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Results of a search for faint galaxies in voids*

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Abstract. We present the results of a search for intrinsically faint galaxies towards three regions with known voids and the Hercules supercluster. The intention was to identify galaxies of low luminosity in order to find possibly a galaxy population in the voids. Within these selected fields we increased the range of observations in comparison with the recent large field surveys which revealed the non-uniform spatial distribution of galaxies. The limiting magnitude was raised by about 5 magn., the limiting surface brightness by 2 mag/□″ , and the limiting diameter reduced to less than 1/3. The individual observational data of our sample are published in the previous Paper I (Hopp et al. 1995) which describes our search strategy and contains B and R magnitudes, apparent diameters, redshifts and galaxy types of about 200 newly identified objects. Their luminosity distribution demonstrates a relatively high percentage of dwarfish galaxies.

As the essential result of our survey we have to point out that no clear indication of a void-population was found. The majority of our objects lie outside voids in regions where the already known galaxies are concentrated. Some are located in the middle or near the edges of voids. They appear to be rather isolated, their distances to the nearest neighbour are quite large. Only few of our objects seem to be real void galaxies. Even in the three nearest and rather well defined voids we do not find any hitherto unknown galaxy.

Key words: large scale structure of the Universe – galaxies: redshift

1. Introduction

Recent large field redshift surveys like the "Center for Astrophysics Survey" (CfA, Huchra et al. 1983) or the "Southern Sky Redshift Survey" (SSRS I, da Costa et al. 1988) revealed a picture of the universe, where galaxies are concentrated in clusters and sheetlike structures. These surround large spheroidal regions apparently almost empty of galaxies with velocity diameters up to 5000 km/s, the so called voids (for details see the review of Giovanelli & Haynes 1991). These surveys are based on previous galaxy catalogues limited either to B magnitudes brighter than 15.5 (e.g. CGCG, Zwicky et al. 1961-1969) or to diameters larger than 1′.0 (e.g. UGC, Nilson 1973) as well as in surface brightness. The majority of galaxies in these catalogues are luminous objects of relatively high surface brightness, while the portion of dwarf systems is restricted to a few percent.

Therefore one may ask whether the void structure is affected by an observational bias due to the limitations of the catalogues employed. They might be surmounted if the observations penetrate deep enough to reach less luminous galaxies. For the comprehension of the formation and evolution of galaxies, it is doubtless of fundamental importance to know the real nature of the voids. Are they depleted of galaxies or occupied by a population different from the one in their surroundings?

Some theoretical models like the galaxy formation scenario in biased cold dark-matter dominated cosmologies (Dekel & Silk 1986, Hoffman et al. 1992) predict a smoother distribution of less luminous galaxies compared to the giants. Other authors stated the importance of special kinds of dwarf galaxies as Irregulars (Binggeli et al. 1988) or low surface brightness (LSB) objects (Schombert & Bothun 1988) for a proper determination of the galaxy number density and the large scale structure of the universe. Recent specially designed redshift surveys of dwarf as well as LSB galaxies (Bothun et al. 1986, Eder et al. 1989, Salzer et al. 1990, Binggeli et al. 1990, Thuan et al. 1991 a,b, Schombert et al. 1992, Pustil'nik et al. 1995) find similar spatial distributions of massive and less luminous galaxies, with notable differences however.

It was our intention to overcome the limitations of previous surveys in magnitude, diameter and surface brightness as well as to be independent of published galaxy catalogues and their restrictions. For that we obtained deep direct images, taken towards the central region of nearby well defined voids already known from literature. Estimating diameters and applying morphological criteria we tried to single out foreground galaxies and

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* Partly based on observations obtained at the European Southern Observatory, La Silla, Chile. Partly based on data-base query to the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

to get interesting candidates for follow-up spectroscopy. To increase the fields covered, the same was done using POSS plates. Only galaxies fainter than B = 15.5 were taken into account. For further details see Kuhn (1994) and Paper I.

As the further discussion will show, this object selection is an important as well as a critical procedure. On our deep plates and CCD frames one finds of course a multitude of faint predominantly background galaxies, far too many for spectroscopy. On the one hand, our selection criteria were rather successful, as the luminosity distribution of our sample demonstrates, but another question is whether these criteria are adequate for identifying void galaxies. We cannot exclude that we failed to find a considerable number of interesting objects.

2. Observations

Since the observations are described in detail in Paper I, only a short summary will be given here. Four regions were chosen for our program. In two of them the line of sight crosses several known voids behind each other. From the two void regions VN2 and VN4 selected for their emptiness and from the cluster A2151 we obtained deep direct images on the prime focus of the Calar Alto 3.5m telescope. Using photographic plates together with the K3 field corrector a field of roughly 1 □° was mapped for each exposure. In addition, using a Tektronix 1024^2 pix CCD-chip for scanning, a mosaic of frames with roughly another 1 □° field in total was covered towards the void region VN8.

On these images we searched for galaxies with diameters larger than 1.″5 and identified 637 objects (Sample 2 of Paper I). Of these 178 objects with diameters above 5.″5 were selected (Subsample 2 of Paper I). Finally, 77 objects were chosen for follow-up spectroscopy due to their non-giant morphology (e.g. late types or LSB's) and spectroscopic information as well as redshifts could be derived for all of them.

Additional POSS plates towards VN2, VN8 and A2151 were searched through for objects with diameters larger than 21″. From the 922 objects found within about 150 □° (Sample 1 of Paper I) we selected 362 candidates according to the same morphological criteria (Subsample 1 of Paper I). Of these 77 were classified as targets of first priority and 285 of second priority (Table 2 of Paper I). Because of limited observing time redshifts have been measured only for 61 objects of both priorities. Due to the low field density of the selected objects the spectroscopy for both samples had to be done by single-slit observations.

Besides the redshift, Paper I contains apparent B and R magnitudes, colour, mean surface brightness, apparent major and minor diameters and the morphological type for nearly all of our galaxies. The same data for the additional 15 galaxies, found on the POSS plates towards VN2 and VN8, are given in the appendix here. They have been obtained in two later observing runs.

A further 40 galaxies of Table 10, Paper I and the appendix are included in the following discussion: 18 "Back-up objects" plus 22 indicated with a preceding N (15 in Sample 1, 5 in Sample 2, 2 Back-up). Of the former, a few are brighter than $B = 15.5$.

Newly measured redshifts are therefore available from 193 galaxies in total: 91 "POSS"- , 82 "K3/CCD"- and 20 "Back-up"-objects. For 185 of these, B and R magnitudes are known.

3. Statistics

3.1. Photometric properties

In the following Figs. 1 and 2, all of our newly observed objects are considered jointly.

Their B magnitudes (Fig. 1a) lie between 15.5 and 20.5 (apart from the 7 Back-up galaxies with B≈15) thus being up to 5 magn. fainter than the galaxies of the CfA and other large scale surveys limited to $B \leq 15.5$.

Fig. 1b shows the $B - R$ colours being spread from 0.5 to 2.0 magn. The distribution resembles that of irregular galaxies (Gallagher & Hunter 1987). Obviously the sample contains a considerable percentage of late type galaxies comprising young stellar populations.

The distribution of the mean angular diameters (corresponding to the arithmetic mean of the major and minor axes measured at the B = 25/□″ isophote level) is shown in Fig. 1c. In accordance with our selection rules they are considerably smaller than those of recent diameter selected surveys. The SSRS I of da Costa et al. (1988), for instance, adopted a lower diameter limit of 60″.

For the distribution of the mean surface brightness (SB) of our galaxies see Fig. 1d. About 76% have fainter SBs than the mean of the CfA galaxies (B = 22.9/□″, Bardelli et al. 1991). But only 2% of our objects are classical LSB galaxies with SB ≥ 24/□″ (Thuan et al. 1987). So they are not more abundant than in the CfA sample (Huchra et al. 1993).

Information about the morphological types of our objects is given in Table 3 of Paper I. Here we do not differentiate between the various groups.

3.2. Radial velocities v_r

The distribution peaks at 12500 km/s (Fig. 2a), see also Fig. 2 of Paper I. Almost 70% of all galaxies are concentrated between 5000 km/s and 20000 km/s, whereas 44% lie beyond 15000 km/s and therefore outside of the following cone diagrams. On the other hand, no galaxy with less than 4500 km/s was found, revealing that our sample does not contain objects within the nearest voids.

3.3. Absolute magnitudes (H_0 = 75 km/s/Mpc)

Fig. 2b shows the absolute magnitude distributions of our complete sample (185 galaxies with known v_r and B magnitudes) as well as of all ZCAT galaxies with B<15.5 towards the four regions VN2, VN8, VN4 and A2151 within the fields of our search (195 objects, field sizes 67, 83, 1 and 4 □°). The ZCAT catalogue of Huchra et al. (1993) contains all galaxies with so far published redshifts. Although it is not a statistically-controlled data base we use it here and in Sect. 4 because of its greater quantity of data (cf. Fairall et al. 1991).

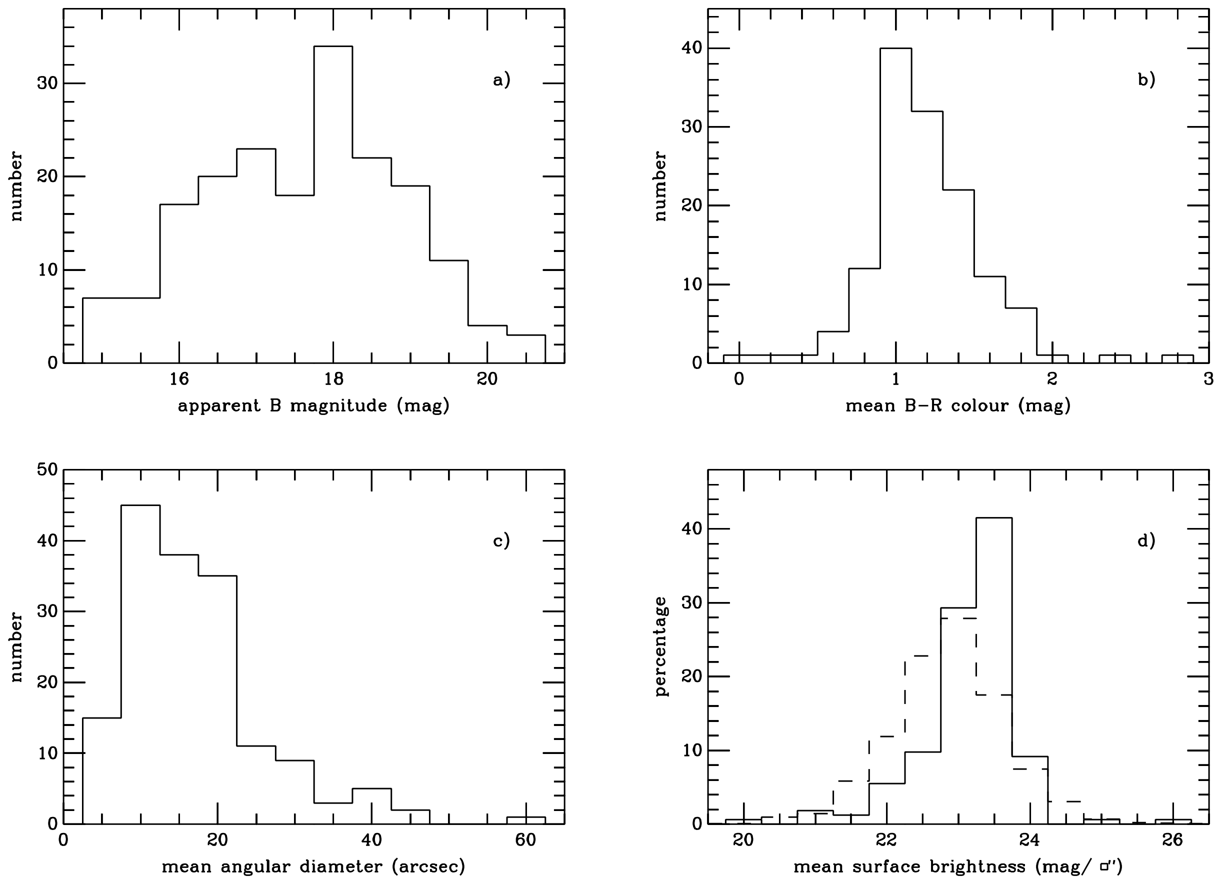

Fig. 1. **a** Distribution of apparent B magnitude for 185 sample galaxies (bin size 0.5 magn.). **b** Distribution of mean B − R colours for 134 sample galaxies (bin size 0.5 magn.). **c** Distribution of mean angular diameters for 164 sample galaxies (bin size 5″). **d** Distribution of mean surface brightness for 164 sample galaxies (solid line) and for 1550 CfA galaxies in the northern hemisphere (dashed line) (bin size 0.5 magn.).

Compared to the ZCAT selection our sample is shifted towards lower luminosities by more than 1 magn.: The median brightness of our galaxies is −19.3, compared to −20.5 for ZCAT or −20.1 for CfA galaxies selected in the same way. 9.7% of our galaxies are fainter than $M_B = -17$, compared with 1.0% of the ZCAT sample. Thus, while a lot of our galaxies are rather luminous objects, our sample contains indeed more non-giant galaxies due to the fainter limiting magnitude of our survey and the morphological selection criteria. On the other hand we did not find any extreme dwarf beyond $M_B = -15$ although those should be detectable up to 9500 km/s for $B_{lim} = 20.5$

The absolute magnitude as a function of radial velocity for our galaxies is shown as Fig. 3. The shaded part emphasizes the known fact that at larger v_r the CfA sample includes only high luminosity objects (beyond 10000 km/s brighter than $M_B = -20$). There is practically no overlap of the areas where the CfA galaxies and ours are located. In line with our intentions we found pretty many relatively nearby galaxies of lower luminosity as the diagram shows. But our sample still contains a lot of background objects as already mentioned in relation to Fig. 2b.

3.4. Completeness

Rough information on the completeness of our search can be gained in this way: As a result of our fainter limits we should find additional galaxies in these regions where the CfA galaxies are concentrated. Their number can be estimated by means of the CfA luminosity function derived by de Lapparent et al. (1989). At v_r = 5000 km/s, for instance, the limiting absolute magnitude of the CfA galaxies is −18.6, while for our survey it is either −15.1 (Sample 1, B_{lim} = 19.0) or −13.6 (Sample 2, B_{lim} = 20.5). Integration of the luminosity function up to these limits indicates that we should find about 5.5 (Sample 1) or 8.1 (Sample 2) times more galaxies within a fixed volume with this mean v_r. In a volume, defined by a field of 100 □° around the observed directions and a depth of Δv_r = 1000 km/s, there are 10 to 30 galaxies in the CfA concentrations. So referring to similar field sizes the POSS Sample 1 should contain about 100 new galaxies around 5000 km/s for each field. This is not the case, as the cone diagrams (Fig. 4-7) immediately show.

In this context, however, one has to take into account that of the initially nearly 1000 newly identified objects on the POSS plates (Sample 1) redshifts have been derived from less than 10% (see Sect. 2). Because of that, despite the considerably

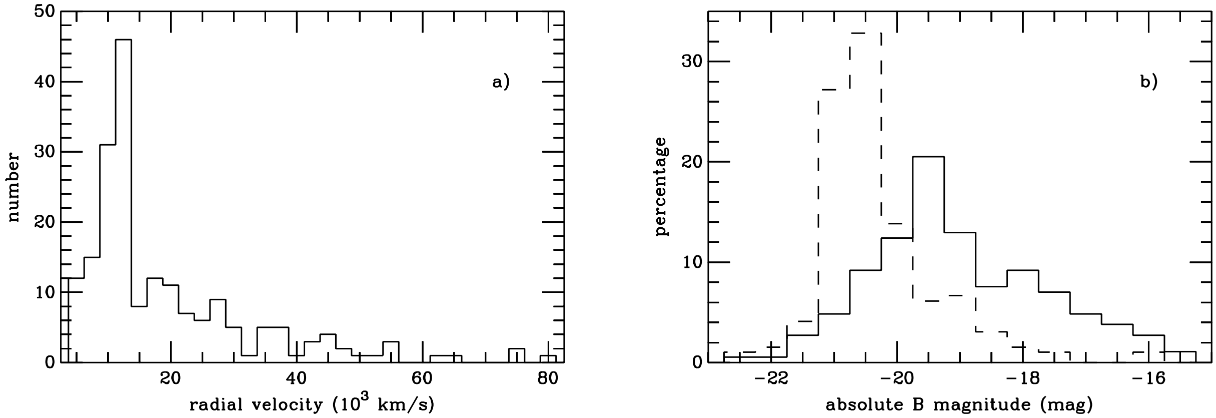

Fig. 2. a Distribution of radial velocities for 193 sample galaxies (bin size 2500 km/s). **b** Distribution of absolute B magnitudes for 185 sample galaxies (solid line) and for 87 ZCAT galaxies from the same volume as our sample (dashed line) (bin size 0.5 magn.).

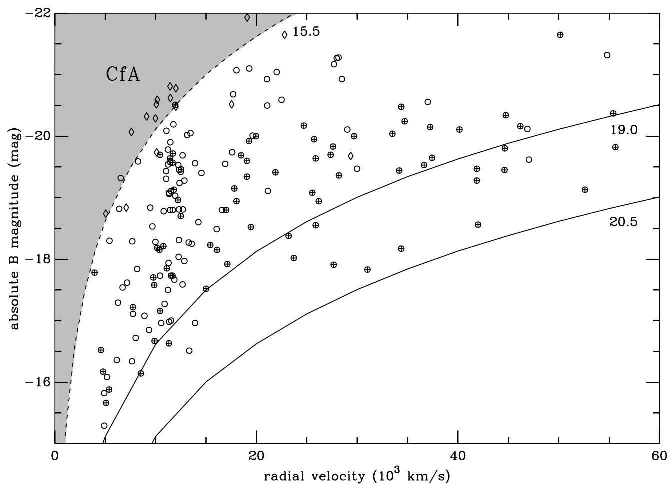

Fig. 3. Absolute B magnitudes as a function of radial velocities. Empty circles indicate POSS galaxies, crossed circles K3/CCD objects and rhombs stand for Back-up galaxies. Dashed line: limit of the CfA extension with $B_{\rm lim}$ = 15.5. Solid lines: limits for surveys with $B_{\rm lim}$ = 19.0 and $B_{\rm lim}$ = 20.5.

larger field surveyed, just half of our total 193 galaxies with known v_r come from the POSS sample. Therefore it is not surprising that this sample is incomplete in the sense that we caught by spectroscopy not more than a small percentage of the galaxies we are aiming at.

The case of the deeper K3/CCD sample is something different. On account of the much smaller fields of about 1 □° we can expect at most a few objects, in agreement with the observational results. In these fields galaxies of smaller apparent diameter could be selected due to the 4.5 times larger scale of the K3/CCD images compared to the POSS plates (Sect. 2). Furthermore, nearly half of the finally selected objects have afterwards been observed spectroscopically. This means a far better portion than that for the POSS sample. Nevertheless it remains statistics of small numbers.

4. Spatial distribution

Fig. 4-7 show in the form of α- and δ-cone diagrams how our objects are distributed in space in comparison to the ZCAT galaxies (l.c.). Here we use again the ZCAT since its greater quantity of data allows better mapping of the voids (Fairall et al. 1991). The figures comprise galaxies up to 15000 km/s velocity distance. Of ours 105 are plotted in total, the rest lies beyond this limit. The dashed lines indicate the approximate boundaries of the voids considered.

4.1. Void VN2 (I, II, III)

In the region surveyed by us, three voids, nearly empty of ZCAT galaxies, with roughly 2500 km/s diameter are located behind each other at central velocities of about 3500, 7000 and 10000 km/s (Fig. 4a and b). The pattern of concentrations and filaments envelopping and separating these voids vanishes at least beyond 11000 km/s due to the growing incompleteness of the ZCAT sample. Our observations cross the first void (I) and touch the two others (II, III). None of our galaxies is situated in void I or in front of it. The majority of them belongs to the already known accumulations whereas about a dozen lie at the outskirts of the voids II and III. Only two galaxies are clearly in the void II: They appear in both cone diagrams projected into this void. But one has to notice that in particular void II is not well defined. Of the 74 galaxies observed by us in this region 30 are at distances beyond 15000 km/s.

4.2. Void VN8 (I, II)

The dominant feature in the region of VN8 (Fig. 5a and b) is the filament of the Perseus-Pisces supercluster at about 5000 km/s velocity distance. With the central velocity of 3000 km/s a clearly defined void (I) is located in front of it. Another less populated area of about 4000 km/s extension appears behind it between 6000 and 10000 km/s distance (II). Our observations cross both of these regions. Again none of our galaxies is to be found within void I. Apart from a few exceptions all are situated

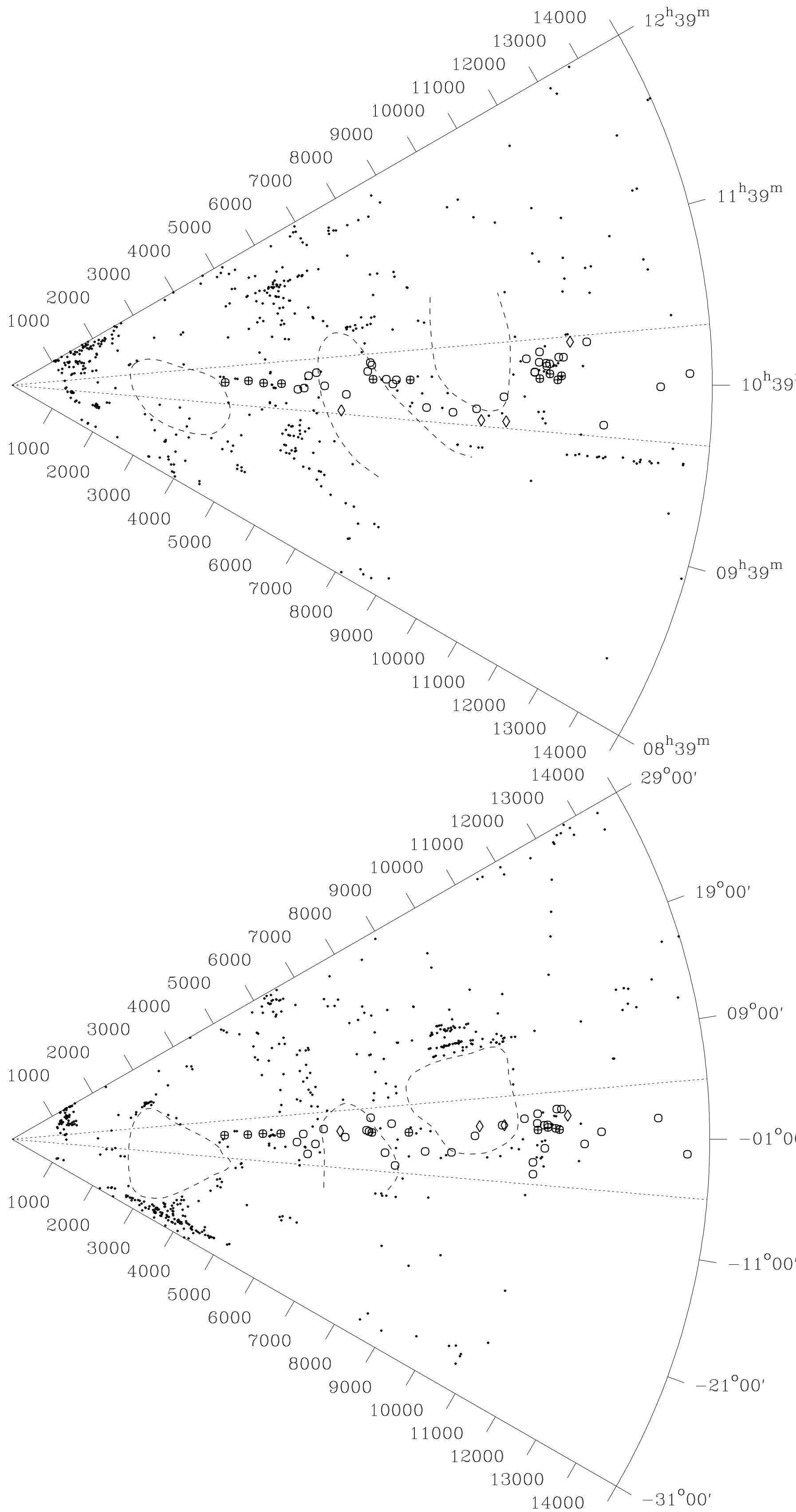

Fig. 4. a,b Cone diagrams for the void region VN2. Right ascension of 455 ZCAT galaxies (upper diagram) and declination for 510 ZCAT galaxies (lower diagram) as well as for 44 sample galaxies are plotted as a function of radial velocity up to a limit of 15000 km/s. All ZCAT and the sample galaxies with a distance of less than 5° from the coordinate planes are projected into these planes. The three voids I, II and III situated behind each other are indicated by the dashed lines. Dotted lines show the limits of the region surveyed by us. Symbols are the same as in Fig. 3.

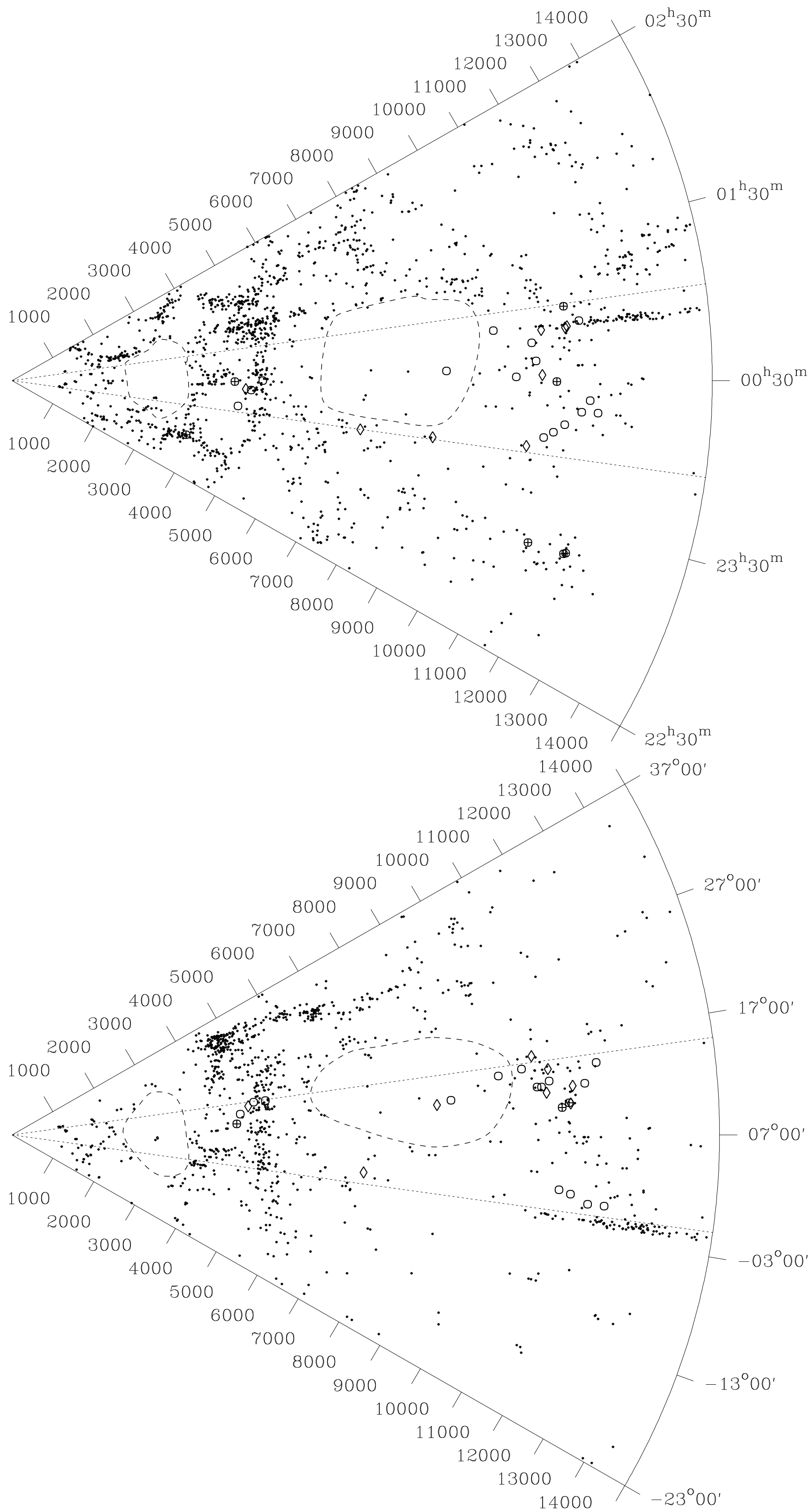

Fig. 5. a,b Cone diagrams for the void region VN8. Right ascension of 1439 ZCAT galaxies (upper diagram) and declination for 993 ZCAT galaxies (lower diagram) as well as for 30 sample galaxies are plotted as a function of radial velocity up to a limit of 15000 km/s. All ZCAT and the sample galaxies with a distance of less than 10° from the coordinate planes are projected into these planes. The two voids I and II situated behind each other are indicated by the dashed lines. Dotted lines show the limits of the region surveyed by us. Symbols are the same as in Fig. 3.

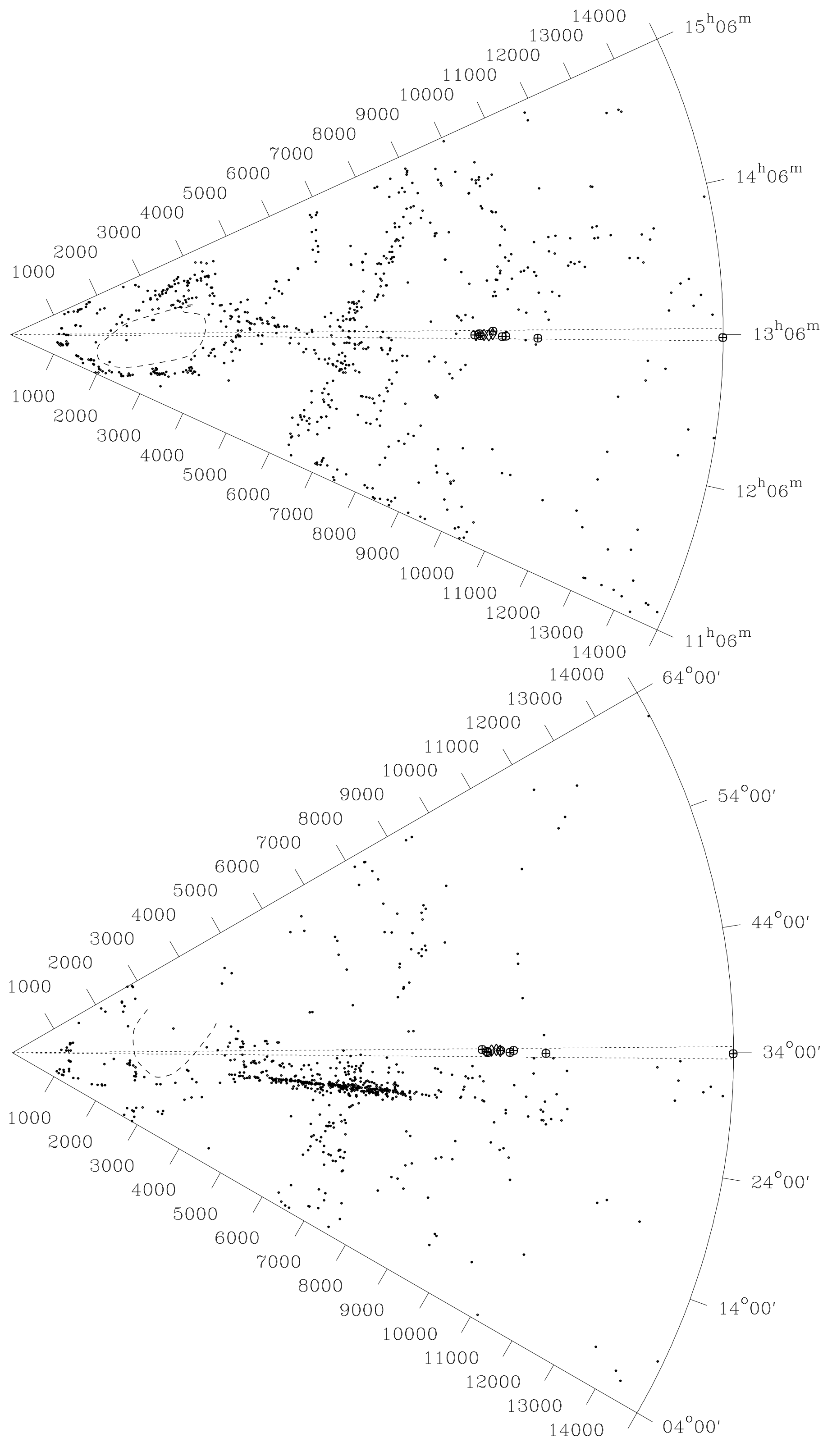

Fig. 6. a,b Cone diagrams for the void region VN4. Right ascension of 701 ZCAT galaxies (upper diagram) and declination for 707 ZCAT galaxies (lower diagram) as well as for 11 sample galaxies are plotted as a function of radial velocity up to a limit of 15000 km/s. All ZCAT and the sample galaxies with a distance of less than 5° from the coordinate planes are projected into these planes. The void is indicated by the dashed line. Dotted lines show the limits of the region surveyed by us. Symbols are the same as in Fig. 3.

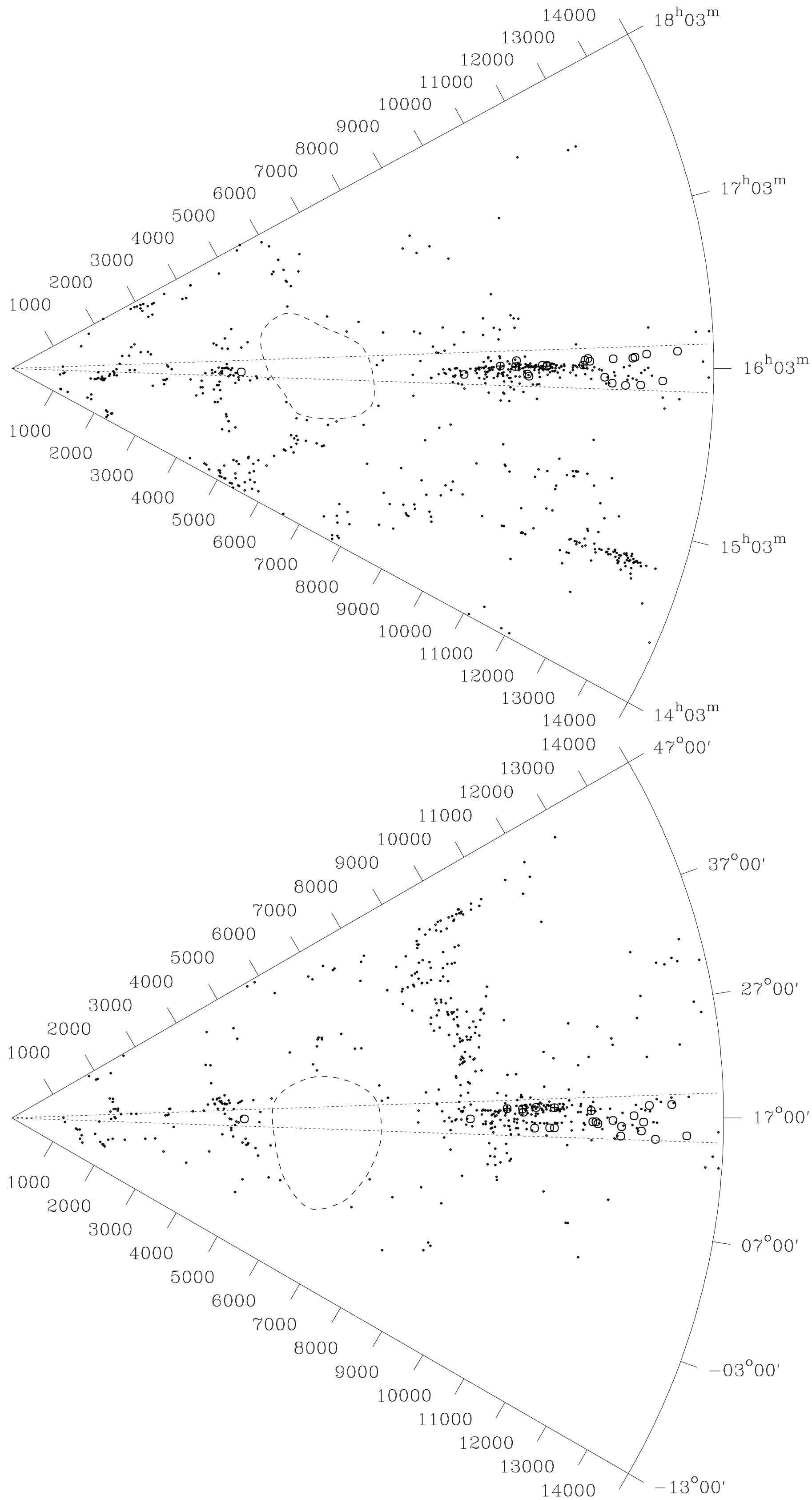

Fig. 7. a,b Cone diagrams for the void region in front of A2151. Right ascension of 588 ZCAT galaxies (upper diagram) and declination for 517 ZCAT galaxies (lower diagram) as well as for 24 sample galaxies are plotted as a function of radial velocity up to a limit of 15000 km/s. All ZCAT and the sample galaxies with a distance of less than 5° from the coordinate planes are projected into these planes. The void is indicated by the dashed line. Dotted lines show the limits of the region surveyed by us. Symbols are the same as in Fig. 3.

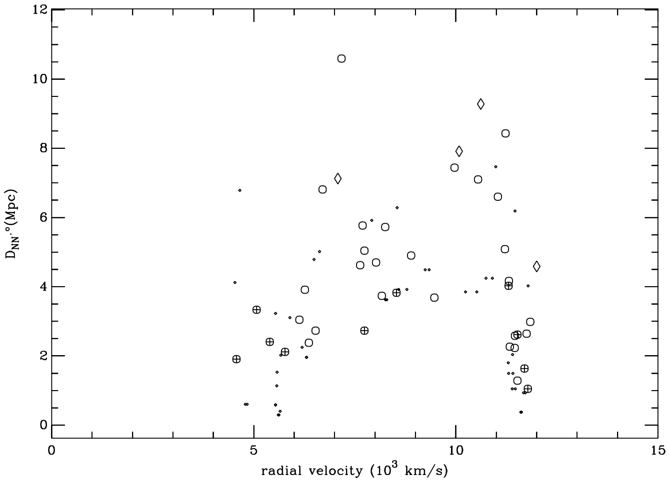

Fig. 8. Nearest neighbour distances of the 44 ZCAT galaxies brighter than 15.5 magn. (points) and of the 40 sample galaxies (symbols as in Fig. 3) in a 10 × 10 □° field between 4500 and 12000 km/s in the region VN2.

in the surrounding sheets or further away than 15000 km/s (26 of 55 observed ones within the marked cones of Fig. 5a and b). Only one object appears in both cone diagrams projected into VN8 II and can therefore be considered as a real void galaxy.

4.3. Void VN4

We limited our observations of this region to one field of 0.79 □° size (Table 6, Paper I) and have measured the radial velocities of 23 galaxies. The interesting void is situated at about 3500 km/s (Fig. 6 a and b). Behind it, between 6000 and 10000 km/s, one hits parts of the "Great Wall". In the δ-diagram the Coma-cluster appears at 30° between 5000 and 9000 km/s. Ten of the galaxies found by us form a small cluster with $v_r \approx 10000$ km/s. Their absolute magnitudes are $M_B \leq -16.5$. Remarkably enough none of our objects is located at smaller distances. 13 of the 23 observed ones are at 15000 km/s or farther away. Again we did not detect one single new galaxy within the near void.

4.4. Region A2151

Figs. 7a and b show the region comprising the cluster A2151 at $v_r \approx 12000$ km/s. This field was originally chosen to test our selection criteria in the environment of a rich cluster where luminosities down to $M_B = -14$ at least are to be expected. Furthermore, a rather extended void seems to be located in front of the cluster around 6500 km/s. With $B_{lim} = 20.5$ of our sample we should be able to identify objects until $M_B = -15.5$ at the cluster distance. But besides one single galaxy in the foreground no one was found in the empty area. Of the 30 objects observed 23 belong to the A2151 cluster or the Hercules Supercluster. They have absolute magnitudes $M_B \leq -16.3$ which demonstrates that we did not quite reach the expected brightness limit. Six galaxies are beyond 15000 km/s.

4.5. Nearest neighbour analysis

The cone diagrams demonstrate the galaxy distribution by two-dimensional projections. Another way to characterize the spatial correlations is by calculating the distance D_{NN} of a galaxy to its nearest neighbour (e.g. Salzer 1989). First, the separation between each of our galaxies and its nearest ZCAT neighbour was calculated taking into account as well such ones a little outside the observed cone. Next, D_{NN} was determined for the ZCAT galaxies in the observed cone to ZCAT galaxies inside and outside the cone. We did this for the 4 regions observed by us.

Fig. 8 shows the result in the case of VN2. Here the velocity range considered was restricted from 4500 to 12000 km/s: Our sample contains no objects nearer than this lower limit while beyond the upper one the ZCAT selection is severely incomplete. The accumulations of the ZCAT galaxies are reflected by small D_{NN} values down to 0.5 Mpc at 5500 and 11500 km/s. A clear separation of our objects from the others is indicated by values above 6 Mpc at 7000 and around 10500 km/s. These galaxies are situated in sparsely populated regions as Figs. 4a and b have already demonstrated. They could be considered as void galaxies but we should again point out that the borders of those depleted areas are not well defined.

The D_{NN} diagrams of the VN8, VN4 and A2151 fields give no further insight in addition to what the cone diagrams are already demonstrating.

4.6. Discussion

The presented results are of a mixed nature. On the one hand, we found several objects near the edges of voids as in the cases of VN2 II and III as well as in VN8 II. Moreover, two galaxies are clearly situated in the midst of VN2 II and one galaxy in VN8 II. One has to take into account though that at velocity distances approaching 10000 km/s the boundaries of the voids are not very clear since the ZCAT sample is thinning out and the structures are defined by less and less galaxies of growing luminosity.

On the other hand, and this result we consider as the most remarkable one of our search, not a single hitherto unknown galaxy did show up within the nearby voids VN2 I, VN8 I and VN4. Situated at about 3000 km/s velocity distance these voids are rather well defined by the field of the surrounding ZCAT galaxies and more or less completely empty. Another interesting case is the apparently huge void located in front of A2151 at about 6000 km/s where we did not make a strike as well. In these places the density contrast between inside and outside the void boundaries appears to be considerable, but our findings do not allow to quantify this ratio.

Evidently the majority of our objects is similarly distributed as the ZCAT galaxies. In this respect our results differ not fundamentally from these of the surveys quoted in the introduction. This means, as other authors had already pointed out, too, that the empirical findings are not in favour of the biased galaxy formation scenario.

Table 1. Observational Data for 15 galaxies chosen from the Subsample 1 as well as 2 "N"-galaxies. They were observed in two further runs in October and December 1994 with the same setup as described in Paper I, using focal reducers at the Calar Alto 3.5m telescope and at the La Silla 2.2m telescope. Column 1: name, Cols. 2 and 3: 1950 coordinates, Col. 4: integral B magnitude, Col 5: integral R magnitude, Cols. 6 and 7: major and minor axis diameters, Cols. 8 and 9: heliocentric redshift and its error, Col. 10: the morphological type (see Paper I for explanation). A preceeding "N" in the name indicates galaxies nearby to the sample object with identical name, that could be observed together with one long slit setting.

Name	R.A.			Decl.			B	R	D	d	z	dz	Type
(1)	(2)			(3)			(4)	(5)	(6)	(7)	(8)	(9)	(10)
	h	m	s	°	′	″	m	m	″	″			
HN1321	10	56	19.0	-02	30	54	16.63	15.51	21	15	0.04118	0.00050	Scd
O0467-087	10	27	27.0	-01	26	42	—	16.24	14	10	0.03324	0.00073	Sc
O0467-124	10	24	31.0	-02	23	06	—	14.85	28	13	0.06435	0.00035	Sc
O0991-001	10	42	59.0	-03	44	12	—	15.94	22	15	0.04845	0.00081	PSab
O0991-004	10	44	46.0	-04	27	12	16.33	15.21	39	20	0.03741	0.00003	PSc
NO0991-004	10	44	46.0	-04	27	12	17.83	16.05	26	10	0.09681	0.00098	Edg
O0991-008	10	44	36.0	-05	09	00	—	17.28	3	2	0.03745	0.00099	LIrr
O0991-009	10	42	8.0	-05	04	24	—	14.52	27	19	0.02753	0.00054	PE
O0010-044	00	05	10.0	12	46	06	—	17.83	9	6	0.03840	0.00036	LIrr
NNO0010-044	00	05	10.0	12	46	06	—	16.90	5	4	0.18277	0.00056	ESO
O0010-055	00	04	5.0	12	16	24	—	17.68	11	3	0.01631	0.00032	LIrr
O0823-006	00	31	44.0	14	24	42	—	17.44	10	9	0.03633	0.00048	Sch
O0823-109	00	21	56.0	14	08	06	—	15.59	21	21	0.04167	0.00071	Scd
O0823-113	00	21	2.0	14	48	12	—	17.02	18	9	0.01727	0.00027	LIrr
O1274-002	00	44	20.0	14	42	42	—	—	—	—	0.11447	0.00068	—
O1274-006	00	50	22.0	14	59	18	—	16.81	16	12	0.12343	0.00037	Sch
O1274-037	00	54	29.0	12	11	24	—	16.93	9	6	0.04091	0.00000	Sch

4.7. Summary

- On deep direct images, taken in the direction of previously known nearby voids, as well as from POSS plates of the same regions we tried to select intrinsically faint galaxies for follow-up spectroscopy. More than 1000 candidates have been identified. The intention was to search for a suspected void-population.
- Redshifts and other properties were finally measured of about 200 objects.
- The percentage of luminous background-galaxies proved to be still rather high demonstrating the difficulty of the pre-selection procedure. More than 40% of our sample galaxies have radial velocities above 15000 km/s.
- The majority of the closer objects lies in areas where the already known galaxies are concentrated. Some are located within voids, but we did not find indications of a widespread void-population.

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Appendix: additional observational data

See Table 1.

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