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Objectively selected samples of galaxy multiplets : an analysis of observed properties

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Abstract.
A method of searching for multiplets in a large catalogue of galaxies with measured redshifts is described. Compact Groups samples having different local and global characteristics are generated when the algorithm is applied to ZCAT catalogue. Both local and environmental galaxy density have been computed thus allowing to define truly isolated compact groups as well as compact groups in dense and medium dense environments. We find 40% of our compact groups to be isolated while as much as 20% are identified in high density structures.

1. Introduction

Triggered by early work on individual groups of galaxies (e.g. Burbidge and Sargent, 1971) which pointed out some puzzles and apparent contradictions, Hickson (1993) produced the first catalogue of Compact Groups of Galaxies by inspecting the Palomar Survey Prints according to "sensible" criteria of compactness isolation and population. The addition of further studies, and in particular the measurement of redshifts for all the 463 galaxies forming the 100 groups of the original list (Hickson et al., 1992), have changed somewhat the scenario (Hickson, 1997). What seemed to be a "complete" sample turned out to be contaminated by chance superposition, many groups lost one or more members and 8 had to be rejected. The "Hickson Compact Group" (HCG) catalogue quickly became a focal point of interest. Studies at different wavelengths revealed a complex nature of the structures: in optical images interactions and merging became apparent for many galaxies, 21 cm radio emission studies revealed deficiency of hydrogen in spirals (Rood and Williams, 1989, Williams, McMahon and van Gorkom, 1991) and VLA continuous non-thermal radiation evidenced the presence of supernova remnants and recent star formation as well as sign of nuclear activity in the core of some of the galaxies (Menon and Hickson, 1985, Menon, 1992). Star formation signs were also found in infrared studies (Hickson et al. 1989). X-Ray emission was studied using ROSAT and several groups were detected (see Ponman, this conference). It also emerged that some of HCGs are actually parts of larger groups far more extended (Ramella et al. 1994, de Carvalho et al, 1997, Ribeiro et al, 1998). The main questions are the isolation criteria and how truly isolated any structure is. The scientific interest on groups of galaxies has grown to the point that several international conferences have been organized in the last decade, this one being the most recent. The scientific motivation for the work presented here is to find clues about the influence of the environment on the formation and evolution of galaxies hosted in galaxy structures like pairs, compact groups, loose groups and clusters. In order to proceed by steps one needs to sort out the problems on rather small scales first. In the present work we present preliminary considerations on the problem of groups of "a few" galaxies and study how these are distributed within different environments.

A Hubble constant $H_0 = 100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ has been assumed throughout the paper.

2. The "Objective" Search Method

With the compilation of large galaxy redshift databases it is now possible to define criteria, similar to Hickson's original two dimensional criteria but in 3D, to search for companion galaxies in volumes of a given size. In principle if the redshift catalogue coincides with the real galaxy distribution one can immediately answer the question: how many compact groups are there in the nearby Universe, and are they really isolated? Of course the first question here is: what is the definition adopted for a compact group? In other words, how many galaxies should we find in how small a volume? Moreover, a compact group is isolated if no other galaxy is found in a "large" volume around the group. Here again what is meant by "large"? In the following the results of a search on ZCAT giving 60,000 galaxies with measured redshifts and distributed on the whole sky are presented. The criteria adopted are a 3D version of Hickson's i.e. three or more galaxies within an area of radius **r** are considered part of a compact group if their redshifts differ by less than 1000 $\mathrm{km\,s^{-1}}$. Actually, Hickson's criteria are somewhat different. He gave a lower limit of four galaxies, but after redshift measurements were carried out on HCGs it turned out that a sizable fraction of quadruplets were triplets. This we decided to keep three as the lower limit for the definition of a CG.

In order to quantify compactness the following values for **r** have been chosen: 30, 50, 70, 100 kpc so that the corresponding volume of space roughly doubles at each step (actually from 30 kpc to 50 kpc the volume more than doubles, **r**=25 and **r**=35 were tried, the difference in samples is negligible and therefore the round values were adopted). Once a CG was detected by the search program a volume contained within a radius **R** = 0.5 Mpc and **R** = 1 Mpc was inspected for the presence (or absence) of other galaxies in a redshift range of $\pm 1000\ \mathrm{km\,s^{-1}}$. Neighbours to our CGs are all galaxies within **r** and **R**.

Preliminary run of our algorithm on "complete " galaxy catalogues (Falco et al. 1999, Paturel et al. 1989) give results largely in accordance with those obtained using ZCAT. Within the uncertainties which result from the ZCAT incompleteness the following questions can be addressed:

• Does the number of CGs increases when the area in which they are contained increases? If yes, what does the growth curve look like? Allowing **r** to increase will decrease the group compactness but possibly also increase the number of compact groups with 4 or more members.

These effects can be studied in order to reach a reasonable compromise and sort a value for **r** which is the most suitable one.

- Given **r**, how many compact groups found are in HCG? and how many are new compact groups?
- Which is the most favourable environment for compact groups, i.e. are most compact groups hosted in dense, sparse or medium dense environments?

Our samples are extracted from ZCAT with an automated algorithm. Therefore we are presently checking the "isolated" CGs on DSS images in order to verify that no "obvious" galaxies have been left out because of no available redshift measurement (Focardi et al, in preparation).

3. Automatically detected CG samples

Our CG samples have been generated using different values for the parameters **r** and **R**. Parameter **r** controls the local CG scale, while **R** gives a rough estimate of the global environment. The results obtained running the algorithm on ZCAT with different values for local parameter **r** are summarized in table 1.

Table 1. Number of compact groups as a function of search radius **r**.

r (kpc)	n=3	$< dist >$	n=4	$< dist >$	n>4	$< dist >$
30	168	11	38	11	15	13
50	293	19	106	20	38	23
70	423	27	159	29	94	34
100	606	39	238	41	167	48

Notes: n refers to the number of members in the compact groups, $< dist >$ indicates the mean projected distance (kpc) of the CG members from the group center.

If CGs had a typical scale we would expect their number not to increase with **r**. Conversely, if they do not show a typical dimension their number should increase with the searching area, and their true nature would be somehow questionable.

CGs total number as a function of **r** is shown in fig. 1

The increasing trend with **r** is visible and systematic. Even though the number of detected CGs does not increase as the "searching area" there does not seem to be a characteristic CG size up to 100 kpc.

Still if CGs with different multiplicity are compared a typical scale seems to come out.

Figure 2 shows the relative fraction of triplets over quadruplets, triplets over CG with at least 4 members, and quadruplets over GCs with higher multiplicity. The fraction of triplets decreases from **r**=30 kpc to **r**=50 kpc where it reaches a stable value, whilst the fraction of quadruplets stabilizes further out at **r**=70 kpc.

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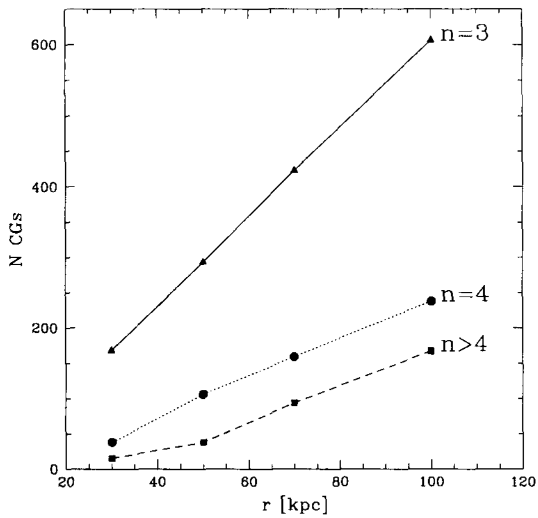

Figure 1. Total number of detected CGs as a function of **r**.

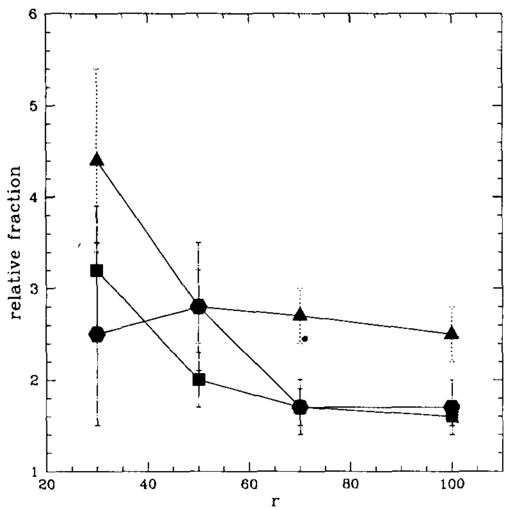

Figure 2. Relative fraction of triplets over quadruplets (triangles), of triplets over CGs with at least 4 members (squares), of quadruplets over higher multiplicity CGs (hexagons) as a function of increasing **r**. Poissonian errors are shown.

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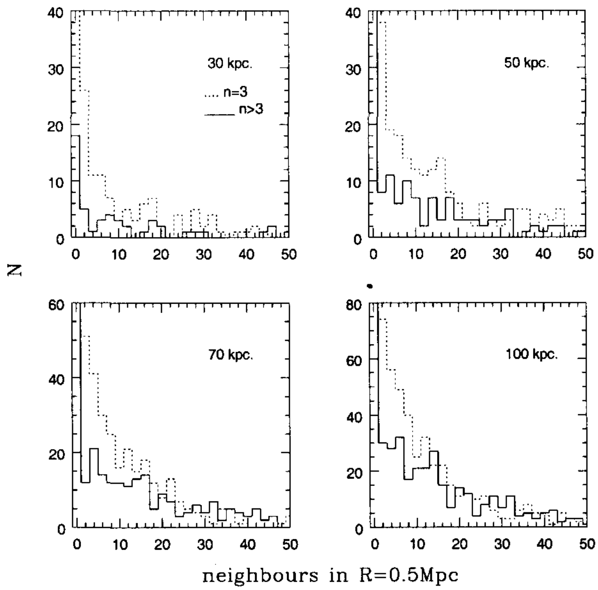

Figure 3. Detected CGs for different values of r vs. number of neighbours surrounding the CG within **R** = 0.5 Mpc.

Therefore we are likely to have found a typical searching "scale" for discriminating between triplets and higher multiplicity CGs. It appears that 30 kpc is the best choice for a CG sample strongly biased towards triplets, while 70 kpc produces a CG sample in which groups with 5 or more members become relevant. The value of **r**=50 kpc is thus an appropriate choice: it guarantees a high galaxy density (the mean distance to the center is around 20 kpc) while still maintaining a high fraction of CGs with at least 4 members (see fig. 2).

Galaxies (with $cz \leq 10{,}000\ \mathrm{km\,s^{-1}}$) belonging to CGs, at **r**=50 are ≈ 900 in number, this implies that ≈ 2.2 % of all ZCAT "nearby" galaxies are located in CGs. Exclusion of triplets from this computation reduces the fraction to $\approx$ 1%.

4. CGs and their environment

Environmental density of each detected compact group has been computed assigning two different values to the global parameter **R**.

The choice of both, **R**=0.5 Mpc and **R**=1 Mpc allows to roughly sample the environment on scales one order of magnitude larger than the CGs. Moreover at **R**=1 Mpc we reach scales comparable with those of galaxy clusters and groups, thereby allowing to locate detected CGs within larger structures.

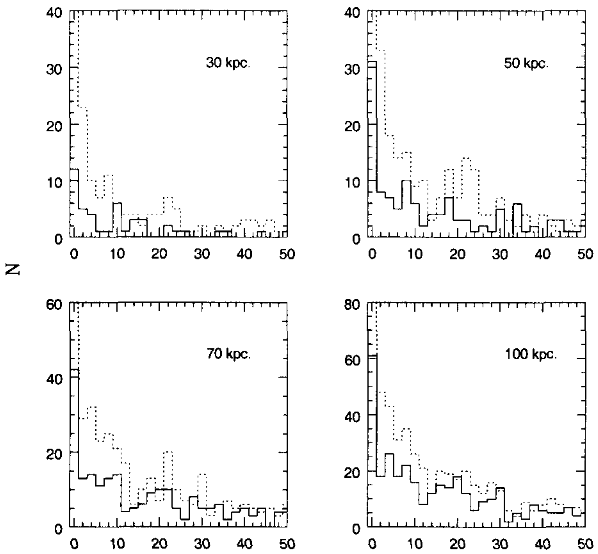

Figure 4. Detected CGs for different values of **r** vs. number of neighbours surronding the CG within **R**=1. Mpc, dotted line corresponds to triplets, solid line to CGs with n $\geq$ 4.

The number of detected CGs as a function of the number of neighbours for each chosen value of **r** and **R** is shown in fig. 3 and fig. 4. At **r** = 30 kpc and partially at **r** =50 kpc both **R** give similar results indicating that besides being an optimal choice for detecting triplets, **r** = 30 also sorts out isolated structures. Distributions get more and more different when **r** is increased, indicating that the looser the CG, the higher the chance of being part of a larger structure. Concerning CGs having 4 or more members, it appears that they are less likely than triplets to reside in sparse density environment (N $\leq$ 10). Within dense environments (more than 20 neighbours) the numbers of triplets and quadruplets become comparable. The number of detected CGs (with 4 or more members) in environment with different galaxy density and for different values of **R** are shown in table 2 and table 3.

5. Is there a preferred environment for CGs?

We have shown that the total number of CGs increases with **r** (fig 1) and that CGs are found within a large variety of global environments. One then might wonder whether the increase in the number of CG is related to their surrounding environment.

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Table 2. Number of CG (4 or more members) within different environments computed for **R**= 0.5 Mpc.

N(neigh.)	$r = 30$	$r = 50$	$r = 70$	$r = 100$
0	11	27	43	65
1-5	13	33	53	82
6-10	9	20	29	60
11-15	3	12	33	58
16-20	5	12	26	33
>20	12	40	69	107

Table 3. Number of CG (4 or more members) within different environments computed for **R**=1 Mpc.

N(neigh.)	r=30	r= 50	r=70	r=100
0	7	20	26	39
1-5	14	26	43	66
6-10	4	16	30	52
11-15	8	11	17	24
16-20	3	11	20	38
>20	17	60	117	186

Fig. 5 shows that the number of CGs belonging to different environments, computed at **R**=0.5 Mpc, increases with **r** with different slopes. This might imply the presence of a typical environment for CGs.

Fig. 6 shows the total number of CGs in different environments for each value of **r**. Environmental bins and **R** correspond to the ones shown in Fig 5. Triplets and multiplets with at least 4 members are shown. A peak corresponding to low density environments (1-5 neighbours) is evident for each **r** thus indicating that a typical environment of 1 to 5 neighbours might be a "common" feature of compact groups, this consideration holds especially for triplets.

A similar behaviour is found when density is computed at **R**=1 Mpc the major difference being that more neighbours are detected and thus less CGs are left in low density regions. The low density peak is still evident, suggesting the presence of a "nearby" loose population.

We might attempt a rough estimate of the average population of CGs belonging to different environments. To do that we have to sharply differentiate the environment. Adopting **r**=50 kpc and **R**=0.5 Mpc and the following definitions: 0-3 neighbours = isolated, 4-20 neighbours = medium density, >20 neighbours = high density, we find that CGs are equally likely to be found in

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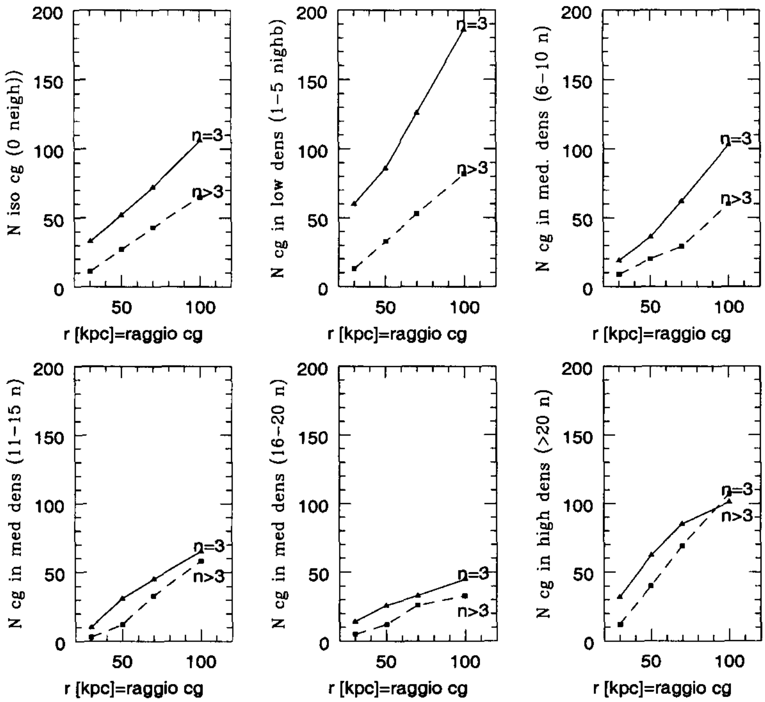

Figure 5. Total number of detected CGs as a function of **r**. Each panel refers to CGs (triplets and n > 3 multiplets) belonging to different environment. Number of detected neighbours refers to **R**=0.5 Mpc.

isolated and medium density environments ($\approx$ 40%) and that as much as 20% of CGs are found in dense environments. Our definition implies overdensities of 50 - 100 for quadruplets in "isolated loci" and overdensities of less than 15 for quadruplets in "dense loci".

The number of isolated CGs becomes larger ($\approx$ 50%) when the average group compactness is increased (**r**=30 kpc) while the fraction of CGs in dense environments keeps constant. Whether CGs in dense environment are real bound systems or rather transient configurations in a larger structure has to be checked.

6. Comparison with HCGs

Our automated procedure has generated large CG samples, and provided environmental information for each of them. The issue now is to verify how physical our samples are, as ZCAT (or any other whole sky catalogue) is not a "complete" catalogue. To get a first, rough estimate of how reliable our samples are

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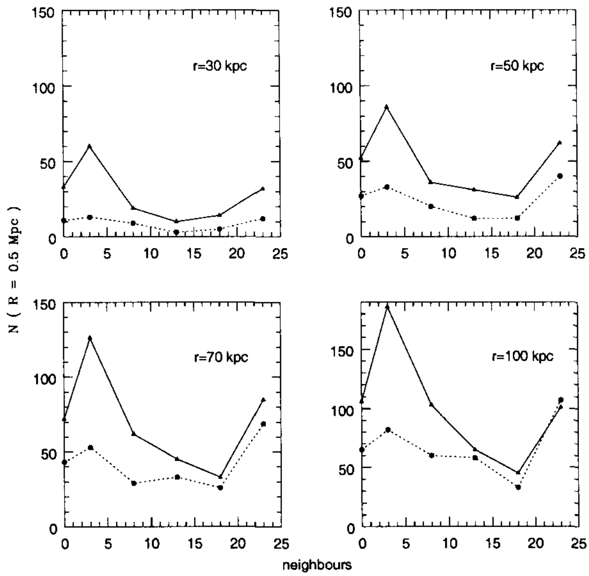

Figure 6. Total number of detected CGs as a function of neighbours. Solid line refers to triplets, dashed line to quadruplets.

we checked for overlap with HCGs. We test the accordance with HCGs only for CGs with 4 or more members, as this was one of Hickson's original selection criteria. The number of HCG triplets is therefore reduced only to the limited fraction of "false" multiplets. At r=30 kpc we identify 53 CGs, 10 of which are HCGs. At r=50 kpc we identify 144 CGs, 37 of which are HCGs. AT r=70 there are 253 CGs, 48 are HCGs. At r=100 there are 405 CGs, 59 are HCGs. Hickson's catalogue includes 69 groups with at least 4 members, thus we get 14%, 54%, 70% and 86% of Hickson's Compact Groups when running our CGs search program with r=30, 50, 70 and 100 kpc. Actually we do find many more CGs than Hickson, mostly because we have applied no isolation criterion, and indeed most of our new CGs are non isolated. In any case, a considerable fraction ($\approx$ 50 %) of HCGs also turned out to be not isolated, being embedded in loose groups.

Comparison with Garcia (1995) and Iovino's (Prandoni et al. 1994, Iovino this conference) CG samples shows an overlap corresponding to 50 % and 17 % respectively.

Our sample includes $\approx$ 50 new isolated CGs , whose true "isolation" is presently under check (Focardi et al., in preparation).

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7. Conclusions

An automated objective search has provided several samples of compact groups having different compactness and environmental density.

A search radius of 50 kpc seems to be the optimized choice for CG detection as it guarantees adequate samples of high multiplicity ($n \geq 4$) CGs while maintaining extremely high galaxy density.

The fraction of isolated CGs is maximum when the smallest search radius is adopted.

Approximately 20 % of detected CGs are located within dense structures.

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