11-10-1998

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K. R. Müller
Dartmouth College

W. Freudling
European Southern Observatory

R. Watkins
Dartmouth College

G. Wegner
Dartmouth College

The Astrophysical Journal, 507:L105–L108, 1998 November 10

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K. R. Müller
Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755-3528;
European Southern Observatory, Garching bei München, Germany; kmueller@eso.org
W. Freudling
European Southern Observatory and Space Telescope–European Coordinating Facility,
Karl Schwarzschild Strasse 2, D-85748 Garching bei München, Germany
and
R. Watkins[1] and G. Wegner
Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755-3528
Received 1997 November 12; accepted 1998 September 8; published 1998 September 24

ABSTRACT

In order to investigate the reality of large-scale streaming motion on scales of up to 150 Mpc, we have studied the peculiar motions of ~200 early-type galaxies in three directions of the South Equatorial Strip at distances out to ~20,000 km s^{-1}. The new Automatic Plate Measuring Facility South Equatorial Strip Catalog ($-17\fdg5 < \delta < +2\fdg5$) was used to select the sample of field galaxies in three directions: (1) 15^h10^m–16^h10^m; (2) 20^h30^m–21^h50^m; (3) 00^h10^m–01^h30^m. New *R*-band CCD photometry and spectroscopic data for the galaxies are used. The fundamental plane distance-indicator relation is calibrated with Coma cluster data, and a correction for inhomogeneous Malmquist bias is applied to the distance estimates. A linear bulk flow model is fitted to the peculiar velocities in the sample regions, and the results do not reflect the bulk flow observed by Lauer and Postman (LP). Accounting for the difference in geometry between the galaxy distribution in the three regions and the LP clusters confirms the disagreement; assuming a low-density CDM power spectrum, we find that the observed bulk flow of the galaxies in our sample excludes the LP bulk flow at the 99.8% confidence level.

Subject headings: cosmology: observations — galaxies: distances and redshifts — galaxies: elliptical and lenticular, cD — galaxies: fundamental parameters — large-scale structure of universe

1. INTRODUCTION

There is strong observational evidence for the existence of large-scale flows in the local universe, induced by gravity (see Strauss & Willick 1995). The dipole anisotropy of the cosmic microwave background (CMB) radiation provides a natural velocity reference frame for the analysis of galaxy motions. The dipole anisotropy, determined from *COBE*, implies that the Local Group (LG) moves with respect to the CMB rest frame at 627 ± 22 km s^{-1} toward $l = 276^\circ \pm 3^\circ$, $b = +30^\circ \pm 3^\circ$ (Kogut et al. 1993). If this has a kinematic origin, then sufficiently far away the peculiar velocities should converge to the CMB frame. Indeed, the observed LG motion relative to the rest frame defined by galaxies within 6000 km s^{-1} points toward the Hydra Centaurus–Great Attractor region, which is within ~40° of the CMB dipole direction.

The observed LG motion toward the Hydra Centaurus–Great Attractor region points within ~40° of the CMB dipole direction. However, until recently only the region within about 6000 km s^{-1} had been well sampled.

Until now, the only studies that have reported measurements of the velocity field as far out as 15,000 km s^{-1} are those of Lauer & Postman (1994; hereafter LP), using the brightest cluster galaxies as distance estimators, and Riess, Press, & Kirschner (1995), using Type Ia supernovae. LP checked the convergence of the LG dipole motion to the CMB dipole, with a surprising result: a strong signature of a very large-scale bulk flow was seen with an amplitude of 689 ± 178 km s^{-1} in the direction $l = 343^\circ$, $b = +52^\circ$. The LP study implies that the local rest frame fails to converge to the CMB frame, even in regions with radii ~15,000 km s^{-1}. A bulk flow with the statistical significance of this result rules out a whole series of cosmological models at the greater than 95% confidence level (Feldman & Watkins 1994; Strauss et al. 1995); the LP result is in disagreement with all viable models at present.

The LP sample extended to 15,000 km s^{-1}, with an effective depth of ~8000 km s^{-1}. Therefore, the logical next step was to compare the LP result with peculiar velocities as found from applying the Tully-Fisher and fundamental plane methods to galaxies extending further out than any previous peculiar velocity studies. Neither field nor cluster spiral galaxies within 8000 km s^{-1} show evidence of such a motion (Giovanelli et al. 1996, 1998a, 1998b).

In this work, we analyze new and independent measurements of the peculiar velocity field of elliptical field galaxies at a depth similar to that of LP. Most of the galaxies are within 10,000 km s^{-1}, with some as far out as 20,000 km s^{-1}. A sample of 179 early-type galaxies in three selected regions was used to investigate peculiar motions. The first sample region is about 20° from the direction of the LP bulk flow. The second region is almost perpendicular to the first direction, and the third is in a direction on the opposite side of the sky from the first, close to the direction of the Perseus-Pisces region and the south Galactic pole.

2. SAMPLE SELECTION AND OBSERVATIONS

Galaxies were selected from the new Automatic Plate Measuring Facility (APM) South Equatorial Strip Catalog, made available by S. Raychaudhury prior to publication (Raychaudhury et al. 1998). The South Equatorial Strip, which lies be-

[1] Current address: Department of Physics, Reed College, Portland, OR 97202.

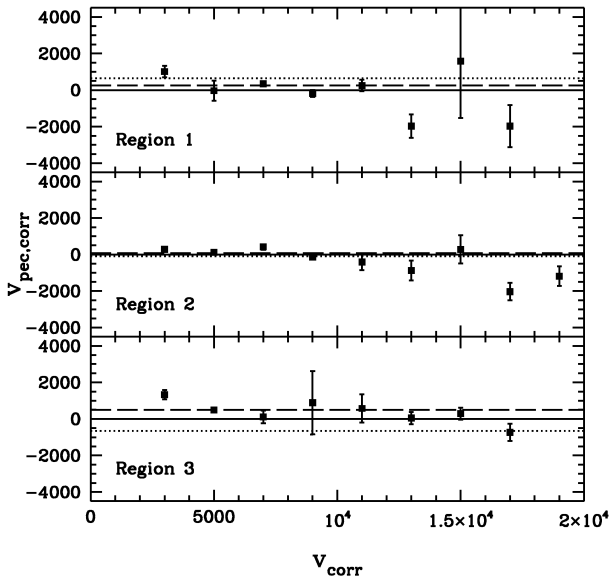

FIG. 1.—Averaged peculiar velocities (in the CMB frame) of early-type galaxies in region 1, *top*, region 2, *middle*, and region 3, *bottom*, after the correction for Malmquist bias. The bin size is 2000 km s^{-1}. The horizontal dashed line shows the weighted bulk flow fit to the data, and the dotted line indicates the prediction corresponding to the bulk flow result of Lauer & Postman (1994).

tween declination $-17^\circ.5$ and $+2^\circ.5$, is an uncharted region in the velocity field because previously no good galaxy catalog existed for this region, and consequently the peculiar motions of galaxies in this strip had never been mapped.

The present sample has well-defined uniform selection criteria. Starting with the APM South Equatorial Strip Catalog with a magnitude limit of $b_j = 17.0$ mag, candidate galaxies in the three regions were examined on the POSS plates and later on CCD images to verify the morphological type. This resulted in a sample of E/S0 galaxies with a magnitude cut that is virtually complete to Kron-Cousins $R = 14.0$. The completeness drops for fainter magnitudes; galaxies down to $R = 15.05$ are included.

Spectra and R-band CCD images of galaxies in the three sample regions were collected during a series of 10 observing runs between 1993 June and 1995 September. Observations were made at the 1.3 m McGraw-Hill telescope and the 2.4 m Hiltner telescope of the Michigan-Dartmouth-MIT Observatory and also at the 4.4 m Multiple Mirror Telescope on Mount Hopkins, Arizona.

The galaxy images were processed and photometric parameters were derived with the procedures and programs described by Freudling, Martel, & Haynes (1991) and Saglia et al. (1997a, 1997b). Azimuthally averaged surface brightness profiles were fitted as the sum of bulge and disk components, and a correction for seeing was applied (see Saglia et al. 1997a). The total magnitude m_{tot} and the half-light parameters $r_{1/2}$ (half-light radius), $\mu_{1/2}$ (mean surface brightness at $r_{1/2}$), and $\langle\mu\rangle_{1/2}$ (mean surface brightness within $r_{1/2}$) were derived.

Spectra were extracted from the spectroscopic observations using the procedures outlined in Wegner et al. (1998). The median signal-to-noise ratio (S/N) per angstrom is 23. The instrumental resolution (FWHM) is ~4 Å, and the spectrograph resolution (dispersion) is ~100 km s^{-1}. Fourier cross-correlation analysis was used to determine values of redshift and velocity dispersion σ from logarithmically rebinned spectra. Velocity dispersions were corrected for aperture effects. The final data as well as full details of the observations, data reduction, and analysis are given in Müller (1997) and Müller, Freudling, & Wegner (1998).

3. PECULIAR VELOCITIES

The fundamental plane (FP) distance-indicator relation was calibrated with data from 40 galaxies in the Coma cluster. Care was taken to use identical instruments and data reduction procedures. Objects were chosen to be E/S0 using earlier studies (e.g., Jørgensen, Franx, & Kjærgaard 1993; Lucey, Bower, & Ellis 1991) and lie mostly within about $0^\circ.5$ of the point midway between NGC 4889 and NGC 4874. The coefficients were fitted by minimizing orthogonal residuals from the plane (as in Jørgensen, Franx, & Kjærgaard 1996). Monte Carlo simulations were used to determine the bias in the coefficients, and a correction for incompleteness was made following a similar procedure to Giovanelli et al. (1997).

The FP for Coma, determined from these data, is best described by the relation

$$\log r_{1/2} = 1.247 \log \sigma + 0.348 \langle\mu\rangle_{1/2} - 8.815,$$

with a measured scatter equivalent to a distance uncertainty of 19.4%. Coma is used as the reference cluster for the calibration of the distance-indicator relation. Coma has a radial velocity of $\simeq$7200 km s^{-1} in the CMB reference frame. The zero point for the FP relation should be determined from a sample with no radial peculiar motion; in the case of Coma, the peculiar velocity is consistent with zero in the CMB frame, as shown by several authors (Faber et al. 1989; Lucey et al. 1991; Jørgensen et al. 1996; Giovanelli et al. 1997; Scodeggio, Giovanelli, & Haynes 1997). The uncertainty in the adopted value for the peculiar velocity of Coma can conservatively be estimated to be about ± 250 km s^{-1}, but the actual choice of the velocity zero point has little effect on the results of the current analysis, as explained below.

A cosmological correction was made to transform the derived distances from diameter distances into true distances. The sample was corrected for inhomogeneous Malmquist bias, which corrects for the effect of fluctuations in the galaxy density along the line of sight (e.g., Willick 1991; Freudling et al. 1995). These density fluctuations were estimated from the new *IRAS* 0.6 Jy Point-Source Catalog redshift survey (Saunders et al. 1994, 1998). This correction changes the bulk flow component constrained by our data (see below) by approximately 30 km s^{-1}.

The final sample contained only the galaxies with photometric and spectroscopic data, both of good quality: 50 galaxies in region 1, 77 galaxies in region 2, and 52 galaxies in region 3. The mean radial peculiar velocities have been calculated in bins of inferred distance of 2000 km s^{-1}. The results are shown in Figure 1. In these plots, all galaxies in a bin were replaced with one point at the distance of the center of the bin with the average value of the peculiar velocity in that bin.

4. ANALYSIS

As a first approach to analyzing the peculiar motions, a linear bulk flow model was fitted to the data in each sample region in order to measure the radial component of the bulk motion. Each data point was assigned a standard deviation according to its distance error, and a weighted average peculiar velocity $\bar{u}$ was determined from the galaxies in each region. The estimated error $\sigma_{\bar{u}}$ of the weighted mean was also found. All available data points were included in the fit; no binning was used.

The results of the weighted fits were $(\bar{u} \pm \sigma_{\bar{u}})$ $(+225 \pm 199)$ km s^{-1} in region 1, $(+145 \pm 162)$ km s^{-1} in region 2, and $(+468 \pm 197)$ km s^{-1} in region 3. The numbers of galaxies with inferred distances $v_{\rm corr} > 10{,}000$ km s^{-1} are small, and also the distance errors are larger at those distances. Therefore, the most distant galaxies do not have a big effect on the weighted averages. The few nearby galaxies, with small distance errors, have a large effect on the weighted fits. If only the galaxies between 5000 and 15,000 km s^{-1} are used, the fits give the following results: $(+146 \pm 243)$ km s^{-1} in region 1, (-9 ± 228) km s^{-1} in region 2, and $(+340 \pm 307)$ km s^{-1} in region 3. This means that the resulting mean velocities are not statistically significant and the radial peculiar velocities are indistinguishable from zero. At first glance, then, the results of this study appear to be inconsistent with the hypothesis of a large bulk motion as suggested by the LP results.

However, a simple direct comparison between the results for the mean velocities in the sample regions and the flows expected according to the result of LP can be misleading. This is because both the mean velocities and the LP bulk flow contain contributions from the incomplete cancellation of velocity modes whose wavelengths are much smaller than the survey scale (Watkins & Feldman 1995). Since the surveys have different geometries, these contributions will be different for the two surveys. It is therefore possible that contributions from smaller scale velocity modes could be the cause of the observed disagreement; two studies of the same universe and the same velocity field could produce different results for this reason.

We tested this possibility by calculating the covariance matrix for the *difference* of the bulk flow of the sample taken as a whole (the galaxies in all three sample regions) $\boldsymbol{U}_E$ and the bulk flow observed by LP $\boldsymbol{U}_{LP}$,

$$R_{ij} = \langle (\boldsymbol{U}_E - \boldsymbol{U}_{LP})_i (\boldsymbol{U}_E - \boldsymbol{U}_{LP})_j \rangle .$$

The covariance matrix takes into account contributions to the measured bulk flow from both actual galaxy velocities and measurement errors; it also properly accounts for correlations between different components of the bulk flow. We calculated R_{ij} using the method outlined in Watkins & Feldman (1995). We use the maximum likelihood estimator for the bulk flow as given in Kaiser (1988):

$$(\boldsymbol{U})_i = A_{ij}^{-1} \sum_q \frac{\hat{r}_{q,j}\, v_q}{(\sigma_q^2 + \sigma_*^2)} ,$$

where

$$A_{i,j} = \sum_q \frac{\hat{r}_{q,i}\, \hat{r}_{q,j}}{(\sigma_q^2 + \sigma_*^2)} .$$

Here galaxies are labeled by an index q and have positions r_q and line-of-sight peculiar velocities v_q with measurement uncertainties σ_q. We assume σ_q to be 19% of a galaxy's distance for individual galaxies in our sample; for the LP clusters we calculate individual distance errors based on the quoted values of α_C (see LP). An additional uncertainty, $\sigma_* = 350$ km s^{-1}, is included to account for deviations from the linear flow field owing to nonlinear effects. In practice, the specific value used for σ_* changes the results of our analysis very little; most of the objects that we are considering are at large enough distance that the errors in their velocities are much larger than this additional term.

To calculate the covariance matrix R_{ij}, one must assume a model for the power spectrum $P(k)$. Most popular models for $P(k)$ are inconsistent with the LP result (Feldman & Watkins 1994; Strauss et al. 1995). However, since a large-scale flow should contribute equally to the bulk flows measured by each survey, the difference $\boldsymbol{U}_E - \boldsymbol{U}_{LP}$ should be almost entirely due to errors in the velocity measurements and to velocity modes on scales that are smaller than that of the surveys. On these scales, several types of measurements have shown consistency with a low-density cold dark matter (LDCDM) ($\Omega_m = 0.3$, $\Gamma = 0.21$) model normalized to *COBE* (see, e.g., Strauss & Willick 1995). We used this model for our representative $P(k)$; we also performed the analysis for a standard ($\Omega = 1$, $\Gamma = 0.5$) CDM (SCDM) model for comparison, even though this model has been shown to be in disagreement with several observations.

Using the model for $P(k)$, we calculated the covariance matrix and the χ^2 for the measured difference between the bulk flows:

$$\chi^2 = \sum_{ij} (\boldsymbol{U}_E - \boldsymbol{U}_{LP})_i\, R_{ij}^{-1} (\boldsymbol{U}_E - \boldsymbol{U}_{LP})_j .$$

This χ^2 can in turn be used to determine the probability that the observed difference in bulk flow could have arisen in a universe with the assumed power spectrum.

Since the three survey regions lie roughly in the plane of the celestial equator, we are in practice restricted to measuring only two components of the bulk flow. By diagonalizing the error matrix for the survey, we determined that the two components of the bulk flow that can be measured with reasonable accuracy lie in a plane perpendicular to the direction $l = 114°$, $b = 23°$ (about 10° from the north pole of the celestial sphere). In this plane, we find the bulk flow for the galaxies in the three regions to lie in the direction $l = 49°$, $b = -45°$ with magnitude 312 km s^{-1} (measured in the CMB frame). Each of the two components of this flow have an uncertainty of approximately 180 km s^{-1}, so our result is consistent with the frame defined by our galaxy sample being at rest.

This flow is quite consistent with expectations calculated assuming the LDCDM model. The component of the LP bulk flow in this plane lies in the direction $l = 349°$, $b = 54°$ with magnitude 822 km s^{-1}. (Note that the magnitude of the LP bulk flow given here is somewhat larger than the 689 km s^{-1} reported by LP; their smaller value has been corrected for "error bias," whereas we are interested in the uncorrected maximum likelihood value of the bulk flow.) The two observed bulk flow vectors are separated by an angle of 110°. The component of the difference vector $\boldsymbol{U}_E - \boldsymbol{U}_{LP}$ in the plane of interest has a magnitude of 982 km s^{-1}.

For the LDCDM model, the two measured components of $\boldsymbol{U}_E - \boldsymbol{U}_{LP}$ give $\chi^2 = 12.7$ for 2 degrees of freedom. Therefore, the possibility of velocity errors and small-scale velocity modes in the LDCDM model producing the observed difference $\boldsymbol{U}_E - \boldsymbol{U}_{LP}$ can be ruled out at the 99.8% confidence level. For comparison, the SCDM model gives $\chi^2 = 8.5$, which corresponds to a 98.6% confidence level. The lower χ^2 for the SCDM model results from two factors. First, the SCDM model has relatively more of its power on smaller scales, where the modes are more likely to contribute to the disagreement between the two observed bulk flows. Second, since the velocity power spectrum is proportional to $\Omega_m^{0.6}\sigma_8$, a larger Ω_m will generally lead to all velocity modes having higher amplitude. However, even in the SCDM model, it is unlikely that the observed difference $\boldsymbol{U}_E - \boldsymbol{U}_{LP}$ could arise from small-scale velocity modes.

The question arises as to how a different choice of the velocity zero point of our fundamental plane, or equivalently, an assumption of a nonzero peculiar velocity for the Coma cluster would effect these results. Changing the velocity zero point has the effect of adding or subtracting a percentage of each galaxy's redshift to its peculiar velocity. This in turn changes the bulk flow of the sample by a vector whose magnitude is proportional to the assumed value of Coma's peculiar velocity $V_{\rm Coma}$. The constant of proportionality and the direction of this vector depend on the geometry of the sample and its assumed velocity errors; for example, we would expect the change in bulk flow to be small for a sample whose galaxies are distributed isotropically. For our sample, the addition to the bulk flow in the plane of interest has a magnitude of $1.18V_{\rm Coma}$ and points in the direction $l = 34°$, $b = -22°$, nearly perpendicular to the LP bulk flow. This can be understood by noting that the contributions to this vector from regions 1 and 3, which lie roughly parallel to the LP bulk flow and in opposite directions, approximately cancel, so that the dominant contribution is from region 2, which is roughly perpendicular to the LP bulk flow. The fact that the change in the bulk flow of the sample has only a small component in the direction of the LP bulk flow implies that changing the velocity zero point is unlikely to significantly improve their agreement.

To study the effect of changing the velocity zero point on our results, we have calculated the confidence level at which our sample rules out the LP bulk flow as a function of $V_{\rm Coma}$. We found that the confidence level was minimum for $V_{\rm Coma} = -430$ km s^{-1}, corresponding to 99.6% and 97.9% for the LDCDM and SCDM models, respectively. It should be noted that the assumption of a positive value for $V_{\rm Coma}$, as found by LP, results in the LP bulk flow being ruled out at higher confidence than for the $V_{\rm Coma} = 0$ case given above.

5. DISCUSSION

The magnitude of the bulk flow observed by LP presents a serious challenge to models of structure formation. However, if such a flow actually exists, its large amplitude should make it readily evident in any peculiar velocity survey that probes similar scales. By studying a sample of galaxies covering three regions in a plane roughly parallel to the LP bulk flow, we have measured two components of the bulk flow on similar scales to the LP survey. Our sample galaxies show no evidence for a large bulk flow. Instead, our results indicate a component of the bulk flow in the sample plane that is consistent with expectations for a LDCDM power spectrum and that lies 110° away from the LP flow.

A further analysis shows that the difference between the observed bulk flows cannot be accounted for by the effects of measurement errors, incomplete cancellation of smaller scale velocity modes, or by the choice of the zero point in the distance relation. Indeed, if we assume an LDCDM model for the power spectrum, we find that for our results, the LP bulk flow can be excluded at the 99.8% level. Since we consider the difference of the bulk flows of two surveys of comparable scale, invoking extra power on scales equal to or larger than the surveys will not alter this result. The observed bulk flows could be reconciled if we have vastly underestimated the power on scales smaller than the surveys, but this would be in conflict with other observations.

G. W. wishes to acknowledge partial support from the Alexander von Humboldt Foundation during a visit to the Ruhr-Universität Bochum and also from NSF grant AST93-47714. K. M. acknowledges financial support from a Dartmouth Fellowship and an ESO Research Studentship and is grateful to Roberto Saglia for the use of his programs for profile fitting and seeing correction.

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