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SPECTROSCOPY AND PHOTOMETRY OF ELLIPTICAL GALAXIES: A LARGE-SCALE STREAMING MOTION IN THE LOCAL UNIVERSE

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ABSTRACT

We present results from a study of the distances and velocities of elliptical galaxies out to ~ 6000 km s^{-1}. Distances are inferred from a new relation between central velocity dispersion and an angular diameter defined by integrated surface brightness. With this we estimate residual velocities $V_{\rm obs} - V_{\rm pred}$ from a smooth Hubble flow.

We find that $V_{\rm obs} - V_{\rm pred}$, in coordinates with respect to the microwave background, exhibits a systematic variation over the celestial sphere. Interpreted as a large-scale bulk flow, this variation implies a mean motion of the ellipticals with respect to the microwave background of 599 ± 104 km s^{-1} in the direction $l = 312° \pm 11°$, $b = 6° \pm 10°$. Analysis of distances to spirals by Aaronson and co-workers and Rubin and co-workers indicate flows for these objects that are roughly comparable in magnitude and direction.

The massive Hydra-Centaurus supercluster participates in the flow with a bulk motion of ~ 1000 km s^{-1} with respect to the microwave background. The Local Group also generally follows the flow but in addition has a peculiar motion of 481 ± 107 km s^{-1} toward ($194° \pm 13°$, $28° \pm 9°$). The one-dimensional rms velocity noise of ellipticals above the mean bulk motion is ~ 400 km s^{-1} but appears to be somewhat patchy on scales of 1000–2000 km s^{-1}.

Our data show that if the microwave dipole anisotropy is due to a motion of the Local Group of ~ 600 km s^{-1}, as conventionally interpreted, this motion is *not* primarily the result of gravitational acceleration by local ($V < 5000$ km s^{-1}) mass concentrations.

Subject headings: cosmic background radiation — cosmology — galaxies: distances — galaxies: general — galaxies: redshifts

I. INTRODUCTION

The dipole pattern in the microwave background radiation (hereafter MWB) has been interpreted as the result of a Local Group motion of ~ 600 km s^{-1} toward $l = 268°$, $b = 27°$ (Smooth and Lubin 1979, and references therein). Approximately 400 km s^{-1} of this motion is toward the Virgo Cluster, comparable to the peculiar motion of the Local Group toward Virgo found by numerous methods (see Davis and Peebles 1983; Dressler 1984), and the amplitude of the infall pattern at the distance of the Local Group (Aaronson *et al.* 1982*a*). This suggests that the entire 600 km s^{-1} motion of the Local Group relative to the MWB might be induced by local mass concentrations like the Local Supercluster. If so, the Local Group should show the same large peculiar velocity relative to a more distant *galaxy* frame and, when averaged over a sufficiently large volume, the galaxies in the distant frame should be *at rest* with respect to the MWB. In fact, Aaronson *et al.* (1986, hereafter ABMHSC) report that, relative to spirals in 10 fairly distant clusters (4000 km s^{-1} $< V <$ 11,000 km s^{-1}), the Local Group has a velocity $V_{\rm LG} = 780$ km s^{-1} toward (255°, 18°), in good agreement in size and direction with the microwave dipole vector.

ABMHSC followed Sandage and Tammann (1984) in suggesting that, if the Hydra-Centaurus supercluster at $V \simeq 3000$ km s^{-1} is much more massive than the Local Supercluster, it might have accelerated the latter to a velocity of 400–500 km s^{-1}. Added to the infall of the Local Group toward Virgo, this could account for the entire microwave dipole anisotropy. Until now, however, there have been too few data for Hydra-Centaurus galaxies to test this model.

In this *Letter* we examine these issues with a new and extensive data set: the distances and velocities to ~ 400 elliptical galaxies. We employ a new method that provides distances to ellipticals accurate to ±25% per galaxy. In contradiction to the ABMHSC model, we find that the entire Hydra-Centaurus supercluster is moving away from the Local Group *more rapidly* than expected for a uniform Hubble flow, which means that it, too, has a large velocity with respect to the MWB. In fact, the Local Group and Hydra-Centaurus motions appear to be part of a much larger flow pattern in which, to first order, all of the galaxies within a sphere of diameter ~ 10,000 km s^{-1} are streaming in the direction defined roughly by the intersection of the Galactic and Supergalactic planes.

II. NEW DATA AND A NEW METHOD OF MEASURING DISTANCE

a) *The Data*

Our sample of elliptical galaxies is essentially magnitude-limited with $B_T \lesssim 13.0$. This and other morphological criteria as discussed in Faber *et al.* (1987) were used to select 577 ellipticals.

There are complete spectroscopic and photometric data for 423 galaxies in the sample, with an average recessional velocity of ~ 3000 km s^{-1}. For about half of the sample, two or more ellipticals are members of a group where the crossing time is comparable to or less than a Hubble time. Group membership and velocities were obtained from an updated version of the catalog by Geller and Huchra (1983), thus reducing the effect of the internal group motions on the recessional velocity of the galaxy. The remaining galaxies are isolated or only loosely associated with other galaxies.

Spectra were obtained by us for each of the galaxies in these two samples. The spectral data, including heliocentric and group velocities, central velocity dispersions, and Mg_2 indices, are fully discussed and tabulated in Davies *et al.* (1987). The spectra were analyzed using Fourier or power spectrum techniques to yield central velocity dispersions good to $\lesssim 10\%$.

Photometry of sample galaxies was accomplished using photoelectric aperture measurements and/or CCD surface photometry. Both our own measurements and data from the literature were cross-correlated, renormalized, and merged into a catalog with ~ 3200 observations, as described in Burstein *et al.* (1987). Because of the numerous cross-comparisons, the zero points in our final catalog should be free of systematic errors at a level of 0.05 mag.

b) *Distribution of the Sample on the Sky*

The distribution of local galaxies is flattened, with the Local Group embedded in the plane. De Vaucouleurs has long emphasized this point for the Local Supercluster (e.g., de Vaucouleurs, de Vaucouleurs, and Corwin 1976), but additional data show that the plane extends over a region several times as large. We demonstrate this in Figure 1, where the distribution of all galaxies larger than 1′.5 in the UGC catalog and 1″.6 in the ESO catalog is mapped in Galactic coordinates ($l = 0°$ at the edges). The Supergalactic plane that bisects the Local Supercluster can be traced around the entire sky, down through the Virgo, Hydra-Centaurus, and Pavo-Indus superclusters, then up through the Perseus-Pisces supercluster and the Ursa-Major cloud. Though not exactly a great (or small) circle, the "plane" is only slightly warped over a diameter of ~ 100 Mpc. Tully (1986) has suggested that the flattening can be traced in the distribution of Abell clusters over an even greater volume.

The size of this coherent planar distribution of galaxies presents a challenge for models that generate large-scale structure from hierarchical clustering of much smaller units. It may be more compatible with a fragmentation picture in which large-scale structures formed first at an early epoch. This issue is beyond the scope of the present discussion, but the existence of this flat structure is relevant to our discussion of large-scale motion, which, we find, lies roughly in this plane.

The elliptical galaxies in our sample are marked as the larger solid squares in Figure 1. They cover the entire sky with good uniformity, except for the zone of Galactic obscuration.

c) *A New Distance Estimator*

The virial theorem implies that central velocity dispersion depends on *both mass and size*. Thus, even with no variation in mass-to-light ratio, one expects the residuals from the Faber-Jackson (1976) relation between velocity dispersion and luminosity to correlate with the scale size of the system. For a sample of cluster ellipticals, Dressler *et al.* (1987) show that Σ_e, the integrated surface brightness within the effective diameter, provides the needed scale length. These data show that, in a three-space of luminosity L (or effective diameter A_e), $\log \sigma$, and Σ_e, ellipticals map out a plane that is canted to all three axes (see also Djorgovski and Davis 1986).

In practice, a newly defined photometric parameter, D_n, the diameter within which the integrated surface brightness is 20.75 B mag arcsec^{-2}, effectively replaces the two free parameters with one. This is because, empirically, $\log D_n$ is a linear combination of $\log L$ and $\log \Sigma_e$ with coefficients in the same ratio as $\log \sigma = 0.38 \log L + 0.23 \log \Sigma_e$, the best-fitting plane. The rms scatter in the σ-D_n relation implies an accuracy in distance measurement of $\lesssim 25\%$ per galaxy, comparable to that of the IR Tully-Fisher method for spirals.

d) *Using the New Distance Indicator*

We have chosen the data for ellipticals in several clusters to define a least-squares relationship between D_n and σ as

$$\log D_n = 1.20 \log \sigma + \text{constant}. \quad (1)$$

The slope of 1.20, different from the "best-fitting" slope of 1.33 in Dressler *et al.* (1987), is the appropriate one for determining distances, as explained in Lynden-Bell *et al.* (1987). With σ in km s^{-1} and D_n in arcseconds, the constant

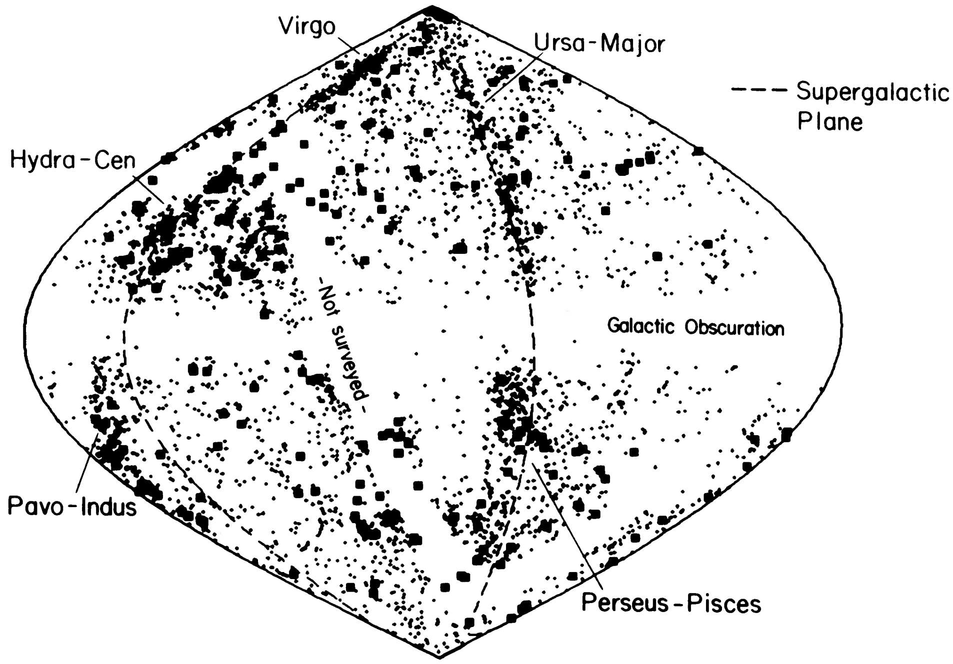

FIG. 1.—The distribution of galaxies on the sky from the UGC ($D > 1'.5$) and ESO ($D > 1'.6$) catalogs (*points*), and the elliptical galaxy sample (*large squares*). The map is in Galactic coordinates with the Galactic center at the edges. The sample galaxies cover the sky with good uniformity. The nearby superclusters are quite apparent in the UGC-ESO sample. Remarkably, the Supergalactic plane, defined originally in the Local Supercluster, passes through or near most of these major concentrations of galaxies within $V \lesssim 5000$ km s^{-1}. The streaming motion for the elliptical galaxies is directed near the intersection of the Galactic and Supergalactic planes.

C is 1.6786 at the distance of the Coma cluster. Although the zero point is not critical for the discussion of nonuniformities in the Hubble flow (errors in the zero point introduce a monopole but not dipole or higher order terms), we note that the zero point for Coma agrees, to a few percent, with that for a similar size field sample at approximately the same observed velocity. The relative distance of the Coma and Virgo clusters from the elliptical galaxies agrees with that found by ABMHSC to $\sim 1\%$.

Through equation (1) we use observed σ to predict D_n, then ratio this to D_n (observed) to find $D_{\text{Coma}}/D_{\text{galaxy}}$. In order to be independent of H_0, distances are expressed in terms of velocity, with the Coma distance set at 7203 km s^{-1}. In practice, a number of corrections need to be made to the spectroscopy, and to the photometry for Galactic extinction, cosmology, and the Malmquist effect. We discuss these fully elsewhere, but note that none of the results discussed below are sensitive to these corrections.

III. NONUNIFORMITIES IN THE HUBBLE EXPANSION FIELD

a) *The Local Group Motion with Respect to Galaxies*

The predicted distance, in terms of velocity, and an observed velocity for each galaxy in the sample map the local expansion field. Figure 2 shows a projection onto the Supergalactic plane of the residual velocities ($V_{\text{obs}} - V_{\text{pred}}$) for those ellipticals within 45° of the plane. The points mark the predicted distance, and vectors (dashed for inward flow, solid for outflow) show the residual velocity from a uniform Hubble expansion. By adding the component of the Local Group's motion with respect to the MWB (614 km s^{-1} toward [268°, +29°]; Fixsen, Cheng, and Wilkenson 1983) in the direction of each elliptical, Figure 2 shows the pattern of residual velocities as seen by an observer *at rest with respect to the MWB*. Of course, residuals can be determined for the radial direction only, so these vectors are lower limits to the motion of each elliptical with respect to the MWB.

Even with the $\lesssim 25\%$ error associated with each point, it appears that the residuals are not randomly distributed. Some of this is due to the association into groups (for which *one* distance and velocity has been adopted), but there also appear to be real correlations over spatial scales of ~ 2000 km s^{-1}.

We model the local expansion field by maximizing the likelihood of obtaining values ($V_{\text{obs}} - V_{\text{pred}}$) in a uniformly expanding universe plus a dipole velocity. Including the effects of infall toward the Virgo Cluster with an amplitude of 250 km s^{-1} for the Local Group, we find that the Local Group has a motion of 481 ± 107 km s^{-1} toward (194° ± 13°, 28° ± 9°) with respect to 289 ellipticals with $V_{\text{obs}} < 6000$ km s^{-1}. This vector is very different in magnitude and direction from the Local Group's motion with respect to the MWB. Thus, the Local Group's motion is not seen in reflex in the elliptical sample, which implies that the sample itself has a large component with respect to the MWB. If we describe this motion as a dipole term in our least-squares solution, we find a bulk motion of the 289 ellipticals of 599 ± 104 km s^{-1} toward (312° ± 11°, 6° ± 10°). The bulk motion of the sample can be seen clearly in Figure 2 as a general tendency of vectors to point from left to right.

The vector describing the bulk flow lies in the plane of Figure 2 in the horizontal direction and is directed near the intersection of the Galactic and Supergalactic planes (see Fig. 1). A particularly striking region of the bulk flow is that of the Hydra-Centaurus Supercluster, where ellipticals have residual

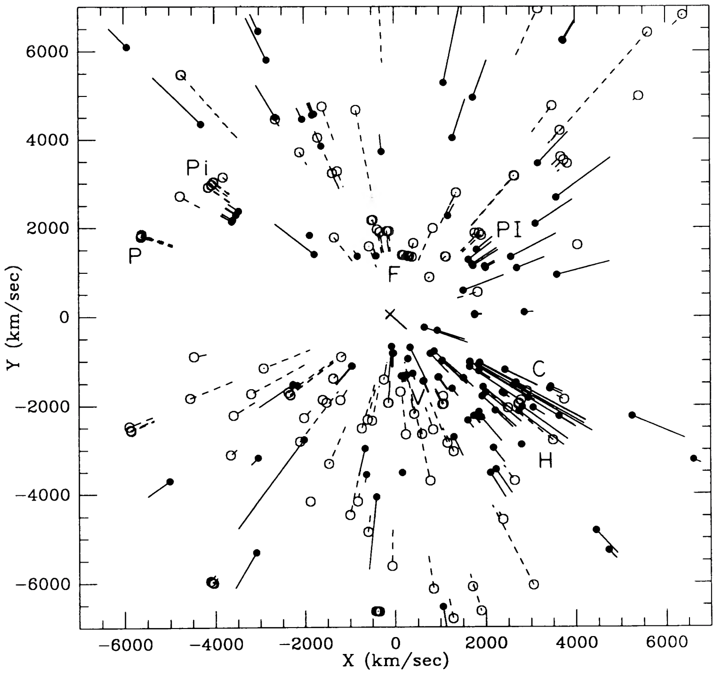

FIG. 2.—The residual velocities from a smooth Hubble for elliptical galaxies in the sample within 45° of the Supergalactic plane, projected onto the plane. The dot or circle marks the predicted distance in velocity units for each galaxy, and the vector shows whether the galaxy is receding (*solid*) or approaching (*dashed*) more rapidly than expected in a smooth, uniform flow. The radial component of the residual velocities are as seen by an observer *at rest with respect to the microwave background*. The central cross marks the position and motion of the Local Group. One component of the 481 km s^{-1} Local Group motion with respect to the sample can be seen as the net "approach" of ellipticals for $Y < 0$ and "recession" for $Y > 0$. The other component is out of the Supergalactic plane. The Hydra-Centaurus Supercluster can be clearly seen to have a large bulk motion of $\sim$ 1000 km s^{-1} with respect to the MWB. The streaming flow of 600 km s^{-1} for the elliptical sample is seen as the tendency of the vectors to point from left to right in the diagram. The figure shows that the motion of the Local Group is typical of a bulk flow over this large region, rather than a perturbation induced inside it. The letters designate concentrations of galaxies: Perseus, Pisces, Fornax, Virgo, Pavo-Indus, Hydra, and Centaurus.

radial velocities of $\sim$ 1000 km s^{-1}. This observation strongly contradicts the model by Sandage and Tammann and ABMHSC in which the massive Hydra-Centaurus concentration is essentially *at rest* with respect to the MWB, and the large Local Group motion is generated by its gravitational pull.

The motion of the Local Group with respect to the MWB, projected onto the Supergalactic plane, is the vector emanating from the origin in Figure 2. This vector is only 44° from the elliptical bulk flow, but has a substantial downward component (toward Virgo, visible in Fig. 2) and also a component out of the plane (not shown). (This peculiar motion is, of course, just the vector [481, 194°, 28°] solved for above.) We conclude that the Local Group participates in the bulk flow but has a substantial peculiar motion of its own. The relation of this peculiar motion to nearby concentrations of galaxies is discussed further by Lynden-Bell *et al.* (1987).

Another way to express our results is to ask the question: To what extent is the motion of the Local Group with respect to the MWB generated by local mass concentrations? Only $\sim$ 200 km s^{-1} of the Local Group's motion with respect to the ellipticals is in the direction of the microwave dipole vector. Therefore, we must add another vector of order 600 km s^{-1} to recover the motion of the Local Group with respect to the MWB. This is, of course, the bulk flow motion discussed above. Because this vector is as large as the microwave dipole vector itself, we conclude that the motion of the Local Group with respect to the MWB is primarily due to mass concentrations *beyond* 5000 km s^{-1}. There is a hint in the larger velocities of the Hydra-Centaurus region (Fig. 2) that we are seeing a shear caused by an accelerating mass that lies just beyond, but the present data is insufficient to make a compelling case.

A further graphic description of the bulk flow is shown in Figure 3, in which we plot the velocity residuals, again with respect to the MWB, as a function of $\cos(\theta)$, where θ is the angle on the sky from the galaxy to the apex of the bulk motion (312°, 6°). Unlike Figure 2, Figure 3 shows all galaxies in the sample, 289 with $V < 6000$ km s^{-1} (*large squares*), and 95 with $V > 6000$ km s^{-1} (*small squares*). If the ellipticals were at rest with respect to the MWB, the slope of their distribution would be zero. The signature of the bulk flow is seen for the large squares as the progression from negative to positive peculiar velocity as the angle swings from the antapex to the apex. The trend does not appear monotonic, but the noise is large and real kinematic features, like the infall of the Local Group toward Virgo [$\cos(\theta) \approx 0$], have not been removed. It also appears that the ellipticals with $V > 6000$ km s^{-1} may, in fact, be at rest with respect to the MWB, but the noise is even larger and the number of points small.

Finally, our maximum likelihood program formally determines an rms "noise" in the Hubble flow of $\sim$ 400 km s^{-1} in one dimension. From Figure 2 it appears that much of this "noise" represents coherent departures over fairly large re-

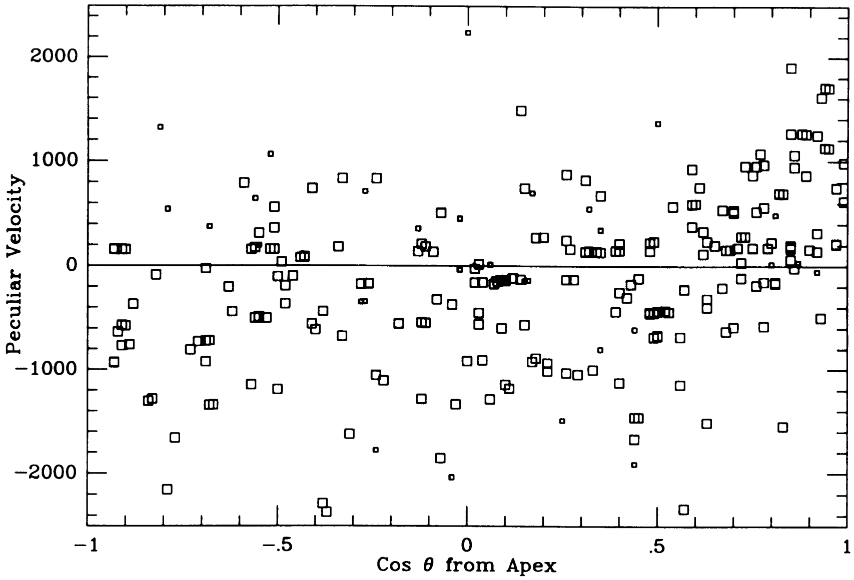

FIG. 3.—The residual velocities from a smooth Hubble flow, again with respect to the MWB, vs. cos(θ), where θ is the angle on the sky from the elliptical galaxy to the apex of the bulk motion. Large squares indicate galaxies for which $V < 6000$ km s^{-1}; small squares indicate $V > 6000$ km s^{-1}. The nonzero slope for the sample indicates that the ellipticals are not, as a whole, at rest with respect to the MWB.

gions of space rather than galaxy-to-galaxy variations. However, a further investigation of the systematic errors in our data will be necessary to confirm that this noise is cosmic in origin. If these large-scale shears are real, and if they describe the motions of spirals as well as ellipticals, then the velocity of 481 km s^{-1} found here for the Local Group is unremarkable—we would have found a similar and often larger peculiar velocity if we inhabited any random region of the sample.

b) Comparison with Other Studies of Local Group Motion

ABMHSC claim to have detected the reflex motion that our sample fails to show. In particular, for spirals in 10 clusters they find a motion of the Local Group of 780 ± 188 km s^{-1} toward (255°,18°). With a vector difference of only 250 km s^{-1}, this result agrees with the microwave dipole vector even better than the expected errors say it should. However, this cluster sample is restricted to the declination range accessible from Arecibo, which, except for the Pisces region, is largely perpendicular to the direction we find for the bulk motion of the ellipticals. Furthermore, their sample is roughly twice as distant as the elliptical sample analyzed here. In view of the large-scale patchiness of peculiar velocities seen in Figure 2, galaxies in this region of space far from the Supergalactic plane could be substantially at rest with respect to the MWB while galaxies *in the plane* participate in a high velocity bulk flow. We tentatively conclude the ABMHSC result does not necessarily contradict the existence of a bulk flow.

Those studies with more complete sky coverage are in much better agreement with the motion found in this study. The data of Rubin *et al.* (1976), when analyzed in the same way as the ellipticals, show a negligible motion of the Local Group of only 238 ± 119 km s^{-1} toward (189° ± 28°, −16° ± 7°) with respect to a sample of 145 spirals with $V < 15000$ km s^{-1}. This corresponds to a bulk flow of 645 km s^{-1} toward (293 ± 12°, 33° ± 25), only 348 km s^{-1} from our result. (Two randomly oriented vectors of ~ 600 km s^{-1} will agree to 350 km s^{-1} only ~ 10% of the time.) A recent retreatment of 45 Rubin *et al.* spirals with infrared magnitudes by Collins, Joseph, and Robertson (1986) reports a similar bulk flow of 970 ± 300 toward (305°,47°). Our reanalysis of the spiral sample by Aaronson *et al.* (1982*b*), in general agreement with their solution, yields a Local Group motion of 273 ± 33 km s^{-1} toward (239° ± 13°, 50° ± 6°), or a bulk motion of 407 ± 43 km s^{-1} toward (281° ± 7°, 11° ± 10°), again only 327 km s^{-1} from the elliptical galaxy solution, and 327 km s^{-1} from the Rubin *et al.* vector.

These discrepancies of ~ 300 km s^{-1} among samples raise the question of the true errors of the determined motions. The errors quoted here are formal errors only and are expected to be too small if velocity residuals are coherent over large patches of space. Our data indicate that the real errors in solar motion solutions are systematic and highly dependent on the volumes and types of galaxies sampled, and as such are likely to be considerably larger than has been thought in the past. Within this model, the bulk motions defined by these three samples are consistent and support the notion that galaxies over a large scale share a common motion with respect to the MWB.

A less clear situation is comparison of our results with those of Hart and Davies (1982). Although they, like us, find a small Local Group velocity of 314 km s^{-1} toward (309°,73°) for their entire sample of 84 spirals, they obtain a quite different value of 436 km s^{-1} toward (264°,45°) when Virgo galaxies are excluded. This result is marginally inconsistent with ours, but their distance estimator has not been checked in a cluster sample, and their analysis method does not properly take account of the Malmquist effect or downweight distant galaxies for their larger errors in linear distances.

IV. CONCLUSION

We report on a systematic variation in apparent velocity residuals of elliptical galaxies over the sky that, when interpreted as a bulk flow, implies a motion of ellipticals over a large volume out to ~ 6000 km s^{-1} of ~ 600 km s^{-1}. A motion consistent with this value is also found for the spiral samples of Aaronson and co-workers and Rubin and co-workers when analyzed similarly. Such a bulk motion over a great volume of space raises severe cosmological questions about the ability of gravity to induce large-scale perturbations on long length scales (Bond 1986; Vittorio, Juszkiewicz, and Davis 1986). These issues are so severe that one is led to reexamine critically the two crucial assumptions on which the large-scale flow interpretation is based: (1) that the MWB defines an absolute cosmic rest frame, and (2) that the intrinsic properties of galaxies are everywhere constant.

The first point is fundamental to cosmology and carries us beyond the bounds of the present *Letter*. The second point, however, is germane. It is indeed worrisome that the elliptical and spiral methods both depend on fundamentally similar power-law relations between velocity width, scale length, and surface brightness. Any regional zero-point variations in these relations could plausibly be correlated between the two galaxy types. On the other hand, we note that both field and cluster ellipticals give completely consistent bulk motion solutions, so any environmental effect, though not excluded, must be rather subtle. On the other hand, the zero point of the Sc I sample of Rubin and co-workers is furthermore of a quite different nature, as it refers to a luminosity function for a class of special objects rather than a zero point of a power law valid over a wide range in luminosities. That the two techniques agree gives substantial support to the interpretation in terms of a bulk flow. However, future independent distance estimates are badly needed, especially those that are completely unrelated to the structural parameters of galaxies.

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