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# VELOCITY DISTRIBUTION OF VIRGO CLUSTER GALAXIES

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## ABSTRACT

We have analyzed several effects of the general population of the Local Supercluster on observed properties of the Virgo Cluster. We identify two subgroups in the field of the Virgo Cluster that are most likely beyond the Virgo distance. Combined with an intrusion of the W cloud into the field of the cluster, this clumped component accounts for ~9% of the galaxies in our sample complete to $m_p = 14.5$. Evidence is also presented of a near Hubble expansion of galaxies in the outer 2° of the cluster suggesting that the flow within the supercluster may be generally retarded, but not very disturbed otherwise. Our numerical models suggest that the large difference between the $T < 0$ and $T > 0$ velocity dispersions cannot have arisen from the accidental inclusion of a smoothly distributed supercluster population and is hardly affected by the subtraction of the clumped component we have identified.

Several different approaches suggest a cluster mean velocity in the range of 960–1000 km s$^{-1}$ with 980 km s$^{-1}$ a "best" estimate.

*Subject headings:* galaxies: clustering — galaxies: redshifts

## I. INTRODUCTION

Since the Virgo cluster was first identified by Shapley and Ames (1926) many studies have attempted to explain its observed properties. Most proposed cluster models tend to be "global" in nature in that they are generally spherically symmetric and require some, more or less, coherent motion of portions of the cluster, such as collapsing (Moss and Dickens 1977) or expanding (Sulentic 1977) shells or both (de Vaucouleurs 1982) to explain the observed velocity distributions. The intrinsic clumpiness of the supercluster region (de Vaucouleurs 1961; Eastmond 1977; Paturel 1979; Tully 1982) and of the majority of clusters in general (Struble and Rood 1982; Geller and Beers 1982), however, suggests that perhaps the key to understanding the structure of the cluster lies in a more "local" approach based on a detailed analysis of individual members and subgroups. That is, it may be necessary to virtually resolve the actual distance to every imputed cluster member.

High-quality redshifts are essential to this program. The Virgo Cluster subtends a radius of ~0.1 radian on the sky so that in a linear flow it would occupy a redshift band whose radius is 10% of its observed redshift (100 km s$^{-1}$). Since typical optical redshifts have external errors of about this magnitude (Rood 1983, hereafter RD), the cluster is unresolved in redshift space. Thus the addition of a relatively large sample of high quality 21 cm (cf. Fisher and Tully 1981, hereafter FT) and optical (Huchra *et al.* 1983, hereafter CFA) redshifts greatly improves the possibility of understanding the cluster.

In the following sections we will not present another cluster model but will analyze several features of the background against which Virgo data should be evaluated. The first is the demonstration of a significant general supercluster contribution to galaxies normally assigned cluster membership, and the second, part of which was suggested in an earlier paper (Ftaclas *et al.* 1981, hereafter Paper I), is the identification of two specific background subgroups in the field of the cluster. In § II the sample is discussed, and in §§ III and IV, respectively, the above described features are discussed, and their effects on the cluster velocity distributions are analyzed in § V.

## II. THE VELOCITY SAMPLE

We have compiled a catalog of galaxies with R.A. between 12 and 13 hours, and declination 0°–20° with measured redshifts as a subset of a larger catalog of galaxy images in this region. We will confine our attention in this paper to those galaxies generally assigned cluster membership. Following de Vaucouleurs (1961) and others, we take the cluster, as in Paper I, to be centered at $\alpha = 12^h27^m$, $\delta = 13.°5$ with a radius of 6.°5. There has been some disagreement in the literature as to specific cluster boundaries (see Mould, Aaronson, and Huchra 1980, hereafter MAH, for a summary) and radii.

Our source of image information is the photometry of the Virgo region by de Vaucouleurs and Pence (1979, hereafter dVP). Based on their distribution of photographic magnitudes ($m_p$; Zwicky, Herzog, and Wild 1961; Zwicky and Herzog 1963) we estimate that our redshift sample is 100% complete to $m_p = 14.5$ (176 redshifts of which four are background) and 85% complete to $m_p = 15.0$ (210 redshifts of which 15 are background). The total sample consists of 252 redshifts of which 29 are background. The distribution of all sample redshifts is shown in Figure 1. It is evident that the Virgo redshift sample is still steeply terminated at 2500 km s$^{-1}$ by the extended "hole" behind the Cluster (Sulentic 1977; Paper I; Davis *et al.* 1982; Ftaclas 1983*a*). Although a few redshifts have appeared at just over this limit, we will maintain the traditional redshift cutoff in what follows. Since this limit differs from the cluster mean by about twice the cluster velocity dispersion, it is not clear whether this cutoff is due to the cluster or a termination of the general supercluster population. A study of the surrounding region (de Vaucouleurs 1961; Eastmond 1977; Davis *et al.* 1982) and estimates of the cluster mean and dispersion velocities would suggest that both populations terminate at about the same redshift. It is in the sense of exceeding 2500 km s$^{-1}$ that the word "background" was used at the beginning of this paragraph.

Apart from the bounds on R.A. and decl., and the cutoff at 2500 km s$^{-1}$, no other judgment about cluster membership is

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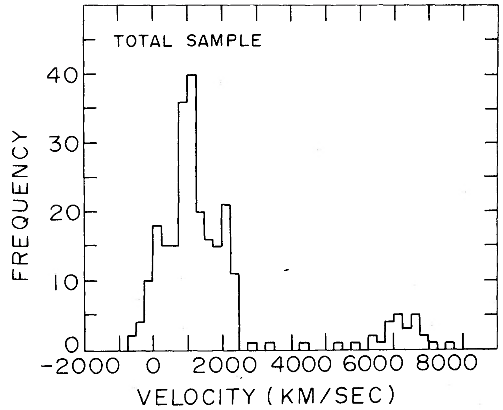


FIG. 1.—The distribution of all observed radial velocities within the adopted boundaries of the Virgo Cluster. Velocities are corrected to the centroid of the Local Group as in RC2.

TABLE 1

SUMMARY OF SAMPLE MEANS AND DISPERSIONS

| Type | $N$ | $\bar{V}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) |
|---|---|---|---|
| E ........... | 21 | 1012 ± 127 | 566 ± 89 |
| L ........... | 47 | 1178 ± 67 | 454 ± 47 |
| t(−) ......... | 11 | 1144 ± 276 | 872 ± 195 |
| T(−) ........ | 79 | 1128 ± 64 | 565 ± 45 |
| | (73) | (1132 ± 63) | (536 ± 45) |
| S ............ | 90 | 1079 ± 83 | 779 ± 58 |
| I ............ | 18 | 846 ± 189 | 778 ± 133 |
| t(+) ......... | 19 | 1371 ± 167 | 716 ± 120 |
| T(+) ........ | 127 | 1090 ± 70 | 783 ± 50 |
| | (98) | (1052 ± 77) | (762 ± 55) |
| T(0) .......... | 17 | 732 ± 180 | 720 ± 127 |
| Total ........ | 223 | 1072 ± 48 | 715 ± 34 |
| | (172) | (1083 ± 51) | (676 ± 37) |

NOTE.—Values in parentheses are those for the complete sample with $m_p \leq 14.5$.

made initially. Our redshifts include all sources published to date combined according to their mean external errors as estimated by RD. Where the error for a particular redshift, as estimated by an observer, exceeds the mean error for that observer, then the larger estimate is used. Where different redshift sources differ by more than one standard deviation, as estimated from their respective errors, then, in the absence of any other information, the redshift from the source with the lowest external error is used. The only exception to the above rule is that 21 cm sources listed by RD as standards are not combined with any other sources, but may be averaged with each other. In general, we have tried to use common sense to arrive at a concensus redshift value. All velocities are corrected to the centroid of the Local Group as in the *Second Reference Catalogue* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RC2).

A morphological type for each galaxy is assigned directly from dVP. For purposes of discussion, we assign the designation S to those galaxies with $T = 0$–7, I to those galaxies with $T = 8, 9, 10$, and t(+) to those galaxies designated solely as " + " (i.e., $T > 0$) by dVP. As is usual, we call galaxies with $T = -1, -2, -3$ lenticulars, galaxies with $T = -5, -6$ ellipticals, and we designate by $t(-)$ those galaxies assigned a " − " $T < 0$) by dVP. With these designations, we define the two sets:

$$\mathrm{T}(+) = \mathrm{S} + \mathrm{I} + \mathrm{t}(+) \quad \text{and} \quad \mathrm{T}(-) = \mathrm{E} + \mathrm{L} + \mathrm{t}(-) .$$

Finally, we designate by T(0) the set of galaxies which have not been assigned any type of dVP. Mean and dispersion velocities are given in Table 1 for each of these groups as calculated using the total redshift sample. Below the entries of Table 1 we have added, in parentheses, values calculated from the complete sample brighter than $m_p = 14.5$. The velocity distributions for the sets T(+) and T(−) are shown in Figure 2.

The results presented in Figure 2 and Table 1 show that the basic features of the velocity distributions that have compelled many studies of the cluster have not gone away with an improved redshift sample. Though the means of T(+) and T(−) are consistent, their dispersions are not, differing by $222 \pm 67$ km s$^{-1}$. Furthermore, the distribution of T(−) appears to be very nearly Gaussian, while that of T(+) is still, at least, trimodal (Sulentic 1980). The clustering of T(+) redshifts near 0 and 2100 km s$^{-1}$ has generally motivated the idea of radially moving shells.

One further feature of the cluster, also pointed out by Sulentic (1980) and more recently by Karachenstev (1982), is that the cluster mean velocity appears to rise with distance from the center. To evaluate this assertion for our sample, we list in Table 2 the means and dispersions for T(+) and T(−) in four angular ranges or zones. Zones 1–3 subtend approximately equal areas on the sky. Zone 4 subtends about half the area surveyed and is equal in area to the combined areas of zones 1–3. As in Table 1, we have added to Table 2, in parentheses, the corresponding entries for the complete sample. According to the values in Table 2, the mean of T(−) has high and low excursions with radius, but it is T(+) whose mean rises most dramatically with radius (a rise of $365 \pm 119$ km s$^{-1}$ between zones 1 and 4). This result suggests that the high- and low-

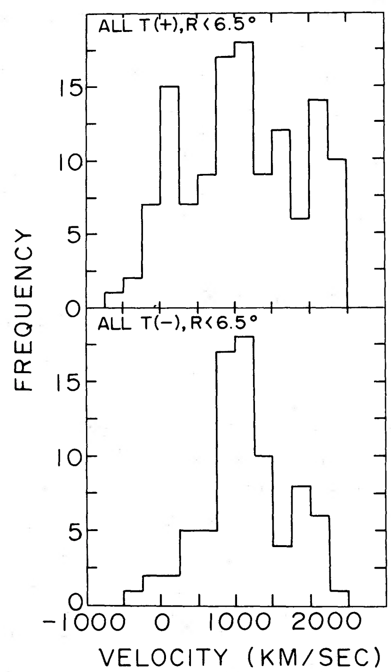


FIG. 2.—Velocity distribution of all T(−)(E/S0/−) and T(+)(S/I/+) sample galaxies with $V < 2500$ km s$^{-1}$.

TABLE 2

SUMMARY OF SAMPLE MEAN AND DISPERSION VELOCITIES BY ANGULAR RANGE

| | | T(−) | | | T(+) | | | TOTAL | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ZONE | ANGULAR RANGE (degrees) | $N$ | $\bar{V}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | $N$ | $\bar{V}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | $N$ | $\bar{V}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) |
| 1......... | 0–2.5 | 32 | 1144 | 547 | 39 | 890 | 855 | 81 | 988 | 758 |
| | | (31 | 1126 | 547) | (31 | 919 | 878) | (62 | 1022 | 739) |
| 2......... | 2.5–3.5 | 10 | 708 | 716 | 29 | 1021 | 875 | 42 | 884 | 849 |
| | | ( 7 | 694 | 498) | (21 | 960 | 795) | (28 | 894 | 741) |
| 3......... | 3.5–4.5 | 15 | 1328 | 541 | 24 | 1256 | 732 | 42 | 1260 | 649 |
| | | (14 | 1335 | 560) | (19 | 1164 | 737) | (33 | 1237 | 673) |
| 4......... | 4.5–6.5 | 22 | 1162 | 408 | 35 | 1255 | 558 | 58 | 1207 | 511 |
| | | (21 | 1152 | 416) | (27 | 1196 | 543) | (49 | 1163 | 496) |

NOTE.—Values in parentheses are those for the complete sample with $m_p \leq 14.5$.

velocity components of T(+) are distributed differently on the sky and that shell models may present an oversimplified picture. Two sources of the increase in cluster mean with angular radius will be explored in the following two sections.

### III. THE GENERAL SUPERCLUSTER CONTRIBUTION

In analyzing possible background contributions to the Virgo mean, Sandage and Tammann (1976, hereafter ST) cautioned that although the predicted effects were small down to 13th magnitude, if the supercluster were found to be a significant density enhancement, there would be a corresponding enhancement in the importance of background effects. The possibility of a large supercluster contribution is supported by Figure 3 which shows velocity as a function of Virgocentric radius for the total sample. The absence of low-velocity galaxies at large radii with no symmetric decrease in the numbers of high-velocity galaxies can be understood in terms of a decreasing cluster velocity dispersion combined with a general supercluster galaxy population. Regardless of the validity of this expansion, the results presented in Table 2 and Figure 3 require that the observed Virgo cluster mean and dispersion velocities will be functions of the assumed cluster radius.

If we assume that the nonlocalized supercluster galaxy count, to a given limiting magnitude, in the field of the cluster is more or less uniform on the sky, then it follows that these galaxies would have their greatest effect in zone 4 which has the lowest surface number density of galaxies. This could account, in part, for the general rise in the mean of T(+) since one would expect these galaxies, in general, to be beyond the cluster. Figure 4 shows the velocity distributions of T(+) and T(−) galaxies in zone 4 that are brighter than $m_p = 14.5$ (throughout the remainder of this section, unless otherwise indicated, all results will refer to the essentially complete sample brighter than $m_p = 14.5$). The asymmetry about the mean discussed above is quite evident in both distributions. Although the calculated means of these distributions are between 1150 and 1250 km s$^{-1}$, they both show peaks at the total cluster mean of $\sim 1000$ km s$^{-1}$. Galaxies with velocities between 2000 and 2500 km s$^{-1}$ have usually been included in the Virgo sample by symmetry arguments based on the negative velocity galaxies being cluster members (ST) and consideration of the total cluster dispersion velocity. In zone 4, however, the dispersion velocity is only $\sim 500$ km s$^{-1}$, yet 8% of the galaxies have $V > 2000$ km s$^{-1}$. Thus the high-velocity galaxies in this region are unexpected both from symmetry and statistical arguments.

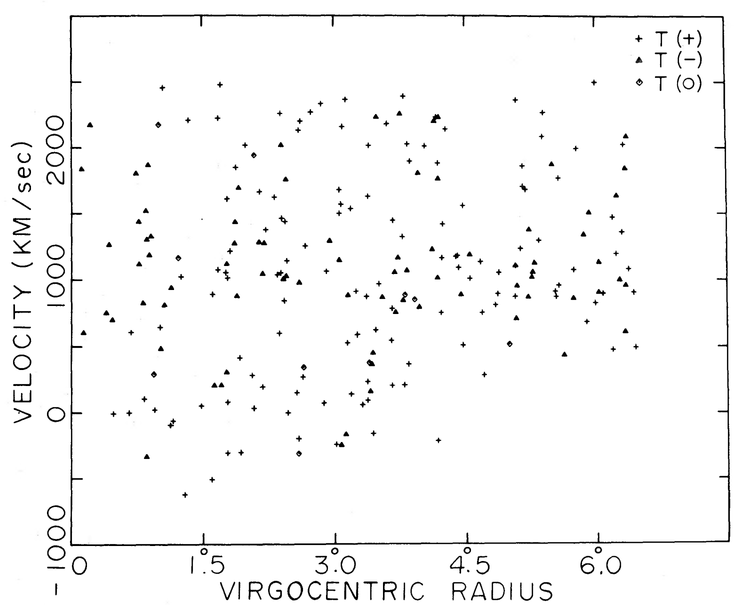


FIG. 3.—Velocity vs. Virgocentric radius for sample galaxies with $V < 2500$ km s$^{-1}$

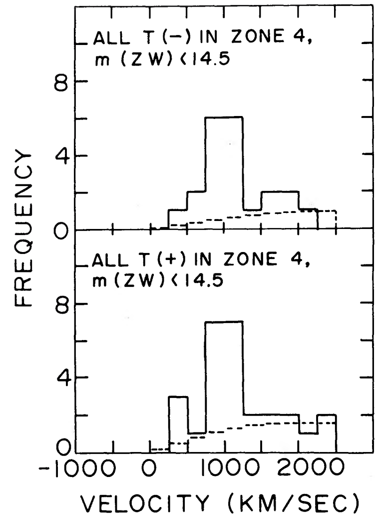


FIG. 4.—Velocity distribution of T(−) and T(+) galaxies in zone 4. Modeled background counts are indicated by the dashed lines.

Also shown in Figure 4 as dashed histograms are the expected velocity distributions of a homogeneous, freely expanding field (Rood 1975) characterized by a density 2.1 times the global mean and a local expansion rate ($H_L$) of 65 km s$^{-1}$ Mpc$^{-1}$ (Ftaclas 1983*b*), observed down to $m_p = 14.5$. The assumed luminosity functions are fits to CFA data by Davis and Huchra (1982, hereafter DH) for T(+) and T(−) galaxies. These fits assume a Schechter (1976) luminosity function, a motion of the Local Group toward Virgo of 440 km s$^{-1}$, and a global expansion rate of 100 km s$^{-1}$ Mpc$^{-1}$. We only multiply the DH normalizations by the factor 2.1. This factor comes from the shell counts of Davis *et al.* (1980, hereafter DT) which gave a galactic number density that was 28.4 times the global mean within 5 Mpc of the Virgo Cluster and roughly constant between 5 and 20 Mpc. Since the mean density within the Local Group distance is ~3 times the global mean (DT, DH), subtracting the contribution to this number made by the galaxies within 5 Mpc of Virgo gives a mean density of 2.1 times the global mean outside 5 Mpc. The assumption of $H_L = 65$ km s$^{-1}$ Mpc$^{-1}$ is based on a Virgo distance of 15.7 Mpc and a cluster redshift of 1019 km s$^{-1}$ (MAH), but our results are not too dependent on this choice.

Considering that we have adjusted no parameters to obtain the predictions plotted in Figure 4, the simplicity of our model, and the intrinsic clumpiness of the supercluster, the predicted amplitudes of high-velocity galaxies seem to agree quite well with the high-velocity tails of the observed distributions for both T(+) and T(−) galaxies (because we have used two different luminosity functions, the predicted distributions for T(+) and T(−) galaxies are independent.) In making these predictions we are not trying to draw dynamical distinctions between cluster and supercluster members but only to evaluate the effects of assigning cluster membership to essentially all galaxies in the cone traditionally called the Virgo cluster. Even if one chooses to call every galaxy in the supercluster a cluster member, the geometry of the situation will result, in general, in an unequal sampling of the region in front of and behind the cluster. Clearly this simple model must fail in some region surrounding the cluster, but it is precisely these galaxies that have the smallest effect on the cluster mean.

In zone 4 the model predicts 11.3 T(+) galaxies [42% of the T(+) population] with mean 1540 km s$^{-1}$ and dispersion 598 km s$^{-1}$, and 5.5 T(−) galaxies [26% of the T(−) population] with mean 1625 km s$^{-1}$ and dispersion 572 km s$^{-1}$. The predicted dispersion of T(+) galaxies when calculated about the mean of all T(+) galaxies from Table 1 is about 770 km s$^{-1}$ which is comparable to the observed T(+) dispersion. This suggests that if one could somehow eliminate these galaxies, it would not significantly decrease the T(+) dispersion. This is not true for T(−), however, where the predicted velocity dispersion calculated about the cluster mean gives 750 km s$^{-1}$ which exceeds the dispersion of T(−) as a whole. Thus we must conclude that if the difference between T(+) and T(−) galaxies has been induced by the inclusion of noncluster galaxies, these galaxies must be clumped, since the subtraction of a uniformly distributed supercluster population will only exacerbate the issue of the difference between T(+) and T(−) dispersions.

The prediction of a significant T(+) general supercluster population in zone 4 can be investigated in several ways. In Figure 5 we have plotted the variation with velocity of corrected face-on diameter, log $D(0)$, calculated as in RC2, for the 27 T(+) galaxies in zone 4, and in Figure 6, the same quantities

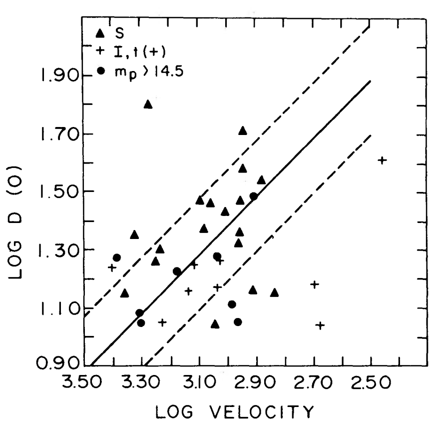


FIG. 5

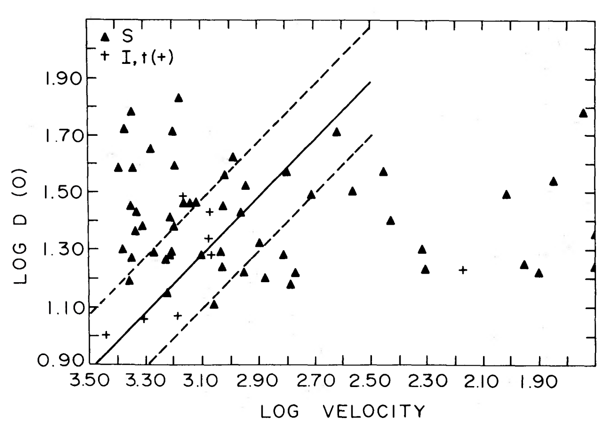


FIG. 6

FIG. 5.—Log-log plot of corrected face-on diameter $D(0)$ from RC2 vs. observed radial velocity for zone 4 T(+) galaxies only. The solid line is the least squares fit to a slope of −1 with the 1 $\sigma$ uncertainty in the fit shown as dashed lines. Galaxies with $m_p > 14.5$ were excluded from the fit.

FIG. 6.—Same as Fig. 5 except for T(+) galaxies in zones 1–3. The regression line is the fit from galaxies in zone 4. Galaxies with velocities < 50 km s$^{-1}$ have been excluded.

for the 71 T(+) galaxies in zones 1–3. Galaxies with $m_p > 14.5$ have also been plotted in Figure 5 because they will be referred to in the following section. They are not used in the subsequent analysis, and it is evident that their inclusion would produce no substantive change. For the galaxies in zone 4 we have fitted a least squares line of slope $-1$ (Hubble relation). If all 27 points are used, we find an intercept of 4.36 and a dispersion of 0.27 about the regression line. After all 2 $\sigma$ rejections, which eliminate three points, the intercept is 4.38, and the dispersion about the regression line is 0.19. The latter values are used to plot the solid line in Figures 5 and 6 with the 1 $\sigma$ range indicated by dotted lines.

The intercept, $4.38 \pm 0.04$, implies a value of log $D(0)$ of $1.38 \pm 0.04$ at the cluster mean of $\sim 1000$ km s$^{-1}$. This is consistent with the mean value of log $D(0)$ for all galaxies in T(+) with $m_p < 14.5$ of $1.39 \pm 0.02$. The intercept implies an intrinsic face-on diameter of $\sim 7h^{-1}$ kpc, where $h$ is $H_L$ in units of 100 km s$^{-1}$ Mpc$^{-1}$. The dispersion about the regression line of 0.19 is consistent with the dispersion in log $D(0)$ of 0.20 for all members of T(+) brighter than $m_p = 14.5$. Thus the least squares line is, in every way, consistent with the properties that one would expect of a Hubble line. It is clear from a comparison of Figures 5 and 6, that the T(+) galaxies in zones 1–3 conform more closely to the lack of diameter-velocity correlation one would expect in a cluster. In Figure 7 we show a similar plot for T(−) galaxies in zone 4 and reproduce the least squares lines from Figure 6. This is justified since the mean and dispersions of T(+) and T(−) galaxy diameters are essentially equal. The fraction of "noncluster" galaxies expected is smaller for T(−) than for T(+), but five to six of these galaxies in zone 4 is certainly consistent with the plot. One of these galaxies (N4233) was listed by de Vaucouleurs (1961) as a possible W cloud member at about twice the Virgo distance.

The analysis of H I depletion as a function of Virgocentric distance presented by Chamaraux, Balakowski, and Gerard (1980, hereafter CH) and by Giovanelli and Haynes (1983) are both consistent with little depletion outside 4°5. CH, for example, calculate an H I depletion parameter, $u$, that is the dimensionless deviation of H I mass from the mean for galaxies of that type and size. A negative value of $u$ implies a deficit relative to the mean. Of the 44 galaxies in the CH sample that fall within our surveyed area, eight are in zone 4. Of these, seven have $u > 0$, while, for the CH sample as a whole, only 10 out of 44 galaxies have $v > 0$. While a lack of H I depletion does not necessarily prove that these galaxies are not cluster members, it is at least consistent with the picture we have presented.

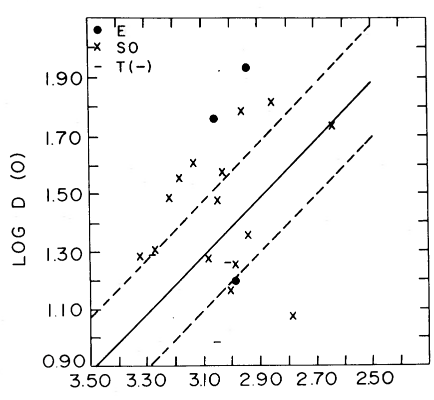


FIG. 7.—Same as Fig. 6 for T(−) galaxies in zone 4

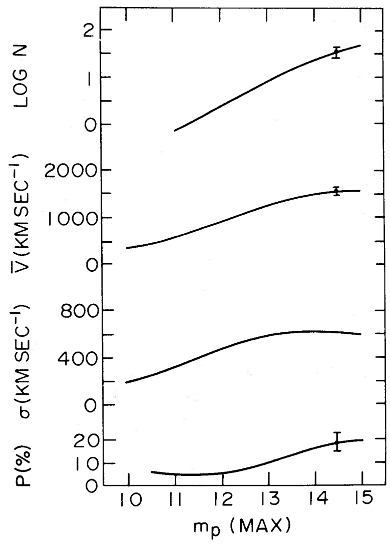


FIG. 8.—Uniform flow model predictions for the expected general supercluster population in the Virgo Cluster.

Consistency with the Hubble line for zone 4 galaxies is perhaps too good since less than half are predicted to lie outside the cluster boundaries. This suggests that perhaps the central concentration region within 5 Mpc of the cluster is not as disturbed as the models of Hoffman, Olson, and Salpeter (1980) and Hoffman and Salpeter (1982) suggest.

The predictions of a uniform flow model are summarized in Figure 8 where we have plotted the logarithm of the predicted total number of galaxies in the field of the cluster, as well as their mean and dispersion velocities, as a function of limiting apparent magnitude. The cutoff at 2500 km s$^{-1}$ limits the rise in the predicted mean and dispersion velocities. As a general estimate of the importance of the general supercluster population, we have also plotted $P$, the predicted number of galaxies expressed as a percentage of all Zwicky images brighter than the assumed magnitude limit. Although $P$ appears to be leveling off beyond $m_p \sim 14$, the number of galaxies with $V > 2500$ km s$^{-1}$ is rapidly increasing with limiting magnitude so the importance of the supercluster contribution should grow with limiting magnitude faster than Figure 8 suggests. Thus simply adding more redshifts to the Virgo sample should not, of itself, resolve the cluster-supercluster ambiguity. Yahil, Sandage, and Tammann (1980, hereafter YST) have predicted that 20% of the galaxies in their sample that appear in the 6° circle around M87 are actually more than 4 Mpc away from the Virgo center. Although this prediction seems close to ours, it actually refers to a brighter limiting magnitude and includes a portion of the central condensation region, so it is difficult to compare directly.

The vertical bars on the curves in Figure 8 indicate the changes in the plotted quantities arising from a variation in $H_L$ of 10 km s$^{-1}$ Mpc$^{-1}$ (no sensible change in dispersion is calculated). The change in the predicted number is anticorrelated with $H_L$, but the predicted mean velocity rises with $H_L$. It is interesting that the equation used by ST to predict the number of field galaxies observed to $m_p = 13$, gives 33 galaxies to $m_p = 14.5$ which is close to our model predictions of 34 galaxies. The agreement is accidental, however, since the earlier estimate took no account of the cutoff at 2500 km s$^{-1}$ or of any overdensity in the supercluster.

One clear prediction of almost any model in which the supercluster is expanding is that the cluster mean should rise with limiting magnitude (MAH). The Virgo mean generally rises up until $m_p = 13$, but then levels or drops slightly to $m_p = 14.5$ (the details depend on the choice of center and radius, but all changes are within the statistical uncertainty of the mean, thus probably not significant). The mean velocity of the 23 galaxies with $14.5 < m_p < 15.0$ is $1270 \pm 176$ km s$^{-1}$, but the mean of the 28 galaxies with $m_p > 15.0$ is $880 \pm 154$ km s$^{-1}$, so there is no clear trend at present. The redshifts of galaxies with $m_p > 15.0$ are generally either very uncertain or come from special searches for dwarf and compact galaxies which were excluded by DH in deriving the global luminosity function. It is possible that by considering two different luminosity functions and spatial distributions for dwarf and normal galaxies one could explain the leveling in the cluster mean (assuming it is significant). It is also possible that increasing the limiting magnitude brings in galaxies just beyond Virgo that are falling toward the cluster.

## IV. THE CLUMPED CLUSTER BACKGROUND

Looking at velocity sections through the supercluster region (cf. Eastmond 1977), many condensations in velocity space as well as in position on the sky can be seen. Simultaneous spatial and velocity coherence strongly suggests a physical association, and we explore below two of the most obvious cases we have found within the cluster boundaries.

### *a) The M Cloud*

We have shown in the previous section that the increase in the mean velocity of T(+) galaxies in zone 4 could be attributed to the contribution of an extended, homogeneous supercluster component. In Figure 9 we show the velocity distribution of T(+) and T(−) galaxies in zone 3 (again with $m_p < 14.5$) together with model predictions. One feature of the observed distribution is the relatively large number of galaxies with $2000 < V < 2250$ km s$^{-1}$. These galaxies are not distributed randomly in zone 3. We show in Figure 10 the spatial distribution of all galaxies in our sampled region with $2000 < V < 2500$ km s$^{-1}$. Circles of radius 4°.5 and 6°.5 have been drawn around the cluster center. The W cloud ($N = 24$, $V = 2198$ km s$^{-1}$, $\sigma = 220$ km s$^{-1}$), first identified by de Vaucouleurs (1961), is clearly visible at $\alpha = 12^h16^m$, $\delta = +6°$. It is likely that part of the apparent consistency of zone 4 galaxies with the Hubble line arises from an encroachment of W-cloud galaxies into the traditional cluster boundaries. From Figures 5 and 7 it is evident that all six zone 4 galaxies with $V > 2000$ km s$^{-1}$ are closely consistent with the Hubble line. From Figure 6, it follows that the cluster does have some relatively large, high-velocity galaxies (expected to be physical members), but these galaxies must be located close to cluster core, as expected.

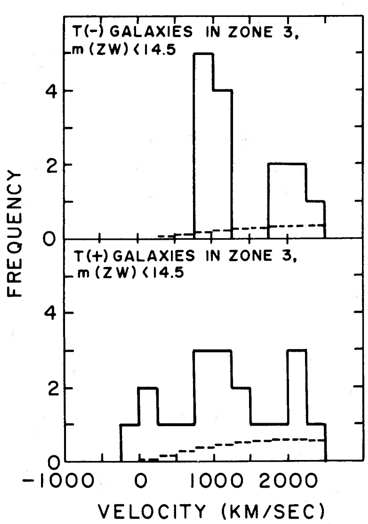


FIG. 9.—Velocity histogram for zone 3 T(+) and T(−) galaxies. Modeled background counts are indicated with dashed lines.

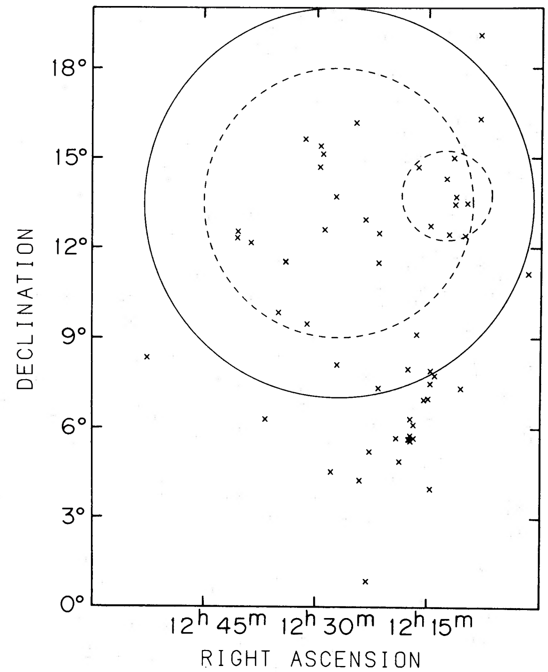


FIG. 10.—Distribution on the sky of all sample galaxies with $2000 < V < 2500$ km s$^{-1}$. The inner dashed circle has radius 4°.5; the outer solid circle has radius 6°.5. The dashed circle at $\alpha = 12^h12^m$, $\delta = +13°45'$ outlines the M cloud.

Another group centered at $\alpha = 12^h12^m.5$, $\delta = 13°45'$ and less compact than the W cloud is also evident in Figure 10. The latter group, which can also be seen in Figure 2, contains within a radius of 1°.5 nine of the 29 cluster galaxies in the plotted velocity range. Thus one-third of the high-velocity cluster galaxies are contained in 5% of the area ($P < 1$%). The existence of this group was indicated in Paper I where it was pointed out that the group was first identified by Shapley and Ames (1929) who deduced, on the basis of magnitudes alone, that it was beyond the Virgo distance. We designate this group the M cloud.

It would appear that the conjecture of Shapley and Ames is essentially correct. In the extensive literature concerning the Virgo Cluster, we could find only two instances of galaxies falling within the cluster boundaries with $V < 2500$ km s$^{-1}$ having been explicitly singled out as background (cf. ST; MAH) and excluded from a calculation of the Virgo mean. One of these, I769, is in the M cloud, and the second, N4152, is the zone 4 galaxy that is within 2° of the M cloud. Table 3 summarizes distance modulus information for M cloud galaxies from various sources. One of these galaxies (N4254 = M99) is large, bright, and well resolved. Its distance modulus information is consistent with its being at the Virgo distance. Because

TABLE 3

M Cloud Galaxies

| NGC/IC | $m_p$ | $T$ | log 10 $D(0)$ | Virgocentric Radius (degrees) | $\mu_0$ | Comments |
|---|---|---|---|---|---|---|
| 4152....... | 12.5 | Sc | 1.35 | 5.39 | 31.76 | de Vaucouleurs 1979, based on optical tertiary indicators. |
| | | | | | 31.65 | de Vaucouleurs 1982, weighted mean of optical and H I data. |
| | | | | | BG | Sandage and Tammann 1976 on luminosity class criteria. |
| | | | | | 31.69 | Buta and de Vaucouleurs 1983, based on ring diameters. |
| 4168....... | 12.7 | E | 1.43 | 4.20 | 31.42 | de Vaucouleurs and Olson 1982, based primarily on optical velocity dispersion. This distance modulus is the largest value of all Virgo Cluster ellipticals, considered by de Vaucouleurs and Olson and is 0.93 mag larger than their assumed Virgo distance modulus. |
| 4200....... | 14.1 | "−" | 1.12 | 3.76 | ... | |
| I769 ....... | 14.1 | "+" | 1.36 | 4.28 | 32.30 | This paper using the blue magnitude–H I velocity profile relation. This object falls 1.4 mag below a best fit line. |
| | | | | | 32.48 | Aaronson, Huchra, and Mould 1979. It falls 1.5 mag below a fit for the infrared magnitude-velocity profile width relation, assuming their Virgo distance of 30.98. |
| | | | | | BG | Classified as background on luminosity class criteria by Sandage and Tammann 1976. |
| 4186....... | 14.9 | Sab | 1.12 | 4.04 | ... | |
| 4189....... | 12.7 | Scd | 1.38 | 3.84 | 31.70 | By de Vaucouleurs 1979 from optical tertiary indicators. |
| | | | | | 32.00 | By de Vaucouleurs 1982, a weighted mean of optical and H I indicators. |
| | | | | | 32.60 | This paper, using the blue magnitude–H I velocity profile relation. This object falls 1.7 mag below a best fit line. |
| | | | | | 31.54 | Buta and de Vaucouleurs 1983, based on ring diameters. |
| 4193....... | 13.4 | Sc | 1.30 | 3.80 | ... | |
| I3061...... | 14.9 | Sc | 1.22 | 3.61 | ... | |
| I3099...... | 15.2 | "+" | 1.13 | 3.10 | ... | |
| 4254....... | 10.2 | Sc | 1.72 | 2.86 | 30.53 | de Vaucouleurs 1982, weighted mean of optical and H I data. |

of its close proximity to the M cloud, we include distance information on N4152 as well in Table 3. For the nine M cloud galaxies (excluding N4254 and including N4152) we find $\langle V \rangle = 2179$ km s$^{-1}$, $\sigma = 121$ km s$^{-1}$. Several additional redshifts that fall in the M cloud velocity and position ranges have been provided by T. X. Thuan (private communication) but are not included in the subsequent analysis. For two M cloud galaxies (N4189 and I769), we have determined distance moduli relative to Virgo using 21 cm line widths for a sample of Virgo spirals from FT. All galaxies have inclinations greater than 30°. *B* magnitudes for these galaxies have been taken from dVP and corrected to face-on according to the precepts of FT. The data are plotted in Figure 11. Note that the deviation of N4189 from the least squares line is even greater than that of I769.

If the M cloud represents a clumped component of the supercluster population treated in the previous section, then we can require that these two features be consistent. We have plotted in Figure 12, M cloud galaxies (symbol M) (including N4152 and N4254) in the log $D(0)$–log $V$ plane reproducing, as well, the best fit Hubble line and dispersion from the previous section. It is evident that, with the exception of N4254, all other imputed M cloud galaxies are consistent with the Hubble line. We note that all six high-velocity galaxies in zone 4 can be assigned to either the W cloud (5) or the M cloud (1), suggesting a supercluster enhancement at about twice the Virgo dis-

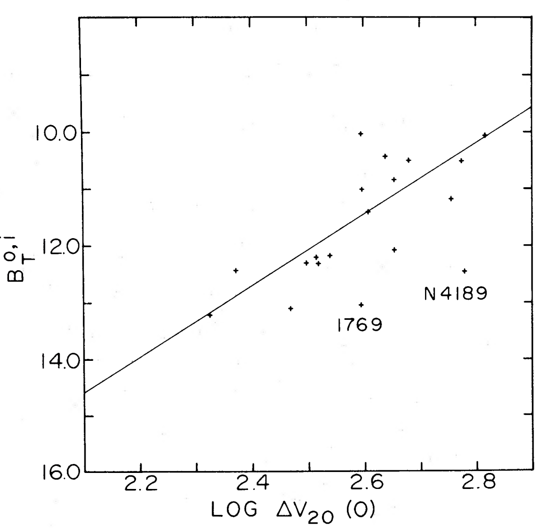


Fig. 11.—Fisher-Tully relation for a sample of Virgo Cluster spirals. Magnitudes are corrected according to the precepts of RC2. The sample includes spirals with $T < 4$, $i > 30°$, and $R < 6\overset{\circ}{.}5$.

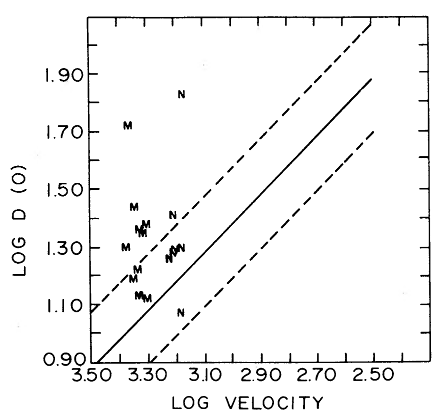


Fig. 12.—Log-log plot of corrected face-on diameter $D(0)$ (as in RC2) vs. observed radial velocity for M cloud and N cloud galaxies. The regression line is as in Fig. 5.

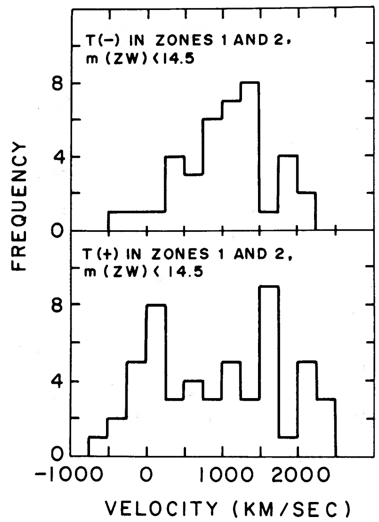


FIG. 13.—Velocity distribution of T(−) and T(+) galaxies in zones 1 and 2.

tance. Paturel (1979) has suggested a "northern extension" of the W cloud.

### *b) The N Cloud*

In Figure 13 we show the velocity distributions of T(+) and T(−) galaxies in zones 1 and 2. In addition to the unusual low-velocity feature that has been the subject of much discussion (cf. ST; Sulentic 1977, 1980; Helou, Salpeter, and Krumm 1979) and an absence of any peak in the T(+) distribution at the cluster mean velocity, there is evident a second enhancement in T(+) between $1500 < V < 1750$ km s$^{-1}$. In Figure 14 we show the position on the sky of all sample galaxies in this velocity range. We see that seven of the 16 sample galaxies in this velocity range fall within 1°.5 of N4421. Although less rich, this group is similar to the M cloud in that it has one bright galaxy (N4321 = M100) in its outskirts, and we designate the group as the N cloud. Of all N cloud galaxies, we could find distance information only for M100, and that is in conflict. De Vaucouleurs *et al.* (1981) give $11.5 \pm 0.8$ Mpc averaging over eight different distance determinations, and de Vaucouleurs (1982) has assigned it a distance of $12 \pm 1.6$ Mpc

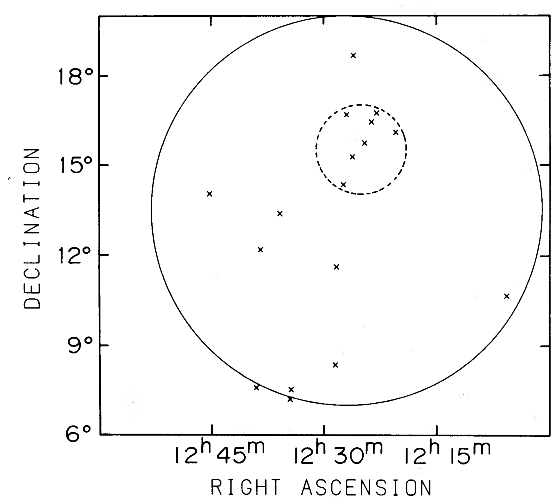


FIG. 14.—Distribution on the sky of galaxies with $1500 < V < 1750$ km s$^{-1}$. The large circle has a radius of 6°.5; the smaller dashed circle outlines the N cloud.

(the uncertainty estimate is ours), based on optical tertiary distance indicators and 21 cm line width. On the other hand, Panagia *et al.* (1980) and Branch *et al.* (1981), applying the Baade-Wesselink method to supernova 1979c, obtain $24 \pm 5$ Mpc and $23 \pm 3$ Mpc, respectively. We have also plotted N cloud galaxies (symbol N) in Figure 12, and M100 does appear to stand apart. The remaining six galaxies, however, are closely grouped in position, velocity, and diameter and totally consistent with the Hubble line. Looking at Figure 7, it is evident that this diameter distribution is not a general property of the galaxies in this velocity band (all N cloud galaxies have $m_p <$ 14.5, so the comparison is appropriate). We believe that most N cloud galaxies are beyond the Virgo distance.

We have identified a clumped supercluster population which can be ascribed to the M and N clouds and an encroachment of the W cloud into the field of the cluster. In the following section we will refer to these galaxies collectively (excluding M99 and M100) as WMN galaxies.

## V. DISCUSSION: THE MEAN VELOCITY OF THE VIRGO COMPLEX

It is unfortunate that the calibration of many relations, and the determination of numbers of great cosmological importance, should depend on the distance to, and mean velocity of, so irregular an assemblage of objects as the Virgo Cluster. Despite the obvious concentrations of galaxies in the regions adjacent to the cluster on the plane of the sky, it is common practice to treat the ~6° Virgo cone as virtually devoid of any other galaxies, as if nature had somehow conspired to give us an unobscured view of the cluster. Given the highly clumped nature of the brighter galaxies in the supercluster found by de Vaucouleurs (1956, 1975) and Tully (1982), this could indeed be the case, but the data presented in the previous two sections would suggest otherwise.

We find that there is good evidence that a significant fraction of the galaxies normally assigned cluster membership are, in fact, distributed along the line of sight of the cluster (the WMN galaxies constitute 9% of the complete sample, and the uniform flow model puts this fraction at ~20%). We would expect that these galaxies have acted to elevate the Virgo mean velocity and increased Virgo distance estimates. The central condensation region referred to earlier is approximately 5 Mpc in radius and about 28 times denser than average. Assuming galaxies to be uniformly distributed in this region (this is manifestly untrue in detail), and allowing for the contribution to this overdensity due to the cluster itself, we find that an additional 28% of the galaxies in our 6°.5 cone brighter than $m_p = 14.5$ are actually spread out between 10 and 20 Mpc from the Local Group and are outside the cluster boundaries. Like the 20% figure given earlier, this estimate depends only on homogeneity and not on any expansion model.

Estimates of the contribution of the central concentration region must be considered as highly uncertain because of the clear dominance of this region by only a few large clouds and the strong concentration of galaxies in this region towards the cluster (Tully 1982; YST). Nevertheless, the likelihood certainly exists for a significant supercluster contribution to the galaxies in the Virgo cone. It may be argued that the risk in assuming that all galaxies in the Virgo cone are at the same distance is perhaps overstated since, in general, brighter galaxies are selected for calibrations and distance determinations. But brighter Virgo galaxies are not free of doubt with regard to their cluster membership (cf. Cowley, Crampton, and McClure 1982; Helou, Salpeter, and Krumm 1979; Sulentic 1977).

The isolation of the M and N clouds would seem at first sight to support the notion of an overestimated Virgo mean velocity, but observational biases weaken this conclusion. The notion of using spatial and velocity coherence to locate possible subgroups clearly works best for background rather than foreground groupings. A subgroup of apparent radius 1°.5, at twice the Virgo distance, would appear to be equal in angular size to the cluster were it to be moved to one-half the Virgo distance. Consideration of the foreground and background volumes alone would argue that more high- than low-velocity groups should affect the Virgo mean velocity. But where one suspects that the cluster has been affected by only a small number (i.e., < 10) groups, then statistical arguments are necessarily weak. It is evident from Figure 6, however, that there does not appear to exist a population of large, low-velocity galaxies in the cluster that would be the clue that a foreground group of any consequence existed. Even the largest galaxies in the cluster are still small compared to the diameter predictions of the Hubble line. Since Figure 6 includes galaxies in the low-velocity enhancement of T(+), and the diameters of these galaxies appear comparable to those of galaxies at the cluster's redshift, we would conclude that there is little evidence that these low-velocity galaxies are significantly closer than the cluster as a whole. A detailed comparison of the diameter distribution of galaxies with velocities near 0 km $s^{-1}$ with that of all galaxies supports this conclusion.

The actual mean velocity of the Virgo complex, that is, the mean velocity of all galaxies that are physically in the sphere defined by the 6°.5 radius, can be estimated in several ways. One is to make a formal subtraction of the predictions of the uniform flow model from the cluster total for the complete sample. Making this subtraction gives 93 (747) km $s^{-1}$ for the T(+) mean (dispersion) velocity and 1048 (482) km $s^{-1}$ for the T(−) mean (dispersion) velocity. As predicted, the difference between the dispersions of the two samples has not risen to 3.6 standard deviations. For T(+) and T(−) combined we get a mean (dispersion) velocity of 974 (645) km $s^{-1}$ (assuming $H_L = 75$ km $s^{-1}$ $Mpc^{-1}$ gives a "corrected" mean of 990 km $s^{-1}$). This value is 125 km $s^{-1}$ below the canonical value of 1100 km $s^{-1}$ (cf. ST) used for many years, 45 km $s^{-1}$ below the value proposed by MAH, and 30 km $s^{-1}$ below the value suggested by Kraan-Korteweg (1981, allowing ~40 km $s^{-1}$ for the difference in apex of the motion of the Local Group). The "corrected" cluster mean velocity predictions of the uniform flow model do not change by more than 10 km $s^{-1}$ if we use the Hubble constant and Virgo distance estimates of Aaronson and Mould (1983), or those of Sandage and Tammann (1982). This is not surprising since we are trying to predict the number and mean velocity of galaxies brighter than $m_p = 14.5$ with $V < 2500$ km $s^{-1}$ in a "typical" supercluster field. This question can be answered by counting, without recourse to theoretical models. Since all models are based on essentially the same image and redshift information, they should give similar results.

Another approach is to argue that if the clumped structure of the supercluster persists at fainter magnitudes, then the WMN galaxies comprise the bulk of the essential portion of the supercluster contribution. Subtracting these galaxies from the complete sample gives 938 (723) km $s^{-1}$ for the T(+) mean (dispersion) velocity and 1080 (501) km $s^{-1}$ for the T(−) mean (dispersion) velocities. In this case the T(+), T(−) dispersion difference remains essentially unchanged so that even the subtraction of a large clumped component dominated by T(+) galaxies does not significantly reduce the dispersion difference (note that subtracting the N cloud galaxies actually raises the dispersion velocity). The total cluster mean (dispersion) velocity drops to 1000 (640) km $s^{-1}$.

Although the values of the cluster mean velocity we have arrived at are within the quoted uncertainties of previous values, they are systematically lower than all of them. Most techniques for predicting a mean velocity for the Virgo Cluster (see the review by Peebles 1977) depend on comparisons with other clusters and are thus subject to the uncertainties in the peculiar velocity of the Local Group. One might hope to use the brightest members as in more regular clusters, but here also there is much ambiguity (cf. Yahil 1981; DH). M49, the first-ranked cluster galaxy, has many velocity determinations which are generally grouped around a value of 900 km $s^{-1}$. M87, the next brightest, has a faint cD-like corona (Carter and Dixon 1978) and has a mean near 1100 km $s^{-1}$. While it is generally acknowledged that these two galaxies bracket the cluster mean, other bright galaxies in Virgo do not at all help to pin down the cluster mean velocity any further. In fact, if we take the 15 Messier objects in our field as a relatively unbiased list of Virgo's brighter galaxies the number weighted mean velocity (dispersion) is 834 (842) km $s^{-1}$.

Luminosity weighting is the logical extension of using the brighter galaxies and provides an added bonus in that it tends to suppress background galaxies. For instance, the WMN galaxies that fall in the complete sample comprise about 9% of that sample yet account for only 3%–4% of the total light. Similarly, the luminosity-weighted mean velocity in the uniform flow model is predicted to be only ~1100 km $s^{-1}$, and, while its galaxies are predicted to be ~20% of all galaxies, they should account for only about 10% of the observed light. The latter number is, of course, subject to enormous fluctuations induced by a few bright foreground objects. There are, however, ambiguities here as well, stemming from the fact that several different models exist in the literature (cf. RC2; FT; Sandage and Tammann 1981; RSA) for correcting galaxies to face-on luminosity. This is of some importance since it was shown in Paper I that the brighter Virgo spirals tend, in the mean, to have their velocities anticorrelated with their inclinations. In Table 4 we have summarized the T(+), T(−) and total mean velocities for the complete sample using several different weighting schemes including the square of the corrected face-on diameter. The sensitivity of the spiral mean to various weighting schemes is apparent as is the difference between using Zwicky and blue magnitudes. This is due largely to the combination of a tendency for Zwicky magnitudes to underestimate the luminosity of brighter, more extended objects (cf. Thuan and Romanishin 1981), and the low velocity of the brighter Virgo galaxies. Using luminosity weighting for the Messier objects only gives a mean in the range of 875–900 km

TABLE 4

LUMINOSITY WEIGHTED MEAN OF THE COMPLETE VIRGO SAMPLE

| Method of Weighting | T(−) $\bar{V}$ (km $s^{-1}$) | T(−) $\sigma$ (km $s^{-1}$) | T(+) $\bar{V}$ (km $s^{-1}$) | T(+) $\sigma$ (km $s^{-1}$) | Total $\bar{V}$ (km $s^{-1}$) | Total $\sigma$ (km $s^{-1}$) |
|---|---|---|---|---|---|---|
| Number | 1132 | 536 | 1052 | 762 | 1083 | 676 |
| $m_p$ (Zwicky) | 962 | 510 | 1160 | 864 | 1050 | 699 |
| $B_T$ (RC2) | 955 | 524 | 1085 | 861 | 1014 | 700 |
| $B_T{}^0$ (RC2) | 959 | 523 | 1042 | 873 | 998 | 715 |
| $B_T{}^{,i}$ (FT) | 955 | 524 | 1030 | 877 | 992 | 725 |
| $B_T{}^{,i}$ (RSA) | 955 | 524 | 1018 | 902 | 991 | 769 |
| $D_0$ (RC2) | 980 | 543 | 915 | 863 | 945 | 735 |

$s^{-1}$ using weighting schemes that depend on blue magnitudes, and 1000 km $s^{-1}$ using Zwicky magnitudes. Thus, had MAH used a different magnitude source, their weighted means would most likely have been comparable to our lower values.

Even though luminosity weighting suppresses background galaxies, it does not altogether eliminate them. Luminosity weighting with the WMN galaxies in the complete sample removed gives a cluster mean in the range 960–980 km $s^{-1}$ for any weighting scheme based on blue magnitudes. With the light expected from the uniform flow model removed, the expected mean is 980 km $s^{-1}$. We would suggest the latter value as a best estimate since it is consistent with several different approaches.

It is interesting how close the uniform flow and clumped approaches are in predicting total mean velocity, particularly when luminosity weighting is used. One large disparity between both these models and our calculations, however, is that a large part of the drop in the cluster mean as a result of luminosity weighting is due to T(−) galaxies. Almost any model of the supercluster would predict that T(+) galaxies comprise the bulk of noncluster galaxies and should show the largest drop. It may be that the velocity of the mass centroid of the E/S0 core of the cluster has been overestimated by number weighting, or as suggested by de Vaucouleurs (1961), the T(−) galaxies may, in the mean, be less distant than T(+) galaxies.

## V. CONCLUSIONS

1. We have identified two subgroups in the field of the Virgo Cluster that are most likely beyond the Virgo distance. Combined with an intrusion of the W cloud into the field of the cluster, this clumped component accounts for $\sim 9\%$ of the galaxies in our complete sample.

2. There is evidence of a near Hubble expansion of galaxies in the outer 2° of the cluster, suggesting that the flow within the supercluster may be generally retarded, but not very disturbed otherwise.

3. Our numerical models suggest that the difference between T(+) and T(−) velocity dispersions cannot have arisen from the accidental inclusion of a smoothly distributed supercluster population and is hardly affected by the subtraction of the clumped component we have identified.

4. Several different approaches suggest a cluster mean velocity in the range of 960–1000 km $s^{-1}$ with 980 km $s^{-1}$ a "best" estimate.

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