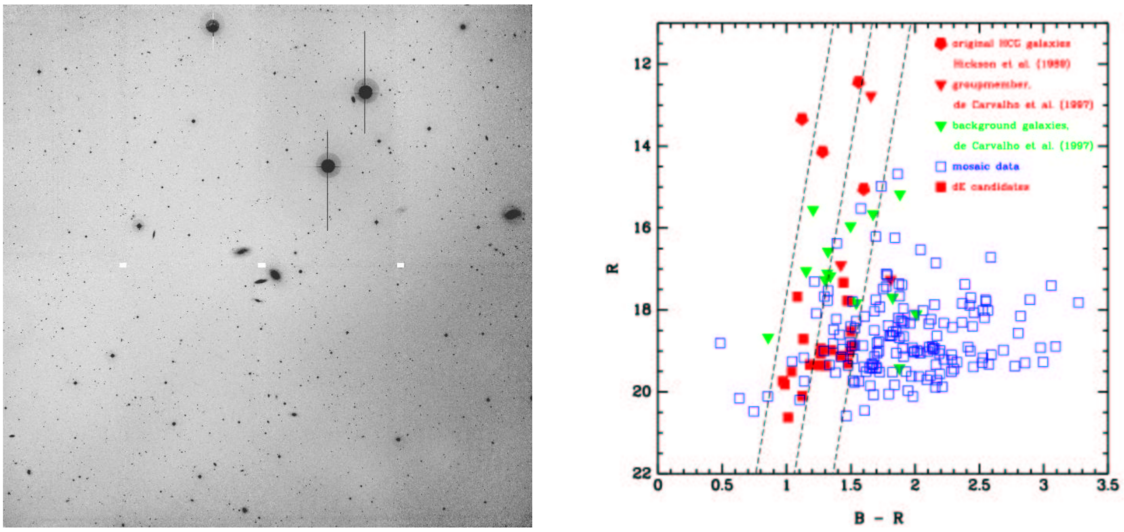

Figure 1: The left panel shows the final reduced mosaic image of HCG 19 in the *R* band. The right panel shows the CMD of galaxies found in the large field around HCG 19.

CRED Version 2.0 [27], which was originally developed for handling and reducing data from the NOAO CCD Mosaic Imager. During the course of the reduction it became apparent that the standard software was incapable to produce images of the quality needed. Thus new reduction solutions had to be developed, especially concerning the flattening of the strong variations in the background values of the individual CCD images. For more information concerning the data reduction see Krusch et al. [14]. The left panel in Figure 1 shows as an example the final reduced mosaic image of HCG 19.

During the object detection and extraction, which was performed using the program Source Extractor [4] between 270 and 5000 galaxies were identified per field. In order to determine the dg candidates of the group, all galaxies were excluded, which are smaller than the smallest identified dg of the Local Group [16] projected to the distance of the CG. The number of possible dg candidates was reduced to between 212 and 470 galaxies. The aim of the work was the determination of the nature of the CGs using dgs. Therefore it had to be ensured, that the sample consists of dgs, which belong to the group. Since no velocity information exist for the remaining dg candidates, their group membership was determined using Color Magnitude Diagrams (CMDs) in this work for the first time.

3. Color Magnitude Diagram

The determination of group membership is a common problem when studying faint galaxy populations in clusters and groups. The most reliable method of taking spectra to determine redshifts for all candidates is a very telescope–time consuming task and is also limited to the brighter galaxies [30]. All studies conducted up to now concerning dgs in CGs have problems to distinguish between real dgs and other unrelated background galaxies. Therefore a method was developed by Krusch et al. [14] to determine the group membership of the galaxies from a preselection using Color Magnitude Diagrams (CMDs) in the absence of redshift information. The investigation of galaxy clusters shows that dE galaxies dominate a certain area in the CMD. The sequence is not a chance distribution of objects, but stands for galaxies of a certain stellar population, which belongs to the galaxy cluster. Secker et al. [26] determined a color–magnitude relation for the dE member galaxies for the Coma Cluster and Conselice et al. [6] determined this relation for the Perseus Cluster. They found that the two clusters have identical dE galaxy sequences within the errors. This relation was used for the determination of the high probability group membership of dwarf elliptical galaxies in the CMDs of the sample HCGs. The right panel in Figure 1 illustrates the CMD of galaxies, which were found in the large field around one of the galaxy groups, around HCG 19. The red pentagons represent the original HCG galaxies. All symbols, except the pentagons represent all dg candidates. For some galaxies radial velocities are known from the literature. Few of them (red triangles) were identified as group members by their radial velocity and the green triangles denote the galaxies, which can be excluded due to their radial velocity. The dashed line represents the color magnitude relation for the red sequence [6, 26] and the 1 σ error. All galaxies lying in the "red sequence" are favoured to be dwarf elliptical member galaxies. All galaxies bluer than the red sequence are high probability dwarf irregular galaxy candidates. All galaxies redder than the red sequence can be excluded being background galaxies. However some background galaxies (green triangles) can be found in this area. For this reason dE and dIrr group members were extracted additionally from a detailed inspection of the morphology, the isophotes, and the radial light profile of the individual galaxies lying in the red sequence and bluewards of the red sequence. In each CG more than 75 % of the galaxies were identified as dEs. This is the first evidence for CGs being physically bound systems.

4. Luminosity Function

With the Luminosity Function (LF) it is possible to relate quantitatively the galaxy content in different environments. The shape of the LFs of these environments is usually modelled using a Schechter function [24]:

$$\phi(M) = \frac{2}{5} ln(10) \phi^* \left(10^{0.4(M^*-M)}\right)^{(\alpha+1)} exp\left(-10^{0.4(M^*-M)}\right) \tag{4.1}$$

with α and M^* as the fitting parameters and ϕ^* the normalization parameter. α determines the slope of the LF at the faint end where e.g. $\alpha = -2$ describes a divergent total luminosity case and $\alpha = -1$ produces a flat differential LF. M^* characterizes the absolute Magnitude at which the LF shows a change in the slope and $\phi(M)$ determines the number of galaxies per unit volume. The LF of HCGs, especially the result detecting a high number of dgs, can give important clues to the understanding of the models of galaxy formation, which predict the existence of many low–mass halos [3, 8, 12, 19]. There small systems form earlier and collapse occurs at progressively large scales with small halos merging into larger units. During that process many of the low mass halos survive. Thus there should be much more dgs than giant galaxies. Comparing the results from literature concerning the shape of the LF in CGs an analogy cannot be found. On the one hand results exist, which point to LFs of CGs similar to the field [21, 13, 31, 17, 10] and on the other hand other results can be found, which strengthen an existence of a dg population in galaxy groups [18, 7, 29, 11]. The different conclusions may be explained by the fact, that the measurement of the

LF generally proves to be difficult due to the different observational selection criteria in samples (e.g. magnitude limited or volume limited such as galaxy groups or clusters) and few information concerning the group membership of galaxies.

Although in general HCGs were well investigated in the last years, the faint end of the LF was sparsely discovered, yet. The LF presented in Figure 2 provides a main improvement to the faint end of the LF of compact galaxy groups. It is based on the results of Krusch et al. [14] reporting the deepest sample of HCGs derived by WFI mosaic data.

The LF was determined for all sample HCG member galaxies down to a magnitude of $B = -12.5$ mag which is near to the maximal depth of the mosaic images lying approximately at -12 mag in the B band. Fringe corrections and the diffuse light correction, which were performed during the reduction of the mosaic data, prevented to determine a precise value for the completeness limit. Nevertheless the limiting magnitude of $B = -12.5$ mag allows to analyze the faint end of the distribution in more detail. The data points in Figure 2 represent all HCG group members. This comprises members discovered and confirmed photometrically (see section 2) as well as the few members investigated spectroscopically by additional studies extracted from literature. Galaxy members lying in the interval -20.25 mag $\leq B \leq -16.25$ mag were binned in 1 mag steps and reflect the number of giant galaxies per interval. They are subject to small number statistics, which is expected due to the definition of HCGs [10]. Faint galaxies, lying in the interval -16.25 mag $\leq B \leq -10.25$ mag, were binned in 0.5 mag steps, which proves to be adequate because the intervals are still larger than the largest estimated magnitude error per galaxy.

The distribution of all sample HCG member galaxies shown in Figure 2 can be divided in two qualitatively distinct parts. At the bright end, from ≈ -20 mag to -16 mag, the distribution can be described by a plateau, which is slightly declining towards fainter magnitude intervals. Beginning at the magnitude interval of ≈ -15 mag the number of galaxies per interval unit rises steeply reaching a maximum at ≈ -12 mag. Thereafter a steep drop can be observed which coincides with the limiting magnitude for the depth of the observations in the B band.

The two quantitatively distinct parts, representing two different galaxy populations were verified by [18] recently. They divided their sample into X–ray dim and X-ray bright groups. The latter do not show such a division, although the LF of the X–ray dim groups (to which all HCGs of their sample belong) does. The empty cirles in Figure 2 detnote the LF of the X–ray dim groups and the dotted lines represent the Schechter fits to the bright and faint part [18]. The faint end of LFs in dense environments like galaxy clusters is dominated by faint galaxies (namely dgs). Comparing the LF in Fig. 2 to that of galaxy clusters [23] implies that HCGs have a higher number density of dgs per giant galaxies than galaxy clusters. The LF of the HCGs shows a steep slope at the faint end, steeper than the Schechter function for field galaxies and also steeper than the slope of the LF of dE in galaxy clusters [14]. According to this, galaxy groups possess a similarity with galaxy clusters. They even possess a higher number density of dEs per luminous galaxy than galaxy clusters. These are arguments for CGs being physically bound systems and not chance configurations of individual galaxies.

The Cold Dark Matter (CDM) theory predicts values of $\alpha \leq -1.6$ for dense environments. The steep rise of the HCG member galaxy data points (Figure 2), which is due to the number of identified dgs strengthens these predictions. A fit to the faint end of HCG galaxies (Figure 2, solid line) provides $\alpha = -1.73$.

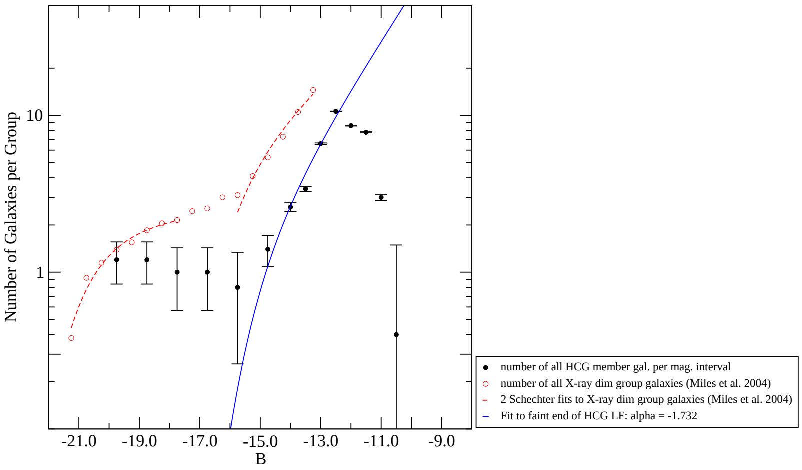

Figure 2: *B* band Luminostiy Function of 5 HCGs (filled circles). The empty cirlces denote the LF of X–ray dim galaxy groups and the according Schechter fits (dotted lines) [18]. The solid line shows the Schechter fit to the faint end of the HCG galaxy sample.

5. Extension and Mass

The investigation of the density distribution of all dgs, which were selected from the 'red sequence' of the CMD and further few galaxies, which belong to the group due to their velocity information showed a density peak in the center, which decreases to the boundaries of the mosaic data [14]. HCG 16, 30 and 42 show a decreasing density distribution, which best fits the results of galaxy clusters, because in both cases dgs are more common in the inner areas. This is another evidence for the physical nature of CGs. In all density distributions member galaxies are found at the boundaries of the mosaic images. This gives a hint, that groups have to be more expanded than 200 – 250 kpc. The whole extent of the CGs was not reached with the mosaic data. In order to determine the extension of the HCGs velocity information and positions are necessary. With their help the mass and with the mass the extension of the group can be determined. For few galaxies velocity information from the literature are known. Objects were chosen, which possess a projected distance smaller than 2 Mpc from the group center as well as a velocity, which is smaller than 500 km/s compared to the average velocity of the group. In order to determine the mass and the extension of the group, the dynamical mass was calculated using the projected mass estimator according to Heisler et al. [9] (equation 5.1) and the radius R_0, the so called zero–velocity–surface, from which galaxies participate in the Hubble expansion was calculated via Sandage [22].

$$M_{dyn} = M_{PM} = \frac{32/\pi \sum_i v_i R_i}{G(N_m - 1.5)} \qquad\qquad R_0 = \left(\frac{8GT^2}{\pi^2} M_{dyn}\right)^{\frac{1}{3}} \tag{5.1}$$

Where N_m is the number of galaxies, v_i the radial velocity of the galaxies, R_i the radial distance from the group center and T the age of the universe. The virial theorem and the projected mass

HCG	N_m	M_{dyn} $[h^{-1}\mathrm{M}_\odot]$	ΔM_{dyn} $[h^{-1}\mathrm{M}_\odot]$	R_0 $[h^{-1/3}$ kpc]	ΔR_0 $[h^{-1/3}$ kpc]
16	15	6.251×10^{12}	5.16×10^{9}	1646	0.94
19	11	1.107×10^{14}	2.94×10^{10}	4292	0.79
30	12	4.270×10^{13}	1.55×10^{10}	3124	0.78
31	10	1.512×10^{14}	3.53×10^{10}	4760	0.77
42	37	6.984×10^{13}	9.78×10^{9}	3680	0.36

Table 1: Dynamical mass (M_{dyn}), the error (ΔM_{dyn}), the radius of the zero–velocity surface (R_0), and the statistical error (ΔR_0) for the sample HCGs (with member galaxies (N_m) in an area of 2 Mpc around the center and a velocity dispersion smaller than 500 km/s); systematic errors: $\Delta M_{dyn} \sim \frac{M_{PM}}{\sqrt{N_m}}$.

estimator, which are used for isotrop and spheric symmetric gravitational bound systems, give very similar results, but the projected mass estimator avoids some of the problems of the virial theorem. In particular it is less sensitive to accidental projections of one galaxy close to another. Concerning the presence of substructures and anisotropy the determination of the virial mass can lead to increased masses, and thus it is incomplete concerning the inclusion of the potential energy of substructures. The M_{PM} is most suitable for the determination of the cluster mass from the galaxy motion [9]. A problem in general are the unknown physical boundaries of the groups, which are due to the sensitivity of the detectors and the criteria, which define a cluster or a group. Groups are mainly triaxial and not spherically symmetric, the distribution of cluster and group galaxies is not isotrop, because of the infall of galaxies and material. As result (Table 1) we receive masses, which differ by about two orders of magnitude. They even reach typical masses of galaxy clusters. The radii lie between 2 and 5 Mpc – they are much larger than 200 – 250 kpc, larger than the area, which was covered by the mosaic data.

6. Summary and Conclusions

We investigated the dg population in compact galaxy groups in order to determine the nature of these systems. From the reduction of the mosaic data between 200 and 470 dg candidates could be identified. Since only for few candidates radial velocities exist in the literature, the group membership was determined using CMDs and structural parameters, like the investigation of the morphology and the radial light profile. Applying these methods more than 75 % of the galaxies were identified as dEs. The result shows, that the number of member galaxies is larger than the number of the original HCG galaxies and further, that the groups may be physically bound systems where dEs were formed due to the influence of their surrounding. The density distribution show concentrations in the center of the groups, which decrease to the boundaries of the mosaic data in the majority of the investigated cases. Further the density distribution shows, that the boundaries of the CGs were still not reached with the mosaic data, so that it has to be assumed, that groups have to be much more extended than 200 – 250 kpc. From the calculation of the extension of the group we obtain radii, which lie between 2 and 5 Mpc. These lie in the order of the extensions of galaxy clusters. This confirms some results from literature, where CGs are not isolated (e.g. [28]), but embedded in larger systems like LGs where they would have been formed by the infall of smaller structures, namely dgs. A preliminary comparison between the predictions of the CDM–theory and the faint end of the LF of HCGs shows, that these results may be consistent.

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