

# The redshift–space two–point correlation function of galaxy groups in the CfA2 and SSRS2 surveys

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Received 9 August 1999 / Accepted 5 November 1999

**Abstract.** We measure the two–point redshift–space correlation function of loose groups of galaxies,  $\xi_{GG}(s)$ , for the combined CfA2 and SSRS2 surveys. Our combined group catalog constitutes the largest homogeneous sample available (885 groups). We compare  $\xi_{GG}(s)$  with the correlation function of galaxies,  $\xi_{gg}(s)$ , in the same volume. We find that groups are significantly more clustered than galaxies:  $\langle \xi_{GG}/\xi_{gg} \rangle = 1.64 \pm 0.16$ . A similar result holds when we analyze a volume–limited sample (distance limit  $78 \text{ h}^{-1} \text{ Mpc}$ ) of 139 groups. For these groups, with median velocity dispersion  $\sigma_v \sim 200 \text{ km s}^{-1}$  and mean group separation  $d \sim 16 \text{ h}^{-1} \text{ Mpc}$ , we find that the correlation length is  $s_0 = 8 \pm 1 \text{ h}^{-1} \text{ Mpc}$ , which is significantly smaller than that found for rich clusters. We conclude that clustering properties of loose groups of galaxies are intermediate between galaxies and rich clusters. Moreover, we find evidence that group clustering depends on physical properties of groups: correlation strengthens for increasing  $\sigma_v$ .

**Key words:** cosmology: large-scale structure of Universe – galaxies: clusters: general – galaxies: statistics

## 1. Introduction

Loose groups of galaxies, the low–mass tail of the mass distribution of galaxy systems, fill an important gap in the mass range from galaxies to rich clusters. Until now, clustering properties of loose groups have been studied on the basis of rather small samples. The results are consequently uncertain and even contradictory. Nevertheless, clustering properties of groups are shown to be robust against the choice of the identification algorithm, provided systems are identified with comparable number overdensity thresholds (Frederic 1995b).

The two–point correlation function, CF, of galaxies and of galaxy systems constitutes an important measure of the large–scale distribution of galaxies (e.g., Davis & Peebles 1983; Bahcall & Soneira 1983; de Lapparent et al. 1988; Tucker et al. 1997; Croft et al. 1997). From galaxies to clusters the two–point correlation function in redshift–space,  $\xi(s)$ , (e.g., Pee-

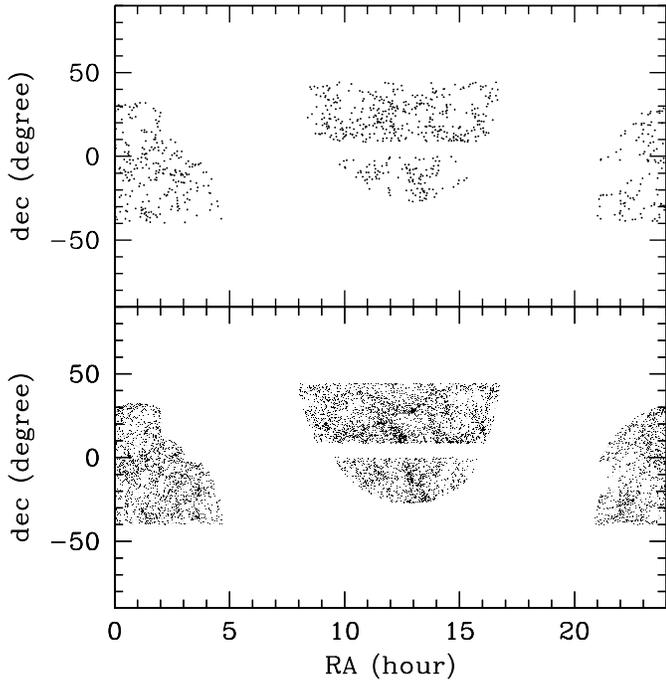
bles 1980), is consistent, within errors, with a power–law form  $\xi(s) = (s/s_0)^{-\gamma}$  with  $\gamma \sim 1.5\text{--}2$  for a variety of systems. The correlation length,  $s_0$ , ranges from about  $5\text{--}7.5 \text{ h}^{-1} \text{ Mpc}$  for galaxies (e.g., Davis & Peebles 1983; Loveday et al. 1996; Tucker et al. 1997; Willmer et al. 1998; Guzzo et al. 1999) to  $s_0 \gtrsim 15 \text{ h}^{-1} \text{ Mpc}$  for galaxy clusters (e.g., Bahcall & Soneira 1983; Postman et al. 1991; Peacock & West 1992; Croft et al. 1997; Abadi et al. 1998; Borgani et al. 1999; Miller et al. 1999; Moscardini et al. 1999).

As far as loose groups are concerned, previous determinations of the CF are very uncertain. From the study of 137 groups (within CfA1) and 87 groups (within SSRS1), Jing & Zhang (1988) and Maia & da Costa (1990) respectively find that the group–group CF,  $\xi_{GG}(s)$ , has a lower amplitude than the galaxy–galaxy CF,  $\xi_{gg}(s)$ . Analyzing 128 groups in a sub–volume of CfA2N, Ramella et al. (1990; hereafter RGH90) find that the amplitudes of  $\xi_{GG}(s)$  and  $\xi_{gg}(s)$  are consistent (see also Kalinkov & Kuneva 1990). Finally, Trasarti–Battistoni et al. (1997) study 192 groups in the Perseus–Pisces region and find that the amplitude of  $\xi_{GG}(s)$  exceeds that of  $\xi_{gg}(s)$ .

The theoretical expectations for the relative strength of the group and galaxy clustering are also contradictory. Frederic (1995b) determines the correlation function for galaxy and group halos in CDM numerical simulations by Gelb (1992) and finds that groups are more strongly correlated than galaxies. In contrast, Kashlinsky (1987), on the basis of an analytical approach to the clustering properties of collapsed systems of different masses, concludes that groups and individual galaxies should be correlated with the same amplitude.

Here we compute the two–point correlation function (in redshift space) for 885 groups of galaxies identified in the combined CfA2 and SSRS2 redshift surveys. This sample is characterized by its large extent (more than five times the volumes previously studied) and by the homogeneity of the identification process (the friends–of–friends algorithm FOFA; Ramella et al. 1997 – hereafter RPG97). Moreover, we compare the group–group CF to that computed for galaxies in order to determine the relative clustering properties of groups and galaxies. Because we use the same galaxy sample where groups are identified, we avoid possible effects of fluctuations due to the volume sampled.

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**Fig. 1.** We show the projection on the sky of the group and galaxy samples (upper and lower panel, respectively).

In Sect. 2 we briefly describe the data; in Sect. 3 we describe the estimation of the two–point correlation function; in Sect. 4 we compute the correlation function of groups and compare it to that for galaxies; in Sect. 5 we summarize our results and draw our conclusions.

Throughout the paper, errors are at the 68% confidence level, and the Hubble constant is  $H_0 = 100 \text{ h Mpc}^{-1} \text{ km s}^{-1}$ .

## 2. Galaxy and groups catalogs

We extract the sample of galaxies from the CfA2 North (CfA2N) and South (CfA2S) (Geller & Huchra 1989; Huchra et al. 1995; Falco et al. 1999), and the SSRS2 North (SSRS2N) and South (SSRS2S) (da Costa et al. 1998) redshift surveys. These surveys are complete to  $m_{B(0)} \simeq 15.5$  and cover more than one–third of the sky, i.e. most of the extragalactic sky. The original papers contain detailed descriptions of the observations and of the data reduction. The velocities we use are heliocentric; they include corrections for solar motions with respect to the Local Group and for infall toward the center of the Virgo cluster (see RPG97 for details). As in previous analyses of the CfA2 surveys (e.g., Park et al. 1994; Marzke et al. 1995), we discard regions of large galactic extinction. The total sample includes 13435 galaxies with radial velocity  $V < 15000 \text{ km s}^{-1}$ .

We use the catalogs of groups identified within CfA2N by RPG97 and within SSRS2 by Ramella et al. (in preparation). The identification method is a friends–of–friends algorithm (FOFA) which selects systems of at least three members above a given number density threshold in redshift space. In particular, RPG97 and Ramella et al. (in preparation) use the number density threshold  $\delta\rho_N/\rho_N = 80$  and a line–of–sight link

**Table 1.** Data samples

Sample	$N_G$	$N_g$
CfA2N	395	5426
CfA2S	139	2104
SSRS2N	123	1697
SSRS2S	228	3083
TOTAL	885	12290

$V_0 = 350 \text{ km s}^{-1}$  at the fiducial velocity  $V_f = 1000 \text{ km s}^{-1}$ . We run FOFA with these parameters on CfA2S and produce a group catalog for this survey, too. The combined catalog contains a total of 885 groups that constitute a homogeneous set of systems objectively identified in redshift space.

The group catalogs are limited to radial velocities  $V \leq 12000 \text{ km s}^{-1}$ , but members are allowed out to  $V \leq 15000 \text{ km s}^{-1}$ . We confine the galaxy sample to  $V \leq 12000 \text{ km s}^{-1}$  and are left with a total of 12290 galaxies.

Table 1 lists the numbers of groups,  $N_G$ , and the numbers of galaxies,  $N_g$ , for each sample. Fig. 1 shows the distribution of the galaxy and group samples on the sky.

## 3. Estimation of the correlation function

We compute the two–point correlation functions in redshift space for groups and galaxies (hereafter  $\xi_{GG}(s)$ , and  $\xi_{gg}(s)$ , respectively). The formalism in the two cases is the same. We define the separation in the redshift space,  $s$ , as:

$$s = \frac{\sqrt{V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij}}}{H_0}, \quad (1)$$

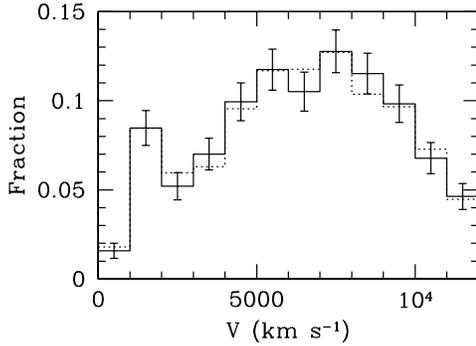
where  $V_i$  and  $V_j$  are the velocities of two groups (or galaxies) separated by an angle  $\theta_{ij}$  on the sky. Following Hamilton (1993) we estimate  $\xi(s)$  with:

$$\xi(s) = \frac{DD(s)RR(s)}{[DR(s)]^2} - 1, \quad (2)$$

where  $DD(s)$ ,  $RR(s)$ , and  $DR(s)$  are the number of data–data, random–random, and data–random pairs, with separations in the interval  $(s, s + ds)$ . We build the control sample by filling the survey volume with a uniform random distribution of the same number of points as in the data. The points are distributed in depth according to the selection function of the surveys,  $\Phi(V)$ .

In order to decrease the statistical fluctuations in the determination of  $\xi(s)$ , we average the results obtained using several different realizations of the control sample. We compute 50 realizations in the case of groups and 5 in the case of galaxies.

Unless otherwise specified, we compute the “weighted” correlation function by substituting the counts of pairs with  $\sum w_i w_j$ , the weighted sum of pairs, which takes into account the selection effects of the sample used. In the case of a sample characterized by the same selection function,  $\Phi(V)$ , volumes are equally weighted and  $w_i = 1/\Phi(V_i)$  is the weight of a group (or galaxy) with velocity  $V_i$ . The appropriate selection function



**Fig. 2.** The velocity distributions of groups (solid line) and of galaxies (dotted line) are compared. The error bands represent  $1 - \sigma$  Poissonian errors.

for a magnitude-limited sample (e.g., de Lapparent et al. 1988; Park et al. 1994; Willmer et al. 1998) is:

$$\Phi(V) = \frac{\int_{-\infty}^{M(V)} \phi(M) dM}{\int_{-\infty}^{M_{\max}} \phi(M) dM}, \quad (3)$$

where  $\phi(M)$  is the Schechter (1976) form of the luminosity function.  $M_{\max}$  is a low luminosity cut-off. We chose  $M_{\max} = -14.5$ , the absolute magnitude corresponding to the limiting apparent magnitude of the survey at the fiducial velocity  $V_f = 1000 \text{ km s}^{-1}$ . This value of  $V_f$  is the same as in RPG97. The Schechter parameters of the galaxy luminosity function, before the Malmquist bias correction, are:  $M^* = -19.1$ ,  $\alpha = -1.1$  for CfA2, and  $M^* = -19.7$ ,  $\alpha = -1.2$  for SSRS2 (Marzke et al. 1994; 1998).

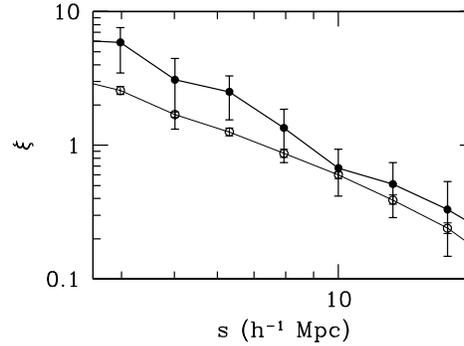
We assume that the group selection function is the same as for galaxies. In fact, the velocity distributions of groups,  $N_G(V)$ , and of galaxies,  $N_g(V)$ , are not significantly different according to the Kolmogorov–Smirnov test (cf. Fig. 2). RGH90 and Trasarti-Battistoni et al. (1997), and Frederic (1995b) make the same assumption for observed and simulated catalogs, respectively.

The different luminosity functions of CfA2 and SSRS2 correspond to different selection functions. For this reason we assign to a group (galaxy)  $i$ , belonging to the subsample  $k$ , the weight given by:

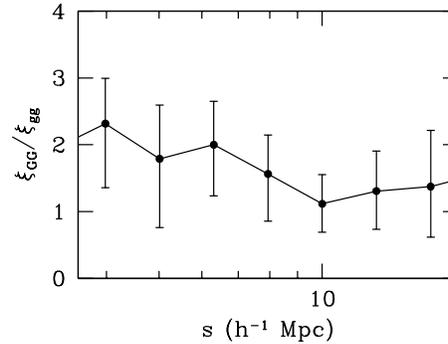
$$w_i = \frac{1}{\Phi_k(V_i) n_k}, \quad (4)$$

where  $n_k$  is the mean number density of groups (galaxies) of that subsample (e.g. Hermit et al. 1996). We compute the density as  $n_k = 1/\mathcal{V}_k \cdot \sum_i [1/\Phi(V_i)]$ , where the sum is over all the groups (galaxies) of the subsample volume,  $\mathcal{V}_k$  (Yahil et al. 1991). In our analysis,  $\mathcal{V}_k$  is the effective volume of the subsample. Because the different selection functions, we also build a control sample for each subsample separately, and, conservatively, we do not consider pairs of groups (galaxies) linking two different subsamples. In this way we also avoid crossing large unsurveyed regions of the sky.

We compute the errors on  $\xi(s)$  from 100 bootstrap resamplings of the data (e.g., Mo et al. 1992). Note that the



**Fig. 3.** The group–group (filled circles), and galaxy–galaxy (open circles) CFs, as computed for the combined sample. The error bands represent  $1 - \sigma$  bootstrap errors.



**Fig. 4.** The ratio  $\xi_{GG}/\xi_{gg}$ , where the CFs are those computed for the combined sample in Fig. 3.

bootstrap–resampling technique, which overestimates the error in individual bins, represents a conservative choice in this work.

#### 4. The group–group correlation function

We plot the group–group CF,  $\xi_{GG}(s)$ , in Fig. 3. In the same figure we also plot the galaxy–galaxy CF,  $\xi_{gg}(s)$ . On small scales ( $s \lesssim 3.5 \text{ Mpc}$ )  $\xi_{GG}(s)$  starts dropping because of the anti-correlation due to the typical size of groups. On large scales ( $s \gtrsim 15 \text{ h}^{-1} \text{ Mpc}$ ) the signal-to-noise ratio of  $\xi_{GG}(s)$  drops drastically. We thus limit our analysis to the separation range  $3.5 \lesssim s \lesssim 15 \text{ h}^{-1} \text{ Mpc}$ .

The main physical result in Fig. 3 is that  $\xi_{GG}(s)$  has a larger amplitude than  $\xi_{gg}(s)$ . This property of the CFs is also evident in Fig. 4, where we plot the ratio  $\xi_{GG}(s)/\xi_{gg}(s)$  on a linear scale. Over the  $s$ -range of interest, the values of the ratio are roughly constant within the errors. In order to give an estimate of the relative behavior of groups and galaxies we compute the mean of the values of the ratio. We obtain  $\langle \xi_{GG}/\xi_{gg} \rangle = 1.64 \pm 0.16$ .

##### 4.1. The CF of rich groups

Groups with a number of members  $N_{\text{mem}} \geq 5$  are generally reliable, as shown both by optical and X-ray analyses (Ramella et al. 1995; Mahdavi et al. 1997). On the other hand, the reliability of groups with fewer members is often questionable.

In particular, the analysis of the CfA2N survey performed by RPG97, and the analysis of a CDM model by Frederic (1995a) show that a significant fraction of the triples and quadruples in group catalogs could be spurious.

We consider the 321 rich groups with  $N_{\text{mem}} \geq 5$ , and find again that groups are more correlated than galaxies. Moreover, we find evidence that the CF computed for richer groups is higher than the CF computed for poorer groups, i.e.  $\langle \xi_{\text{GG,rich}}/\xi_{\text{gg}} \rangle = 1.48 \pm 0.16$  and  $\langle \xi_{\text{GG,poor}}/\xi_{\text{gg}} \rangle = 1.10 \pm 0.14$  (cf. Fig. 5).

The component of spurious groups among poor groups could be responsible for the lower amplitude of the  $\xi_{\text{GG}}(s)$  of poor groups compared to the  $\xi_{\text{GG}}(s)$  of rich groups. In fact, spurious groups should be distributed like non-member galaxies. However, at least part of the observed higher clustering amplitude of rich groups could be due to the existence of a clustering amplitude vs richness relationship. The relationship has been discussed for a variety of systems by several authors (e.g. Bahcall & West 1992; Croft et al. 1997; Miller et al. 1999). Richness is usually taken as a measure of the mass of the system, mass being the real, interesting physical quantity directly related to the predictions of cosmological models.

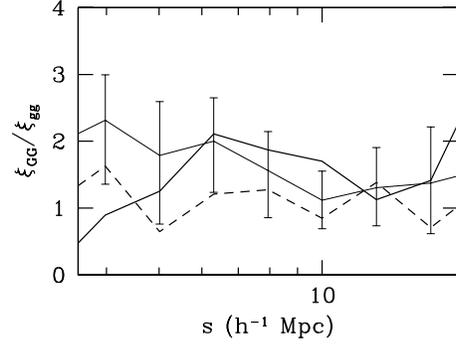
#### 4.2. The CF in the volume-limited sample

For our groups, richness is not a good physical parameter. A better parameter is the group (line-of-sight) velocity dispersion,  $\sigma_v$  (e.g. RPG97). In a magnitude-limited sample any group selection based on velocity dispersion will affect the selection function in an ‘‘a priori’’ unknown way. To avoid this problem, we analyze the volume-limited group sample built by Ramella et al. (in preparation) who run an appropriately modified version of FOFA within volume-limited sub-samples of the CfA2 and SSRS2 galaxy surveys. In particular, we consider the 139 distance limited groups within  $V \leq 7800 \text{ km s}^{-1}$ , roughly corresponding to the effective depth of CfA2. We cut the volume-limited galaxy catalogs in the same way. Within this sample we compute the ‘‘unweighted’’ CF estimator, i.e. we set  $w = 1$  for all groups/galaxies. For this sample the useful  $s$ -range is  $3.5 \lesssim s \lesssim 12 \text{ h}^{-1} \text{ Mpc}$  (see Fig. 6).

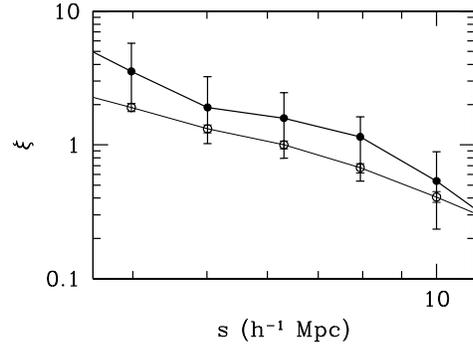
We find that the ratio  $\langle \xi_{\text{GG}}/\xi_{\text{gg}} \rangle$  of the total volume-limited sample is  $\langle \xi_{\text{GG}}/\xi_{\text{gg}} \rangle = 1.58 \pm 0.10$ , similar to that computed for the magnitude-limited sample ( $\langle \xi_{\text{GG}}/\xi_{\text{gg}} \rangle \sim 1.6$ ). This result reassures us about the reliability of the selection function we assume for groups.

In order to check a possible dependence of  $\xi_{\text{GG}}(s)$  on  $\sigma_v$ , we divide the group volume-limited sample into two sub-samples of equal size, one subsample containing groups with  $\sigma_v \geq 214 \text{ km s}^{-1}$ , the other including the remaining low velocity dispersion groups. We find that high- $\sigma_v$  systems are more correlated than those with low  $\sigma_v$  ( $\langle \xi_{\text{GG}}/\xi_{\text{gg}} \rangle = 2.14 \pm 0.37$  and  $\langle \xi_{\text{GG}}/\xi_{\text{gg}} \rangle = 1.29 \pm 0.17$ , respectively). This evidence is in agreement with that found for clusters, and suggests a continuum of clustering properties for all galaxy systems.

In this context, it is appropriate to compare the groups of the volume-limited sample, characterized by the median velocity



**Fig. 5.** The ratio  $\xi_{\text{GG}}/\xi_{\text{gg}}$  for the combined sample (thin line), but, now,  $\xi_{\text{GG}}(s)$  is computed also for groups with at least five member galaxies (thick line) and for groups with less than five member galaxies (dashed line).



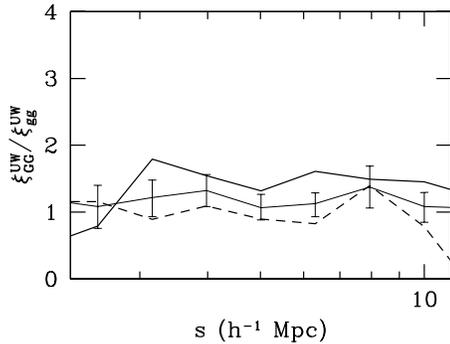
**Fig. 6.** The group-group (filled circles) and galaxy-galaxy (open circles) CFs, as computed for the volume-limited sample.

dispersion  $\sigma_v = 214 \text{ km s}^{-1}$  and by the mean group separation  $d \sim 16 \text{ h}^{-1} \text{ Mpc}$ , to rich clusters ( $\sigma_v \sim 700 \text{ km s}^{-1}$ ;  $d \sim 50 \text{ h}^{-1} \text{ Mpc}$ ; e.g. Zabludoff et al. 1993; Peacock & West 1992). We fit  $\xi_{\text{GG}}(s)$  to the form  $\xi(s) = (s/s_0)^{-\gamma}$  with a non-linear weighted least squares method and find  $\gamma = 1.9 \pm 0.7$  and  $s_0 = 8 \pm 1 \text{ h}^{-1} \text{ Mpc}$ . Note that groups show similar slope but significantly smaller correlation length than optically or X-ray selected clusters, for which  $s_0 \gtrsim 15 \text{ h}^{-1} \text{ Mpc}$  (e.g. Bahcall & West 1992; Croft et al. 1997; Abadi et al. 1998; Borgani et al. 1999; Miller et al. 1999). Our results agree with the predictions of those N-body cosmological simulations that also correctly predict the observed cluster-cluster CF (e.g. cf. our  $(s_0, d)$  with Fig. 8 of Governato et al. 1999).

#### 4.3. The unweighted CF

In order to verify the stability of our results against variations of the weighting scheme, we compute the unweighted CF,  $\xi^{\text{UW}}$ , for the magnitude-limited sample. We find that, as in the weighted case, the amplitude of  $\xi_{\text{GG}}^{\text{UW}}(s)$  is still significantly higher than the amplitude of  $\xi_{\text{gg}}^{\text{UW}}(s)$ ,  $\langle \xi_{\text{GG}}^{\text{UW}}/\xi_{\text{gg}}^{\text{UW}} \rangle = 1.18 \pm 0.05$ . We also find that the amplitudes of  $\xi_{\text{GG}}^{\text{UW}}(s)$  and  $\xi_{\text{gg}}^{\text{UW}}(s)$  are both significantly lower than the weighted estimates.

The differences between the results of the two weighting schemes rise from the fact that the weighted CF weights



**Fig. 7.** The ratio  $\xi_{GG}^{UW}/\xi_{gg}^{UW}$  for the combined sample (thin line), and its nearby (dashed line) and distant (thick line) parts, as computed with the unweighted CF.

each volume of space equally and therefore better traces the clustering of more distant objects. In fact, when we divide the group/galaxy catalogs in two subsamples of equal size according to group/galaxy distances, the distant samples ( $V > 6680 \text{ km s}^{-1}$ ) give CFs with higher amplitude, i.e.  $\langle \xi_{GG,distant}^{UW}/\xi_{GG,nearby}^{UW} \rangle = 2.15 \pm 0.31$  and  $\langle \xi_{gg,distant}^{UW}/\xi_{gg,nearby}^{UW} \rangle = 1.43 \pm 0.08$ . Moreover, the distant samples ( $V > 6680 \text{ km s}^{-1}$ ) give  $\langle \xi_{GG,distant}^{UW}/\xi_{gg,distant}^{UW} \rangle = 1.43 \pm 0.12$  in closer agreement with the result of the weighted analysis. The ratio  $\xi_{GG}^{UW}/\xi_{gg}^{UW}$  for the whole sample, as well as for its nearby and distant parts, is shown in Fig. 7.

As for a physical explanation, the fact that  $\xi_{GG}^{UW}(s) < \xi_{gg}(s)$  could be the consequence of a dependency of clustering on luminosity, since the unweighted CF estimator is more sensitive to the clustering of nearer, fainter groups/galaxies (e.g., Park et al. 1994). In fact, the dependency of clustering on luminosity has been pointed out for the galaxy-galaxy CF (e.g., Benoist et al. 1996; Cappi et al. 1998; Willmer et al. 1998). In addition, the greater strength of  $\xi_{gg}(s)$  could be explained by different clustering properties in different volumes of the Universe: e.g., Ramella et al. (1992) find that the strength of the galaxy CF is very high in the Great Wall. In the volume we examine the two biggest structures, the Great Wall and the Southern Wall, both lie in distant regions (e.g. da Costa et al. 1994) and therefore their weight is larger in the weighted CF scheme. It is reasonable to expect also that distant groups, which are brighter (and presumably more massive) and which preferably lie in the two big structures, are more strongly correlated than nearby groups leading to the observed  $\xi_{GG}^{UW}(s) < \xi_{GG}(s)$ .

## 5. Summary and conclusions

We measure the two–point redshift–space correlation function of loose groups,  $\xi_{GG}(s)$ , for the combined CfA2 and SSRS2 surveys. Our combined group catalog constitutes the largest homogeneous sample available (885 groups). We compare  $\xi_{GG}(s)$  with the correlation functions of galaxies,  $\xi_{gg}(s)$ , in the same volumes.

Our main results are the following:

1. Using the whole sample we find that groups are significantly more clustered than galaxies,  $\langle \xi_{GG}/\xi_{gg} \rangle = 1.64 \pm 0.16$ , thus consistent with the result by Trasarti-Battistoni et al. (1997), based on a much smaller sample. This ratio can be considered a lower limit considering the possible presence of unphysical groups.
2. Groups are significantly less clustered than clusters. In particular, we find  $\gamma = 1.9 \pm 0.7$  and  $s_0 = 8 \pm 1$  for 139 groups identified in a volume–limited sample ( $V \leq 7800 \text{ km s}^{-1}$ , median velocity dispersion  $\sigma_v \sim 200 \text{ km s}^{-1}$ , and mean group separation  $d \sim 16 \text{ h}^{-1} \text{ Mpc}$ ). This result can be compared with that of galaxy clusters ( $s_0 \sim 15\text{--}20 \text{ h}^{-1} \text{ Mpc}$  for systems with  $\sigma_v \sim 700 \text{ km s}^{-1}$  and  $d \sim 50 \text{ h}^{-1} \text{ Mpc}$ ; e.g., Bahcall & West 1992; Croft et al. 1997; Abadi et al. 1998; Borgani et al. 1999; Miller et al. 1999).
3. There is a tendency of clustering amplitude to increase with group velocity dispersion  $\sigma_v$ , which is the better indicator of group mass at our disposal.

We conclude that there is a continuum of clustering properties of galaxy systems, from poor groups to very rich clusters, with correlation length increasing with increasing mass of the system.

*Acknowledgements.* We thank Stefano Borgani, Antonaldo Diaferio, and Margaret Geller for useful discussions. Special thanks to Massimo Ramella for enlightening suggestions. M.G. wishes to acknowledge Osservatorio Astronomico di Trieste for a grant received during the preparation of this work. This work has been partially supported by the Italian Ministry of University, Scientific Technological Research (MURST), by the Italian Space Agency (ASI), and by the Italian Research Council (CNR-GNA).

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