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NEW MEASUREMENTS OF DISTANCES TO SPIRALS IN THE GREAT ATTRACTOR: FURTHER CONFIRMATION OF THE LARGE-SCALE FLOW

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ABSTRACT

Hα rotation curves and CCD photometry have been obtained for 117 Sb–Sc spiral galaxies in the direction of the large-scale streaming flow described in the period 1987–1990 by Dressler *et al.*, Lynden-Bell *et al.*, Dressler and Faber, and Burstein, Faber, and Dressler. By means of the Tully-Fisher relation, these data are used to predict distances to these galaxies and, by comparison with their observed radial velocities, their peculiar motions relative to a smooth Hubble flow. The new data confirm the results of these earlier studies of a coherent flow pattern in a large region called the "great attractor." For the first time, evidence is found for backside infall into the great attractor. Taken as a whole, the data sets for E, S0, and spiral galaxies support the model proposed by Lynden-Bell *et al.* of a large, extended overdensity centered at $\sim 45h^{-1}$ Mpc that perturbs the Hubble flow over a region $\lesssim 100h^{-1}$ Mpc in diameter. Observation of the full "s-wave" in the Hubble flow establishes this scale for the structure, providing a strong constraint for models of structure formation, like those based on hot or cold dark matter.

Subject headings: cosmology — galaxies: distances — galaxies: internal motions — photometry

I. INTRODUCTION

Dressler and Faber (1990, hereafter DF1) report a large-scale coherence in the field of peculiar velocities of elliptical and S0 galaxies in the direction of an extensive concentration of galaxies nicknamed the great attractor (GA). The result agrees well with and extends the work of Dressler *et al.* (1987) and Lynden-Bell *et al.* (1988) (along with other papers in the series, hereafter referred to as 7S). The DF1 data support the simple GA model originally proposed by Lynden-Bell *et al.* (modified by Faber and Burstein 1988) in which a large, approximately spherical overdensity of dimensions $\gtrsim 80h^{-1}$ Mpc influences the peculiar motions of galaxies over a large volume of space and is responsible for a large share of the Local Group's motion of ~ 600 km s^{-1} with respect to the cosmic background radiation (CBR).

The original 7S data covered only the near flank of the GA, leaving unclear the total extent of the flow and the degree of symmetry about the infall center. Nevertheless, even these partial data were a challenge for models of structure formation based on cold or hot dark matter, which appear unable to generate such large, high-amplitude fluctuations in the mass distribution (Bertschinger and Juskiewicz 1988; Groth, Juskiewicz, and Ostriker 1989; Gorski *et al.* 1989, but see also Kaiser 1989). Figure 1*a* shows the DF1 data augmented with other published data for ellipticals and collected into groups where appropriate. These data strengthened the challenge to the models but still failed to probe adequately the backside regions of the GA. In particular, they did not provide convincing evidence for backside infall, a crucial step in establishing the physical reality of the phenomenon and its size and likelihood as a statistical fluctuation in the early universe.

As a follow-on to DF1, we have observed a sample of 117 spiral galaxies in the GA region and determined distances using the Tully-Fisher relation. The purpose of this *Letter* is to present the derived measurements of peculiar velocity for these galaxies and to compare them with the results of the DF1 study of E and S0 galaxies.

II. THE DATA

Work by Tully and Fisher (1977, hereafter TF) pioneered what is now a well-established relation between V_{max} and total luminosity for spirals, providing one of the best estimators of relative galaxy distance. Typically V_{max} is measured from integrated H I 21 cm profiles. Our program relies instead on optical rotation measures using Hα emission, so a demonstration of equivalence is required.

The Supergalactic Plane Redshift Survey (Dressler 1988) includes 1403 galaxies selected from the ESO catalog (Lauberts 1982) in the region $-30° < b < +45°$, $290° < l < 350°$, and larger than 1'.2 in diameter. This survey includes 168 galaxies of types Sb–Sc with inclinations between 55° and 75° based on axial ratios. Late-type spirals were chosen because they provide sufficient Hα emission for a good rotation curve. Our choice to reject types later than Sc was influenced by the observation that their morphology and kinematics tend to be more chaotic. The restricted range in inclination avoided edge-on spirals, for which internal absorption might prevent an accurate measurement of the galaxy's brightness, and systems so face-on that correction of the rotation curve for projection is large.

Spectroscopic observations of 117 of these spirals with $V_{helio} < 7000$ km s^{-1} and regular morphologies were made on eight nights in 1989 April with the du Pont 2.5 m reflector and the Modular Spectrograph with its 85 mm camera. A TI 800 × 800 CCD sampled the spectra at a spatial resolution of 0".86 per pixel and a spectral resolution of 1.52 Å per pixel (69 km s^{-1} per pixel at Hα). A single exposure of 1500 s was taken for each object; in six cases a second exposure was added to increase the signal-to-noise ratio. Generally, the Hα and [N II] lines were seen to extend over the entire optical image of the galaxy as judged from the ESO charts, i.e., to a V isophote ~ 25 mag arcsec^{-2}.

After bias frames were subtracted and flat-field corrections applied, the CCD frames were "rectified" in each dimension so that the final frames were square in wavelength and position. A computer program was used to trace directly from these frames the position of Hα and the pairs of [N II] and [S II] lines. Radial increments of spectra were added until a $S/N > 10$ was achieved. The "velocities" of night sky lines of comparable S/N showed that systematic velocity shifts across the frames were less than 10 km s^{-1} and a typical random error at $S/N = 10$ was less than 10 km s^{-1}.

For the present purpose, maximum rotation velocities were found by making a histogram of ΔV for each recorded value of Hα and [N II] λ6583 to construct a pseudo–line profile analogous to the H I technique. For each galaxy, both a number-weighted and intensity-weighted profile was constructed by summing in bins the Hα and [N II] detections. The width at 20% intensity was calculated separately for the number-weighted and intensity-weighted profiles and a simple average was adopted as V_{max}. A comparison with 23 published values of V_{max} determined with H I 21 cm profiles shows no significant zero-point shift and only moderate scatter. If two very discrepant points are excluded and it is assumed that errors are equally shared by H I and Hα measurements, the implied measuring error is ~ 7%. This result is in good agreement with a similar comparison by Courteau and Faber (1989). In a future paper we will use larger samples to compare methods of extracting the value of V_{max} from Hα data. Although we prefer to use an objective measure for the present discussion, we note that the results given here are unchanged when V_{max} values read directly from the rotation curves are used.

Photometry was obtained in the Gunn r passband with a TI 800 × 800 CCD at the Swope 1.0 m telescope on five photometric nights 1989 April 3–7. The chip was read out in a rebinned mode providing 400 × 400 pixels at 0".86 per pixel. After standard reduction procedures, these frames were used to measure the ellipticity and position angle of each galaxy image and a Gunn r magnitude down to an isophote $\lesssim 1$% of sky, which we will refer to as the "total" magnitude. The total count over sky, measured within concentric ellipses, almost always converged to a well-defined value. Repeat measurements taken on different nights of six galaxies showed internal consistency at the level of 0.03 mag rms. Including systematic errors, we estimate that the final r magnitudes are better than 5% in all cases. Magnitudes were corrected for cosmological dimming and the K-correction, and for Galactic extinction in the r band (following Schneider, Gunn, and Hoessel 1983) by multiplying A_B extinctions from Burstein and Heiles (1984) by 0.56.

To calculate distances from our measurements of r magnitude and rotation velocity, we have transformed to the TF relation of Pierce and Tully (1989) for spirals in the Ursa Major and Virgo clusters. The magnitudes were transformed to Kron-Cousins R by $r = R + 0.36$ (Schild 1983, 1984). Possible systematic errors were minimized by observing standard stars with colors close to those of the sample galaxies. Corrections were made for internal absorption following Tully and Fouqué (1985) to yield "face-on" magnitudes. Galaxy inclinations were calculated from major-to-minor axis ratios following Bothun *et al.* (1985) and rotation velocities were corrected for turbulent broadening following Tully and Fouqué.

Parameters derived from photometry and spectroscopy were assigned quality codes based on, among other factors, whether the rotation curve was observed to reach a maximum (~ 60% of the sample) or whether the position angle derived from photometry agreed well with the ESO catalog position angle used for the spectroscopy. Because no significant correlations with the results described below were found, all of the data are used here. The detailed data, including a detailed description of analysis procedures and these quality tests, will be presented elsewhere.

III. CONFIRMATION OF A LARGE-SCALE COHERENT FLOW

The resultant Hubble diagram for 117 spirals is shown in Figure 1*b*. Observed velocities have been corrected to the CBR frame but not for internal motions in the cases of galaxy groups. Based on the prescription of Lynden-Bell *et al.* and an assumed error in the TF relation of 0.35 mag (Pierce and Tully 1988), the predicted distances have been multiplied by 11% to correct for a homogeneous Malmquist-like bias.

Figure 1*b* agrees well with Figure 1*a*. Its scatter appears consistent with errors of ± 17% for the TF relation, somewhat better than the accuracy of the D_n-σ relation for E and S0 galaxies (see, e.g., Burstein 1989). A large outflow velocity of $\lesssim 1000$ km s^{-1} for $D < 30$ Mpc is again seen, but this time the result is for spirals, mostly field objects outside of groups, and is based on a different technique of distance prediction whose physical basis, as pointed out by Gunn (1989), is likely to be quite different from the D_n-σ relation. As in Figure 1*a*, the peculiar velocity decreases for $D > 30h^{-1}$ Mpc, crossing the Hubble line (no motion with respect to the CBR) at $D \sim 45h^{-1}$ Mpc, which is close to the earlier estimates of the GA center (4200 km s^{-1}; Faber and Burstein 1988) and in good agreement with the peak in the galaxy distribution as measured by Dressler (1988).

The new data significantly increase the number of points *beyond* the GA center ($V_{CBR} > 5600$ km s^{-1}), adding 17 higher accuracy points to the 12 of the E/S0 sample. The new points confirm what was only hinted at previously, namely, a negative deviation from the uniform Hubble line on the far side of the GA that symmetrically matches the positive deviation seen on the near-side. This is an "s-wave" indicative of symmetric infall. We show the combined E, S0, and spiral data in Figure 2*a*. To guide the eye, we also show the spherically symmetric GA model of Faber and Burstein (at a radius of 15° from the GA center) as the dotted line in Figure 2*a*. The pronounced s-wave character of this highly symmetric model is apparent. If the model were refitted to the new E, S0, and spiral data, they would probably push the infall center to a slightly greater distance by about 500 km s^{-1} (note that the apparent zero crossing of 4000 km s^{-1} in Fig. 2*a* is slightly smaller than the assumed distance of 4200 km s^{-1} for the infall center due to the off-center line of sight). Overall, however, the agreement between data and model is quite good, especially when one notes that there were *no* galaxies in the original data on the far side of the GA and, in fact, the major weight of the data lay between 20 and $60h^{-1}$ Mpc from the GA center!

Although the GA model shown in Figure 2*a* is not a fit to the data and is intended only for comparison purposes, the undoubtedly oversimplified description of the motions in the GA region turns out to be a surprisingly good description of

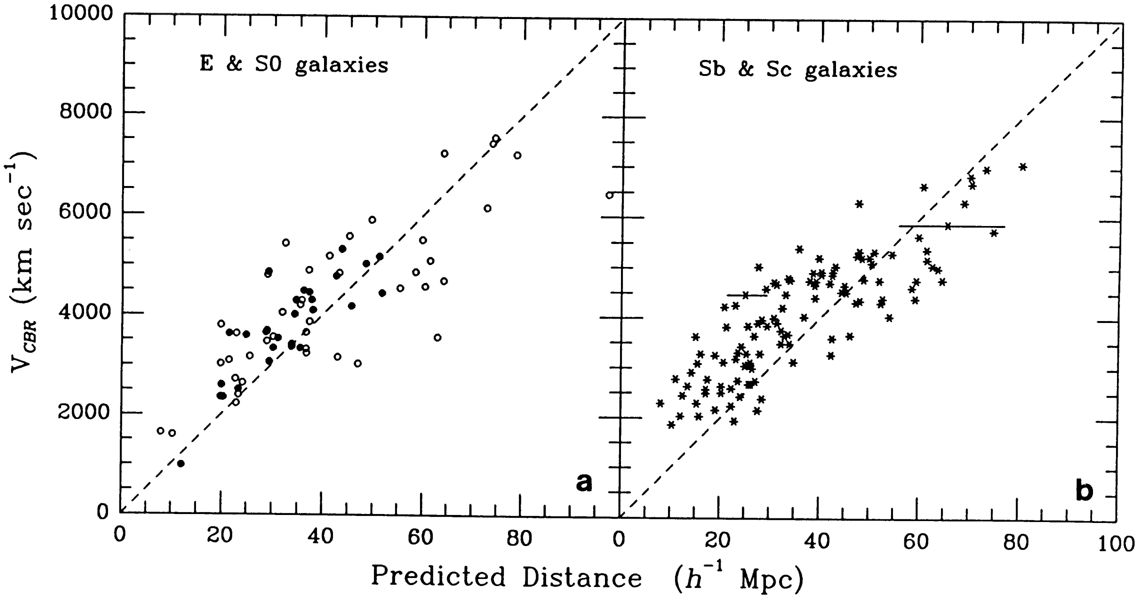

FIG. 1.—(*a*) The Hubble diagram for 156 E and S0 galaxies in the GA region. The data are those of DF1 averaged with and added to published values collected by BFD. Open circles refer to 46 single galaxies; closed circles represent 110 galaxies collected into 27 groups. An explicit correction has been made for the Malmquist-like bias: following Lynden-Bell *et al.*, each distance prediction has been increased by $17/N$%, where N is the number of members in the group. The data confirm the original finding of Lynden-Bell *et al.* of a large outflow out to $30h^{-1}$ Mpc but additionally show a further decline, crossing the Hubble line at $\sim 45h^{-1}$ Mpc, the predicted center of the GA. (*b*) The Hubble diagram for the new data for 117 spirals in the GA region. The new data are in good agreement with the E, S0 data of (*a*) confirming the large outflow for $D < 30h^{-1}$ Mpc and the decline of peculiar motions leading to a Hubble line crossing at $\sim 45h^{-1}$ Mpc. The new data also show, with much less scatter than the data of (*a*), evidence for backside infall into the great attractor. Error bars corresponding to ± 17% uncertainty in distance are shown for two typical galaxies.

the new data. In comparison with the smooth Hubble flow model represented by the unit slope line of Figure 2*a*, the spiral data have $\chi^2/\nu = 7.4$ (assuming 17% distance errors as the only source of scatter), but the comparison with the GA model pictured in Figure 2*a* gives $\chi^2/\nu = 1.6$, a dramatic improvement. Combining both the spiral and E, S0 data, we find that the Kolmogorov-Smirnov test rejects any straight-line fit (a Hubble line of arbitrary slope) as having a probability less than 10^{-4}. Without modification, the Faber-Burstein GA model is an acceptable fit at the 21% confidence level.

The *absolute* peculiar motion of any point in Figures 1*a*, 1*b*, or 2*a*, and also the exact location of the infall center, are uncertain and are affected by the assumed corrections for Malmquist-like bias, as we have noted in previous papers (DF1; Burstein, Faber, and Dressler 1990, hereafter BFD). For example, undoing the homogeneous Malmquist correction in Figure 1*b* would shift all points horizontally to the left by 11% in *D*. We stress, however, that the basic s-wave morphology of Figure 2*a* is immune to such effects, as the simple thought experiment of mentally moving these points (a stretching of the *x*-axis) will show.

As discussed in DF1, apparent infall can appear around high-density clumps due to scattering in the *R* coordinate by errors (inhomogeneous Malmquist-like bias). However, such errors can produce only a *horizontal strip* in Figure 2*a*, not a true s-wave, for which the perturbation persists well above and below the central band. For Figure 2*a* we can see that this is truly the case for $V_{CBR} < 4000$ km s^{-1} and $V_{CBR} > 5500$ km s^{-1}. Moreover, the width of the horizontal stripe between these limits is itself 75% broader for the spiral sample than expected from errors alone, indicating that true motions have been detected in this region as well.

Another way to see the insensitivity of the s-wave result to the correction for Malmquist-like bias is to bin the original raw data horizontally in bins of ΔV_{CBR} rather than in ΔD. The medians in such bins are completely independent of *any* Malmquist-like correction yet still show the s-wave shape. The s-wave is also insensitive to any bulk motion of the entire GA region that might be caused, for example, by a yet more distant mass concentration (Scaramella *et al.* 1989).

In summary, we appear to be seeing a large region of space in which the Hubble law has a slope distinctly less than unity, i.e., a region of compression. This, we believe, is the expected retardation in the Hubble flow caused by the GA overdensity. The reality of this detection in the context of uncertainties like the Malmquist-like bias is highlighted by comparing Figure 2*a* with Figure 2*b*, the Hubble diagram for elliptical and spiral galaxies over the *rest* of the sky. The s-wave seen in the GA region is in marked contrast to the near-featureless Hubble law seen in Figure 2*b*, despite identical treatment of the data.

IV. DISCUSSION

Observation of the symmetric s-wave perturbation in the Hubble diagram, as predicted by the GA model, offers strong confirmation of the conclusion by Lynden-Bell *et al.* that a huge mass overdensity is responsible for a large-scale coherence in the field of peculiar velocities including, in particular, the greater part of the Local Group's motion. The agreement of prediction and data confirm that the original result was not an artifact of the 7S data, and the new spiral sample shows that the result is not technique-dependent. Incorrect assessment of Malmquist-like bias or Galactic reddening cannot produce the s-wave seen in the Hubble diagram. The suggestion by Silk (1989) that the original 7S result is due to a variation in the zero point of the D_n-σ relation becomes highly contrived since

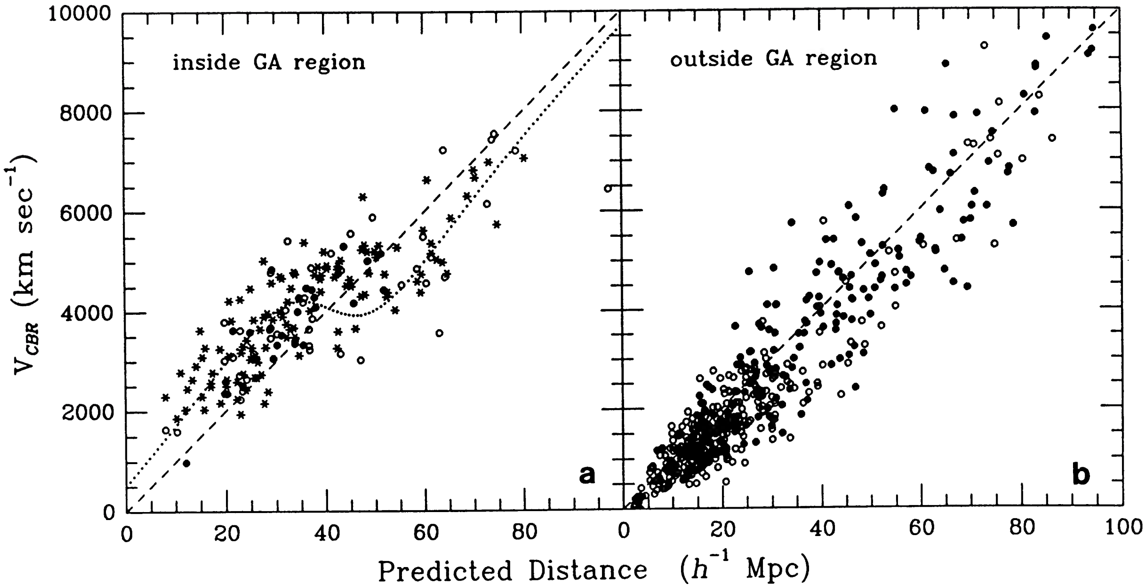

FIG. 2.—(*a*) The combined data sets of Fig. 1*a* for E and S0 galaxies and Fig. 1*b* for spiral galaxies. Symbols are the same as in Figs. 1*a* and 1*b*. The s-curve, Faber and Burstein's GA model (not a fit to the data), is in good agreement with the data, especially considering that the weight of the original data on which this prediction was based came from galaxies on only one side of the GA at distances of 20–60 Mpc from the GA center. (*b*) The Hubble diagram for elliptical and spiral galaxies outside the GA region, i.e., over the rest of the sky. Despite identical treatment of the data, the contrast between this Hubble diagram and the s-wave seen in (*a*) is striking.

the zero point must be double-valued (different at the same density) and vary in such a way as to mimic closely the very velocity field that is expected from the observed galaxy distribution.

Lynden-Bell *et al.* and Faber and Burstein (1988) stressed that the influence of the GA appears to extend well beyond the Local Group, being detectable out to some $20h^{-1}$ Mpc beyond our location. (This can be seen clearly in Fig. 2*b* as the tendency of points with $V \lesssim 2000$ km s^{-1} to lie below the Hubble line.) Adding the results of Figure 2*a*, we can now trace the influence of the GA over a total volume that approaches some $100h^{-1}$ Mpc in diameter, and the end of the s-wave perturbation is not yet definitely in sight. Full validation of the original, spherically symmetric model over its entire volume has not yet been achieved (observations out to $100h^{-1}$ Mpc would evidently be required!), but the new data certainly move the picture in that direction. As such, they further strengthen the already severe challenge to models of structure formation based on hot or cold dark matter.

The GA region with its area of ~ 1 sr now contains ~ 300 galaxies with measured peculiar motions, most within $60h^{-1}$ Mpc. When coverage of comparable density is available for the other 9 sr (excluding the ~ 2 sr around the Galactic plane), it should be possible to make definitive tests of the primordial power spectrum on large mass scales.

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