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REDSHIFT-DISTANCE SURVEY OF EARLY-TYPE GALAXIES: DIPOLE OF THE VELOCITY FIELD

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ABSTRACT

We use the recently completed redshift-distance survey of nearby early-type galaxies (ENEAR) to measure the dipole component of the peculiar velocity field to a depth of $cz \sim 6000$ km s^{-1}. The sample consists of 1145 galaxies brighter than $m_B = 14.5$ and with $cz \leq 7000$ km s^{-1}, uniformly distributed over the whole sky, and 129 fainter cluster galaxies within the same volume. Most of the D_n-σ distances were obtained from new spectroscopic and photometric observations conducted by this project, ensuring the homogeneity of the data over the whole sky. These 1274 galaxies are objectively assigned to 696 objects—282 groups/clusters and 414 isolated galaxies. We find that within a volume of radius ∼6000 km s^{-1}, the best-fitting bulk flow has an amplitude of $|\boldsymbol{v}_b| = 220 \pm 60 \pm 50$ km s^{-1} in the cosmic microwave background rest frame pointing toward $l = 304° \pm 16°$, $b = 25° \pm 11°$. The error in the amplitude includes statistical, sampling, and possible systematic errors. This solution is in excellent agreement with that obtained by the SFI (*I*-band field spiral) Tully-Fisher survey. Our results suggest that most of the motion of the Local Group is due to fluctuations within 6000 km s^{-1}, in contrast to recent claims of large-amplitude bulk motions on larger scales.

Subject headings: cosmology: observations — galaxies: distances and redshifts — large-scale structure of universe

1. INTRODUCTION

Within the gravitational instability framework for the growth of cosmic structures, the peculiar velocity field of galaxies and clusters is a direct probe of density fluctuations of the underlying mass distribution. Among several possible statistics that can be used, measurements of the bulk motion amplitude on different scales are the simplest and provide, at least in principle, constraints on the power spectrum of mass fluctuations. This has motivated several attempts to measure the dipole component of the local peculiar velocity field and to determine the volume within which the streaming motion vanishes in the rest frame defined by the cosmic microwave background (CMB) radiation. At this distance, the distribution of matter within the encompassing volume should explain the ∼600 km s^{-1} motion of the Local Group relative to the CMB rest frame.

Observational searches of large-scale flows date back to the pioneering work of Rubin et al. (1976). Since then, redshift-distance surveys have greatly expanded, the data quality has improved significantly, and several recent attempts have been made using different techniques and samples (e.g., Strauss & Willick 1995). Despite these efforts, the results remain to a large extent controversial. The original claim that the flow field out to $cz \sim 4000$ km s^{-1} is characterized by a coherent, large-amplitude ∼500 km s^{-1} streaming motion (Dressler et al. 1987) relative to the CMB was revised to incorporate a large concentration of mass, the so-called Great Attractor (GA), near $l = 310°$, $b = 10°$ (Lynden-Bell et al. 1988). More recent claims for the existence of a large-amplitude flow of ∼600 km s^{-1}, with a coherence length of ∼100 h^{-1} Mpc (e.g., Willick 1990; Mathewson, Ford, & Buchhorn 1992), suggesting excess power on very large scales, have also received reconsideration from the following standpoints. First, a careful reanalysis of the available data yielded a significantly smaller bulk velocity (Courteau et al. 1993). Second, the analysis of the independent SFI (*I*-band field spiral) Tully-Fisher (TF) survey led to a different characterization of the flow field. Indeed, the SFI velocity field shows that the flow is not as coherent as originally envisioned, exhibiting along the supergalactic plane a bifurcation toward the GA and Perseus-Pisces similar to that predicted from reconstructions of the *IRAS* surveys (e.g., da Costa et al. 1996). Furthermore, the flow within 6000 km s^{-1} is characterized by a strong shear across the volume, in contrast to the picture of a coherent motion of all structures. Recent analyses based on the recalibrated Mark III catalogs lead to a roughly consistent picture with that obtained with the SFI survey (da Costa et al. 1996; Dekel et al. 1999), even though some discrepancies still remain. For instance, Mark III yields a systematically larger amplitude of the bulk motion (∼370 ± 110 km s^{-1}) on scales ∼5000 km s^{-1} as compared with smaller values ($\lesssim$300 km s^{-1}) obtained by applying different techniques to the SFI sample (da Costa et al. 1996; Giovanelli et al. 1998a). In particular, a direct fit to the SFI radial velocities yields a bulk velocity of 200 ± 65 km s^{-1} within the sphere of radius ∼6500 km s^{-1}, consistent with that obtained from the SCI cluster sample (Giovanelli et al. 1998b). These results suggest that a significant fraction of the Local Group (LG) motion is generated on scales $\lesssim$6000 km s^{-1}. While recent direct measurements of the bulk velocity on larger scales (Dale et al. 1999) suggest that this may indeed be the case, other works (Lauer & Postman 1994; Willick 1999; Hudson et al. 1999) argue for the existence of large-amplitude ($\gtrsim$600 km s^{-1}) streaming motions out to a depth of 15,000 km s^{-1}.

In this Letter, we use the recently completed all-sky, homo-

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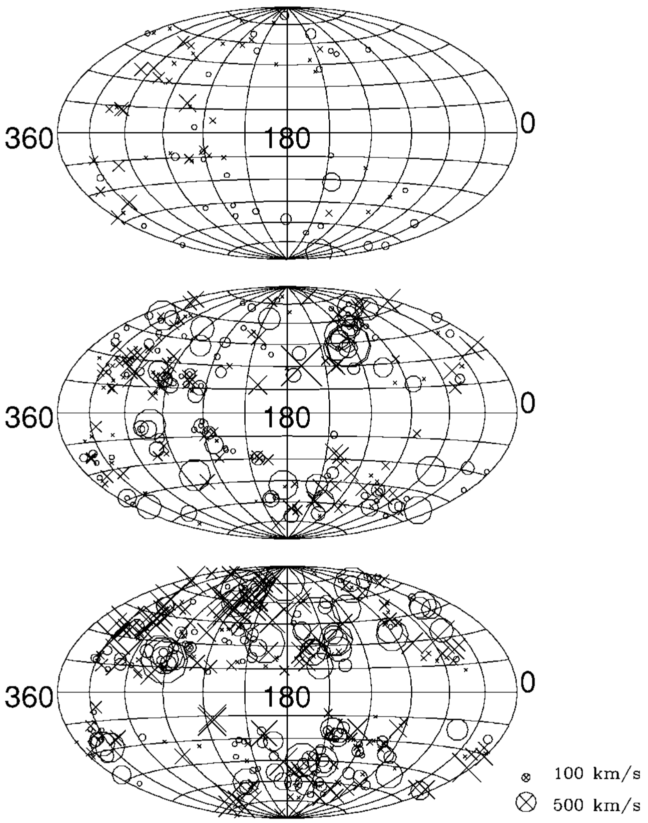

FIG. 1.—Projected distribution in galactic coordinates of the ENEAR peculiar velocity field in different distance shells 2000 km s^{-1} thick in the interval $0 < R < 6000$ km s^{-1}. The velocities are relative to the CMB rest frame, and the different symbols represent infall (*open circles*) and outflow (*crosses*). Their sizes are proportional to the galaxy's peculiar velocity amplitude.

geneous redshift-distance survey of early-type galaxies (ENEAR; da Costa et al. 2000, hereafter Paper I) to study the dipole component of the peculiar velocity field within $cz \lesssim 6000$ km s^{-1}. Our main goal is to compare our results using an entirely independent sample with those obtained by existing TF surveys.

2. THE SAMPLE

In the present analysis, we use the ENEAR redshift-distance survey described in greater detail in Paper I of this series. Briefly, the ENEAR sample consists of ~1600 early-type galaxies brighter than $m_B = 14.5$ and with $cz \leq 7000$ km s^{-1}, with D_n-σ distances available for 1359 galaxies. Of these, 1145 were deemed suitable for peculiar velocity analysis (Paper I). To the magnitude-limited sample, we added 285 galaxies fainter and/or with redshifts greater than 7000 km s^{-1}, 129 within the same volume as the magnitude-limited sample. In total, the cluster sample consists of 569 galaxies in 28 clusters, which are used to derive the distance relation. Over 80% of the galaxies in the magnitude-limited sample and roughly 60% of the cluster galaxies have new spectroscopic and *R*-band photometric data obtained as part of this program. Furthermore, repeated observations of several galaxies in the sample provide overlaps between observations conducted with different telescope/instrument configurations and with data available from other authors. These overlaps are used to tie all measurements into a common system, thereby ensuring the homogeneity of the entire data set. In contrast to other samples, new observations conducted by the same group are available over the entire sky. The comparison between the sample of galaxies with distances and the parent catalog also shows that the sampling across the sky is uniform.

Individual galaxy distances were estimated from a direct D_n-σ template relation derived by combining all the available cluster data, corrected for incompleteness and associated diameter bias (Lynden-Bell et al. 1988). The construction of the template relation was carried out following Giovanelli et al. (1997). From the observed scatter of the template relation, the estimated fractional error in the inferred distance of a galaxy is $\Delta \sim 0.19$, nearly independent of the velocity dispersion.

Since early-type galaxies are found preferentially in high-density regions, galaxies have been assigned to groups/clusters using well-defined criteria imposed on their projected separation and velocity difference relative to the center of groups and clusters, as described in Paper I. Early-type galaxies in a group/cluster are replaced by a single object having (1) the redshift given by the group's mean redshift, which is determined by considering all morphologies, (2) the distance given by the error-weighted mean of the inferred distances, for groups with two or more early-type galaxies, and (3) the fractional distance error given by $\Delta/\sqrt{N}$, where N is the number of early-type galaxies in the group. In some cases, groups were identified with Abell/ACO clusters within the same volume as the ENEAR sample, and fainter cluster galaxies were added, as described in Paper I.

The inferred distances are corrected for the homogeneous and inhomogeneous Malmquist bias (HMB and IMB, respectively). The latter was estimated using the *IRAS* PSCz density field (Branchini et al. 1999), corrected for peculiar velocity effects, following Willick et al. (1997). In this calculation, we also include the correction for the sample redshift limit. It should be noted that this is an approximation since early-type galaxies are biased relative to *IRAS* galaxies. A complete description of the sample used and the corrections applied will be presented in a subsequent paper of this series. As an illustration of the velocity field mapped by the ENEAR objects, we show in Figure 1 the projected distribution of objects in galactic coordinates with the sample split into different distance shells. The different symbols distinguish between objects with positive (*crosses*) and negative (*circles*) peculiar velocities. The peculiar velocities are relative to the CMB rest frame and have been computed from fully corrected distances as described above. For an alternative view of the data, we refer the reader to Paper I. In Figure 1, structures such as the GA at $l \sim 300°$, $b \sim 30°$ and the Perseus-Pisces (PP) complex at $l \sim 120°$, $b \sim -40°$ are easily recognized in the two outermost shells. Note that in these directions, one finds evidence of outflow and infall as expected around mass concentrations. As will be shown in a later paper of this series, the presence of a mass concentration in the PP region is confirmed with the reconstruction of the three-dimensional velocity field and mass distribution; this reconstruction shows that both structures have comparable peak density contrasts. The prominence of the PP complex is perhaps the most significant difference between the reconstructions based on the ENEAR and the 7S samples. The ENEAR-reconstructed fields are also in good agreement with those obtained from the PSCz redshift survey (Branchini et al. 1999), corrected for peculiar velocities, as it will be shown in a forthcoming paper.

TABLE 1
DIPOLE COMPONENT OF THE VELOCITY FIELD

SAMPLE (km s^{-1})	N	UNIFORM $\lvert \boldsymbol{v}_b \rvert$ (km s^{-1})	UNIFORM l (deg)	UNIFORM b (deg)	WEIGHTED $\lvert \boldsymbol{v}_b \rvert$ (km s^{-1})	WEIGHTED l (deg)	WEIGHTED b (deg)
$R < 2000$	77	442 ± 97	310 ± 16	21 ± 10	446 ± 78	308 ± 14	23 ± 8
$R < 4000$	324	147 ± 62	306 ± 18	9 ± 14	350 ± 47	301 ± 10	16 ± 7
$R < 6000$	656	220 ± 42	304 ± 16	25 ± 11	298 ± 38	299 ± 10	18 ± 7

3. MEASUREMENTS OF THE BULK MOTION

One of the primary goals of the ENEAR survey has been to investigate the robustness of previous peculiar velocity analyses using an independent and uniform sample of early-type galaxies probing a comparable volume as the recently completed TF surveys. While many tests are possible and will be explored in more detail in separate papers (e.g., Borgani et al. 2000), here we consider the dipole component of the velocity field. A bulk flow model is the simplest way to characterize the velocity field globally, having been extensively used in previous work (see, e.g., Dekel 2000 for a recent review). To determine the best-fitting bulk flow, we minimize (e.g., Lynden-Bell et al. 1988)

$$\chi^2 = \sum w_i (u_i - \boldsymbol{v}_b \cdot \hat{\boldsymbol{r}}_i)^2, \tag{1}$$

where u_i is the radial component of the peculiar velocity of the ith object in the CMB rest frame, located in the direction $\hat{\boldsymbol{r}}_i$, $\boldsymbol{v}_b$ is the bulk flow, and w_i is the weight given to the ith object in the sample. In our calculations, we use either uniform (equal) weights $w_i = 1$ or $w_i = 1/(\epsilon_i^2 + \sigma^2)$, where ϵ_i is the sum in quadrature of the distance and redshift errors (the latter is negligible in the case of field objects) and σ is the one-dimensional velocity dispersion that is due to true velocity noise generated on small scales.

Table 1 summarizes the bulk flow results obtained using various subsamples extracted from the combined sample of 696 objects within different volumes. For each volume of radius R in units of kilometers per second, Table 1 gives the number of objects in each subsample, the amplitude and direction of the best-fitting bulk motion, and their respective errors, obtained using different weighting schemes. The amplitude of the bulk motion is relative to the CMB rest frame, and its direction is expressed in terms of the galactic longitude and latitude. The errors were estimated from 1000 Monte Carlo realizations generated by adding Gaussian random deviates of the distance errors to the original distances, from which the dispersion of the dipole components are calculated. In Table 1, the weighted solutions assume a thermal component of $\sigma_f = 250$ km s^{-1} that is combined with the object's distance errors in quadrature. The bulk amplitudes listed in Table 1 have been corrected for the error bias obtained by subtracting from the square of the best-fitting value of the bulk velocity the sum in quadrature of the errors in each Cartesian component (Lauer & Postman 1994). The amplitude of this correction is relatively small, ~50 km s^{-1}. We point out that the amplitude of the bulk velocity at 6000 km s^{-1} is insensitive to the Malmquist bias correction. The comparison between the results obtained using raw distances with those corrected only for HMB and those obtained using the full correction are comparable to the estimated errors in the bulk velocity. Typical values for the HMB and IMB corrections are 13% and 4%, respectively. Only the direction of the dipole shows some dependence on the adopted correction. In particular, neglecting the IMB correction yields lower values of b. The good agreement between the direction of the fully corrected ENEAR and those of SFI and Mark III, using different procedures to estimate the IMB, is reassuring.

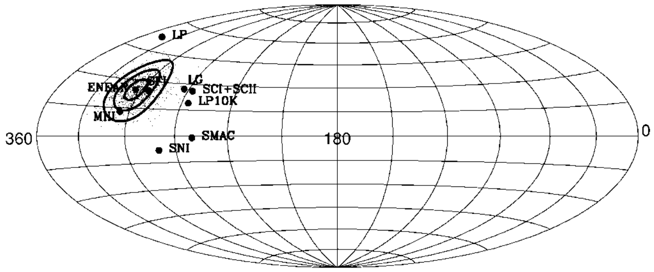

FIG. 2.—Bulk flow direction in galactic coordinates and the direction obtained from 1000 Monte Carlo realizations (*filled circles*). The contours represent 1, 2, and 3 σ error ellipsoids as derived from the Monte Carlo realizations. The figure shows the direction of the LG motion (LG) and the dipole directions obtained by other authors on different scales (see text). We adopt the following notation: LP (Lauer & Postman 1994); MIII (Mark III; Dekel et al. 1999); SFI (Giovanelli et al. 1998a); LP10K (Willick 1999); SCI + SCII (Dale et al. 1999); SNI (Riess et al. 1997); SMAC (Hudson et al. 1999).

From the direct fit of the radial velocities using equal weights, we find that $\lvert \boldsymbol{v}_b \rvert = 220 \pm 42$ in the direction $l = 304° \pm 16°$, $b = 25° \pm 11°$ within a radius of $cz \sim 6000$ km s^{-1}. Note that this value is smaller than the preliminary value reported earlier by Wegner et al. (2000), which was not corrected for the error bias and was determined before the full sample had been assembled. A somewhat larger value is obtained when objects are weighted by their distance errors, but the amplitude is still less than 300 km s^{-1} and essentially in the same direction. The direction of the ENEAR dipole is compared in Figure 2 with other recent estimates measured on similar scales (~5000–6500 km s^{-1}) using the SFI (Giovanelli et al. 1998a) and the revised Mark III (Dekel et al. 1999) samples. The contours represent the 1–3 σ confidence levels derived from the Monte Carlo simulations. Perhaps the most interesting result is the excellent agreement in both direction and amplitude between the ENEAR and SFI dipole solutions, probably the two most homogeneous all-sky samples currently available for the analysis of peculiar velocity data. Particularly important is the well-known fact that early-type (E and S0) and late-type (Sc) galaxies probe distinct regions of the galaxy distribution—while spiral galaxies are found predominantly in low-density regions and are more uniformly distributed, the distribution of elliptical galaxies is clumpier, delineating more clearly the most prominent nearby structures. Equally important is the fact that the peculiar velocities used in the two studies are based on independent distance relations involving different measurements and corrections. In Figure 2, we also show the direction of the dipoles recently measured on larger scales. The results obtained on scales of ∼6000 km s^{-1} are consistent, in both direction and amplitude, with those measured on much larger scales using the SCI + SCII sample. Combined, these results suggest that while most of the LG motion stems from fluctuations within 6000 km s^{-1}, some contribution also comes from larger scales where a better agreement between the dipole direction and the LG motion is found. It is important to note, however, that currently there is very little agreement among various determinations of the dipole on scales $\gtrsim$10,000 km s^{-1}.

To evaluate the possible impact of sampling effects directly from the data, we have also computed the dipole solution by splitting the sample into field galaxies and groups/clusters. We find that for $R \sim 6000$ km s^{-1}, these subsamples yield bulk velocities of ∼175 km s^{-1} for groups/clusters and ∼240 km s^{-1} for field galaxies, with errors on the order of ∼70 km s^{-1}. These velocities are somewhat higher (∼300 km s^{-1}) when the objects are weighted by their distance error. However, in this case, the mean weighted depth is small, for instance, ∼2400 km s^{-1} in the case of field galaxies. The results obtained for field galaxies and groups/clusters are, individually, in good agreement with the amplitude and direction of the dipole obtained from TF surveys (Giovanelli et al. 1998a). We conclude that on scales of ∼6000 km s^{-1}, the sampling error is small and comparable to the estimated random error of the bulk velocity ($\lesssim$40 km s^{-1}). Adding this value in quadrature to that estimated from the simulations, we estimate the random error to be ∼60 km s^{-1}. Another potential source of error in the bulk velocity are systematic uncertainties in the distance arising from mismatches in the velocity dispersion scale. Typically, the correction applied to σ for different runs is less than 0.020 dex, with an uncertainty of 0.009–0.018 dex, which in principle could lead to large errors in the amplitude of the bulk flow. However, given the large number of runs covering each region of sky and the fact that the observed galaxies in each run were selected randomly, we estimate this contribution to be at most ∼45 km s^{-1} in each hemisphere. On the other hand, the uncertainty in the offset between measurements of the velocity dispersion from northern and southern observations is estimated to be $\lesssim$0.006 dex, as determined from the sample of galaxies observed from both hemispheres. This uncertainty corresponds to about 1.5% in distance or to ∼50 km s^{-1}, which we take as an upper limit to the systematic error in the measured bulk velocity.

4. CONCLUSIONS

Using a sample of 1274 early-type galaxies in 696 objects comprising 414 isolated galaxies and 282 groups/clusters, drawn from the recently completed all-sky ENEAR redshift-distance survey, we have computed the dipole component of the local velocity field to a depth of ∼6000 km s^{-1}. Our main conclusion is that the streaming-motion amplitude of the ensemble of galaxies within the largest volume considered is small, ∼ 200 km s^{-1}. Similar small amplitudes are obtained when the sample is split into isolated galaxies and groups/clusters, indicating that sampling effects are relatively minor on these scales. The amplitude and direction of the ENEAR dipole agree well with the results obtained from similar analysis using the SFI TF survey. This is a remarkable considering the differences in selection criteria, morphological composition, and spatial distribution between the two samples and the fact that the peculiar velocities are derived using different distance relations. Small bulk velocities have also recently been obtained using new TF data (Courteau et al. 2000) as well as other distance indicators (see Dekel 2000 for a review). If these results are confirmed, the peculiar velocity field observed locally can easily be accounted for by the currently popular cosmological models.

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