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ON THE VIRGO SUPERCLUSTER AND THE MEAN MASS DENSITY OF THE UNIVERSE

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ABSTRACT

Recent measurements of the anisotropy of the microwave background radiation of the local Hubble flow suggest that the local group of galaxies has a motion of 300–500 km s^{-1} directed toward Virgo. If this velocity is generated by the Virgo supercluster, it provides a powerful test of the cosmological parameter Ω. Using a catalog of redshift data complete to $m_b = 14.0$ we have computed the mean overdensity $\bar{\delta}$ toward the Virgo cluster to be $\sim 2.0 \pm 0.3$. When combined with a nonlinear spherically symmetric flow model around Virgo we derive $\Omega \sim 0.4 \pm 0.1$. Thus the measured mass-to-light ratio of the universe continues to rise with increasing scale size of measurement.

Subject headings: cosmology — galaxies: clusters of

I. INTRODUCTION

The concept of massive, dark halos is gaining reluctant acceptance among astronomers because there is simply no other viable way to describe the "missing" mass in rich clusters or the flat rotation curves of spiral galaxies. Recent very high-quality data by Peterson (1979) show the high mass-to-light ratio in binary galaxies studied by Turner (1976*a*, *b*) is not the result of measurement errors, and long-slit spectra of spirals by Rubin, Ford, and Thonnard (1980) indicate that virtually all Sc spirals have flat rotation curves, indicating $M(r) \propto r$ to the limits of their sensitivity.

Ostriker, Peebles, and Yahil (1974) pointed out that observed mass-to-light ratios are an almost linear function of measurement scale. To date no upper limit to this behavior has been observed, and it is thus of considerable interest to extend the measurement of mass-to-light ratios to as large a scale as possible.

The Virgo supercluster offers a unique opportunity for study because it is possible to use our local group of galaxies as a test body in the gravity field of the supercluster. Both the microwave isotropy measurements (Smoot and Lubin 1979; Cheng *et al.* 1979) and the recent 21 cm infrared magnitude studies of Aaronson *et al.* (1980) indicate a peculiar velocity component in the Virgo direction that may be as large as 400–500 km s^{-1}. Other studies using less reliable distance indicators have led to similar but smaller estimates of peculiar motion (Yahil, Sandage, and Tammann 1980; de Vaucouleurs and Bollinger 1979; Schechter 1980). These results are summarized in Table 1.

Because random velocities adiabatically decay in an expanding universe, we suggest that this motion relative to the Hubble flow has been induced by the mass overdensity of the local supercluster. Although the microwave anisotropy vector is 43° off the Virgo direction, isotropy of the Hubble flow at 5000 km s^{-1} found by Aaronson *et al.* (1980) suggests that a local lump causes our peculiar velocity in the Virgo direction rather than some very large distant lump. The transverse peculiar motion implied by the microwave anisotropy could be caused by a very distant perturbation, which will not affect our analysis.

A mass lump δM at a distance r from us will induce a peculiar velocity $v_p \approx gt \approx G\delta M/(r^2 H_0)$. Suppose the initial linear spectrum of mass perturbations had a power-law behavior $\langle(\delta M/M)^2\rangle^{1/2} \approx M^{-1/2-(n/6)}$, and that we are on the edge of the perturbation. Then $v_p \propto M^{-(1+n)/6}$, and unless $n < -1$, the nearest large lump will dominate the measured velocity field. The observed shape of the two-point correlation function is evidence for a white noise initial spectrum, $n = 0$ (Peebles 1974). Counter arguments suggesting $n = -1$ are somewhat in dispute (see Fall 1979 for a review).

If the nearest large lump, Virgo, is indeed responsible for our peculiar motion, then

$$v_p \approx G\frac{\delta M}{r^2}\frac{1}{H_0} \propto \bar{\delta}\Omega v_{\rm H},$$

where $\bar{\delta}$ is the mass overdensity with respect to the mean density of the universe averaged over the volume of the Virgo cluster interior to the radius of the local group, and $v_{\rm H}$ is the Hubble velocity $H_0 r$. A detailed treatment of the comoving expansion in a linear perturbation analysis of a spherically symmetric density distribution yields (Gunn 1977; Peebles 1976)

$$v_p/v_{\rm H} \approx \tfrac{1}{3}\bar{\delta}\Omega^{0.66}.$$

We have also computed the exact nonlinear problem in the spherically symmetric case with results shown in Figure 1 (see also Silk 1974; Yahil, Sandage, and Tammann 1980). These solutions are obtained simply by matching two Friedmann solutions with different densities but equal ages. Nonspherical models are not unique but will result in nearly identical behavior for $v_p/v_{\rm H} < 1$ (White and Silk 1979).

II. THE MEAN OVERDENSITY OF VIRGO

We have for the past several years been working on a spectroscopic survey of bright galaxies in the northern sky, which shall soon be complete for $m_B \leq 14.5$, $|b| \geq 40$, $\delta \geq 0$. For this analysis we use the catalog to $m = 14.0$, where it is at present more than 99% complete. Details will be reported elsewhere (Davis *et al.* 1980); here we only briefly describe the overall characteristics of the sample.

The mean velocity of galaxies in the sample is $\sim$3000 km s^{-1}, well beyond Virgo. In the northern sky it is clear there is a strong overabundance of nearby galaxies, and an underabundance of galaxies between 3000 and 6000 km s^{-1}, a "hole" between Virgo and Coma. This is immediately apparent in the data because the mean $V/V_{\rm Max}$ is 0.4, not 0.5 as would be expected in a uniformly distributed sample (Schmidt 1968).

In order to compute the overdensity of Virgo, we have computed counts of galaxies (or luminosity) in shells concentric with the Virgo cluster. These counts are compared with counts in a randomly distributed data set having a luminosity function identical to the observed luminosity function. This method introduces additional statistical error, but the true error is dominated by systematic effects discussed below.

TABLE 1

ESTIMATES OF v_p

Velocity	Source
380±75	Smoot and Lubin 1979
480±75	Aaronson *et al.* 1980
350±50	de Vaucouleurs and Bollinger 1979
290±30[a]	Yahil 1980
190±130	Schechter 1968

[a] Calculated with respect to the centroid at the local group as defined by Yahil *et al.* 1977.

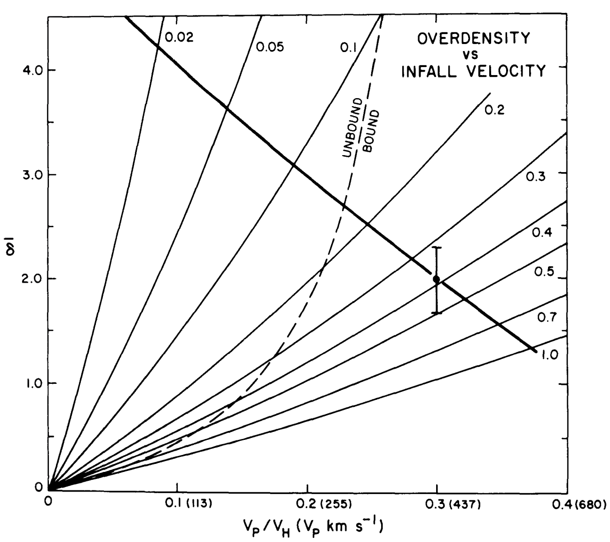

FIG. 1.—The mean overdensity of Virgo vs. $v_p/v_{\rm H}$ for various values of Ω. The x-axis is also labeled with v_p, using a recessional velocity to Virgo of 1020 km s^{-1}. The measured overdensity is prescribed by the heavy line, and is marked at the favored position as given by the anisotropy of the Hubble flow and microwave background radiation. The error bar is an estimate of the 90% confidence limit of our determination of $\bar{\delta}$. Models to the right of the dotted line are bound to Virgo.

We use B_0 magnitudes for the brighter galaxies, and Zwicky magnitudes for the fainter objects. Zwicky magnitudes have substantial error ($\sigma \sim 0.3$ mag) and a small systematic offset in Volume 1. Our results are unchanged if this systematic error is corrected. We assume that the galactic extinction is negligible because we use only galaxies with $b \geq 40°$. To eliminate the effect of dwarf galaxies in Virgo, we set a luminosity limit on the sample by using only galaxies observable to a minimum velocity of 2000 km s^{-1} (809 galaxies with $v < 6000$ km s^{-1}). The results are completely insensitive to this lower luminosity cutoff, and are also insensitive to whether the counts are number weighted or luminosity weighted.

The peculiar velocities induced by Virgo are not negligible compared to the Hubble flow, and it is crucial to correct the observed velocities by a model for the Virgocentric flow before converting to distance. Without such a correction, Virgocentric distances are underestimated and therefore densities are overestimated, roughly by a factor $(1 - v_p/v_{\rm H})^2$. The number density of galaxies about Virgo varies approximately as r^{-2}; if the mass-to-light ratio is constant, the induced peculiar velocity will vary as r^{-1}. We emphasize this model will apply only to the outer regions of Virgo which have not yet virialized. Galaxies within 6° of the Virgo core and with observed velocities less than 2000 km s^{-1} are assumed to be at the Virgo center. Small-scale peculiar motions are assumed to have negligible effect on the computation of distance. We use $H_0 = 100$ km s^{-1} Mpc^{-1}, and correct measured velocities for 300 km s^{-1} galactic rotation; in agreement with Mould, Aaronson, and Huchra (1980) we adopt a mean recessional velocity of 1020 km s^{-1} for the Virgo cluster. Table 2 lists the counts and ratio of counts to the random sample when binned in 5 Mpc thick shells. We have assumed here $v_p/v_{\rm H} = 0.3$ ($v_p = 437$ km s^{-1}).

The mean overdensity δ is sensitive to $v_p/v_{\rm H}$ but is not at all sensitive to the details of the flow model. Our

TABLE 2

VIRGOCENTRIC SHELL COUNTS

Distance[a] (Mpc)	No. of Galaxies (809 total)	Number Weighted[b] $(1+\delta)$	Luminosity Weighted[b] $(1+\delta)$
0–5	131	28.4	29.5
5–10	67	1.7	1.4
10–15	169	2.3	2.3
15–20	132	1.8	1.8
20–25	97	1.2	1.1
25–30	71	1.0	1.0
30–35	49	0.7	0.7
$\bar{\delta}$		2.12[c]	1.83[c]

[a] Assumes $v_p/v_{\rm H} = 0.3$ at local group distance and $H_0 = 100$ km s^{-1} Mpc^{-1}.

[b] 600 objects in background sample.

[c] Within local group radius.

results can be scaled to arbitrary v_p/v_H; the heavy line in Figure 1 shows the computed δ as a function of the assumed v_p/v_H.

To generate the random sample, it is necessary to determine the luminosity selection function in a method unbiased by large-scale density inhomogeneities. We use a rank statistical method similar to one devised by Turner (1979) and used by Kirschner, Oemler, and Schechter (1979). Suppose $T(r)$ galaxies are observed within distance r but could have been detected to distances $\geq r$. Suppose also that $N(r)$ objects are observed whose maximum observable distance is within r and $r + \Delta r$. The integrated luminosity function $\varphi(r)$ satisfies

$$\frac{d}{dr} \ln \varphi(r) = \frac{N(r)}{T(r)\Delta r} \equiv A(r) .$$

We fit a fourth-order polynomial to $A(r)$ and then integrate the result to find $\varphi(r)$. As expected, the luminosity function fits a Schechter-type function moderately well. The $\varphi(r)$ determined above is used to generate randomly distributed samples covering the same angular extent in the sky. The overall normalization of the random sample must be considered separately.

The hole in redshift space behind Virgo shows up as a negative density for the Virgo cluster. This is not expected but raises a difficult issue. We can never be certain of having found the ensemble mean number density of the universe; at best we can only hope for consistent measurements among different samples.

We can measure the two-point covariance function $\xi(r)$ directly by taking the ratio of the number of pairs of galaxies at a given separation to the number of random pairs at the same separation. If the two-point covariance is assumed to be positive definite on all scales in the mean, then by adjusting the number of random galaxies so that $\xi(r)$ is zero at scales of 30 Mpc and larger, we derive an upper estimate of the ensemble mean to be 74% of the measured sample, or 600 galaxies. If, however, $\xi(r)$ should be negative, say -0.2, at 30 Mpc because of the large hole behind Virgo, then we compute the ensemble mean to be 660 galaxies.

Complete redshift information exists for galaxies brighter than 13.0 in the south galactic pole. This southern sample has a luminosity density consistent with best estimates of the "universal" number density (Davis, Geller, and Huchra 1978; Kirschner, Oemler, and Schechter 1979; Faber and Gallagher 1979). If we scale it to the different solid angle and magnitude of our northern sample, then again 600 is the number of expected galaxies in the mean sample. This is the number we use in the random sample to derive the values of $\delta(r)$ in Table 1. We find $\bar{\delta}$ to be 2.12 for a number-weighted analysis and to be 1.83 for a luminosity-weighted analysis.

As an independent measurement we have computed the mean density of galaxies volume-limited to 30 Mpc with $m_B < 13.0$, for which we have complete full-sky coverage. With no correction for Virgocentric flow the luminosity density of the northern galactic cap is 2.5 times the luminosity density of the southern galactic cap for the magnitude-limited 13.0 sample (Davis, Geller, and Huchra 1978). In the southern sky this volume-limited number density of galaxies is 2.77×10^{-3} Mpc^{-3}, while in the north after making the Virgocentric flow correction we find the mean density within a 15 Mpc radius of the Virgo center to be 8.15×10^{-3} Mpc^{-3}, which gives $\bar{\delta} = 1.94$, consistent with our previous estimate.

A conservative estimate of the systematic errors of the analysis suggests $1.7 < \bar{\delta} < 2.3$, implying that for $v_p/v_H = 0.3$, $0.3 < \Omega < 0.5$. Unless v_p/v_H is substantially overestimated, the estimate of a large Ω is unavoidable. This result is totally independent of the true value of H_0.

III. DISCUSSION

We have used the local group as one test particle to measure the excess gravity of the Virgo supercluster. It is obviously important to verify that the infall is a general property of galaxies on the outer fringes of Virgo. Such studies have recently been undertaken and are continuing (Schechter 1980; Yahil, Sandage, and Tammann 1980; Tonry 1980; Aaronson *et al.* 1980); all these studies require some kind of secondary distance indicator, which has considerable uncertainty. Our value of $v_p/v_H = 0.3$ is consistent with most of the estimates summarized in Table 1. In due course it should be possible to map the Virgocentric flow precisely.

Figure 1 is marked with a dotted line indicating which solutions are bound to Virgo and which are not. With almost all the present estimates of $\bar{\delta}$ and v_p/v_H, it is clear that the local group is bound to Virgo, and will eventually begin to fall toward Virgo.

How can our high value of Ω (or M/L) be reconciled with the much lower estimates of mass-to-light ratios commonly found for individual galaxies and small groups of galaxies? Figure 2 is a plot of measured mass-to-light ratios versus scale size. We use $H_0 = 100$ km s^{-1} Mpc^{-1} and B_T magnitudes (see Faber and Gallagher 1979). This plot is similar to the plot of Ostriker, Peebles, and Yahil (1974) except now we have one data point at a scale size of 15 Mpc. The dotted line indicates $M/L \propto R$. Shown are mean M/L_{B_T}'s for galaxies as determined by nuclear dispersions and rotation curves. The results for binaries, small groups, and rich clusters are derived from the virial theorem applied to discrete systems, while the area marked "cosmic energy" results from application of the cosmic energy theorem to the whole sky 13.0 catalog (Davis, Geller, and Huchra 1978). This last method does not require assignment of galaxies to distinct clusters, but is rather a "statistical virial theorem." Note that the overall trend is unmistakable; the M/L ratio increases as the measuring scale increases, and as the density contrast decreases. The dotted line indicates $\Omega = 1$ ($M/L_{B_T} = 1400$). It is interesting to note that the curve of M/L versus scale size may be approaching an asymptotic limit, although the data are still too uncertain to determine this limit.

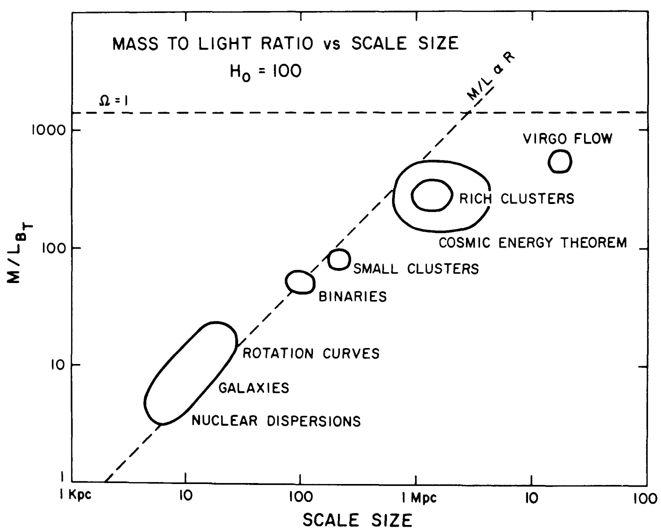

FIG. 2.—Typical measured mass-to-light (B_T) ratios as a function of measuring scale. Only M/L determinations in galactic nuclei are not dominated by the unseen heavy halo. The horizontal dotted line is the critical M/L ratio in an Einstein-de Sitter Universe if the luminosity density of the southern sky is typical of the mean.

What is the dark matter that dominates the dynamics of systems larger than 100 kpc? Apparently it does not cluster as strongly as does the light-emitting component of the universe. If the unseen matter so heavily outweighs the visible galaxies, there is no reason why mass-to-light ratios should be constant, and there may well exist massive systems which emit essentially no light. If such systems are weakly clustered with visible matter, they will be detectable only in large-scale measurements. At each scale size one translates the measured M/L into a "universal" Ω by assuming M/L ratios are constant for that scale and above. The $\bar{\delta}$ we measured is merely the mean overdensity in the light distribution, and may not be the overdensity in the mass distribution. Further measurements on even larger scales will be required to determine whether we have approached a meaningful measure of Ω.

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