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Environments of Seyfert galaxies

II. Statistical analyses

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Abstract. Environments of 104 Seyferts and 138 comparison galaxies have been analyzed based on measurements on the Palomar Sky Survey plates. Our basic idea was to have large enough measuring circles to enable good elimination of background galaxies and to compare the environments of Seyfert 1 and 2 galaxies. Seyferts were also compared with normal galaxies.

The Seyferts were found to have on the average about two times more companions than the control galaxies. The satellites are concentrated mainly around late-type and non-compact peculiar Seyfert 2 galaxies, which may each have several companions. On the other hand, Seyfert 1 galaxies of all morphological types have on the average the same number of companions as normal galaxies. Seyferts as a whole do not appear in interacting systems more frequently than normal galaxies (Dahari-type tests) giving further evidence that the satellites are concentrated around a few objects only. Of type 2 Seyferts only peculiar galaxies are preferentially in interacting systems, whereas type 1 Seyfert neighbourhoods are normal or even deficient of companions. The difference in the environments of Seyfert 1 and Seyferts 2 galaxies disagrees with the Unified Model of AGN's according to which these two Seyferts types should represent similar objects seen from different viewing angles.

While comparing Seyferts with normal galaxies our conclusions disagree with the previous studies as shown in the discussion. However, the apparent incompatibilites of the results in different works can be understood on the basis of morphological sample selection, problems in background galaxy elimination or bias in redshift between the compared samples. Particularly we tested the methods by Dahari (1984) and Fuentes-Williams & Stocke (1988).

Key words: galaxies: clustering – interactions – Seyfert

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1. Introduction

The idea that galaxy interactions may lead to enhanced galactic activity has a long history. Since the early days of Baade & Minkovski (1954) through the seminal paper by Toomre & Toomre (1972) to the "feeding the monster" paper by Gunn (1979) and the landmark paper by Larson & Tinsley (1978), this idea has been elaborated.

Several simulations of the recent years have shown that galaxy interactions can lead to material transport towards the nucleus (Byrd et al. 1986; Noguchi 1988; Hernquist 1989; Shlosman et al. 1990; Barnes & Hernquist 1991; Salo 1991). Tidal interactions cause perturbations in the kpc scales throughout the galaxy. Self-gravitating instability may further reduce the angular momentum of the gas component to the range necessary for it to fall to the potential fueling region, which extends to about one parsec. This may lead to star bursts in the nuclei, or if the gas content is large enough, to the formation of an active galactic nucleus (Shlosman 1990).

Nevertheless, the physical link between galaxy interactions and activity has turned out difficult to prove. Observationally and theoretically the connection is clearest for Starburst galaxies (Heckman 1990), whereas Seyferts in the context of this scenario (Schlosman 1990) are faced with energetic and scale problems related to tidal effects and size of active galactic nuclei. Observational studies fall into two primary categories: comparisons of local environments of known Seyferts to those of non-Seyfert galaxies, and comparisons of the rate of Seyfert nuclei in the samples of interacting and non-interacting galaxies. Many of these studies address the correlation between galaxy interactions and Seyfert activity, but the results are partially contradictory.

Environments of Seyfert galaxies have been studied by Petrosian (1982), Dahari (1984), MacKenty (1989) and Fuentes-Williams & Stocke (1988). In the first three papers clear evidence was found that Seyferts have excess of near neighbours. On the other hand, Fuentes-Williams & Stocke found only a marginal excess of companions, and only in the case that companions smaller than 15 kpc were considered. Concerning those works where Seyferts have been searched for in samples of in-

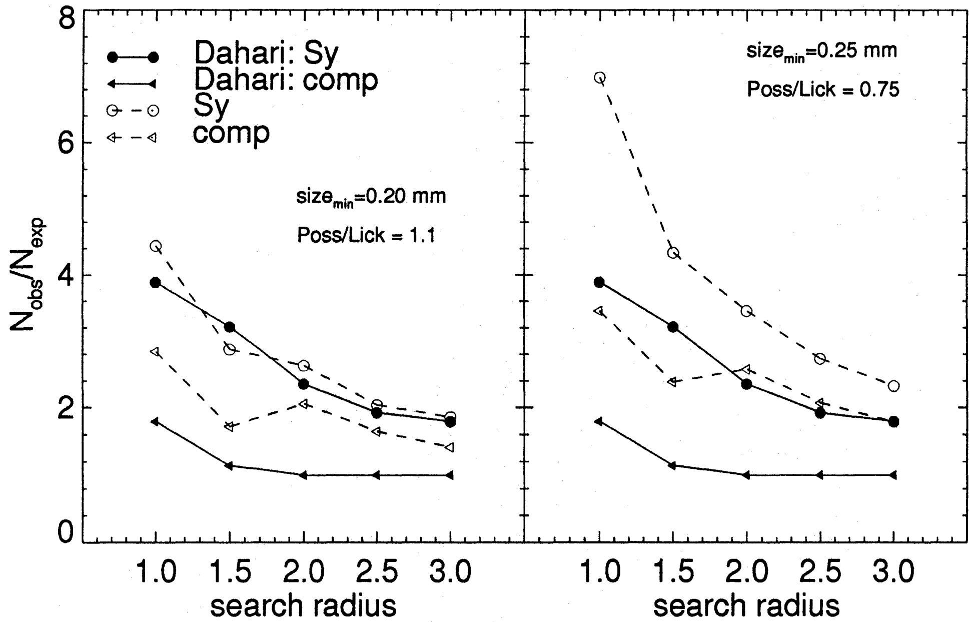

Fig. 1. Ratio of the observed number of galaxies with close companions to the expected value, $N_{\rm obs}/N_{\rm exp}$, based on the probability function $P_{\rm T}$ explained in the text. Full lines are redrawn from Dahari (1984), while dotted lines are based on the present study. We restrict our Seyfert and comparison samples to $z \leq 0.03$ in order to imitate Dahari's sample. For each Seyfert the probability of having at least one companion within the given search radius (in galaxy diameters) is calculated, based on the background density in Shane's maps. The ratio between the observed number of Seyferts with companions is then compared to the expected number in the sample. Following Dahari, for the comparison sample the same probability distribution is assumed as for Seyferts. The results are shown for to limiting measurement sizes, 0.2 and 0.25 mm. Note that the POSS/Lick ratio depends on this limiting galaxy size

teracting galaxies the results are equally incompatible. While Keel et al. (1985) and Dahari (1985) found evidence that interactions forster Seyfert nuclei, Bushouse (1986) and Sekiguchi & Wolstencroft (1992) found no such a tendency. Also the results concerning the environments of type 1 and type 2 Seyferts are confusing. According to MacKenty and Petrosian Seyfert 2 galaxies have more companions than type 1 objects, whereas Dahari (1984) found no significant difference between the two types.

Due to the complexity of this kind of comparisons objections can be marshaled against any of the above mentioned studies. In this paper we try to analyze possible reasons for these apparently contradictory conclusions and, particularly to study the correlation of Seyfert- and morphological types with the environmental properties. The sample selection, measurements and selection effects are explained in Laurikainen et al. (1994, hereafter Paper I). In Sect. 2 we analyze the methods used, Sect. 3 and 4 report the results, Sect. 5 reviews the results available in the literature and Sect. 6 summarizes the conclusions. A Hubble constant $H_0 = 100\,{\rm km\,s^{-1}\,Mpc^{-1}}$ is used throughout the paper if not otherwise mentioned.

2. Methods of analysing Seyfert neighbourhoods

Comparison of the published results is complicated due to the variety of different statistical methods used. For example, the results obtained by the methods originally applied by Dahari (1984) and by Fuentes-Williams & Stocke (1988, hereafter FWS) are not directly comparable, as the Dahari-test takes into account only the nearest neighbour, whereas the FWS's tests include all nearby companions. Instead of introducing some entirely new statistical method we apply both Dahari's and FWS's methods to our sample. In this Section we anylyze these methods and try to understand the original results with our new dataset.

2.1. Dahari's method

Dahari uses the Poisson distribution function in calculating for each galaxy the probability P of having at least one another galaxy within the radius S from its center:

$$P = 1 - {\rm e}^{-\pi\rho(S^2 - 0.25D_{\rm gal}^2)}$$

where ρ is the number density of background galaxies per square degree and $D_{\rm gal}$ is the galaxy diameter (S and $D_{\rm gal}$ are expressed in degrees). The latter term in the exponent accounts for the area hidden by the central galaxy. In order to test whether the observed number of galaxies with companions in the sample is statistically larger than the expected number of optical pairs Dahari constructs the total density function $P_{\rm T}(K,N)$, which expresses the probability of finding exactly K pairs in N trials of the survey. The significance of the difference between observed ($N_{\rm obs}$) and expected number ($N_{\rm exp} = \langle P_{\rm T}(K,N)\rangle = N\langle P\rangle$) can be assessed by comparing it with the dispersion of $P_{\rm T}(K,N)$.

We first try to reproduce Dahari's calculations. He determined the $P_{\rm T}(K,N)$ distribution for Seyferts using the optical

Table 1. Dahari-type tests at $S = 3D_{\rm Sy}$ varying the different parameters

Sample	$\langle P \rangle$	$N_{\rm obs}$	$N_{\rm exp}$	$N_{\rm obs}/N_{\rm exp}$	Relative excess
Test 1: $P_{\rm T}(\rho_{\rm comp} = \rho_{\rm Sy}, D_{\rm comp} = D_{\rm Sy})$, $D_{\rm neigh} \geq 0.2$ mm, $z < 0.03$, POSS/Lick = 1.1: ("principal Dahari-type test"):					
Sy	0.259	32	18.1	1.77	1.30
comp	0.259	30	22.0	1.36	
comp(S)	0.259	15	12.4	1.21	
comp(early)	0.259	15	9.6	1.57	
Test 2: As test1, but $D_{\rm neigh} \geq 0.25$ mm POSS/Lick = 0.75 ("principal Dahari-type test")					
Sy	0.193	29	13.5	2.14	1.30
comp	0.193	27	16.4	1.64	
comp(s)	0.193	13	9.3	1.40	
comp(early)	0.193	14	7.1	1.96	
Test 3: $P_{\rm T}(\rho_{\rm comp} = \rho_{\rm Sy}, D_{\rm comp} \neq D_{\rm Sy})$, $D_{\rm neigh} \geq 0.25$ mm:					
Sy	0.193	29	13.5	2.15	1.17
comp	0.156	27	13.2	2.04	
comp(S)	0.154	13	7.4	1.76	
comp(early)	0.158	14	5.8	2.40	
Test 4: $P_{\rm T}(\rho$ from POSS, $D_{\rm comp} \neq D_{\rm Sy})$, $D_{\rm neigh} \geq 0.25$ mm:					
Sy	0.205	29	14.4	2.02	0.91
comp	0.143	27	12.2	2.22	
comp(S)	0.134	13	6.4	2.02	
comp(early)	0.155	14	5.7	2.43	
Dahari:					
Sy	0.213	31	17.9	1.73	1.70
comp	0.213	56	55.0	1.02	

galaxy densities based on Lick counts (Shane, 1975), converted to correspond his Palomar Sky Survey (POSS) measurements. The same probability function was assumed for comparison galaxies, taking into account only the difference in the sample sizes (not the difference in background densities or galaxy sizes). We have repeated this procedure for our Seyfert and comparison galaxy sample, for various values of the search radius S: Fig. 1 compares our results with those given by Dahari (1984) in his Fig. 3. As indicated in Paper I the limiting size in Dahari's work is supposed to be about 0.25 mm. However, as the limiting size is rather uncertain, the results for our completeness limit 0.20 mm are also displayed. In both cases, the POSS/Lick conversion ratio appropriate for our sample is applied. While calculating the surface area hidden by the central object galaxy inclination is also taken into account.

According to Fig. 1, the same qualitative behaviour is observed with both limiting sizes, Seyferts and comparison galaxies showing an increase in $N_{\rm obs}/N_{\rm exp}$ as S is decreased. As the differences between $N_{\rm obs}$ and $N_{\rm exp}$ are several times larger than the standard deviation of $P_{\rm T}$, this indicates the existence of nearby physical companions. For Seyferts the values of $N_{\rm obs}/N_{\rm exp}$ are clearly larger than for comparison galaxies. The systematically increased $N_{\rm obs}/N_{\rm exp}$ values for 0.25 mm size limit are in agreement with the theoretical considerations of Paper I, according to which the relative fraction of physical companions should increase with increased size limit (see Fig. 10 in Paper I). For Seyferts, our results agree with Dahari's original results, allowing for the uncertainty in the POSS/Lick conversion. However, in the Dahari's original curves, $N_{\rm obs}/N_{\rm exp} \approx 1$ for comparison galaxies unless $S \leq 1.5 D_{\rm gal}$, which deviates from our result. The deviation can not be accounted by background uncertainty being rather related to the selection of the comparison samples (see below).

There are several factors affecting the expected probability of finding neighbouring galaxies. In the following we test more closely the parameters ρ and $D_{\rm gal}$ involved in P, and

Table 2. Tests applying FWS method ($H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ for comparison with FWS)

Sample (N)	S(kpc)	$N_{\rm neigh}$	$R_{\rm min}$ (kpc)	D1	D2	D3
$\mathrm{Sy_{high\,z}}$ (58)	1000	20.0[c]	175	1.96[c]	0.57	2.82
	500	6.1[c]		1.20	0.53	2.80
	250	1.7		0.69	0.45	2.74
$\mathrm{Sy_{low\,z}}$ (60)	1000	10.8[c]	192	1.36[c]	0.56	3.26
	500	3.9[c]		0.95	0.53	3.24
	250	1.5		0.66	0.49	3.21
$\mathrm{Sy_{proj}}$ (29)	1000	21.3[b]	163	2.31[b]	0.85[a]	4.93
	500	7.0[a]		1.51[a]	0.80	4.91
	250	2.2		0.96	0.73	4.84
$\mathrm{Sy_{non-proj}}$ (50)	1000	14.1[b]	188	1.52[b]	0.47[a]	2.14
	500	4.5[a]		0.98[a]	0.44	2.13
	250	1.5		0.61	0.39	2.08
Sy (104)	1000	16.1[b]	181[b]	1.74[c]	0.58[c]	2.92[c]
	500	5.2[c]		1.13[c]	0.54[c]	2.90[c]
	250	1.7[b]		0.71[b]	0.48[b]	2.85[b]
comp (133)	1000	12.1[b]	255[b]	1.10[c]	0.29[c]	1.46[c]
	500	3.5[c]		0.63[c]	0.26[c]	1.45[c]
	250	1.1[b]		0.37[b]	0.23[b]	1.42[b]
comp(S) (72)	1000	11.1	282	0.98[a]	0.26[a]	1.40[a]
	500	3.1[a]		0.54[a]	0.23[a]	1.38[a]
	250	0.8[a]		0.31[a]	0.21[a]	1.36
comp(early) (61)	1000	13.4	224	1.24[a]	0.32[a]	1.54[a]
	500	4.1[a]		0.74[a]	0.29[a]	1.53[a]
	250	1.3[a]		0.43[a]	0.25[a]	1.50
FWS:						
Sy(53)	1000	10.0	225			
comp(30)	1000	8.1	305			

Significance in Mann-Whitney U-test, comparing samples $\mathrm{Sy_{high\,z}}$ vs. $\mathrm{Sy_{low\,z}}$, $\mathrm{Sy_{proj}}$ vs. $\mathrm{Sy_{non-proj}}$, Sy vs. comp, and comp(S) vs. comp(early), respectively. The significance p indicates the probability of compared samples having identical median values:
[a] $0.01 < p < 0.05$
[b] $0.001 < p < 0.01$
[c] $p < 0.001$

the effect of the POSS/Lick ratio. Some of the results are collected in Table 1, showing the mean probability $\langle P \rangle$ of finding at least one neighbouring galaxy, the observed ($N_{\rm obs}$) and theoretically expected ($N_{\rm exp}$) numbers of galaxies with neighbours, the ratio $N_{\rm obs}/N_{\rm exp}$, as well as the "relative excess", $(N_{\rm obs}/N_{\rm exp})_{Sy}/(N_{\rm obs}/N_{\rm exp})_{\rm comp}$ between Seyferts and comparison galaxies. In all these tests the search radius $S = 3D_{\rm gal}$, the other parameters being indicated in the table. The "principal Dahari-type tests" (Table 1: test1 and test2), as well as the values denoted by Dahari, correspond to Fig. 1.

The probability function for comparison galaxies was calculated in three different ways:

1. First, as above in the "principal Dahari-type tests", using the Seyfert probability function also for the comparison galaxies (Table 1: tests 1 and 2).

2. Secondly, by using the measured diameter for each comparison galaxy, but still replacing the background galaxy densities of the comparison galaxies with those obtained for Seyferts from the Lick counts (test 3).

3. Thirdly, by using the background obtained directly from the POSS plates (test 4), the background being the average density within the distance of 500–700 kpc from the main galactic center (the outermost zone 700–750 kpc was excluded as the measurements might be incomplete near the border). The same method was used also for the Seyferts.

First of all, the Dahari-type test is very sensitive to the adopted POSS/Lick ratio. Dahari estimated it from measurements of five $1^\circ \times 1^\circ$ areas on POSS plates, with about 20% standard deviation. Our measurements yielded similar uncertainty. As $N_{\rm exp}$ is almost directly proportional to the assumed background density, it changes proportional to POSS/Lick ratio. However, this is not important, as the correction affects identically the Seyferts and the comparison galaxies, the "relative excess" remaining constant. On the other hand, a good method of estimating the background galaxy densities was found to be important while calculating the estimated number of optical superpositions for comparison galaxies. This affects directly the "relative excess".

The tests imitating Dahari's calculations (test 1 and 2) would indicate that Seyferts clearly appear more frequently in interacting systems than normal galaxies ("relative excess"= 1.3) being in rough agreement with the result by Dahari. When individual galaxy diameters are used (test 3) the ratio $N_{\rm obs}/N_{\rm exp}$ for the comparison sample increases thus reducing the difference between the Seyfert and the comparison samples ("relative excess"= 1.17). Finally, when the proper elimination of background galaxies is used (Test 4), the environments of the Seyferts and the comparison galaxies become practically equal, ("relative excess"= 0.91).

Two conclusions can be made from the above analysis. First of all, while applying Dahari's original method ("principal Dahari-type tests") we can reproduce his result for Seyferts but not for comparison galaxies. This must follow from the way his comparison sample was selected: for example if they were galaxies with generally lower background density, the use of Seyfert backgrounds would overestimate the number of expected optical superpositions. An interesting point is that by choosing a subsample of Seyferts that is not projected on any Zwicky's cluster they behave in the "principal Dahari-type test" similarly to the Dahari's comparison sample ($N_{\rm obs} \approx N_{\rm exp}$). This supports the idea that the lack of an excess number of galaxies with companions in Dahari's comparison sample could be largely due to sample selection. Thus, it is not likely that the difference in the environmental properties of Dahari's and our control samples could be due to different morphological selection: we show later (see discussion of Fig. 4b) that the environ-

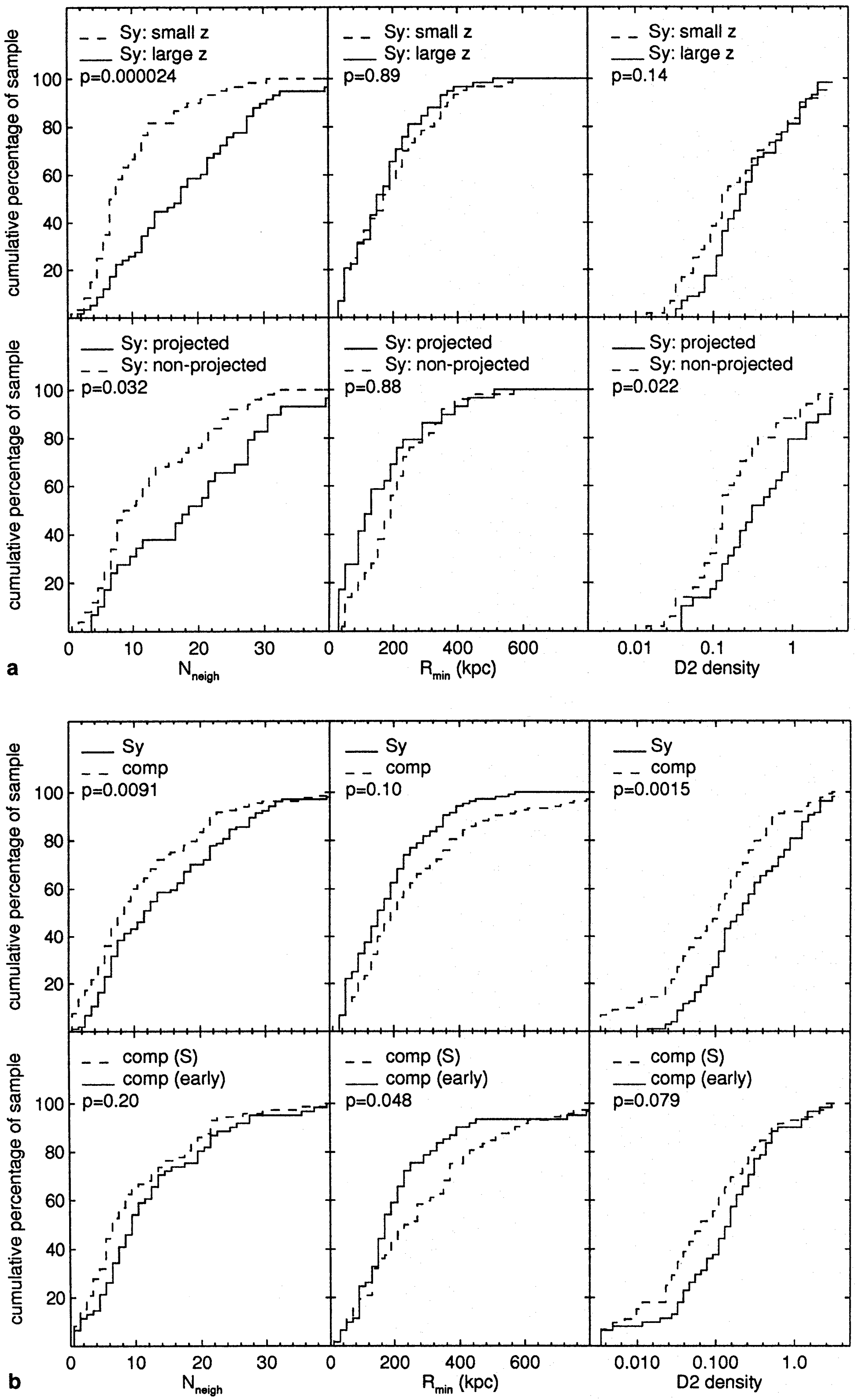

Fig. 2a and b. Comparison of various samples with the method by Fuentes-Williams and Stocke (1988). The cumulative distribution of the number of "associated" galaxies, $N_{\rm neigh}$, the distance to closest companion, $R_{\rm min}$, and the $D2$-density parameter are shown. The values given in each frame indicate the probability of the data following similar distributions, calculated with the KS-test

ments of our spirals and early-type galaxies appear very similar in the Dahari-type tests.

A second conclusion concerns the disappearence of "relative excess" when proper background galaxy estimates are used for both samples. This indicates the delicateness of the Dahari-type tests. This is a strong argument against the result obtained by Dahari, who argued that Seyferts as a group appear about five times more often in interacting systems than normal galaxies (however, in later Sections, where Dahari-type tests with accurate background galaxy estimates are used, we will show that certain subgroups of Seyferts indeed show excess of nearby companions).

2.2. Method by FWS

FWS apply several tests, which emphasize different aspects of galaxy interactions. The parameters they use are the following:

$N_{\rm neigh}$: the total number of "associated" galaxies (explained below) within the entire measured area.

$R_{\rm min}$: the projected distance (kpc) between the central galaxy and its nearest "associated" galaxy.

D1: $\Sigma_i(d_i/r_i)$, where d_i= projected diameter of the $i^{\rm th}$ galaxy (Mpc) and r_i = projected distance (Mpc) between the central galaxy and the $i^{\rm th}$ galaxy.

D2: $\Sigma_i(d_i/r_i)^2$

D3: $\Sigma_i(d_i^{2.4}/r_i^3)$

FWS study the distributions of these quantities and search for differences between their Seyfert and comparison samples. Since $N_{\rm neigh}$ takes into account all galaxies within the considered surface area it measures cluster properties rather than close interactions. For the same reason D1, although being a weighted measure of galaxy density, is probably a rather insensitive measure of close associations of galaxies. On the other hand, the parameters D2 and D3, giving strong weight to near neighbourhoods should be good indices of tidal interactions.

2.2.1. Test of the redshift bias

In the following we estimate the consequences of the redshift bias (Paper 1, Sect. 2.3) in the tests by FWS. We imitated their redshift distributions for Seyferts and comparison galaxies by constructing two Seyfert subsamples (mean z = 0.0193 and 0.0307 corresponding to FWS control galaxies and Seyferts, respectively). As the mean physical properties of the samples are rather similar we can study the consequences of the redshift difference only. Holmberg diameters were used and only galaxies larger than one fourth of the main galaxy diameter were considered. The foreground and background galaxies were eliminated using the criterion 15 kpc $\leq D_{\rm neigh} \leq$ 50 kpc assuming same distance as for the central galaxy (H_0 = 75 km s^{-1} M pc^{-1} was used in FWS tests in order to compare our results with theirs), the remaining objects being the "associated" galaxies, considered as true companions by FWS. In Fig. 2 the distributions of $N_{\rm neigh}$, $R_{\rm min}$ and D2 are shown in the manner similar to FWS. In addition, Table 2 collects our results for all the FWS-type test parameteres, for the limiting search areas 1000 kpc (our total measurement area in FWS units), 500 kpc and 250 kpc.

Figure 2a (uppermost row) shows that the redshift difference between the compared Seyfert subsamples causes a dramatic effect on the cumulative distribution of $N_{\rm neigh}$, the average number of "associated" galaxies being clearly larger at high redshifts. In addition to testing the difference of the compared distributions by Kolmogorov-Smirnov test we used also the Mann-Whitney U-test to measure the statistical confidence levels of the compared samples having different median values. Both tests give similar results. The significance levels in U-tests are indicated by letters in Table 2, while those in KS-tests are shown in Fig. 2. Both methods confirm that the distributions of $N_{\rm neigh}$ are significantly different. Another test parameter showing a larger number of "associated" galaxies at high redshifts at a statistically confident level is D1. On the other hand D2 and D3 show no such a tendency D3 giving even a contrary result. It is worth noticing that the values of D2 and D3 are independent of the size of the measured surface area, whereas D1(Sy$_{\rm high\,z}$) / D1(Sy$_{\rm low\,z}$) and $N_{\rm neigh}$(Sy$_{\rm high\,z}$)/$N_{\rm neigh}$(Sy$_{\rm low\,z}$) drop towards unity when the diameter of the measured circle is reduced from 1000 kpc to 250 kpc (see Table 2). D2 and D3 are independent of the search radius because they measure numbers of physical companions, whereas D1 and $N_{\rm neigh}$ are heavily dominated by background galaxies. The value of $R_{\rm min}$ is quite similar for both Seyfert subsamples.

All the tests by FWS (done similarly as we did) for their Seyferts and comparison galaxies showed only a marginal number excess of "associated" galaxies around the Seyferts. This is very suprising taking into account their redshift bias. In fact, the value of $N_{\rm neigh}$ by FWS for Seyferts is smaller than expected solely due to the redshift bias (in Paper I we showed that $N_{\rm neigh}$ should be proportional to z due to optical background), implying that their Seyfert sample might actually be underrepresented by companions in comparison with normal galaxies (their ratio $N_{\rm neigh}(Sy)/N_{\rm neigh}$(control) = 10/8.1 = 1.2, instead of 1.6 expected due to the redshift bias). Also D1 in the tests by FMS should depend on z and therefore show more companions around Seyferts than around comparison galaxies, but this is not the case. As D1 and $N_{\rm neigh}$ measure mainly the background density of galaxies, this strongly suggest that the comparison galaxies of FWS might be located at generally richer sky areas. On the other hand, the other parameters being more related to nearby neigbours (D2, D3 and $R_{\rm min}$) showed similar behaviour for our Seyfert subsamples, selected on the basis of the redshift, as the Seyfert and comparison samples in FWS's test. In our case this independence from z is expected, as Seyferts at low and high z are expected to possess similar near neighbourhoods, whereas in the case of FWS it can be caused either by Seyferts and comparison galaxies having similar environmental properties (as was their conclusion) or it can be a consequence of the same bias that suppresses differences in $N_{\rm neigh}$ and $D1$.

2.2.2. Cluster effects

We also study how much the FWS method is affected by projections on Zwicky's clusters. In Paper I two Seyfert samples were chosen for this purpose. By applying FWS test for these samples, those projected on clusters are found to have denser environments (according to parameters $N_{\rm neigh}$ and D1 and to lesser extent according to D2) than the non-projected galaxies (Fig. 2a; second panel, Table 2). However, as the search radius is reduced the result is no longer statistically significant.

2.2.3. Conclusions of the methods

The Dahari-type tests and the test parameters D2 and D3 are good indices in studies of small-scale environronmental properties of galaxies. However, they measure two different aspects: while the Dahari-type tests estimate how often galaxies have at least one physical companion, the FWS-type tests show number densities of all "associated" galaxies. D1 and $N_{\rm neigh}$ are dominated by background galaxies when large search areas are used, which makes them unreliable measures of physical companions. It is worth stressing that the Dahari test is independent of redshift, whereas the FWS-type tests are not. However, D2 is almost redshift independent, being dimensionless quantity dominated by nearby neighbours so that the size of the counting circle is irrelevant.

While applying these tests there are several points to be taken into account. In the Dahari-type test the critical point is the use of correct background galaxy density. Even the most reliable tests by FWS (D2 and D3) are somewhat sensitive to background galaxies counted as "associated" galaxies, if too large counting circle is used.

3. FWS-type tests for the principal samples

We next apply the FWS method for our principal samples of Seyferts and comparison galaxies. The tests show at statistically significant level that Seyferts clearly have more "associated " galaxies than the control galaxies (Fig. 2b; first panel, Table 2). This is clearest according to the parameters D2 and D3, which have mean values about twice larger for the Seyferts than for the comparison galaxies. The parameters D1 and $N_{\rm neigh}$ show a smaller effect, as physical galaxy associations are now diluted by background objects. The dilution effect in D1 is evidenced by the fact that the ratio D1(Sy)/D1(comp) increases with decreasing search area, because near to the Seyferts physically associated companions dominate, whereas at large distances background objects dominate.

Possible morphological selection is not expected to affect the results, because the density excess of "associated" galaxies we found for Seyferts is clearly more significant than that of the early-type galaxies in comparison with the late-type comparison objects (see Fig. 2b; lower panel, Table 2). As explained in Paper I possible redshift bias of the comparison sample probably is not significant.

Our results strongly disagree with those obtained by FWS. As we found that Seyferts have higher "associated" galaxy densities than normal galaxies by a factor of two (tests D2 and D3), according to the same tests FWS found only a marginal density excess of "associated" galaxies. Due to dilution by background objects the parameters D1 and $N_{\rm neigh}$ show misleadingly similar tendencies in these two works showing clear but rather small excess of companions around Seyferts in comparison with normal galaxies. Also, our results are statistically significant ($p < 0.001$), whereas in FWS's study the confidence levels are only marginal. While applying no galaxy size limit and using D3 and $R_{\rm min}$ FWS found that the Seyferts clearly have more companions than the control galaxies. We don't understand this, because if true, similar result should have been obtained also according to D2. Also, as shown in Fig. 7 of Paper I, inclusion of all measured companions should affect so that relatively more optical companions are counted at low redshifs, not at large redshifts, especially while applying $N_{\rm neigh}$ and D1.

4. Dahari-type tests and galaxy density profiles for the principal samples

Our Seyfert and comparison galaxy samples will be analyzed in the following applying the Dahari-type tests and calculating galaxy density profiles, the latter enabling consideration of multiple galaxy interactions. We do the tests first using the whole redshift range $z = 0.01 - 0.043$ and then limiting to distances below $z = 0.03$. The first choice gives the maximum galaxy number for statistics and the second choice limits to unbiased Seyfert sample. For example, early-type Sy 1 galaxies are biased toward larger redshifts than Sy 2 galaxies of the same morphological type (see Fig. 1c in Paper I): this bias is removed by restricting to small z. As a lower limit for the neighbouring galaxy size we use the completeness limit of measurements (0.2 mm), and companion galaxies larger than 50 kpc (assuming the distance of the central galaxy) are eliminated as foreground galaxies. For the sample at $z \leq 0.03$ we additionally restrict the physical galaxy size to be larger than 5.7 kpc, to assure that all true companions are found with equal probability independent of z (0.2 mm corresponds to 5.7 kpc physical size at $z = 0.03$).

In the Dahari-type tests the background galaxy density is determined individually from the POSS plates, by taking a mean value at a distance of 500–700 kpc from the main galaxy center. The probability function is calculated separately for the Seyfert and for the comparison galaxy samples. Dahari's method is first applied in its original form by giving the search radius in main galactic diameters (hereafter "relative Dahari-type test"), and secondly by giving it in kiloparsecs (hereafter "absolute Dahari-type test"). The first way of using the Dahari's method makes the test independent of possible redshift biases between the compared samples, whereas the second way of using it compensates biases in the distributions of absolute diameters while assuming no redshift bias. We first compare the Seyferts with the control galaxies and then investigate the environmental differences between type 1 and type 2 Seyferts. Finally, the correlation between environmental properties and morphological types is studied.

4.1. *Seyferts vs. comparison galaxies*

The number density profiles shown in Fig. 3a (upper panel) indicate that Seyferts clearly have more companions than normal galaxies, which is shown also quantitatively in Table 3a. In Fig. 3 the profiles for the comparison galaxies are drawn by two ways: using the redshifts of the Seyfert galaxies (thin lines) and using the redshifts estimated by assuming that each of them has the size $D_{\rm Holm} =$ 20 kpc (thick lines). In Paper I this average size

Table 3. Neighbouring galaxy numbers, $N_{\rm phys}$, and densities ρ within S = 50 and S = 50–200 kpc. The indices (1) and (2) refer to the two ways of calculating ρ explained in the text

Sample(N)	$\rho(1)_{50}$	$\rho(2)_{50}$	$\rho(1)_{50-200}$	$\rho(2)_{50-200}$	$\langle N_{{\rm phys}_{50}} \rangle$	$\langle N_{{\rm phys}_{50-200}} \rangle$
3a. $D_{\rm neigh} > 0.2$ mm, z = all:						
Sy	4.4	2.9	1.8	1.3	0.5	1.5[a] comp
comp	2.1	1.9	1.5	1.1	0.3	0.5[a] Sy, Sy2
comp (S)	2.4	1.7	1.1	1.0	0.2	−0.1[a] comp(early)
comp (early)	1.8	2.0	1.9	1.3	0.3	1.3[a] comp(S)
$Sy_{\rm proj}$	5.6	3.1	1.8	1.3	0.6	1.1
$SY_{\rm non-proj}$	3.3	2.6	1.9	1.3	0.4	1.1
Sy1	2.8	2.1	1.9	1.3	0.3	1.0[a] Sy2
Sy2	6.1	3.4	1.7	1.4	0.8	2.0[a] comp, Sy1
Sy1 (early)	2.9	3.0	1.9	1.3	0.4	1.1
Sy1 (late)	3.2	1.9	2.6	1.2	0.2	0.6
Sy1 (pec)	2.6	1.8	1.3	1.2	0.2	0.8
Sy2 (early)	2.5	1.7	1.5	1.4	0.3	2.7
Sy2 (late)	4.1	4.0	1.3	1.3	1.2	2.4
Sy2 (pec)	7.7	4.3	1.8	1.4	0.7	1.5
3b. $D_{\rm neigh} > 5.7$ kpc, $z < 0.03$:						
Sy	6.3	5.4	2.3	1.8	0.4	1.0
comp	4.5	3.1	1.2	1.1	0.1	0.1
comp (S)	6.3	4.1	1.3	0.9	0.2	−0.1
comp (early)	2.1	2.0	1.2	1.4	0.1	0.4
Sy1	3.9	2.8	2.4	1.6	0.1	0.8
Sy2	8.3	7.8	2.2	1.9	0.5	1.1
Sy1 (early)	3.6	3.8	1.7	1.6	0.2	0.8
Sy1 (late)	1.1	1.6	1.3	1.1	0.1	0.2
Sy1 (pec)	6.0	3.2	3.6	2.0	0.1	1.2
Sy2 (early)	6.5	4.6	1.8	2.0	0.3	1.2
Sy2 (late)	9.2	10.6	1.7	1.5	0.7	0.7
Sy2 (pec)	9.0	8.2	3.2	2.3	0.6	1.6

[a] Significance in Mann-Whitney U-Test: $0.001 < p < 0.05$

was deduced from Monte-Carlo simulations for a galaxy size distribution following Holmberg (1975) measurements, taking into account the Malmquist bias. It is worth noticing that the two redshift estimates give very similar profiles. In the galaxy density profiles there is a strong narrow peak at a distance smaller than 50 kpc, and the same accumulation of companions is visible up to 200 kpc (called as a "secondary bump" in the following).

In Table 3 the mean numbers of physical companions $N_{\rm phys}$ and the number density relative to the background density ρ are shown within the inner 50 kpc, and in the "secondary bump". $N_{\rm phys}$ was obtained by subtracting the number of background galaxies estimated from the density in the zone 500–700 kpc. Two ways of calculating the relative galaxy densities are applied. The first takes the mean over the ratios $\rho_{50}/\rho_{500-700}$ of each galaxy (ρ_1), and the second takes the ratio of the mean ρ_{50} and mean $\rho_{500-700}$ (ρ_2). The value of ρ_1 is more sensitive to a few exceptional galaxies in the sample than ρ_2, giving more weight to individual galaxies. Comparison of the two densities can be used as a measure of the reliability of the obtained results.

The Seyferts were found to have 1.5–2.1 times larger galaxy density (according to ρ_1 and ρ_2) and 1.7 times more companions than the comparison galaxies within the inner 50 kpc (Fig. 3a; upper panel, Table 3a). The corresponding numbers at the distance 50–200 kpc are 1.2 and 3.0, the difference in the mean number of physical companions being statistically significant (remarks in the last column in Table 3 indicate comparisons with other samples yielding significantly different median values). Note that statistical confidencies could be tested only in the secondary bump ($N_{{\rm phys}_{50-200}}$), where enough large number of galaxies appeared. When limiting to $z < 0.03$ and neighbouring galaxy size to correspond to $D_{\rm comp} \geq 5.7$ kpc, the results are even clearer (Fig. 3b; upper panel, Table 3b). A probable reason for this is that the background is smaller while limiting the absolute galaxy size thus making the real features more visible. Again, the two redshift estimates give similar results. We tested that the result is not affected by any bias in cluster properties in Zwicky's fields between the compared samples.

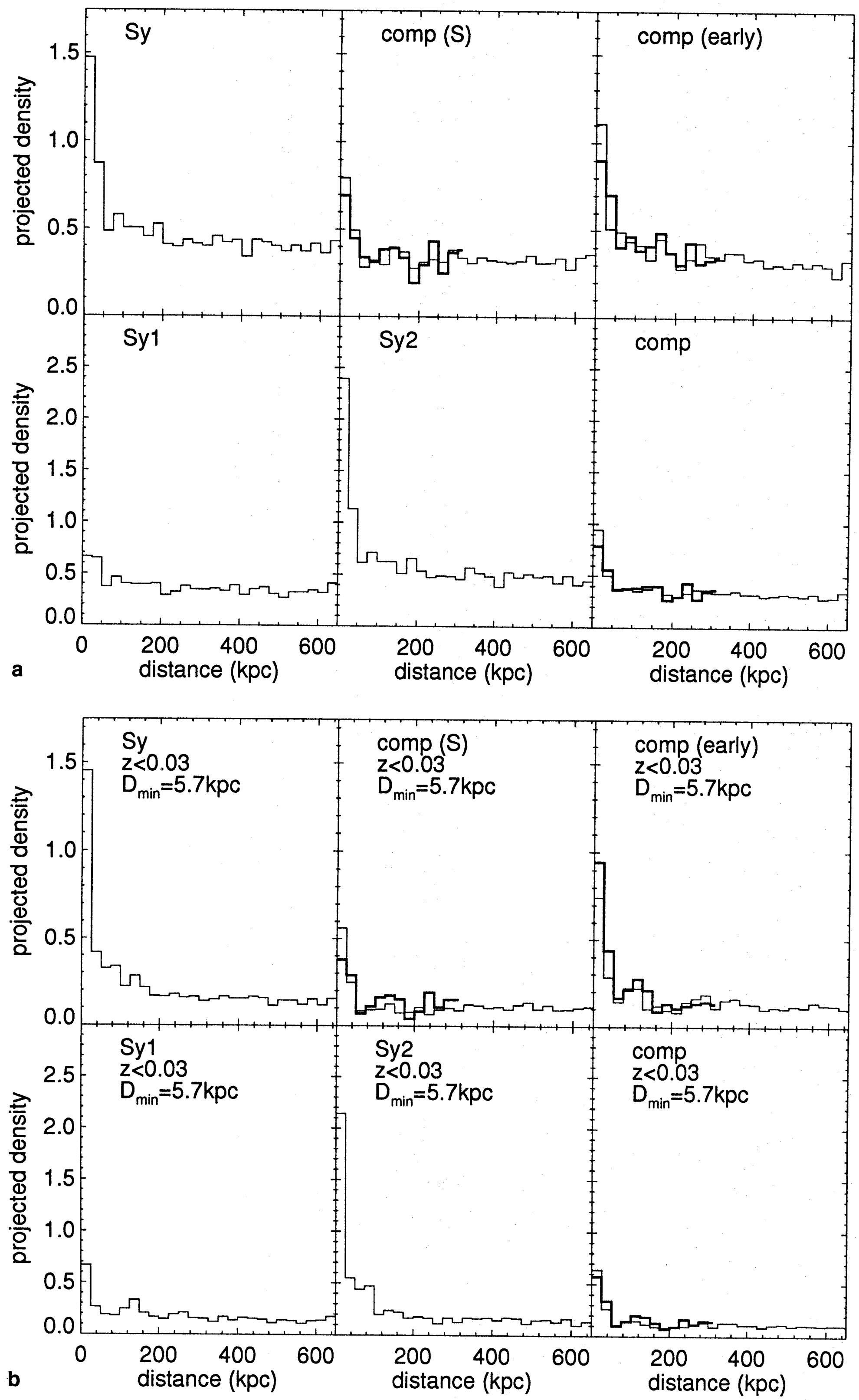

Fig. 3a and b. Histograms of the projected densities of neighbouring galaxies for principal samples (in units of companions/main galaxy/ 10^4 kpc^2). In **a** all measurements (size $\geq$ 0.20 mm) are used while in **b** only main galaxies with $z < 0.03$ are included and neighbouring galaxy size is limited above 5.7 kpc. For comparison samples the thin and thick solid lines refer to the two methods for estimating their redshift (based on the corresponding Seyfert redshift and calculated from a fixed linear diameter, respectively)

On the basis of these results it is somewhat suprising that our preliminary Dahari-type test at $S = 3D_{\rm gal}$ (Sect. 2.1 Table 1; test 4) did not show any number excess of interacting Seyferts in comparison with normal galaxies. In Fig. 4a (upper panel) the Dahari-type tests are extended to cover a large range

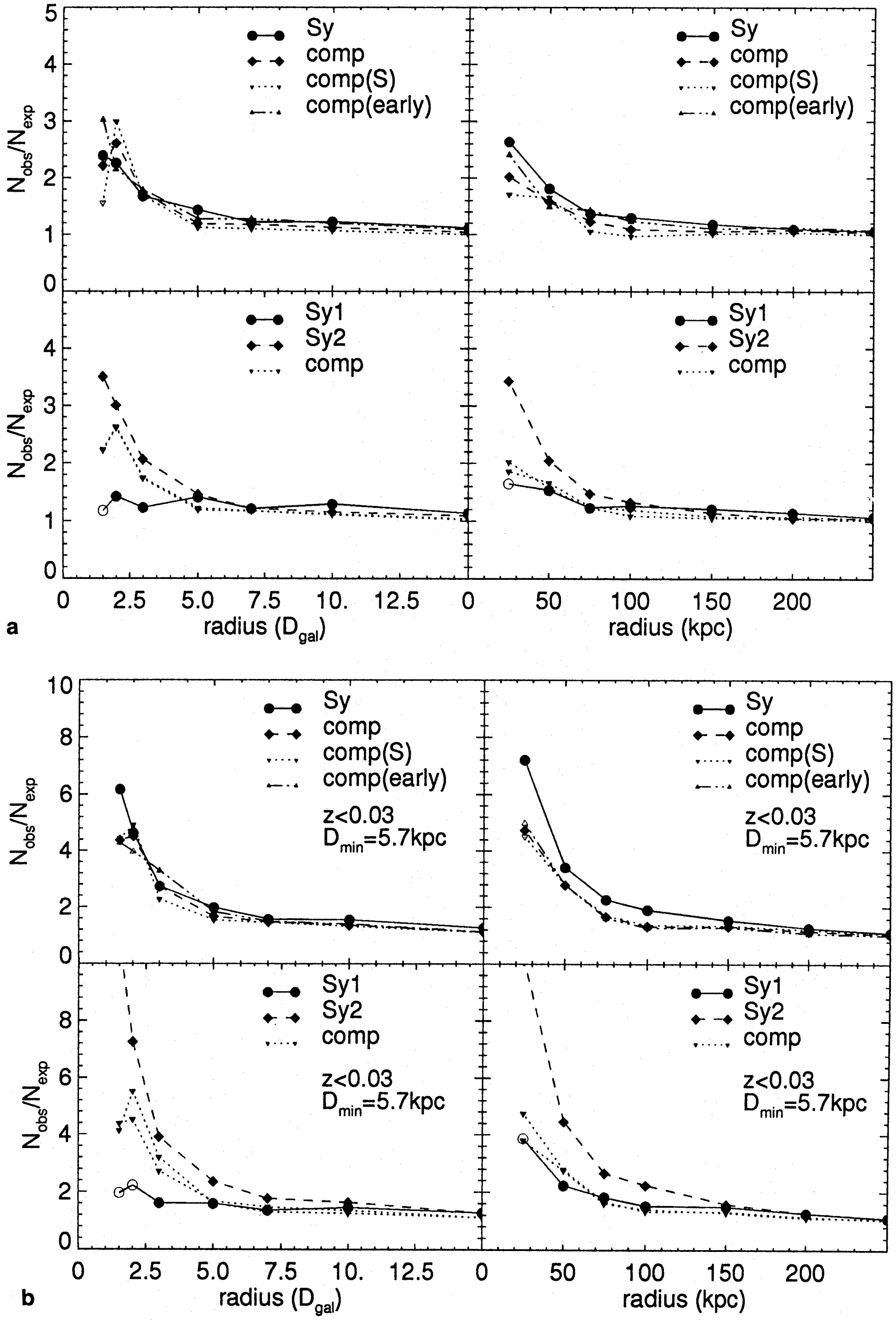

Fig. 4a and b. Dahari-type tests for the samples displayed in Fig. 3 a and b. In the left hand panels the search radii are counted in main galaxy diameters ("relative Dahari-type test"), while in the right fixed kpc values are used ("absolute Dahari-type test"). For the comparison sample (comp) the two different redshift estimates are shown in the lower panels. Open symbols stand for the cases where $N_{obs} \leq 5$

of search radii the results being given both in "relative" and "absolute" search area units. For the comparison galaxies two lines are shown (Figs. 4a and 4b) corresponding to the two different redshift estimates. Both types of tests confirm the result of the preliminary Dahari-type test. Also, the two redshift estimates for the comparison galaxies give similar results. While limiting to redshifts below 0.03 and $D_{comp} < 5.7$ kpc (Fig. 4b; upper panel) a marginal relative excess of interacting Seyferts is found in the "absolute Dahari-type test". In that case Seyferts appear 1.3 times more often in interacting systems than normal galaxies (at $S = 50$ kpc).

We conclude that Seyferts as a group do not have more frequently companions than normal galaxies (Dahari-type tests). However there must be some Seyferts with many companions (radial profiles). This conclusion is in agreement with our result obtained by applying the FWS-type methods (Sect. 3).

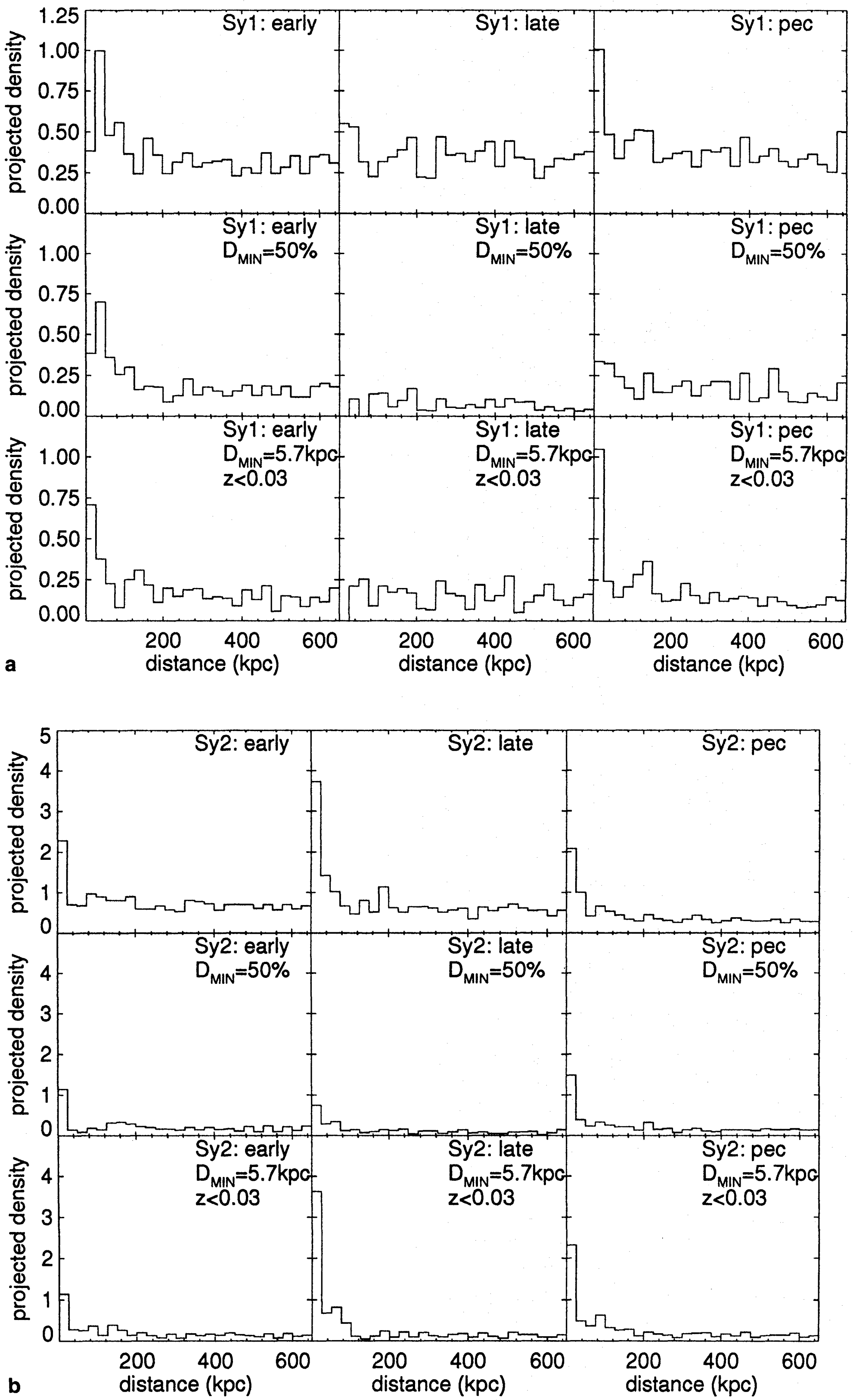

Fig. 5a–c. Same as Fig. 3, but the Seyfert samples are further divided based on morphological types (upper and lower panels). **a** shows profiles for Seyfert 1 galaxies, **b** for Seyfert 2 galaxies and **c** for comparison galaxies. Also shown are distributions of neighbours with size of at least one half of the main galaxy (middle panel in **a**, **b** and **c**)

4.2. Seyfert 1 vs. Seyfert 2 galaxies

A comparison of the number density profiles of Seyfert 1 and Seyfert 2 galaxies, shown in Fig. 3a (lower panel, Table 3a) indicates that the number excess of companions around Seyferts appears only for type 2 objects. Seyfert 2 galaxies have 1.6–2.2 times larger relative densities and 2.7 times more companions than normal galaxies within the inner 50 kpc, whereas the mean

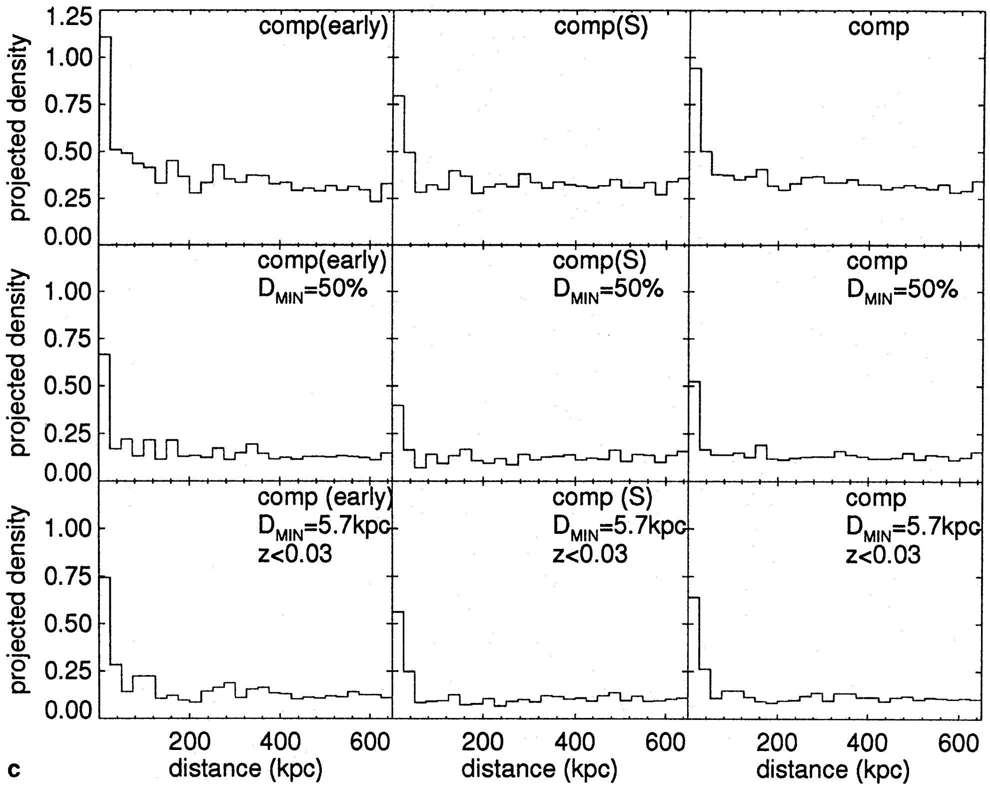

Fig. 5. (continued)

environmental properties of type 1 Seyferts are normal. Also the "secondary bump" in the profile at a distance of 50–200 kpc from the central galaxy is induced by type 2 Seyferts. These tendencies are even more pronounced while limiting to $z \leq 0.03$ (Fig. 3b; lower panel, Table 3b).

The "relative Dahari-type test" shows an interesting phenomenon for type 1 Seyferts: they are even *less* frequently associated with companions than normal galaxies (Fig. 4a and b; lower panels). However, this tendency is only marginal in the "absolute Dahari-type test". On the other hand, type 2 Seyferts appear several times more frequently in interacting systems than the comparison galaxies. This is evidenced according to both Dahari-type tests, the exact value depending on the search radius. Again the features are more clear at low redshifts ($z \leq 0.03$). The result is independent of the way of determining the redshifts of the comparison galaxies.

4.3. Morphological type vs. Seyfert type

We next study whether there exists a correlation between the environmental properties of Seyferts and the morphological types of the galaxies (Figs. 5, 6, 7 and 8, Table 3). Morphological types are roughly divided to the following groups: E-SOa (early-type), Sa-ScI (late-type) and peculiar galaxies (pec). Peculiar galaxies here include the groups Irr-pec-S and "others", being explained in Paper I in Sect. 5.4.

All Seyfert 1 galaxies show normal density profiles within the inner 50 kpc (see Figs. 5a and c). More detailed inspection of the calculated galaxy densities (Table 3a) shows that early-type Seyfert 1 galaxies may have a small number density excess of companions being 1.5–1.6 within the inner 50 kpc while compared with the control galaxies of the same morphological type. For late-type and peculiar Seyfert 1 galaxies the satellite densities are similar to those of the comparison galaxies. For the lack of proper comparison sample peculiar galaxies are here compared with late-type galaxies. Also the Dahari-type tests (Figs. 6 and 7) illustrate that Seyfert 1 galaxies have not exceptionally rich nearby environments for any of the morphological types investigated. According to the "relative Dahari-type test" (Fig. 6) Seyfert 1 galaxies of all morphological types appear even *less* frequently in interacting systems than the comparison objects. However, this result is only marginal in the "absolute Dahari-type test" (Fig. 7). At $z \leq 0.03$, with a limiting galaxy size of 5.7 kpc there are too few galaxies in the immediate neighbourhoods of the parent galaxies for reliable Dahari-type tests.

On the other hand, the environmental properties of type 2 Seyferts are found to be strongly correlated with the morphological types of the galaxies. The number density profiles (Figs. 5b and c) show that late-type and peculiar Seyfert 2 galaxies clearly have more companions than the control galaxies. However, although the number of companions within the inner 50 kpc (N_{phys}) is larger for late-type than for peculiar galaxies (1.2 vs. 0.7), their relative densities are less different (4.0–4.1 vs. 4.3–7.7). In principle this could be explained by background effects, because in our sample the background galaxy density is smaller for peculiar- than for late-type galaxies. However, it is more plausible that the companions of Seyfert galaxies are concentrated 1) around some late-type galaxies, each having several companions, and 2) around peculiar galaxies, each having only one or few companions. In fact, this is evidenced also

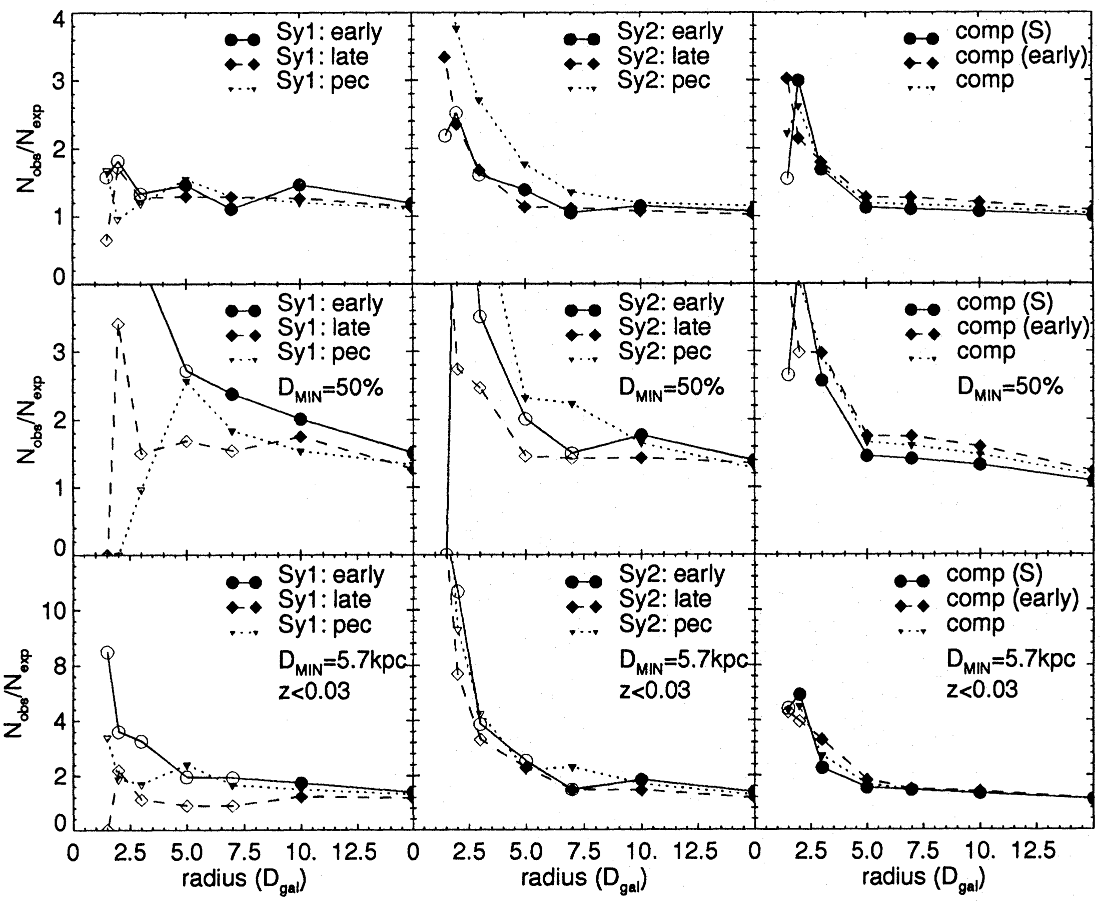

Fig. 6. Dahari-type tests for the samples displayed in Fig. 5. The search radii are counted in main galaxy diameters

by the Dahari-type tests (Figs. 6 and 7, upper panels) showing that only peculiar galaxies as a group appear more frequently in interacting systems than the control galaxies. At $z \leq 0.03$ this is not clear anymore (Figs. 6 and 7; lower panels), probably because the statistics become too poor. The galaxy density peaks obtained in the profiles of peculiar galaxies are solely due to Irr-pec-S galaxies, whereas compact galaxies ("others") have normal environments (Fig. 8). The number density of companions around early-type Seyfert 2 galaxies is rather similar to that obtained for the control galaxies (Figs. 5b and c, upper and lower panels; Table 3).

We conclude that the environmental properties of Seyfert 1 and Seyfert 2 galaxies compensate in the sense that Seyferts as a group appear in interacting systems not more often than normal galaxies. Actually only non-compact peculiar type 2 Seyferts appear more frequently in interacting systems than the control galaxies, whereas Seyfert 1 galaxies may even lack companions. Some late-type and non-compact peculiar Seyfert 2 galaxies have many companions.

4.4. Sizes of the galaxies

The sizes of the companions were investigated by repeating the Dahari-type tests and profiles while limiting to companion sizes exceeding 50% of the main galaxy diameter (Figs. 5, 6 and 7). This kind of relative galaxy size limitation is reasonable in a sense that massive companions are expected to have stronger tidal effects on the main galaxy than smaller companions. However, it also worth noting that in the case of very nearby encounter the absolute size and physical properties of the companions become important: a gas rich companion may be responsible of the quantity of gas required to fuel the nucleus. When limiting to large companions the density peak within the inner 50 kpc for late-type Seyfert 2 galaxies is strongly reduced (Fig. 5b; middle panel). This is because late-type Seyfert 2 galaxies are on the average 6.4 kpc larger than early-type or peculiar galaxies so that the size restriction eliminates almost all of the rather small companions (compared with the parent galaxy size) of the late-type Seyferts. Seyfert 1 galaxies of all morphological types probably lack this kind of companions (Fig. 5a; middle panel). Lack of companions around late-type Seyfert 1 galaxies is visible also in both Dahari-type tests (Figs. 6 and 7; middle panels). However, for the small number of galaxies these tests are not statistically very reliable, evidenced also by the fact that the two different ways of calculating the satellite densities give rather different results.

The mean physical properties of the galaxies are shown in Table 4. In the Table N refers to the total number of galaxies, M_V is the absolute visual magnitude of the central galaxy and D_{gal} and D_{neigh} are central and comparison galaxy diameters (for

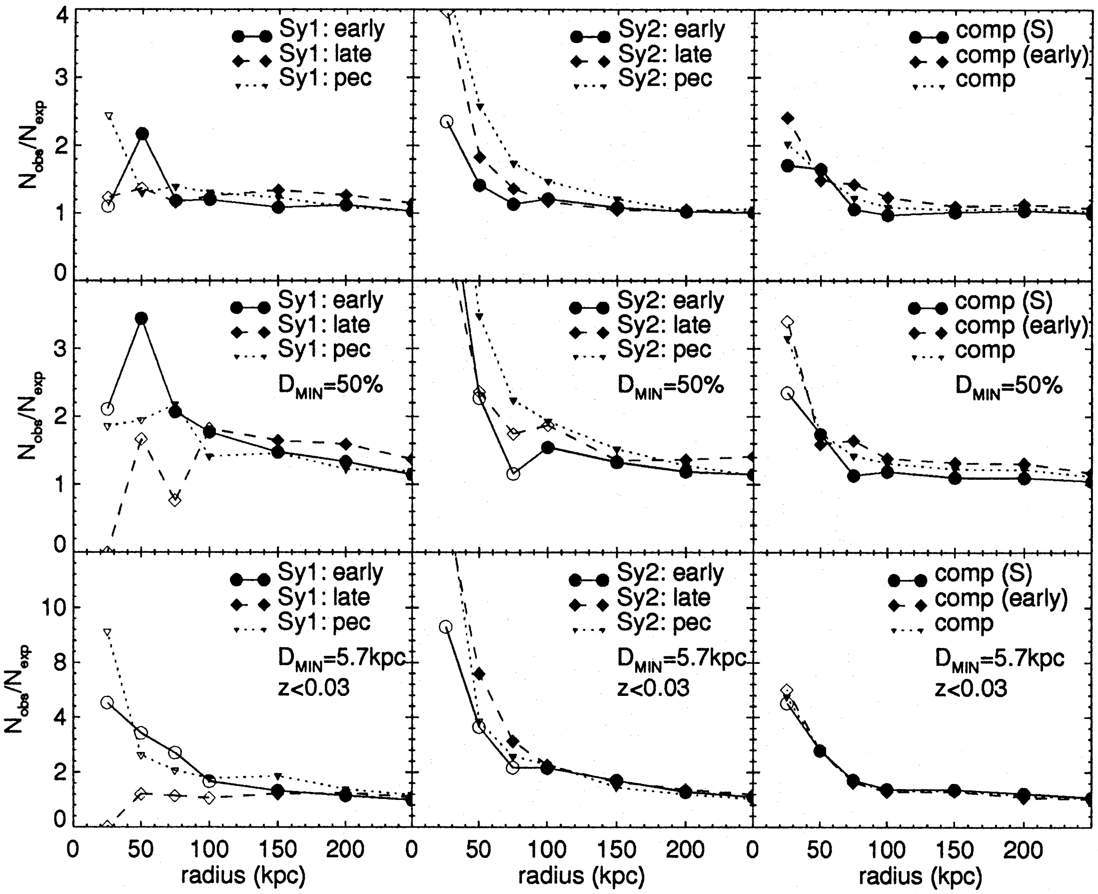

Fig. 7. Dahari-type tests for the samples displayed in Fig. 5. Fixed kpc values are used for the search radii

neighbours within 50 kpc). Seyferts of all morphological and Seyfert types are found to have companions with equal sizes being on the average 5–6 kpc in diameter. These mean sizes are similar to those found for the control galaxies. As the detection limit of the physical companions increases with redshift, the absolute mean size naturally also increases, which most probably accounts for the small size differences of the companions between different morphological types of the Seyfert galaxies. Table 4 also shows that late-type Seyferts are bigger and absolutely brighter than Seyferts of other morphological types.

Interacting late-type galaxies of both Seyfert types are found to be about 3 kpc larger than their non-interacting counterparts. This may be partly caused by small, companion deficient compact Seyferts lying preferentially at large distances.

5. Discussion

Studies of the link between galaxy interactions and the Seyfert phenomenon fall into two primary categories: comparisons of the optical morphology and local environments of known Seyferts to normal galaxies, and comparisons of the incidence rates of Seyfert nuclei in samples of interacting and non-interacting galaxies. However, the conclusions of these investigations are partially contradictory as was shown for example by Heckman (1990) in his review article. In the following we shortly summarize the main results largely following Heckman (1990) and Osterbrock (1993), and then try to understand them on the bases of our own results. The main characteristics of the various studies are collected to Tables 5 and 6.

5.1. Incidence rate of Seyferts in the samples of interacting galaxies (see Table 5)

Keel et al. (1985) compare the incidence rate of Seyfert nuclei in two samples: (1) a complete sample of physical galaxy pairs ("pairs" sample), and (2) galaxies selected from the Arp's Atlas of Peculiar Galaxies ("Arp" sample) representing strongly interacting galaxies. The incidence rate of Seyferts was 10.6% in the "pairs" sample and 8.2% in the "Arp's" sample in comparison with 5.6% found for the control galaxies. The result for the "pairs" sample is only marginally significant (at 2σ level). The "Arp's" sample by Keel et al. is even deficient of Seyfert nuclei, because these galaxies are more luminous than their control galaxies: among the absolutely brightest galaxies an increasingly high percentage are Seyferts (Osterbrock 1984), implying that the "Arp's" sample should in fact contain clearly more Seyferts than the control sample.

Dahari (1985) divided his interacting galaxies into six classes representing the proximity of the galaxies, and com-

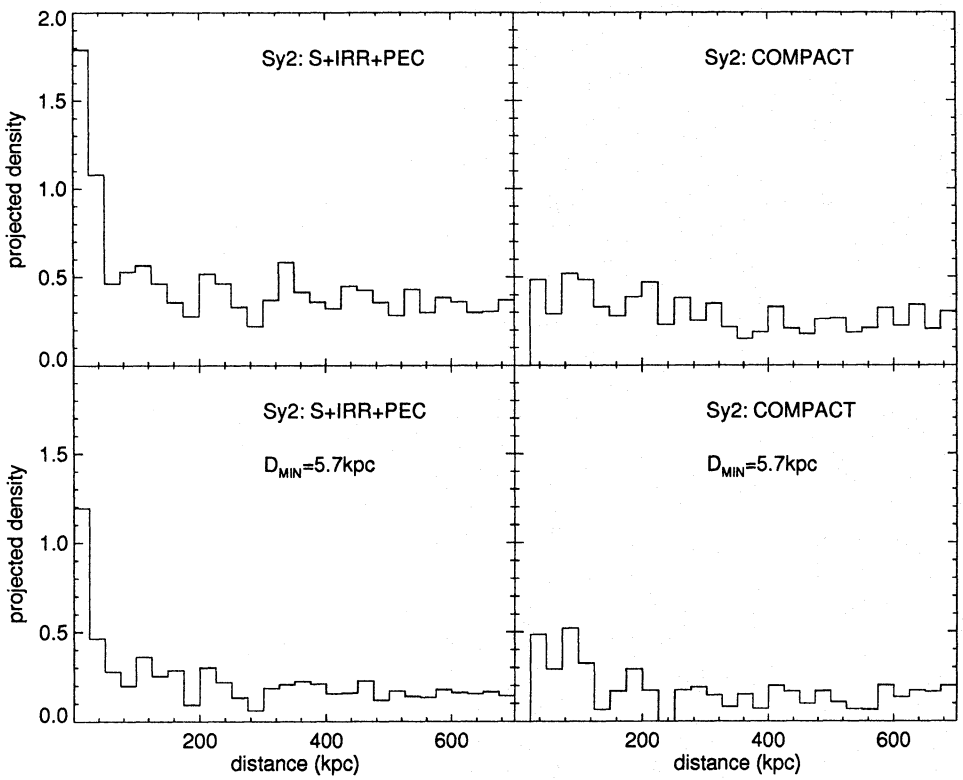

Fig. 8. Histograms of the projected densities of neighbouring galaxies for peculiar Seyfert 2 galaxies. The left hand panels show peculiar galaxies belonging to the class S-Irr-pec, and the right panels those belonging to the class "compact". The lower panels show the corresponding diagrams but limiting to neighbouring galaxy sizes > 5.7 kpc

Table 4. Some physical parameters of the Seyferts and of the comparison galaxies. Dispersions of the mean values are also shown

Sample	N	$z(\times 10^4)$:	$-\overline{M}_V$	$\overline{D}_{gal}$(kpc)	$\overline{D}_{neigh}$ (kpc)
Sy ($0.01 < z < 0.043$)					
Sy1 (early)	17	271 ± 90	19.6 ± 0.9	13.7 ± 5.6	6.7 ± 3.9
Sy1 (late)	16	289 ± 78	20.1 ± 0.8	20.8 ± 7.9	6.7 ± 5.6
Sy1 (pec)	21	268 ± 88	19.5 ± 0.9	14.9 ± 6.8	8.9 ± 3.9
Sy2 (early)	12	172 ± 46	19.0 ± 0.5	13.1 ± 5.1	5.4 ± 2.7
Sy2 (late)	13	207 ± 78	20.0 ± 0.6	19.7 ± 5.6	6.2 ± 4.1
Sy2 (pec)	22	277 ± 72	19.5 ± 0.8	14.0 ± 5.1	9.1 ± 4.8
comp ($0.01 < z < 0.02$)					
comp (early)	11	153 ± 22	$19,5 \pm 0.7$	15.0 ± 4.9	4.4 ± 1.9
comp (S)	9	152 ± 24	18.7 ± 1.3	16.4 ± 4.9	5.8 ± 2.3
comp	20	152 ± 22	19.2 ± 1.1	15.6 ± 4.8	5.1 ± 2.2
Sy ($z < 0.02$)	31	152 ± 25	19.2 ± 0.7	15.4 ± 7.5	5.2 ± 2.8

pared galaxies pertaining to the classes IAC=4,5 and 6 (strongly interacting), and to IAC=2 and 3 (weakly interacting), with non-interacting objects. Galaxies in the class 6 are the most proximate and the most distorted ones showing for example tidal features. He found that the fraction of Seyfert nuclei was 13.2% and 5.6% for the strongly and weakly interacting galaxies, respectively, compared with 4.6% for the control objects. The number excess of Seyferts among the strongly interacting galaxies is statistically significant at the confidence level of 2.5σ. Dahari did not apply any brightness correction analogous to that made by Keel et al. The luminosity correction would make Dahari's results even more similar to those found by Keel et al.

Bushouse (1986) reports a deficiency of Seyfert nuclei among strongly interacting galaxies, the incidence rate being 1% vs. 5% at a significance level of about 85% when tested against Keel & Stauffer control sample used also by Dahari (see Heckman 1990). Also the sample by Sekiguchi & Wolstencroft (1992, hereafter SW) for strongly interacting galaxies shows a deficiency of Seyfert nuclei being 3.1% in comparison with 4.6% for their control sample. SW did not apply any luminosity correction. Inclusion of spirals only did not essentially change the conclusion (2.6% vs. 4.6%).

The main reasons suggested for these incompatible results are "the bad luck due to the low confidence levels in many of the studies ($2 - 3\sigma$) and that the probability of detecting a Seyfert nucleus in an interacting system is a complex function of the detailed properties of the interaction and of its constituent galaxies" (Heckman, 1990). Indeed, Heckman (1990) takes the pessimistic view that samples of the order of 100 galaxies are not large enough to make final conclusions in a convincing fashion. However, in our opinion the results are not as inconsistent as one would think at first sight.

We suppose that morphological selection of galaxies is the most important factor responsible for the variety of the above results. A hint to a similar conclusion is given by Whittle (1992a) while attempting to correlate emission line velocity dispersion with tidal effects. He found that [O III] FWHM in Seyferts is related to the distortion level of the parent galaxy so that the line width increases with growing distortion level, except in a case of extremely distorted galaxies. It is important to note that the correlation of line width is stronger with the distortion level than with the Dahari's interaction class, which tells more about relative size and proximity of a companion than about the distortion level. We next compare the sample selections of the above mentioned surveys.

The samples by Bushouse (1986) and SW are exclusively morphologically selected samples including only very distorted galaxies. An additional selection criterion by SW is that the galaxies must also be detected in IRAS point source cataloque, thus possibly biasing the sample towards starburst galaxies. Although the galaxies of Bushouse's sample are not selected on the basis of IRAS detection all of them have considerable far-infrared fluxes. This implies that in practice the two samples are very similar. On the other hand, Keel et al. (1985) and Dahari (1985) select their samples randomly from catalogs of interacting galaxies paying no attention either to galaxy morphology or detection in the IRAS point source cataloque.

There is a tendency throughout all the five works (including this work), indicating that very distorted systems avoid Seyfert activity. This can be seen in the "Arp" sample by Keel et al., among the most disturbed galaxies classified as 6 by Dahari, as well as in the samples by Bushouse and SW. The three last mentioned samples even lack Seyferts in comparison with non-interacting galaxies. The fact that our Seyfert sample includes only one merger is consistent with this result. Marginally larger number of Seyferts among the "Arp" sample by Keel et al. compared with the samples by Bushouse and SW (8.2% vs. 1% and 2.9%) might be due to small differences in their sample selection: while Keel et al.'s "Arp" sample is entirely based on the Arp's Atlas of Peculiar Galaxies, of the Bushouse's sample only 50% of the galaxies belong to the Arp's Atlas.

Inspection of the mean redshifts and absolute blue magnitudes of the above samples confirm that morphological selection, rather than redshift or absolute magnitude selection is the main reason for the variety of the results. SW noticed that at large redshifts the spectral slit covers a larger part of the galaxy than at lower redshifts. Accordingly, starbursts surrounding the Seyfert nuclei were suggested to be more pronounced in the spectra at large distances thus diluting the Seyfert phenomenon. This was suggested by SW to explain the difference between their results and those obtained by Dahari and Keel et al. Indeed, the mean redshift of their sample is larger than that in the two other samples mentioned. However, redshift most probably is not the explanation because the result by SW is similar to that obtained by Bushouse, even though the galaxies by Bushouse are clearly more nearby ones than the galaxies in SW's sample. It is also worth noticing that only a few galaxies in SW's sample are composite objects.

The main tendencies that can be sorted out of these studies are that Seyferts avoid very distorted systems and that interacting galaxies, when selected without any morphological criterion, have larger incidence rate of Seyferts than non-interacting galaxies.

5.2. *Environments of Seyfert galaxies (see Table 6)*

There are two statistical investigations concerning the environments of Seyfert galaxies showing that Seyferts appear clearly more frequently in paired systems than normal galaxies, namely the studies by Dahari (1984) and MacKenty (1989). Also Petrosian (1982) found that Seyferts have a tendency to have companions, but he had no comparison sample. The contrary result was obtained by FWS (however, they found a small excess of interacting Seyferts while using no lower size limit). At first sight our Dahari-type test results are in disagreement with the three first studies, as we found that Seyferts appear as frequently in paired systems as normal galaxies. According to the FWS-type tests we found that Seyferts have larger companion galaxy densities by a factor of two, in comparison with normal galaxies, which is in contradiction with the result by FWS (applying the same tests) who found that Seyferts have nearly normal environments. However, as discussed in Sect. 2.2.1 their result is heavily affected by a redshift bias between the compared samples.

The reasons addressed in the literature to explain the variety of the results are quite similar to those for the variable success of finding Seyferts in samples of interacting galaxies, namely sample selection and low statistical significance of the results. For example, randomly selected samples of field galaxies are supposed to be more weighted toward late-type galaxies than the Seyfert samples. Accordingly, as there is the well known morphology-density relationship showing that early-type galaxies are preferentially located in regions of higher galaxy density, the control samples by Dahari and MacKenty are suggested to be biased towards lower galaxy densities. However, recent studies by Whittle (1992b) and Granato et al. (1993) have shown that even 30% of Seyferts 1–1.5 may be late-type spirals. Another possible selection effect is that proposed by Osterbrock (1993), namely that Seyfert 1 and 2 galaxies are not equally represented in the samples. For example the Seyfert sample by FWS may be deficient of type 2 objects, as they picked up galaxies from relatively early Seyfert catalogs. According to Osterbrock, as there is some evidence (MacKenty 1989) that Seyfert 2 galaxies have more companions than type 1 Seyferts, this could at least partially account for the negative result obtained by FWS. However, on the basis of the analyses presented in this paper we suppose that the main reasons for the conflicting results

Table 5. Review of the studies searching Sy-nuclei in samples of interacting galaxies (H_0 = 100 km s^{-1} Mpc^{-1})

	Keel et al. (1985)	Dahari (1985)	Bushouse (1986)	Sekiguchi & Wolstencroft (1992)
$N_{\rm tot}$	61/99	162	94	84/93
Mean z	0.0064/0.0199	0.0103/0.0145/ 0.0134	0.023	0.031/0.030
Δz	0.0004–0.060	0.0012–0.0527	0.0038–0.0405	0.0027–0.1300
Mean $M_{\rm B}$	−18.8/−19.7	−19.6/−19.8/−20.1	−19.7	–
Sample sel.	(1) A complete sample of spiral pairs and groups from the cat. of Albada with close companions. Physical ass. confirmed from local surface densities of gal. (must be of comparable brightness). (2) Spiral galaxies from Arp's Atlas of Peculiar galaxies (1966) having clear evidence of tidal distortions.	Spiral galaxies from the Vorontsov-Velyamninov's Atlas of Interacting Galaxies (1959), irregulars and cluster galaxies being excluded. Seyferts are devided to 6 groups of increasing tidal interaction. The following groups are considered seperately: (1) 4, 5, 6: strongly interacting gal. (2) 2,3: weakly interacting gal. (3) 6: very distorted	Morphologically selected sample containing only pairs of gal. that exhibit features of strong tidal interactions. Of sample gal. 45% belong to Arp's Atlas of Peculiar galaxies (1966)	Morphologically selected IRAS detected sample containing galaxies with tails, loops of material or debris and distorted pairs with comparable sized galaxies. Galaxies are from the cat. of Arp & Madore (1987).
	Control sample: 87 spirals from Keel (1983).	Conrol sample: 172 spirals from Keel (1983) and Stauffer (1982) (interacting galaxies excluded).	Control sample: spirals from Keel (1983), and Philips et al (1983).	Control sample: the same as in Dahari's work.
Conclusions:	(1) Marginal excess of Sy-nuclei: 10.6% vs. 5.6% (at 2σ-level). (2) Lack of Sy-nuclei: 8.2% vs. 5.6%, but Sy:s brighter than control gal.	(1) Excess of Sy-nuclei: 13.2% vs. 4.6% (2) No excess of Sy-nuclei: 5.6% vs. 4.6% (at 2.5σ-level) (3) The most disturbed spirals lack Sy:s	No excess of Sy-nuclei: 1% vs. 5% (stat. sign. 85%)	No excess of Sy-nuclei (2.6% vs. 4.6% if only spirals incl., and 3.1% vs. 4.6% including all morphol. types).

are largely related to problems in estimating the contamination by background galaxies (Dahari, MacKenty, FWS) and redshift bias between the compared samples (FWS).

Elimination of the background galaxies is a serious problem in many of the previous statistical studies, affecting especially the results by FWS. The importance of good estimation of background galaxies must be emphasized also for the Dahari-type tests, although the method itself takes the background into account. Our large database made possible to determine the background galaxy densities with the same resolution as the measurements in immediate neighbourhoods of the central galaxies. This was found to be an essential improvement compared with the original Dahari-type test, in which the background galaxy density was estimated from Lick counts. Accordingly, the large incidence rate of Seyferts with companions in comparison with normal galaxies disappeared. The same problem as in Dahari's work most probably is involved also into the study by MacKenty (1989), who applied Dahari's method.

Seyfert 2 galaxies are found to have more companions than Seyfert 1 galaxies according to Petrosian (1982), MacKenty (1989) and this work. On the contrary, according to Dahari (1984) Seyfert 2 galaxies appear in paired or multiple systems as frequently as Seyfert 1 galaxies. Petrosian and MacKenty included only type 1 and type 2 Seyfert galaxies, whereas Dahari and this work take into account also intermediate types. However, it is worth noticing that while we include only the types 1–1.5 to the first Seyfert category and the types 1.8–2.0 to the Seyfert 2 category, Dahari includes all types up to 1.9 to the

Table 6. Review of the environmental studies of Seyfert galaxies

	Petrosian (1982)	Dahari (1984)	MacKenty(1989)	FWS	Our sample
POSS	blue	blue	red	blue	blue
Redshift	≤ 0.05	≤ 0.03	0.01–0.04	0.01–0.05	0.01–0.043
Det. limit		$18.3m_{pg}$	0.2 mm[d]	$D > 0.25D_{Sy}$	19.1 mpg
Phys.ass.	$0.5D_{Sy} \leq S \leq 2D_{Sy}$	$S \leq 3D_{Sy}$	$S \leq 10D_{Sy}$, $S \leq 3D_{Sy}$	$15\,kpc \leq D_{neigh} \leq 50\,kpc$	$S \leq 3D_{Sy}$, $S \leq 50$ kpc, all
Searching diam.	1.13 Mpc	$3D_{Sy}$	1.13 Mpc	1.5 Mpc	1.5 Mpc
N_{Sy}/N_{field}	161/	84[c]/256	51/51	53/30	104/133
N_{Sy1}/N^{a}_{Sy2}	92/60[b]	44/58	28/11		49/55
N_{neigh}(tot)	1460(Sy)	279(Sy)	836(Sy) 527(comp)	528(Sy ass.)[e] 243(comp ass.)	9070(Sy) 12880(comp)
Comp. sample sel.	No comp. sample.	3 closest randomly selected neighbours having major axis diam. of $0.75D_{Sy} < D < 1.5D_{Sy}$. No match in z, mag or morphol. type. Sy's in rich clusters excluded.	The closest gal. having major axis diam. in the range: $0.75D_{Sy} < D < 1.5D_{Sy}$. No match in z mag or morphol. type.	Random selction from the Redshift Survey from Huchra (1989). Intention to match in z, mag. or morphol. type.	Two closest neighbours, one early- and one late-type galaxy randomly selected, having major axis diam. $0.65D_{Sy} < D < 2.00D_{Sy}$. No match in z, mag or morphol. type.
Sky backgr.	Counts of gal. near the Sy in 4 circles of the same diam. as the Sy.	Mean number density from Lick counts used in the probability function.	No sky substraction.	No sky substraction	Measurements at a distance 500–700 kpc from the main galaxy center.
Conclusions:	Sy's participate in the tendency of gal. to cluster.	Sy's have clearly more often companions than normal galaxies (15% vs. 3%) in pairs and 8.2% vs. 3% among Arp's gal.)	Sy's have clearly more often companions than field galaxies. (71% vs. 26%)	Sy's have only marg. more often comp. than normal gal. (if any) and more frequently only when small companions considered.	Sy's as a group have comp. as often as normal gal., but some Sy's have many companions. The number excess concentrated around peculiar and late-type Sy2 galaxies.
	Type 2 Sy's have comp. more often than type 1 Sy's.	Both types have similar environm.	Type 2 Sy's have comp. more often than type 1 Sy's.		Sy2 gal. have more often and more comp. than Sy1 gal.

[a] Type 1: 1.0–1.5, and Type 2: 1.8–2.0.
[b] The rest of the galaxies in the sample are unclassified.
[c] Marginal Seyferts excluded.
[d] Completeness limits in 0.4 mm.
[e] These are numbers of "asiciated galaxies", because FWS do not give the total number of measured objects.

first category. Therefore, in the Dahari's work the two Seyfert classes may be mixed thus probably explaining the similarity of the environments of the two Seyfert types.

5.3. *Putting it all together*

While comparing the studies, which in some sense are comparable (not very distorted systems), namely the "pairs" sample by Keel et al. (1985), the strongly interacting galaxy sample by Dahari (1985), and the Seyfert samples by Dahari (1984) and MacKenty (1989), Seyferts are found to appear more frequently in paired systems than normal galaxies. Another tendency found in all these works (including this work) is that Seyferts avoid very distorted systems. The number excess of interacting Seyferts in comparison with normal galaxies varies between 1.9–5.0 being strongest in Dahari's (1984) work. It is only the present work (and FWS), in which the probability of finding a Seyfert galaxy with a companion is the same as for the control galaxies. However, the similarity between the results by Dahari (1984, 1985), Keel et al. and MacKenty may be partly a mere coincidence. Namely as shown in Sect. 2.1 the number excess of Seyferts with companions in Dahari's (1984) and MacKenty's works may be strongly affected by background density estimates so that in reality in these works the Seyferts may have rather similar mean environmental properties as the comparison galaxies. In that case how could it be explained that the samples of interacting galaxies (Keel et al. 1985; Dahari 1985) still show large incidence rates of Seyferts?

Our discovery that spirals and non-compact peculiar type 2 Seyferts appear more frequently among interacting systems than Seyferts in general, has implications while interpreting the results of the randomly selected interacting galaxy samples. Accordingly, we expect to see a number excess of Seyfert 2 galaxies in these samples. Indeed, there is a tendency that Seyferts found among interacting galaxies are preferentially type 2 objects. The numbers for type 2 and type 1 Seyferts are 12/2 in Dahari's (1985) sample, 3/1 in SW and 9/3 and in the "pairs" sample by Keel et al. (1985). Therefore the incidence rates of Seyferts found in interacting galaxy samples are compatible with our results concerning the different morphological types and activity classes of the Seyferts.

Although the large scatter of the results available in the literature is now more understandable, we are still faced with the question: after all, do galaxy interactions trigger Seyfert activity or not? Maybe the role of galaxy interactions is only to induce star bursts in some already existing Seyfert 2 galaxies. However, if it is true that Seyfert 1 galaxies lack companions in comparison with normal galaxies, this might suggest long lasting effects of dynamical friction in the vicinity of these galaxies which has led to a removal of companions. Therefore, a real indication of galaxy interactions as a triggering mechanism to Seyfert activity might be the *lack* of nearby companions, not the overabundance of satellites. This is something we plan to address observationally.

Our results have also an implication to the 'unified' theory of Active Galactic Nuclei. The standard 'unified' model tells us that Sy 1 and Sy 2 galaxies are drawn from the same parent galaxy population, but are viewed more nearly perpendicular or parallel to the polar axis of central dusty torus (Krolik & Begelman 1988). The bases for the 'unified' scheme for Seyferts was laid down by Antonucci & Miller (1985), who found that in plane-polarized radiation the Seyfert 2 galaxy NGC 1068 has the spectrum of a Seyfert 1 object, with broad Hβ and Fe II emission features. The interpretation proposed was that there is a "hidden BLR" in the nucleus where radiation does not escape directly to us because of strong obscuration close around it, but which does escape along the axis and is scattered towards us by free electrons. The higher redshift counterparts of Sy1 and Sy2 galaxies, narrow line region galaxies (NLRG) and broad line region galaxies (BLRG) are suggested to be unified in a similar fashion (Barthell 1989; Antonucci & Barvainis 1990). Our finding that Sy1 and Sy2 galaxies have clearly different environments is incompatible with the 'unified' theory: if the two Seyfert types were drawn from the same parent population they should also live in similar environmental conditions.

6. Conclusions

The environments of 104 Seyferts and 138 comparison galaxies have been analyzed from the blue POSS plates. Companions were searched for within the circles of 1.5 M pc diameters down to a limiting magnitude of 19.1 $m_{\rm pg}$ (complete to 18.9 $m_{\rm pg}$). The database consists of 23284 companions which is substantially more than in any previous work thus enabling more accurate elimination of background galaxies and more thorough investigation of the galaxy environments. We also showed that many at first sight incompatible results can be understood on the basis of problems related to background galaxies and morphological selection, bringing for example the results obtained for the samples of interacting and noninteracting galaxies compatible with those obtained by us for the Seyfert sample. Also the varying success of finding Seyferts among interacting systems can be explained. Our main conclusions are summarized in the following:

(1) Seyferts appear in paired systems as frequently as normal galaxies (Dahari-type tests), but have on the average more companions, which means that some Seyferts have many companions (profiles and FWS-type tests). Profiles and the tests D2 and D3, which best measure numbers of physically associated galaxies, show that Seyferts have about 2 times more companions than normal galaxies within the inner 50 kpc, and about 3 times more in the "secondary bump" at 50–200 kpc from the parent galaxy center. The conclusions are independent of the way of estimating the redshifts of the comparison galaxies.

Our results disagree with those obtained by Dahari and by FWS. Namely Dahari found that Seyferts appear about five times more frequently in interacting systems than normal galaxies, and according to FWS (applying the same tests as we did) the Seyferts have on the average nearly as many companions as the control galaxies. The difference between our result and that obtained by Dahari can be explained by problems in his estimate of background galaxy density, whereas the difference to FWS results is due to a redshift bias between their Seyfert and comparison galaxy samples.

(2) Type 1 and type 2 Seyferts have dramatically different environments. While type 2 Seyferts have many companions the mean density of the neighbouring galaxies of type 1 Seyferts is normal. Also the frequency of finding Seyfert 2 galaxies in interacting systems is clearly larger than for normal galaxies, whereas Seyfert 1 galaxies appear in interacting systems as often or even *less* frequently than the control galaxies.

(3) Environments of Seyferts were found to be strongly correlated with the morphological types of the galaxies, companions being largely concentrated around late-type and non-compact, peculiar Seyfert 2 galaxies. On the other hand, only peculiar Seyferts appear more frequently in paired systems in comparison with the comparison galaxies. This implies that among late-type Seyferts there are only a few companion rich galaxies many of them having rather normal environments. For type 1 Seyferts the morphological type is less essential with respect to the environmental properties, galaxies of all types having rather similar, companion poor environments.

(4) Average sizes of the companions of Seyfert galaxies are typically 5.2 kpc at $z = 0.01$–0.02 for all Seyfert types and morphologies. The sizes are equal to those found for companions of normal galaxies at the same redshift range.

Our finding that Sy1 and Sy2 galaxies live in different environments is incompatible with the 'unified' theory of Seyfert galaxies.

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