THE GALACTIC NEIGHBOURHOOD

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ABSTRACT

Several properties of the 131 galaxies known within 9.1 Mpc are investigated. 88 of these galaxies are concentrated into eight groups, leaving 33 percent of true field galaxies. There are E/S0 and S0 galaxies among the field galaxies; their types must be of cosmogonic origin. The groups have small velocity dispersion which limits the mean mass-to-light ratio for the different types of group galaxies to $\mathfrak{M}/L <$ 20. Within the supergalactic plane the deviation from an ideal Hubble flow are small: the changes of $\Delta H_0/<H_0>$ with distance and direction are not larger than ten percent; the radial component of the peculiar motion of field galaxies is <25 km s^{-1}. The differential luminosity function of S/Im galaxies is well approximated by a Gaussian with $<M> = -15^m.7$ and $\sigma = 3^m.3$. The luminosity function of E/S0 galaxies is much flatter with a possible minimum, separating true E's and dwarf ellipticals (Reaves, 1977). The sample galaxies are strongly concentrated toward the supergalactic plane; at a distance of 4 Mpc of the plane the luminosity density drops to half its value. There is also a pronounced luminosity density decrease with increasing distance from the Virgo cluster centre; at a distance of 30 Mpc the density has decreased by more than a factor of 10^4. The best estimate of the mean luminosity density within a sphere of 30 Mpc radius centered on the Virgo cluster is $1.5 \cdot 10^8 L_\odot$ Mpc^{-3}.

This is a first attempt to determine the mean properties of galaxies within a distance-limited sample. Such a sample should be as complete as possible for intrinsically faint galaxies, but it should also contain a statistically significant number of galaxies. The best compromise seems to be a velocity limit of 500 km s^{-1}, corresponding to a distance limit of 9.1 Mpc (a value of H_0 = 55 km s^{-1} Mpc^{-1} is assumed throughout; Sandage and Tammann, 1976).

I. THE SAMPLE DEFINITION

The catalogue of galaxies known with $v_0 \leq 500$ km s^{-1} is given elsewhere (Kraan and Tammann, 1978). It contains 184 entries. Galaxy types are from Sandage and Tammann (1978) and other sources. The magnitudes are in general in the B_T system (de Vaucouleurs et al., 1976); for some fainter galaxies they are still provisional. The magnitudes are corrected for galactic absorption (Sandage, 1973) and for the full amount of internal absorption (Holmberg 1958; 1964; with minor modifications for

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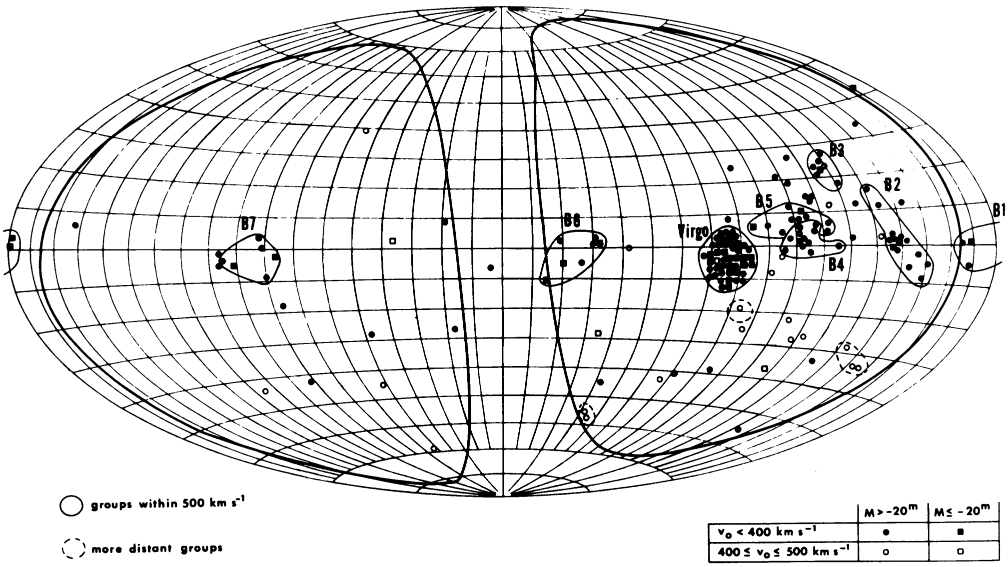

Fig. 1: The sample galaxies projected onto the sphere of supergalactic coordinates (the Local Group members are excluded). The "zone of avoidance" (|b| < 15°) is delineated with a heavy line. The concentration of the galaxies toward the supergalactic equator is apparent. 46 galaxies lie within 4°.8 of the Virgo cluster center (the area is shown here too large); they are bona fide members of this cluster (including the only known seven galaxies outside the Local Group with negative corrected velocities, disqualifying the assumption that these galaxies could be foreground objects, cf. Sandage and Tammann, 1977). The boundaries of seven nearby groups are shown with full lines; all sample galaxies within these boundaries are considered as group members. Six galaxies with 400 < v_o < 500 km s^{-1} have been proposed as members of more distant groups (de Vaucouleurs, 1975); these groups are schematically shown with broken lines.

the most edge-on galaxies). Absolute magnitudes of Local Group and M 81 group members are derived from individual distance determinations; for all other galaxies they are calculated from the radial velocity v_o (corrected to the Local Group; cf. Yahil et al., 1977) and H_o. A justification of this procedure is given below (section IV).

It is believed that the present sample is essentially complete for absorption-corrected magnitudes of 12^m.0 for E/S0 galaxies and of 11^m.5 for all later types (Sa-Im). At a distance of 9.1 Mpc this corresponds to a relatively bright completeness limit in absolute magnitude of -18^m.3. But it should be noted that - whatever the luminosity function - galaxies with ≦ -18^m.3 contain > 90 percent of all light.

II. THE DISTRIBUTION AT THE SPHERE: GROUP AND FIELD GALAXIES

The distribution in supergalactic coordinates of the galaxies in the present sample is shown in Fig. 1. Three striking results emerge: (1) The galaxies are strongly concentrated toward the supergalactic plane; (2) The galaxies are concentrated to form groups; (3) 46 galaxies fall within 4°.8 of the Virgo cluster centre. They are certain members of this cluster and lie therefore outside the 9.1 Mpc limit. They are excluded in the following discussion. Seven additional galaxies have also been excluded because they may belong to more distant groups (de Vaucouleurs, 1975). This

Tab. 1: The Distribution with Type

	E	S0	Sa-Sd	Sdm-Im	Irr	Σ
$<-18^m_.3$	2 6%	2 6%	26 76%	4 12%	1 (3%)	34
$>-18^m_.3$	15 16%	5 5%	11 12%	63 67%	1 (1%)	94

leaves 131 galaxies which are known within a distance limit of 9.1 Mpc; they are referred to in the following as the "sample galaxies". Only 60 sample galaxies are contained in the Shapley-Ames (1932) catalogue.

The distribution of the sample galaxies according to type is given in Tab. 1. The distribution is strongly luminosity dependent. Because it is also dependent on position (there are clusters known with only E/S0's) the relative type distribution has no general meaning.

A. Groups of Galaxies.

Allowing for the projected position and to some degree for individual distances and velocities it is possible to define seven groups containing 62 sample galaxies. The following facts speak in favour of the reality of these groups: (1) Five of the groups are historically well established; only two groups were formerly believed to be part of a larger complex (B4 and B5 in the CVn cloud); (2) With a minimum of 5 and an average of 9 members with known redshift the groups are exceptionally well defined; (3) All group members have $v_0 < 400$ km s^{-1} (the only exception is the most distant M 101 group), it is therefore very unlikely that additional group members could be found outside the 500 km s^{-1} limit; (4) All galaxies within the group boundaries are included; (5) The inclusion of any additional outlying galaxy would more than double the total kinetic energy of that respective group; it is a priori improbable that the galaxy, which is in projection the most outlying member, should have the highest kinetic energy. (6) The groups are well separated in projection and - according to several distance indicators - in space; (7) The group galaxies are much more concentrated toward the supergalactic plane than the field galaxies (cf. Fig. 7).

There remain only a few ambiguities: Six dwarf galaxies between the B3, B4, and B5 group have been assigned to the field; if they were treated as members of any of these groups the following conclusion would not be altered because their total light and mass is negligible. The group B7 may actually consist of two separate groups, a nearer southern group (containing NGC 55 and 300) with $\langle v_0 \rangle = 136$, $\sigma = 21$ km s^{-1}, and another group with $\langle v_0 \rangle = 248$, $\sigma = 39$ km s^{-1}.

The seven groups, B1 to B7, and the Local Group (Yahil et al., 1977) are listed with some of their properties in Table 2. The groups contain all types of galaxies, but true E/S0 members are rather rare. Of the 18 E/S0 group members

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Tab. 2: Groups within $<v_o> = 500$ km s^{-1}

Group	Brightest Member	n_{Gal}	E/S0	Sa-Sd	Sdm-Im	Distance (Mpc)	Mean radius (Mpc)	Total Lum. ($10^{10} L_{\odot}$)	Lum. Dens. Contrast	$<v_o>$	$\sigma(v_o)$
LG	M31	26	13	3	10	-	1.5	11.03	37	-	45
B1	IC 342	5	1	3	1	4.1	0.5	7.41	865	224±23	50
B2	M81	15	1	4	8+2 Irr	3.3	0.6	4.36	229	240±22	83
B3	M101	7	-	4	3	6.9	0.5	5.31	383	368±23	60
B4	NGC 4449	12	1	2	9	4.7	0.6	1.54	77	257±8	27
B5	NGC 4736	10	-	4	6	6.3	1.0	4.98	49	347±8	25
B6	NGC 5128	7	2	2	3	6.5	1.0	13.87	179	232±21	56
B7	NGC 55	6	-	5	1	3.3	0.5	5.54	570	192±28	68

only four are true E's (Maffei 1 being the only bright one, the others - M 32, NGC 147 and 185 - being at the faint end), one is E/S0, and three are S0's. The remaining E's have $M_B > -14^m$ and should be classified as dwarf ellipticals (dE). The dE's are known so far to occur only in groups and in the Virgo cluster (Reaves, 1956; 1977). They may constitute a separate type of galaxies as further elaborated in section V. - Among the group members are also the only two old-population irregulars, the irregulars of type II (abbreviated here as Irr).

All sample galaxies together have a luminosity of $6.6 \cdot 10^{11} L_{\odot}$. Within the sample volume of $3.16 \cdot 10^3$ Mpc^3 this corresponds to a mean luminosity density of $2.1 \cdot 10^8 L_{\odot}$ Mpc^{-3}. The ratio of the luminosity density within each group and the mean density defines what is given in Table 2 as luminosity density contrast. It can be seen that the Local Group is not only the most extended group (its size is independent of H_o) but also the group with the lowest contrast. This effect would be enhanced if a larger value of H_o would have been chosen. This speaks against values of H_o larger than 55. (It should be noted, however, that the Local Group shows a clear luminosity concentration toward the centre, and the knowledge of faint dwarf members in other groups may not be complete yet).

The last column of Table 1 contains the velocity dispersion within the groups. These values are surprisingly small. It is clear that these small values can only be found if exceptionally good redshift determinations are available. For the present sample of nearby galaxies with many 21 cm-redshifts this is the case. But since the typical mean errors of optical redshifts are in the order of 100 km s^{-1} (Sandage, 1978) it is in general quite difficult to find the true velocity dispersions of groups.

B. Field Galaxies.

Fortythree sample galaxies, i.e. 33 percent, cannot be assigned to any group. As mentioned above some of these galaxies may still be group members, but the majority are certainly true field galaxies. The strongest evidence for this result is the widely different concentration toward the supergalactic plane, the group galaxies having a mean distance ζ from this plane of less than 1 Mpc and the field galaxy one of more than 2 Mpc. Since the true galaxy density decreases with increasing ζ the chance is considerably reduced to ever find group associations for the field galaxies.

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Tab. 3: Field Galaxies

Type	n	Example	ζ (Mpc)	n_{total}	Fraction
E	0	-	-	4 + 10 dE	-
E/S0	3	NGC 3115	-6.1	4	75 %
S0	3	NGC 404	0.5	6	50
Sab-Sb	2	NGC 2683	-3.5	6	33
Sbc-Sd	9	NGC 2903	-5.1	31	29
Sdm-Im	26	NGC 2188	-8.5	67	39

All types of galaxies are represented among the field galaxies with the exception of pure E's, dwarf ellipticals (dE's) and old-population irregulars (Irr's). The lack of E's and Irr's is hardly significant because of their small number within the present sample. The absence of field dE's is intriguing: it could be an observational effect in view of the difficult detection (due to low surface brightness) and redshift determination of these galaxies, - but since there are not even candidates known to be field dE's it is a reasonable working hypothesis that they may be confined to groups and clusters.

Table 3 gives examples for field galaxies of different type. These galaxies have exceptionally high ζ values. The one exception is the S0 galaxy NGC 404, but this galaxy is quite isolated. The galaxies in Table 3 are therefore most likely true field galaxies.

In spite of the fact that no true E galaxy is known in the field, early-type galaxies taken together (E to S0, excluding dE's) are locally at least as likely to be field galaxies (43 percent) as later-type galaxies (36 percent).

The scarcity of early-type galaxies within the small groups of the present sample, the occurrence of several E/S0 galaxies in the rich Leo group, and the preponderance of these galaxies in rich clusters suggest a positive correlation between the relative number of early-type galaxies and the population size of the galaxian aggregate. This could be taken as evidence that spirals evolve into S0 and/or E galaxies and that this transition is more pronounced in rich clusters with strong interaction between the member galaxies. However, the fact that early-type galaxies do occur as isolated field galaxies proves that not all early-type galaxies can be formed by this process. Their origin must be cosmogonic.

III. THE MASS OF GROUP GALAXIES

An application of the virial theorem to the groups B1 to B7 gives virial masses which differ by more than a factor 100. To reduce the scatter of individual groups it is probably best to compare the total kinetic energy with the total potential energy contained in these groups.

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Adopting conventional mass-to-light ratios of 4, 20, and 30 (in solar units) for S/Im, S0, and E galaxies, respectively, one finds that the overall kinetic energy is T = $(1.9 \pm 0.3) \cdot 10^{52}$ J and that the overall potential energy is $\Omega = 1.25 \cdot 10^{52}$ J.

If one assumes that the groups are relaxed one finds $2T/\Omega = 3.0$, which would suggest that the above mass-to-light ratios are too low by this factor. However, due to the small velocity scatter in the groups the crossing times are very long (1.4 to $8 \cdot 10^{10}$ yr). It is therefore very questionable whether the groups should be assumed to be relaxed. All what one can then require is that the groups have negative total energy. In this case the adopted mass-to-light ratios are too small by only a factor of 1.5. This would roughly correspond to a mean mass-to-light ratio of all types of galaxies in the present groups of $\mathfrak{M}/L = 17$. But actually this is an upper limit because the groups may very well have positive total energy (with crossing times equal to or exceeding their age) and therefore may be in expansion. The result of $\langle\mathfrak{M}/L\rangle \lesssim 20$ (out to radii of the order of 1 Mpc) - and probably less for S/Im galaxies - can only be avoided for the present group members if one forcefully attributes additional, outlying members to the groups. From the present material this would seem to be quite artificial.

In a pioneering paper Kahn and Woltjer (1959) have shown, that the apparent approach of M 31 and our Galaxy gives a handle to the mass determination for these galaxies. The discussion of modern observations requires in fact that $\mathfrak{M}$ (M 31 + Galaxy) $> 2.8 \cdot 10^{11}\ \mathfrak{M}_\odot$ (Yahil et al., 1977) or $= 8 \cdot 10^{11}\ \mathfrak{M}_\odot$ (Lynden-Bell and Lin, 1977). With a combined luminosity of these two galaxies of $10^{11}\ L_\odot$ this corresponds to $\mathfrak{M}/L > 2.8$ or $= 8$. The result for these two spirals is in excellent agreement with the above result for the groups B1 to B7. It is further strengthened by the fact that there are other groups outside the present sample which lead to similar $\mathfrak{M}/L$ values (Materne and Tammann, 1976).

Other investigations of groups have occasionally led to higher mass-to-light ratios. These results are based on more distant groups. Since the definition of groups becomes more difficult with increasing distance and since the quality of the observations (magnitudes and velocities) is typically inferior at larger distances, the higher $\mathfrak{M}/L$-values should probably be given lower weight.

Pairs of galaxies also tend to yield relatively low mass-to-light ratios in agreement with the present groups (Karachentsev, 1977). Higher masses have been derived by Turner (1976) for a sample of pairs with an optically determined mean velocity separation of 205 km s^{-1}, but this sample raises still statistical problems (van Albada and Freeman, 1977), and in addition with a mean external error of at least 140 km s^{-1} for a single velocity observation (as suggested by six new 21 cm-velocities) the signal-to-noise ratio remains rather precarious.

In the case of spiral galaxies $\mathfrak{M}/L \gtrsim 10$ would imply the presence of massive halos. The best evidence for such halos came from the very extended, flat rotation curves of some edge-on spirals (Krumm and Salpeter, 1977). However, the large HI extent of these galaxies has not been confirmed by Sancisi (1977).

The conclusion that the sample galaxies have $\langle\mathfrak{M}/L\rangle < 20$ leaves the problem of the stability of clusters unsolved. The nature of the so-called missing mass in aggregates with large velocity dispersion lies outside the scope of this paper. It is well possible that the missing mass resides in a few (E) galaxies which are, for some reason, not represented within the groups of the present sample.

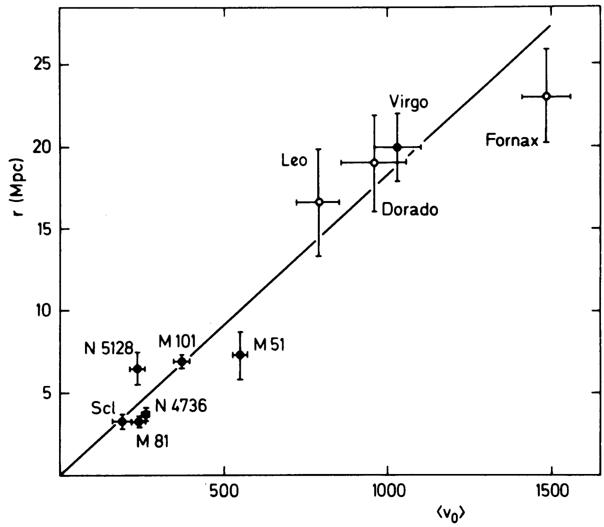

Fig. 2: The distance - mean velocity relation for six nearby groups with particularly well determined distances (Tammann, 1977) and for the Virgo cluster (Sandage and Tammann, 1976). Three relatively nearby, rich groups or clusters are added (open circles) whose distances are known relative to the Virgo cluster (Visvanathan and Sandage, 1977). The full drawn line corresponds to H_o = 55 km $s^{-1}Mpc^{-1}$.

IV. LIMITS ON THE DEVIATIONS FROM AN IDEAL HUBBLE FLOW

One can think of three types of deviations from an ideal Hubble flow: A. A distance dependence of H_o; B. A directional dependence of H_o; and C. Peculiar motions of groups and field galaxies. Their possible size shall be investigated in the following.

A. The Distance Dependence of H_o.

Good distance determinations from three or more independent methods are available for some nearby groups and clusters. They define a Hubble diagramme as shown in Fig. 2. The expansion is well represented by a single value for H_o of 55 out to a distance of ~ 25 Mpc (cf. also Tammann, 1977). Several distance indicators beyond that limit - ScI galaxies (Sandage and Tammann, 1975), supernovae (Branch, 1977), and brightest group and cluster galaxies (Sandage, 1975; Sandage and Hardy, 1973) - exclude any significant changes of H_o beyond this limit.

B. The Directional Dependence of H_o.

The individual values H_i of the Hubble constant for several well-studied groups and galaxies (within $<v_o>$ = 1600 km s^{-1}) are plotted versus the supergalactic longitude in Fig. 3. Also shown is the suggested variation of H_i with longitude (de Vaucouleurs, 1976). The two sets of data are in clear contradiction. This suggests that the individual deviations from the mean value H_o = 55 are due to still remaining problems of the distance determinations. An exact solution for the possible variations depends very much on the weight attributed to a single value of H_i. In any case the change of $\Delta H/<H_o>$ with direction is smaller than 0.15 (Sandage and Tammann, 1976) and probably still smaller (0.08) within an even larger volume (Sandage, 1975). This

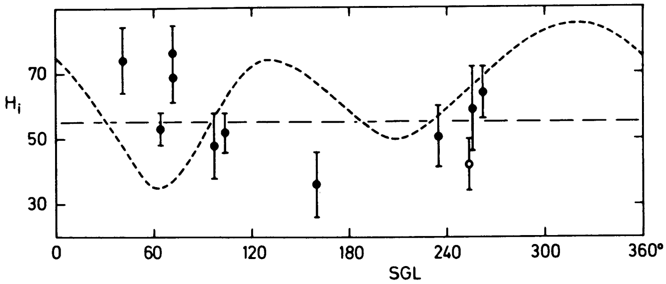

Fig. 3: The Hubble constant H_i versus the supergalactic longitude. The points represent the same groups as shown in Fig. 2. The somewhat more distant Grus group ($<v_0> = 1580$ km s^{-1}) is added as an open circle. The dashed curve represents roughly the change of H_i with longitude as suggested by de Vaucouleurs (1976). The almost perfect anticorrelation between the points and the dashed curve strongly suggests that the deviations from $<H_0> = 55$ km s^{-1} Mpc^{-1} are not real, but due to remaining errors of the distance determinations.

conclusion is also compatible with the Rubin-Ford effect, even if its size is taken at face value (Rubin, 1977).

It has been proposed that the local frame of inertia has large systematic motions ($\sim$ 500 km s^{-1}) with respect to distant ScI galaxies (Rubin, 1977) and to the 3K-background radiation (Smoot et al., 1977). If these, mutually hardly compatible motions, are real it is clear that they must involve very large volumes. The above limit of $\Delta H/H_0 \lesssim 0.1$ for $<v_0> \lesssim 3000$ km s^{-1} requires that the co-moving volume has a radius of $\gtrsim$ 50 Mpc.

C. The Peculiar Motions of Galaxies.

The groups within 20 Mpc in Fig. 2 deviate from the mean Hubble line by $\sigma = 93$ km s^{-1}. This value, however, is still strongly affected by errors of the distance determinations. Allowing for these errors one finds that no group deviates significantly from the mean Hubble line by more than 50 km s^{-1} (Tammann, 1977). The true deviations could be still considerably smaller. As for the Local Group Visvanathan and Sandage (1977) have shown that its peculiar motion in the direction of the Virgo cluster is smaller than the error of the mean cluster velocity ($\pm$ 60 km s^{-1}).

The velocity distribution of the field galaxies within 9.1 Mpc is plotted in Fig. 4. No field galaxy is known with $v_0 < 100$ km s^{-1}! This limits the peculiar motions of the Local Group and of the field galaxies to less than 100 km s^{-1} (cf. Fisher and Tully, 1975). The assumption that the field galaxies have constant space density leads to a still more stringent limit: Monte Carlo calculations show that their observed velocity distribution can be understood if their random motions are $\sim$ 35 km s^{-1}. This value is in good agreement with an earlier, independent determination (Sandage and Tammann, 1975a).

The lowest upper limit for the peculiar motions of field galaxies is set by the expectation that they should have smaller random velocities than galaxies within groups. The observed velocity dispersion in groups can be as low as 25 km s^{-1} (e.g. B4 and B5); therefore the radial component of the peculiar motions of field galaxies are probably smaller than this value.

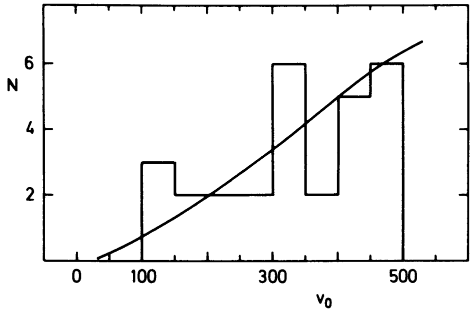

Fig. 4: The velocity distribution of field S/Im galaxies of the present sample. The curved line is calculated under the assumption of constant space density and allowing for the discrimination of intrinsically fainter galaxies at larger distances (the luminosity function of Fig. 5 is used to determine the effect). Note that there is no galaxy with $v_0 < 100$ km s^{-1}.

An important proviso should be made. The test galaxies for which the above limits on the non-Hubble motions were derived lie all close to the supergalactic plane. It can therefore not be excluded that the motions perpendicular to the plane were larger. In addition the peculiar motions of field galaxies were derived from nearby objects ($v_0 < 500$ km s^{-1}); it can therefore not be excluded that the peculiar motions are larger at larger distances.

In any case for the present sample there is observational evidence that groups have random radial motions of less than 50 km s^{-1} and field galaxies of less than 25 km s^{-1}. This is a justification for the above procedure to derive luminosities for the sample galaxies from radial velocities and H_0. For even the nearest field galaxies with $v_0 = 100$ km s^{-1} the error in distance becomes < 25 percent corresponding to < $0\overset{m}{.}5$ in luminosity. The same upper limit is derived for the error of even the nearest groups.

V. THE LUMINOSITY FUNCTIONS

The determination of the faint end of the galaxian luminosity function is hampered by the fact that existing catalogues are very incomplete for intrinsically faint galaxies. (The Shapley-Ames catalogue does not contain galaxies with $M \gtrsim -15\overset{m}{.}5$). Therefore the present sample is particularly well suited to define the faint end of the luminosity function, especially if only nearby subsamples are studied, for which the completeness of dwarf galaxies is exceptionally good. In the following the luminosity functions of S/Im and E/S0 shall be investigated separately.

A. The Luminosity Function of S/Im Galaxies.

There are clear indications that the luminosity functions of Sa, Sb and Sc galaxies differ systematically. The small present sample does not allow to investigate these types separately. It should be stressed, however, that their combination is forced. On the other hand the distinction between Sc and Im galaxies is probably basicly a function of luminosity. There is no spiral known with $M > -16^m$ and no Im galaxy with $M < -20^m$. In the transition interval the ratio of spirals to irregulars decreases monotonically toward fainter luminosities. Also all other known parameters change smoothly from Sc to Im galaxies. The lumping of these two types seems therefore natural.

The subvolume within which the knowledge of S/Im galaxies is most complete is represented by the Local Group and the M 81 group. Very few if any S/Im

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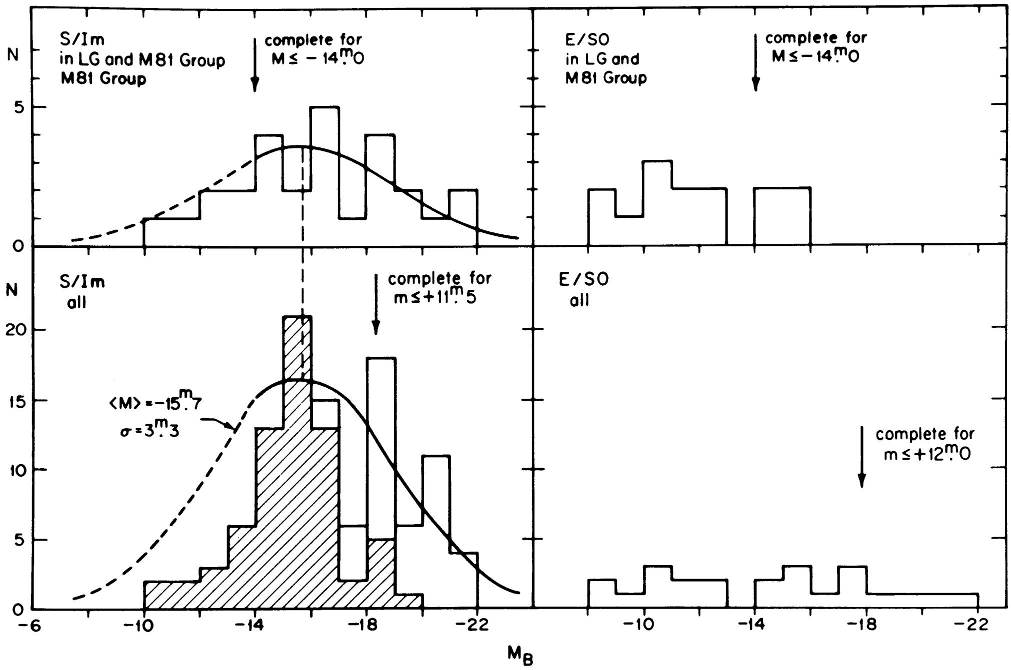

Fig. 5: The differential luminosity function for S/Im galaxies (left side) and E/S0 galaxies (right side). The upper panel is for members of the Local Group and the M81 group only. It is likely that all galaxies brighter than M_B = -14^m.0 are known in these two groups. The best fitting curve for the S/Im galaxies is a Gaussian with $\langle M_B \rangle \approx -15^m.7$ and σ (M) ≈ 3^m.3. The lower panel shows all known galaxies within 9.1 Mpc ($v_0 \leq 500$ km s^{-1}). The Sa-Sd galaxies (white histogramme) and Sdm-Im galaxies (hatched area) are fully compatible with the same Gaussian luminosity function as in the upper panel. The S/Im galaxies are fully corrected for internal absorption; their completeness limit is therefore somewhat brighter than for E/S0 galaxies.

galaxies can have remained undiscovered which are more luminous than IC 1613 and HoI. The one additional candidate is the newly discovered, probable Local Group dwarf in Sagittarius (Cesarsky et al., 1977). Considering that even HoIX with M = -13^m.5 in the M 81 group is a relatively easy object, leads to the conclusion that essentially all S/Im galaxies brighter than -14^m are known in these two groups. And the observation that the advent of IIIaJ plates and 21 cm-surveys have so far contributed only very few additional Im members of the Local Group and the M 81 group strongly suggests that the number of undiscovered objects even considerably fainter than -14^m must be quite limited.

The differential luminosity function for this subsample is shown in Fig. 5. The distribution shows a maximum near -15^m.7 which, from the above remarks on completeness, is almost certainly real. The distribution of galaxies brighter than -14^m can be well fitted by a Gaussian with <M> = -15^m.7 and σ = 3^m.3. The Gaussian predicts that about three faint Im galaxies remain to be discovered in the subsample. This small number may be somewhat too conservative because the error of the mean magnitude is almost 1^m: if <M> = -14^m.7 then there could be still ~12 undiscovered faint Im's.

The rarity of very faint Im galaxies is further supported by a recent

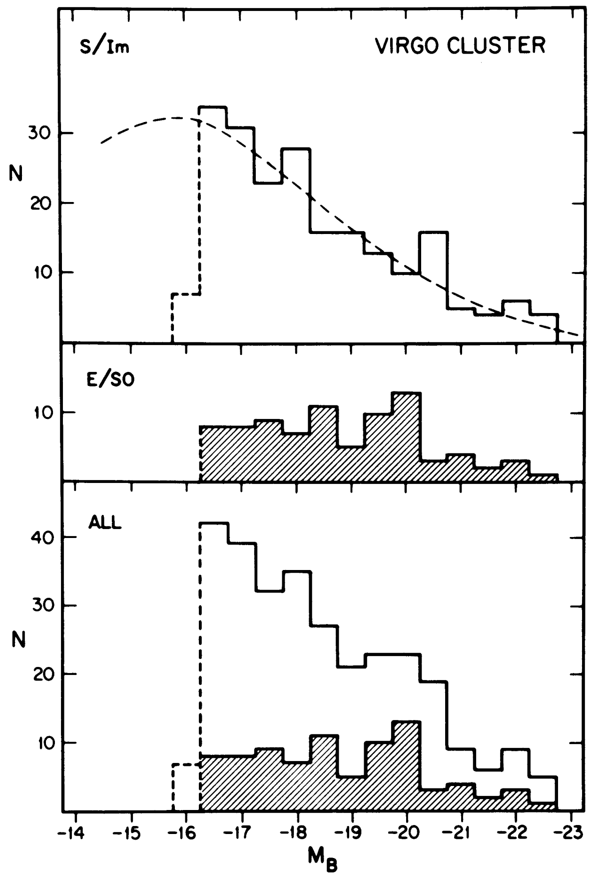

Fig. 6: The differential luminosity function of Virgo cluster members (Sandage and Tammann, 1978). The same Gaussian is fitted to the S/Im galaxies as in Fig. 4. The S/Im galaxies (upper panel) and E/S0 galaxies (middle panel) are combined in the lower panel. Note, however, the striking difference between the luminosity functions of these two groups of types.

21 cm-survey of the M 81 group (Sargent and Lo, 1977), which has provided only a few additional members, and also by the absence of faint Im's in the Virgo cluster (Reaves, 1977a).

The differential luminosity function of all S/Im galaxies in the present sample is also shown in Fig. 5. The Gaussian luminosity function of the nearby subsample represents a very satisfactory fit for these extended data. The same Gaussian fits also perfectly well the bright wing of the luminosity function of S/Im galaxies in the Virgo cluster (Fig. 6).

The peaked luminosity function of S and Im galaxies has been anticipated to some degree by Holmberg (1969) who found that the luminosity function of spiral galaxies only can be represented by a Gaussian. Incidentally it should be remarked that the present luminosity function is reminescent of Hubble's (1936) Gaussian luminosity function with $\langle M \rangle = -14^{m}_{.}2$, but with much smaller dispersion of $\sigma = 0^{m}_{.}84$. However, his function was based on the old distance scale and on only Shapley-Ames galaxies. The partial agreement is therefore fortuitous.

It should be recalled that all absolute magnitudes of S/Im galaxies in the

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present paper are corrected for the full amount of internal absorption. (The mean correction amounts to 0ᵐ42; note that the internal absorption not only decreases the true luminosity of a galaxy, but that it also tends to flatten the luminosity function at its bright end). It has first been pointed out by Kiang (1961) that some form of absorption correction (he choose a correction to face-on orientation) is necessary in order to free the galaxy luminosities from random (?) orientation effects and to derive meaningful luminosity functions. There are many problems which require an absorption-corrected luminosity function, e.g. the true mass-to-light ratios, the mean energy spectrum and the total energy production of S/Im galaxies, as well as the relative luminosities of S/Im and (absorption-free) E galaxies. It could be argued that it would be preferable to have absorption-uncorrected luminosity functions to derive the mean luminosity density in very large volumes and the brightness of the cosmic sky light. However, the greatest uncertainty of these two parameters comes from the unknown relative frequency of S/Im and E galaxies within very large volumes, and there is therefore no reason to aim for an otherwise meaningless (uncorrected) luminosity function.

There is a suggestion in the present sample that the S/Im galaxies in groups have a wider luminosity dispersion than the field galaxies. This would mean that very bright spirals and very faint irregulars occur preferably in groups. But in view of the small sample and of the selection effects the difference is not significant.

One could imagine that the faintest irregulars cannot bind their hydrogen and that this were the explanation for the scarcity of such systems. However, the observed relative hydrogen richness of dwarf irregulars (cf. Huchtmeier et al., 1976) contradicts this explanation. It seems therefore that the shape of the luminosity function of S/Im galaxies is tied to their formation process.

B. The Luminosity Function of E/S0 Galaxies.

The few known E, S0 and dE galaxies within the Local Group and the M 81 group do not define a luminosity function (cf. Fig. 5). The same holds true for these galaxies within the whole sample because of the incompleteness bias. There is however a strong suspicion that the luminosity function is at its faint end considerably flatter than for S/Im galaxies. This suspicion is supported by the E/S0 members of the Virgo cluster, which are completely known to ~ -16ᵐ25 (Fig. 6).

The Virgo cluster E/S0 members make it even possible that their differential luminosity function has a broad maximum between ~ -18^m and -20^m. Evidence for such a maximum has been given earlier by Abell (1975) for the luminosity function of several clusters. In any case the Virgo cluster contains very few early-type galaxies with ~ -14^m to -15^m, which gives strong support for a m i n i m u m of the luminosity function (Reaves, 1977a). Beyond this minimum, toward fainter magnitudes, the number of galaxies increases again according to Reaves (1977). It was proposed above to restrict the designation dE to these rather numerous, very faint galaxies. Their lower luminosity limit is yet undetermined.

The luminosity functions derived here contradict only seemingly previous determinations (for a good review see Felten, 1977). The typical observational limit for earlier investigations was $\lesssim -15^m$, and down to this limit the total number of galaxies may increase indeed and may possibly be represented by an e-function. But it seems now very unlikely that such an e-function should be extrapolated - as originally suggested by Zwicky (1957) - toward fainter magnitudes.

The present results indicate that the problem of "the" luminosity

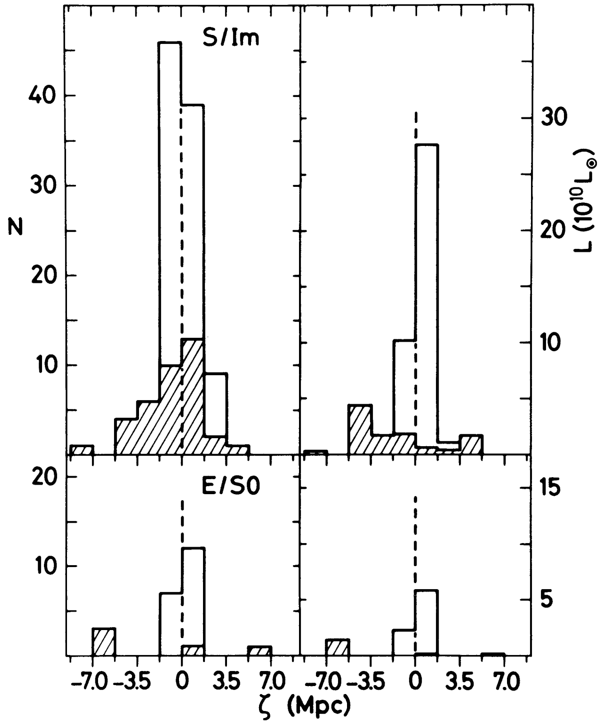

Fig. 7: Left side: The number distribution of S/Im galaxies (upper panel) and E/S0 galaxies (lower panel) of the distance ζ from the supergalactic plane. Right side: The luminosity distribution in function of ζ for S/Im galaxies (upper panel) and E/S0 galaxies (lower panel). Galaxies in groups are shown as white histogrammes, field galaxies as hatched areas. (Note: the concentration toward the plane appears somewhat exaggerated because the sample subvolumes decrease with increasing ζ).

function is more complex than generally assumed. Different types of galaxies have clearly different luminosity functions. The overall luminosity function depends therefore on the relative frequency of different galaxian types. Since this relative frequency is strongly dependent on position (e.g. intra- and extra-cluster regions) the overall luminosity function cannot have a general character. This dependence on position is even more severe because S/Im galaxies may have different luminosity functions inside and outside of groups, and because dE galaxies may be confined to aggregates of galaxies.

VI. THE LUMINOSITY DISTRIBUTION WITHIN THE METAGALAXY

In this section systematic changes are investigated of the luminosity density within the present sample volume. Beyond this it is attempted to describe the luminosity distribution - as contributed by E/S0 and S/Im galaxies - within a volume centered on the Virgo cluster and with a radius of ~ 30 Mpc. This volume has frequently been designated as the Local Supercluster. This term is avoided here as too programmatic; instead the name Metagalaxy shall be used. The reason is that the total mass within the volume appears to be concentrated in a disc with a strong radial density gradient, and that there is only one major density maximum in the centre of the system, all other density fluctuations being of secondary and tertiary

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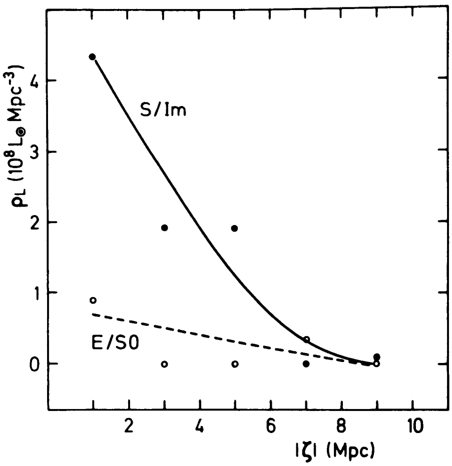

Fig. 8: The luminosity density of S/Im galaxies (filled circles; full line) and of E/S0 galaxies (open circles, dashed line) in function of the distance ζ from the supergalactic plane.

importance. This picture has little to do with superclusters, which are commonly assumed to consist of two of more comparable members (clusters). (For practical purposes the designation "supergalactic coordinates" are retained).

A. The Luminosity Distribution Perpendicular to the Supergalactic Plane.

The present sample volume was cut with equidistant planes parallel to the supergalactic plane into ten subvolumes. The distribution of the sample galaxies and their combined luminosities within these subvolumes is shown in Fig. 7. The histogrammes do not reflect the true density run with distance ζ from the supergalactic plane (because of the variable size of the subvolumes), but they do show (1) a roughly symmetric distribution about the supergalactic plane; (2) a strong concentration toward this plane; (3) a more pronounced concentration of group galaxies than of field galaxies; and possible (4) a stronger flattening of the system containing S/Im galaxies than that of the E/S0 galaxies.

The true luminosity densities of the subvolumes (combining volumes with equal values of ζ) are plotted - separately for E/S0's and S/Im's - in Fig. 8. In spite of some scatter of the individual points the S/Im galaxies exhibit a clear trend: the mean density of $4.2 \cdot 10^8\ L_\odot\ \mathrm{Mpc}^{-3}$ within 2 Mpc from the plane decreases to half its value at $\zeta = 4$ Mpc and decreases by more than a factor of 10 at $\zeta \approx 8$ Mpc. Only 15 percent of the light in the sample volume is carried by E/S0 galaxies; most of this fraction is contained in only a few galaxies. Therefore a well determined density gradient cannot be expected for this type of galaxies. Indeed it is not much more than a guess that the E/S0 galaxies are also concentrated toward the supergalactic plane and that this concentration is possibly less pronounced than for S/Im's. It would be, of course, of far-reaching significance if the lesser concentration of E/S0's could be substantiated.

The degree of concentration of the local galaxies is surprisingly high: 75 percent of their total light lies within $\pm$ 4 Mpc of the plane. Within $\zeta < 3.5$ Mpc almost all light is contributed by group members, above this limit it comes from field galaxies, although the latter carry only 18 percent of the total light.

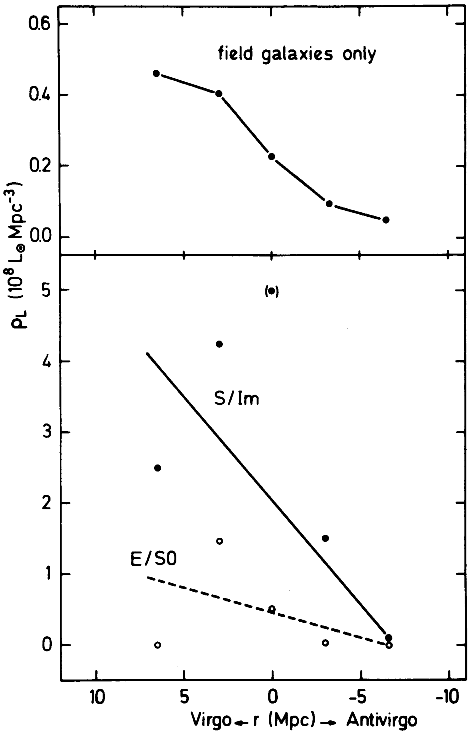

Fig. 9: Lower panel: The luminosity density of S/Im galaxies (filled circles, full line) and E/S0 galaxies (open circles, dashed line) in function of the distance from the Virgo cluster centre. The local value, containing the Local Group, is shown in parentheses. Only galaxies within 4 Mpc of the supergalactic plane are considered. The corresponding relation for field galaxies only is shown in the upper panel.

B. The Radial Luminosity Distribution Within the Metagalaxy.

Analogous to the previous paragraph the sample volume was cut into five subvolumes by equidistant planes perpendicular to the supergalactic plane and to the line of sight toward the Virgo cluster centre. The luminosity densities contributed by E/S0 and S/Im galaxies within the different subsamples are plotted in Fig. 9. Only galaxies with $\zeta < 3.5$ are considered here in order to minimize the variable (!) contribution of low-density regions at high ζ -values. Due to the grouping of galaxies the individual points have a large scatter, but they exhibit a clear trend: the density decreases by roughly a factor of 10 from the subvolume nearest to the Virgo cluster to the most distant subvolume. The trend is well confirmed if only the field galaxies are considered; although their number is smaller they show less scatter because they are free of clumping effects (cf. Fig. 8).

It has been known for a long time that the galaxy density is much higher in the Virgo direction than in the Anti-Virgo direction (Shapley and Ames, 1932; Reiz, 1941; Sandage et al., 1972), but the present result is surprising in as far as the density gradient is still so steep in a sample volume 20 Mpc away from the Virgo cluster.

The next aim shall be to derive the radial density distribution within the whole Metagalaxy. A first attempt to do this comes from Jones (1976). The solution is repeated here with independent data, combining the present sample (with $\zeta < 3.5$ Mpc) with observations of galaxies within 10° of the Virgo cluster centre (Sandage and

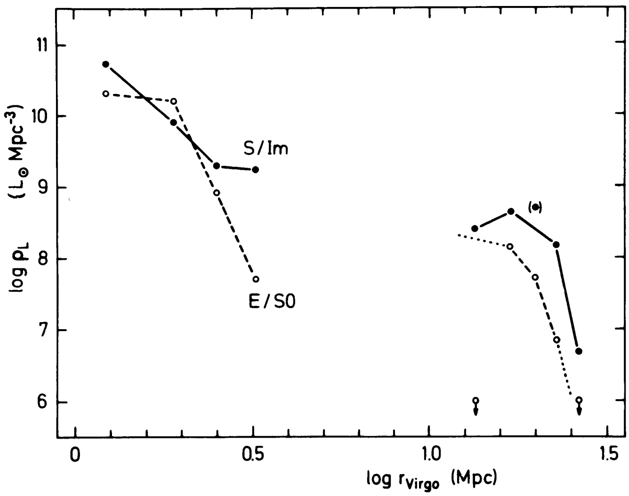

Fig. 10: The decrease of the luminosity density ρ_L with the distance from the Virgo cluster centre (logarithmic scale). The data for the outer regions are from Fig. 9; the data for the inner regions ($r \leqslant 3.5$ Mpc) are from Sandage and Tammann (1978). The symbols are the same as in Fig. 9.

Tammann, 1978). The resulting density profile is shown in Fig. 10.

The luminosity density varies from a central volume of 1.5 Mpc radius to a distance of 28 Mpc by about four decades. Almost everywhere the luminosity density of S/(Im) galaxies is higher than of E/S0 galaxies. The present data do not define the densities between r = 3.5 and 10 Mpc. A density minimum may exist in this range, as weakly hinted at by the E/S0 galaxies. Such a minimum is expected for a bound cluster embedded in a freely expanding field. The eventual prove or disprove for the existence of the minimum shall have important consequences.

If one assumes rotational symmetry of the Metagalaxy the density profiles of Fig.10 can be integrated. Using a linear interpolation (in log-log) for the range r = 3.5 to 10 Mpc probably leads to an upper limit of the total metagalactic light. The integration gives then $0.8 - 2.3 \cdot 10^{13} L_\odot$ with about 20 percent of the light in E/S0's. The range of total luminosity is determined by two extreme assumptions: (1) the flattening of the Metagalaxy is everywhere the same as determined in paragraph A; and (2) the true luminosity distribution is more or less spherical. The mean luminosity density in a sphere of 28 Mpc radius, centered on the Virgo cluster, becomes then $\sim 1.5 \cdot 10^8 L_\odot$ Mpc^{-3} within a factor of two. With the above mean mass-to-light ratio of < 20 this corresponds to a mean mass density of $< 2 \cdot 10^{-31}$ g cm^{-3}. If one allows for enough "missing mass" to bind the inner 3 Mpc of the Virgo cluster ($\mathfrak{M}/L \approx 140$) the mean density is increased to only $< 3.9 \cdot 10^{-31}$ g cm^{-3}. This is less than 0.07 times the critical Einstein-de Sitter density.

The present investigation concerns a tiny volume and it is not meant to have a bearing on the large-scale structure of the universe. But any cosmological model must allow for at least one cell with the properties described above.

Acknowledgements. We owe to Dr. A. Sandage for unpublished data and most stimulating discussions. Others - too numerous to be named here - have contributed with their suggestions and discussions. Dr. J. Materne has kindly performed the virial calculations for the groups of galaxies. We thank Mrs. M. Saladin and Mr. D. Cerrito for having made the manuscript ready for reproduction. Support of the Swiss National Science Foundation is gratefully acknowledged.

REFERENCES

Abell, G.O. 1975, Galaxies and the Universe, ed. A. and M. Sandage and J. Kristian, Chicago: The University of Chicago Press, p. 616.
Albada, T. S. van, and Freeman, K.C. 1977, private communication.
Branch, D. 1977, Supernovae, ed. D. N. Schramm, Dordrecht; Reidel, p. 21.
Cesarsky, D.A., Laustsen, S., Lequeux, J., Schuster, H.-E., and West, R.M. 1977, preprint.
Felten, J.E. 1977, Goddard Space Flight Center Preprint, X-602-77-162.
Fisher, J.R., and Tully, R.B. 1975, Astron. Astrophys. 44, 151.
Holmberg, E. 1958, Medd. Lund Obs. Ser. II, Nr. 136.
Holmberg, E. 1964, Ark. f. Astron. 3, 387.
Holmberg, E. 1969, Ark. f. Astron. 5, 305.
Hubble, E. 1936, The Realm of Nebulae, New Haven: Yale Univ. Press, p. 159.
Huchtmeier, W.K., Tammann, G.A., and Wendker, H.J. 1976, Astron. Astrophys. 46, 381.
Jones, B.J.T. 1976, M.N. 174, 429.
Kahn, F.D., and Woltjer, L. 1959, Ap.J. 130, 705.
Karachentsev, I.D. 1977, this volume.
Kiang, T. 1961, M.N. 122, 263.
Kraan, R., and Tammann, G.A. 1978, in preparation.
Krumm, N., and Salpeter, E.E. 1977, Astron. Astrophys. 56, 465.
Lynden-Bell, D., and Lin, D.N.C. 1977, M.N. 181, 37.
Materne, J., and Tammann, G.A. 1976, Proceedings of the Third European Meeting, ed. E.K. Kharadze, Tbilisi, p. 455.
Reaves, G. 1956, A.J. 61, 69.
Reaves, G. 1977, Proc. Conference Evolution of Galaxies and Stellar Populations, New Haven: Yale Univ. Press, in press.
Reaves, G. 1977a, private communication.
Reiz, A. 1941, Lund Obs. Ann. No. 9.
Rubin, V.C. 1977, I.A.U. Coll. 37, 119.
Sancisi, R. 1977, I.A.U. Symp. 77, in press.
Sandage, A. 1973, Ap.J. 183, 711.
Sandage, A. 1975, Ap.J. 202, 563.
Sandage, A. 1978, in press.
Sandage, A., and Hardy, E. 1973, Ap.J. 183, 743.
Sandage, A., and Tammann, G.A. 1975, Ap.J. 197, 265.
Sandage, A., and Tammann, G.A. 1975a, Ap.J. 197, 313.
Sandage, A., and Tammann, G.A. 1976, Ap.J. 210, 7.
Sandage, A., and Tammann, G.A. 1976a, Ap.J. 207, L1.
Sandage, A., and Tammann, G.A. 1978, in preparation.
Sandage, A., Tammann, G.A., and Hardy, E. 1972, Ap.J. 172, 253.
Sargent, W.L.W., and Lo, K.Y. 1977, Ann. Report Director Hale Obs. 1976/77.
Shapley, H., and Ames, A. 1932, Harvard Ann. 88, No. 2.
Smoot, G.F., Gorenstein, M.V., and Muller, R.A. 1977, preprint.
Tammann, G.A. 1977, I.A.U. Coll. 37, 43.
Turner, E.L. 1976, Ap.J. 208, 304.
Vaucouleurs, G. de 1975, Galaxies and the Universe, ed. A. and M. Sandage and J. Kristian, Chicago: The University of Chicago Press, p. 557.
Vaucouleurs, G. de 1976, Ap.J. 205, 13.
Vaucouleurs, G. de, Vaucouleurs, A. de, and Corwin, H.G. 1976, Second Reference Catalogue of Bright Galaxies, Austin: University of Texas Press.
Visvanathan, N., and Sandage, A. 1977, Ap.J. 216, 214.
Yahil, A., Tammann, G.A., and Sandage, A. 1977, Ap.J. 217, 903.
Zwicky, F. 1957, Morphological Astronomy, Berlin: Springer, p. 224.

DISCUSSION

Peebles: This is a very elegant presentation, but I do think there are some ambiguities. Your conclusion that the peculiar velocity must be much less than 100 km s^{-1} need not conflict with the idea that we are moving at 300 km s^{-1} or more peculiar velocity. All that is needed is that we and the nearby galaxies are moving bodily (say, toward the Virgo cluster). And I have the impression that the M/L values depend on the detection of group members, so for example one can obtain many different values of M/L for the M81 group depending on how one defines it.

Tammann: We are of course fully aware of your result that we and our immediate neighbourhood may partake in a systematic journey toward the Virgo cluster (1976, *Ap. J.*, 205, 318). But it seems to us that newer observational evidence (as referenced in the text) tends to limit the size of any peculiar motions and/or to increase the minimum volume which could possibly move as one body.

The M81 group gives a relatively high M/L value, whereas other groups (e.g. the IC 342 group) give very low values. This could mean that the true M/L values change from group to group, or that the virial solutions scatter considerably - for various reasons - about the true value. It seemed to us reasonable to assume the latter and to determine one mean M/L for all groups.

Davis: What, if any, galactic absorption corrections have been included in your analysis?

Tammann: It has been believed for a long time that the galactic absorption could be derived from galaxy counts, until Noonan (1971,*Ap. J.*, 76, 190) showed that faint galaxies are unsuited for this purpose because their number is affected by uncontrolled cosmological effects, and brighter galaxies are too scarce to define the absorption at higher latitudes. We have therefore relied on the cosec-law of colour excesses (Sandage 1973; Visvanathan and Sandage 1978, in press) which implies $A_B \propto 0\overset{m}{.}13(\text{cosec } b - 1)$. We have, however, neglected the patchiness of galactic absorption, because we feel that this effect is not yet sufficiently controlled.

Huchra: (1) Do you correct the volume you use to derive the luminosity density for the effect of galactic absorption?

(2) Your sample is very small, volumewise only a few thousand cubic megaparsecs, so you have almost no information on the bright end of the luminosity function where the mean galaxy density is $\sim$ .001 or less - there is a moderate chunk of luminosity there which you know nothing about in this sample.

Tammann: As to your question: one sixth of our sample volume lies at $|b|<15^{o}$. You might therefore want to increase the mean luminosity density by 17 percent. However, it is questionable whether a bulk correc-

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tion - even if of moderate size - should be applied, because the mean luminosity density within this subvolume is not below average. We think it is best to wait until we know how many low-latitude galaxies will actually be added by future searches.

Your remark on the brightest galaxies is well taken. But do you want us to extend our sample volume to contain the nearest quasars? It is inherently impossible to gain maximum information on dwarf and (super-) giant galaxies within the same sample volume.

Silk: One of your important conclusions was that the luminosity function is very different for elliptical and spiral galaxies. Would you comment on the various other studies in the literature that, while admittedly on different samples, have found luminosity functions which are often similar for both ellipticals and spirals?

Tammann: One of the few previous attempts to derive the luminosity function separately for E and S galaxies comes from Holmberg (1969): he also found widely different luminosity functions for the different galaxy types.

Zeldovich: What is the distribution of galaxies perpendicular to the supergalactic plane?

Tammann: The concentration toward the supergalactic plane is (at least locally) surprisingly strong: all groups lie within 3.5 Mpc of the plane and 75 percent of the total light lies within 4 Mpc. We shall be more specific on this problem in the written version of our talk.

van Woerden: I fear your census of galaxies with $V_o < 500$ km s^{-1} may be less complete than you think. (1) Several galaxies may be hidden in the zone of avoidance; the recently discovered Circinus Galaxy shines through a galactic window, but others may be hidden by heavy absorption. (2) There are certainly many southern dwarf irregulars for which no velocity is available yet.

Tammann: We fully agree that there are countless dwarf galaxies to be discovered. However, the question for us is: (1) how many of them are Im's? (2) are any of them members of the Local Group and the M81 group? and (3) what is the number of the latter per absolute-magnitude interval? After all our luminosity function for S/Im's galaxies predicts that half of them are fainter than $-15^{m}.7$ and hence too dwarfish to enter the Shapley-Ames catalogue. The next local Im's to be discovered must help us to fill up the low-luminosity end of the Gaussian luminosity function. But it would take dozens and dozens of nearby(!) dwarf Im's to make the maximum near $-15^{m}.7$ disappear.

When I talked about completeness of the sample it was not with reference to the number of galaxies, but to the total light within the sample. Essentially all light is carried by the brightest galaxies, very few of which should be lacking in the sample.

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Turner: A comment on your carefully corrected (internal absorption, inclination, etc.) magnitudes - these corrections certainly decrease the quoted values of M/L; this is somewhat illusory, however, because for the issue of mass discrepancies (e.g., rotation curve M/L vs. cluster virial M/L) or for computing values of $\Omega(=(M/L)L)$, the luminosities are merely labels (bookkeeping devices) for the mass. It is only necessary to measure the luminosities always in some (any) standard way. Put differently, neither the virial mass discrepancies nor the value of Ω would be affected at all if every galaxy suddenly (and miraculously) changed its luminosity by any constant factor. Converting your preferred value of $\Omega(0.04)$ to a M/L value in the usual, relatively uncorrected luminosity system would give $\langle M/L \rangle \gtrsim 30\ M_{\odot}/L_{\odot}$, I think. For the comparison of dynamical M/L values to stellar population values requires, as you emphasized, careful evaluation of luminosities.

Tammann: I have always considered the mass-to-light ratio to be the ratio of the true mass and the true luminosity. There may be applications where one wants to transform this physical quantity into a more "label"-like parameter. But to avoid confusion one should clearly distinguish between the two things, and for an observer the primary goal should be - I think - to determine the first-mentioned quantity.

Kiang: (1) Faint galaxies are still being discovered in the Local Group. Such galaxies would not have been discovered in any other group. Hence I don't think that your sample is as complete at the low-luminosity end as you say, nor that the general luminosity function is a peaked one.

(2) In calculating the luminosity density, the correction for internal absorption should not be made. True, I was the only one of all the authors who made this correction when deriving the luminosity function, but James Felten has now convinced me that, at least for the purpose of getting the luminosity density, this should better not be made. (Felten's point is that we must use the flux that eventually emerges from the galaxy.)

Tammann: I am happy about your first comment, because it indicates that our proposal of a peaked luminosity function for S/Im galaxies is at least not trivial.

Your second comment, however, is a great surprise for me. I have always been very impressed by your original proposal that internal absorption corrections should be applied. We shall give arguments in the written version of our paper why we believe that this is still correct.

Ostriker: When you found the mean sizes, velocity dispersions and (M/L) ratios, did you take straight number weighted averages or did you consistently weigh each galaxy by its luminosity? The luminosity weighted mass to light ratio is the one needed for cosmological discussions where we multiply the mean luminosity density by $\langle M/L \rangle$.

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Tammann: The virial masses are calculated according to the precepts set out by Materne (1974, *Astron. Astrophys.*, 33, 451). They are therefore strictly luminosity-weighted.

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