Redshift-Distance Survey of Early-Type Galaxies. IV. Dipoles of the Velocity Field

L. N. da Costa [1,2], M. Bernardi[1,3,4], M. V. Alonso[5], G. Wegner[6]

C. N. A. Willmer[2,7], P. S. Pellegrini[2], M. A. G. Maia[2], S. Zaroubi[4]

Received ____________________; accepted ____________________

[1]European Southern Observatory, Karl-Schwarzschild Strasse 2, D-85748 Garching, Germany

[2]Departamento de Astronomia, Observatório Nacional, Rua General José Cristino 77, Rio de Janeiro, R. J., 20921, Brazil

[3]Universitäts-Sternwarte München, Scheinerstr. 1, D-81679, München, Germany

[4]Max Planck Institut für Astrophysik, Karl-Schwarzschild Strasse 1, D-85740, Garching, Germany

[5]Observatorio Astrónomico de Córdoba, Laprida 854, Córdoba, 5000, Argentina

[6]Department of Physics & Astronomy, Dartmouth College, Hanover, NH 03755-3528, USA

[7]UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, USA

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 $cz \sim 6000$ kms^{-1}. The sample consists of 1145 galaxies brighter than $m_B = 14.5$ and $cz \leq 7000$kms^{-1}, uniformly distributed over the whole sky, and 129 fainter cluster galaxies within the same volume. The great majority of the $D_n - \sigma$ distances were obtained from new spectroscopic and photometric observations conducted by this project, ensuring the homogeneity of the data over the whole sky. For peculiar velocity analysis, galaxies have been assigned to groups/clusters using a well-defined criterion combined with information about groups objectively identified from the complete redshift surveys from which the ENEAR sample was drawn. In the present analysis, we consider a total of 1274 galaxies in 696 objects – 282 groups/clusters and 414 isolated galaxies. We find that within a volume of radius ~ 6000 kms^{-1}the best-fitting bulk flow has an amplitude of $|\mathbf{v_b}| = 149 \pm 41$ kms^{-1}in the CMB restframe, pointing towards $l = 304° \pm 11°$, $b = 25° \pm 14°$ only 30° from the direction of the Local Group motion. This solution is in excellent agreement with that obtained by the SFI Tully-Fisher survey. Our results suggest that most of the motion of the Local Group is due to fluctuations within 6000 kms^{-1}, in contrast to recent claims of large amplitude bulk motions on larger scales.

Subject headings: cosmology: observations – galaxies: large-scale structure – galaxies: cosmic flows

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 amplitude of the bulk motion 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 determine the depth of the volume in which the streaming motion vanishes in the restframe defined by the Cosmic Microwave Background radiation (CMB). At this distance, the motion of the Local Group should converge to the measured dipole anisotropy of the CMB, and the distribution of matter within the encompassing volume should explain the ~ 600 kms^{-1}motion of the Local Group.

Observational evidence for the existence of large-scale flows date far back to the 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 flowfield out to $cz \sim 4000$kms^{-1}is characterized by a coherent, large-amplitude ~ 500 kms^{-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, near $l = 310°$, $b = 10°$ (Lynden-Bell et al. 1988). The later claims of a large amplitude flow ~ 600 kms^{-1}, with a coherence length of $\sim 100h^{-1}$ 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 re-analysis of the available data yielded a significantly smaller bulk velocity (Courteau et al. 1993). Second, the analysis of the independent SFI TF-survey led to a different characterization of the flowfield. Indeed, the SFI velocity field showed a bifurcation of the flow towards the Great Attractor and Perseus-Pisces, similar to that seen in the predicted velocity field obtained from reconstructions of *IRAS* catalogs (e.g., da Costa et al. 1996). Furthermore, the flow within 6000 kms^{-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 SFI TF-survey and the re-calibrated Mark III catalogs lead to a roughly consistent picture (da Costa et al. 1996; Dekel et al. 1999), even though some discrepancies still remain. In particular, Mark III yields a systematically larger amplitude of the bulk motion $\sim 370 \pm 110$ kms^{-1}on scales ~ 5000 kms^{-1}as compared to values $\lesssim$300 kms^{-1}obtained by applying different techniques to the SFI sample (da Costa et al. 1996; Giovanelli et al. 1998a; Eldar et al. 1999). In particular, a direct fit to the SFI radial velocities yields a bulk velocity of 200 ± 65 kms^{-1}within the sphere of radius ~ 6500 kms^{-1}consistent with that obtained from the SCI cluster sample (Giovanelli et al. 1998b). These results strongly suggest that on scales $\sim$ 6000 kms^{-1}the Hubble flow may have converged to the CMB frame. While there is supporting evidence that this may indeed be the case from recent direct measurements of the bulk velocity on larger scales (Dale et al. 1999), other works (Lauer & Postman 1994; Willick 1999; Hudson et al. 1999) argue for the existence of large amplitude ($\gtrsim$600 kms^{-1}) streaming motions out to a depth as large as 15,000 kms^{-1}, ruling out that the Hubble flow has converged to the CBM frame at smaller distances. Given the far reaching implications that these large-scale motions would have on currently popular cosmological models it is clear that this issue is of great interest. It is important to point out that the direction of the bulk motions detected on large scales do not agree in direction and in some cases have not been confirmed by subsequent work (e.g., Colless et al. 1999; Múller et al. 1998).

In this paper we use the recently completed all-sky, homogeneous redshift-distance survey of early-type galaxies (ENEAR, da Costa et al. 1999, hereafter Paper I) to study the dipole component of the peculiar velocity field within $cz \lesssim$6000 kms^{-1}. Our main goal is to compare our results with those obtained by other Tully-Fisher surveys probing a comparable volume but sampling the underlying velocity field in different ways and peculiar velocities estimated using distinct distance indicators. In section 2, we briefly describe the sample, while in section 3 the bulk motion relative to the CMB restframe is computed, using a direct likelihood fit of the observed radial velocities, and compared to previous determinations. Our main conclusions are summarized in section 4.

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 roughly 1600 early-type galaxies brighter than $m_B = 14.5$ and with $cz \leq 7000$ kms^{-1}, for which $D_n - \sigma$ distances are available for 1359 galaxies. Of these 1145 were deemed suitable for peculiar velocity analysis according to well-defined criteria (Paper I; Alonso et al. 2000b), and 569 galaxies in 28 clusters. Over 80% of the galaxies in the magnitude-limited sample and roughly 60% of the cluster galaxies have new spectroscopic and photometric data obtained as part of this program. Furthermore, repeated observations of several galaxies in the sample (Alonso et al. 2000a; Wegner et al. 2000) provide overlaps between observations conducted with different telescope/instrument configurations and with data available from other authors. These overlaps are used to tie all observable quantities into a common system and ensure the homogeneity of the entire dataset. The comparison between the sample of galaxies with distances and the parent catalog also shows its uniformity across the sky.

Individual galaxy distances were estimated from a direct $D_n - \sigma$ template relation derived by combining all the available cluster data (e.g., Bernardi et al. 2000a,b). 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 (Bernardi et al. 2000b).

Since early-type galaxies tend to be 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. These systems were identified using objective algorithms applied to the available magnitude-limited samples, comprising all morphological types, with complete redshift information probing the same volume. For membership assignment we used published group catalogs for CfA, SSRS and CfA2 (Geller & Huchra 1983; Maia, da Costa & Latham 1988; Ramella et al. 1997) and unpublished results (e.g., Ramella et al. 1999). The characteristic size and velocity dispersion of these groups/clusters were used to establish the membership of the ENEAR early-types, as described in Paper I. We find isolated galaxies, groups with only one early-type, and groups with two or more early-types. Early-type galaxies in a group/cluster are replaced by a single object having: a redshift given by the mean group redshift, determined considering galaxies of all morphological types; a distance given, for groups with two or more early-types, by the error-weighted mean of the inferred distances of the early-type galaxies in the group/cluster; and a fractional distance error of $\Delta/\sqrt(N)$, where N is the number of early-types in the group. In some cases groups were identified with Abell/ACO clusters within the same volume of the ENEAR sample and for 22 cases we added fainter members as described in Paper I. In the analysis below we compute the dipole component of the velocity field as probed by all objects, and by splitting the sample into two independent sub-samples consisting of field galaxies and groups/clusters. The inferred distances are corrected for the homogeneous Malmquist bias. The possible impact of inhomogeneous Malmquist bias and the redshift limit adopted were estimated using Willick et al. (1997) utilizing the reconstructed PCSz density field (Branchini et al. 1999). A complete account of the sample used and the corrections applied will be presented in a subsequent paper of this series (Alonso et al. 2000b). Figure 4 shows the peculiar velocity field mapped out by the ENEAR objects.

3. Measurements of the Bulk Motion

The simplest model for the peculiar velocity field is that of a bulk flow. To determine the best-fitting bulk flow we minimize (e.g., Lynden-Bell et al. 1988)

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

where u_i is the radial component of the peculiar velocity of the i^{th} object in the CMB restframe, located in the direction $\hat{\mathbf{r}}_i$, $\mathbf{v}_b$ is the bulk flow and w_i is the weight given to the i^{th} object in the sample. In our calculations we use either uniform weights $w_i = 1$ or

$$w_i = \frac{1}{\epsilon_i^2 + \sigma^2}, \tag{2}$$

where ϵ_i, is the sum in quadrature of the distance and redshift errors (neglected in the case of field objects), and σ is the one-dimensional velocity dispersion due to true velocity noise generated on small scales.

Table 1 summarizes the bulk flow results for the combined sample of 696 objects made up of isolated galaxies and groups/clusters. The table gives for each volume of radius R in units of kms^{-1}, the number of objects in each sub-sample, the amplitude and direction, and their respective errors, of the best-fitting bulk motion obtained using the different weighting schemes as indicated. The amplitude of the bulk motion is relative to the CMB restframe 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 random Gaussian deviates of the distance errors to the original distances, from which the dispersion of the dipole components are calculated. In the table, the solutions obtained weighting the objects by their distance error assume a thermal component of $\sigma_f = 250$ kms^{-1}. The bulk amplitudes listed in Table 1 have been corrected for the error-bias as advocated by Lauer & Postman (1994), subtracting from the best-fitting value of the amplitude the sum in quadrature of the errors in each Cartesian component. Our best estimate of the bulk motion of the volume within a radius of $cz \sim 6000$ kms^{-1}is that given by uniform weighting the objects which yields $|\mathbf{v}_b| = 149 \pm 41$ in the direction $l = 304°$, $b = 25°$. Note that this result is independent of the weighting scheme. This solution is compared in Figure 2 to other recent estimates on similar scales ($\sim 5000 - 6500$ kms^{-1}) based on the SFI/SCI (Giovanelli et al. 1998 a,b) and the revised Mark III (Dekel et al. 1999) samples. The contours represent the 1-3σ confidence levels, derived from the Monte-Carlo simulations. For comparison we also show the direction of the dipoles recently measured on larger scales using different techniques and samples (Lauer & Postman 1994; Dale et al. 1999; Dekel et al. 1999, Hudson et al. 1999, Willick 1999), as described in the figure caption. The corresponding bulk velocities range from 200 kms^{-1}to 750 kms^{-1}.

Perhaps the most interesting result is the excellent agreement both in 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 fact that, as shown in Paper I, early-type (E and S0) and late-type (Sc) galaxies probe distinct regions of the galaxy distribution - while spirals are found predominantly in low-density regions and are more uniformly distributed, the distribution of ellipticals is clumpier, delineating more clearly the most prominent nearby structures. Equally important is the fact that the inferred distances used in the calculation of the peculiar velocity are based on distinct distance relations involving different observable quantities and corrections. Both solutions are within 30° from the CMB dipole and suggest that the convergence length may have been reached.

Splitting the sample we have also considered the sub-samples of groups/clusters and isolated galaxies separately. The results are shown in Table 2 are similar to Table 1. Note that on large-scales all samples yield small amplitude flows ($\lesssim$300 kms^{-1}), except for the field sample when galaxies are weighted by their distance error. However, in this case the mean weighted depth is small $\sim$ 2400 kms^{-1}and the bulk velocity reflects the motion on smaller scales which should approach that of the LG, as is the case for the smallest volume considered. For groups/clusters the bulk velocity is comparable or smaller than the bias-error, in which case we set the bulk velocity to zero, already on scales $cz \sim 4000$ kms^{-1}. Since field galaxies and groups/clusters sample in different ways the underlying velocity field the difference in the dipole direction serves as a direct measure of the contribution of any sampling bias to the uncertainty in the direction of the streaming motion.

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 $\sim$ 6000 kms^{-1}. Our main conclusion is that the amplitude of the streaming motion of the ensemble of galaxies within the largest volume considered is small and consistent with a null velocity at the 3σ level. Similar small amplitudes are obtained when the sample is split into isolated galaxies and groups/clusters.

The amplitude and direction of the ENEAR dipole agrees remarkably well with that obtained from similar analysis using the SFI TF-survey (Giovanelli et al. 1998a). This is a remarkable result since these samples have different selection criteria, sample different regions of space and the peculiar velocities are derived using different distance relations. This direction is also consistent with that obtained from a POTENT analysis of the Mark III catalog (Dekel et al. 1999), although the measured bulk velocity of Mark III is significantly larger than that for the ENEAR and SFI. Further support for small bulk velocities comes from recently presented reports derived from the analysis of the velocity field as determined using distinct techniques such as surface brightness fluctuation (Tonry et al. 1999), nearby SNIa (Riess 1999) and an independent TF-survey (Courteau et al. 1999).

The following conclusions seem to emerge from these analyses using distinct samples and distance indicators: 1) the peculiar velocities we measure are real and not artifacts of systematic variations of scaling relations; 2) the larger amplitudes obtained by earlier work may be due to systematic errors introduced by assembling data from different sources; 3) similar systematic effects and sampling problems may be the root cause for the large amplitude bulk velocities being currently observed on larger scales, similar to what happen in the past on scales 4000-6000 kms^{-1}. If our results are confirmed the peculiar velocity field observed locally can easily be accounted for by currently popular cosmological models.

The authors would like to thank C. Rité and O. Chaves for their contribution over the years. Special thanks to E. Branchini. MB thanks the Sternwarte München, the Technische Universität München, ESO Studentship program, and MPA Garching for their financial support during different phases of this research. MVA is partially supported by CONICET, SecyT and the Antorchas–Andes– Vitae cooperation. GW is grateful to the Alexander von Humboldt-Stiftung for making possible a year's stay at the Ruhr-Universität in Bochum, and to ESO for support for visits to Garching which greatly aided this project. Financial support for this work has been given through FAPERJ (CNAW, MAGM, PSSP), CNPq grants 201036/90.8, 301364/86-9 (CNAW), 301366/86-1 (MAGM); NSF AST 9529098 (CNAW); ESO Visitor grant (CNAW). PSP and MAGM thank CLAF for financial support and CNPq fellowships. The results of this paper are based on observations at Complejo Astronomico El Leoncito (CASLEO), operated under agreement between the Consejo Nacional de Investigaciones Científicas de la República Argentina and the National Universities of La Plata, Córdoba and San Juan; Cerro Totolo Interamerican Observatory (CTIO), operated by the National Optical Astronomical Observatories, under AURA; European Southern Observatory (ESO), partially under the ESO-ON agreement; Fred Lawrence Whipple Observatory (FLWO); Observatório do Pico dos Dias, operated by the Laboratório Nacional de Astrofísica (LNA); and the MDM Observatory at Kitt Peak

REFERENCES

Alonso, M. V., Bernardi, M., Wegner, G. et al. 2000a, in preparation

Alonso, M. V., Bernardi, M., da Costa, L.et al. 2000b, in preparation

Bernardi, M. et al. 2000a, in preparation

Bernardi, M. et al. 2000b, in preparation

Branchini, E., Teodoro, L., Frenk, C. S., et al. 1999, MNRAS, 308, 1

Colless, M., Saglia, R. P., Burstein, D., Davies, R., McMahan, R. K., & Wegner, G. 1999, in Cosmic Flows: Towards and Understanding of Large-Scale Structure, eds. S. Courteau, M. A. Strauss, & J. A. Willick, ASP Conf. Ser., astro-ph/9909062

Courteau, S., Faber, S. M., Dressler, A., & Willick, J. A. 1993, ApJ, 412, L51

Courteau, S., Willick, J. A., Strauss, M. A., Schlegel, D., & Postman, M. 1999, in Cosmic Flows: Towards and Understanding of Large-Scale Structure, eds. S. Courteau, M. A. Strauss, & J. A. Willick, ASP Conf. Ser., astro-ph/9909385

da Costa, L. N., Freudling, W., Wegner, G., Giovanelli, R., Haynes, M. P., & Salzer, J. J. 1996, ApJ, 468, L5

da Costa, L. N., Bernardi, M., Alonso, M. V., Wegner, G., Willmer, C. N. A., Pellegrini, P. S., Rité, C., & Maia, M. A. G. 1999, AJ, submitted (Paper I)

Dale, D. A., Giovanelli, R., Haynes, M. P., Campusano, L. E., Hardy, E., & Borgani, S. 1999, ApJL, 510, 11

Dekel, A., Eldar, A., Kolatt, T., Yahil, A., Willick, J. A., Faber, S. M., Courteau, S., & Burstein, D. 1999, ApJ, 522, 1

Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R., & Wegner, G. 1987, ApJ, 313, 42

Eldar et al. 1999, in preparation

Geller, M. J., & Huchra, J. P. 1983, ApJS, 52, 61

Giovanelli, R., Haynes, M. P., Freudling, W., da Costa, L. N., Salzer, J. J., & Wegner, G. 1998a, ApJ, 505, L91

Giovanelli, R., Haynes, M. P., Slzer, J. J., Wegner, G., da Costa, L. N., & Freudling, W. 1998b, AJ, 116, 2632

Hudson, M. J., Smith, R. J., Lucey, J. R., Schlegel, D. J., & Davies, R. L. 1999, ApJ, 512, L79

Lauer, T. R., & Postman, M. 1994, ApJ, 425, 418

Lynden-Bell, D., Faber, S. M., Burstein, D., Davies, R. L., Dressler, A., Terlevich, R., & Wegner, G. 1988, ApJ, 326, 19

Maia, M. A. G., da Costa, L. N., & Latham, D. W. 1989, ApJS, 69, 809

Mathewson, D. S., Ford, V. L., & Buchhorn, M. 1992, ApJS, 81, 413

Müller, K., Freudling, W., Watkins, R, & Wegner, G., 1998, ApJL, 507, 105

Ramella, M., Pisani, A., & Geller, M. J. 1997, AJ, 113, 483

Ramella, M., et al. 1999, in preparation

Riess, A. G. 1999, in Cosmic Flows: Towards and Understanding of Large-Scale Structure, eds. S. Courteau, M. A. Strauss, & J. A. Willick, ASP Conf. Ser., astro-ph/9908237

Riess, A. G., Davis, M., Baker, J., Kirshner, R. P. 1997, ApJ, 488, 1

Rubin, V. C., Roberts, M. S., Thonnard, N., Ford, W. K., 1976, AJ 81, 719

Strauss, M. A., & Willick, J. A. 1995, Physics Reports, 261, 271

Tonry, J. L., Blakeslee, J. P., Ajhar, E. A., Dressler, A. 1999, ApJ, submitted, astro-ph/9907062

Wegner, G., Willmer, C. N. A., Bernardi, M. et al., 2000, in preparation

Willick, J. A. 1990, ApJ, 351, L5

Willick, J. A., Courteau, S., Faber, S. M., Burstein, D., Dekel, A., & Strauss, M. A. 1997, ApJS, 109, 333

Willick, J. A., & Strauss, M. A. 1998, ApJ, 507, 64

Willick, J. A. 1999, ApJ, 522, 647

This manuscript was prepared with the AAS LaTeX macros v4.0.

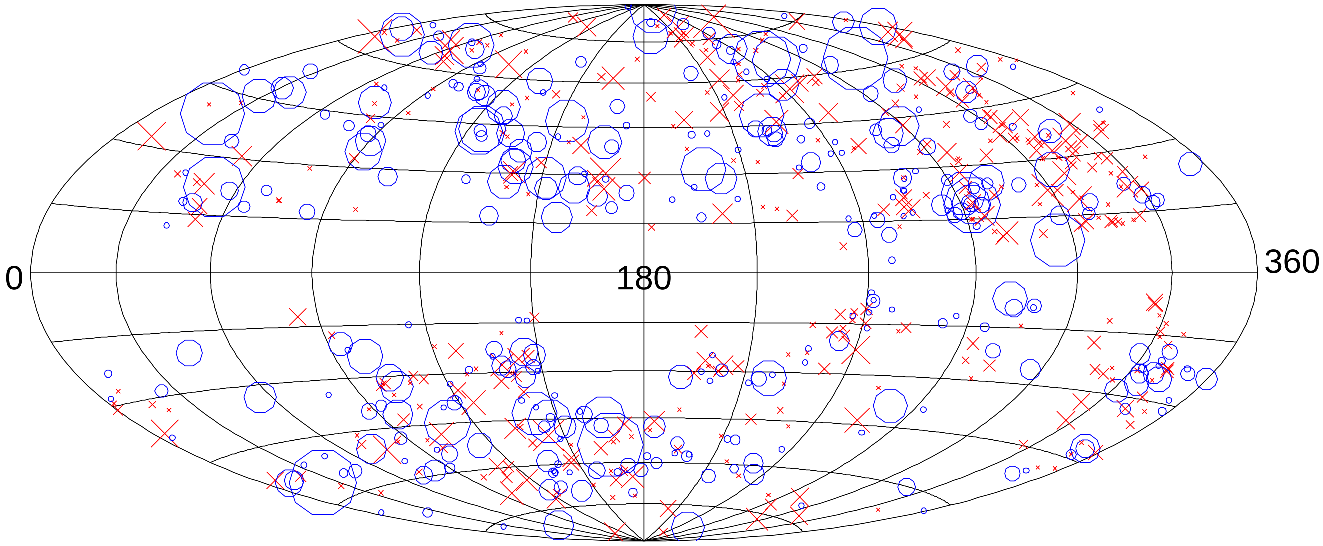

Fig. 1.— Sky projection in galactic coordinates of the ENEAR peculiar velocity field in the CMB resframe. Open circles indicate infall, and crosses outflow.

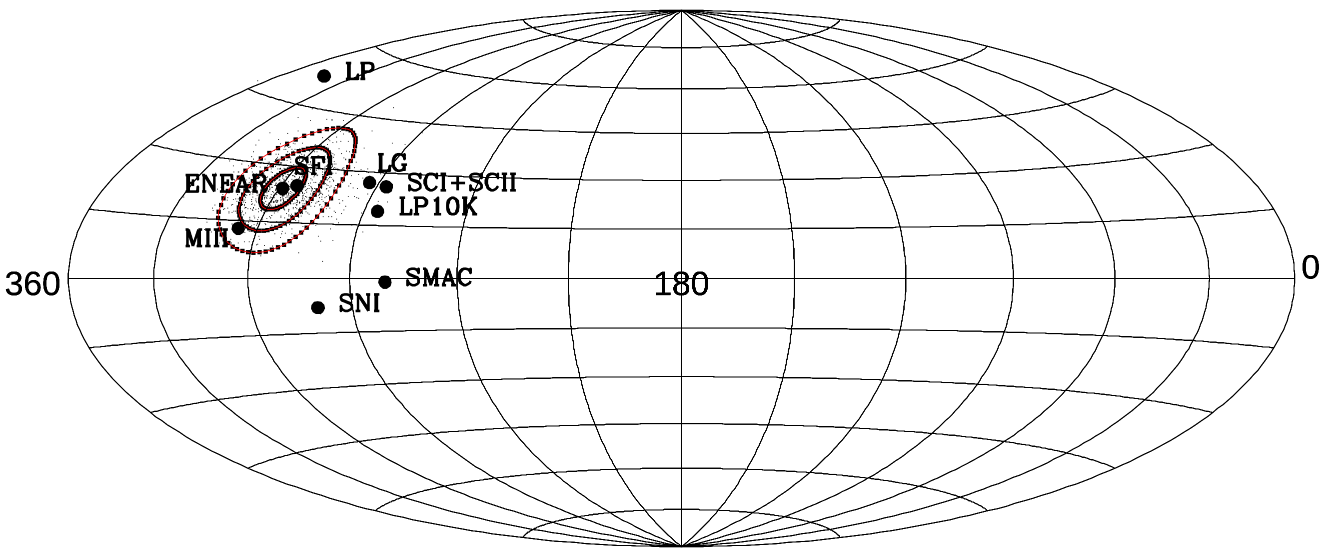

Fig. 2.— The bulk flow direction in Galactic coordinates and the direction obtained from 1000 Monte-Carlo realizations (dots). The contours represent 1, 2, and 3σ error ellipsoids as derived from the Monte-Carlo realizations. In the figure we show the direction of the LG motion (LG) and the dipole directions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

Table 1: Dipole Component of the Velocity Field

Sample	N	$\|\mathbf{v}_b\|$ (kms^{-1})	l (degree)	b (degree)	$\|\mathbf{v}_b\|$ (kms^{-1})	l (degree)	b (degree)
Objects		UNIFORM			WEIGHTED		
$R < 2000$ kms^{-1}	86	241 ±88	310 ±15	21 ±9	192 ±64	304 ±7	28 ±14
$R < 4000$ kms^{-1}	353	102 ±53	306 ±11	9 ±14	238 ±44	299 ±10	22 ±6
$R < 6000$ kms^{-1}	595	149 ±41	304 ±11	25 ±14	191 ±40	299 ±9	24 ±6

Table 2: Dipole Component for Field Galaxies and Groups/Clusters

Sample	N	$\|\mathbf{v}_b\|$ (kms^{-1})	l (degree)	b (degree)	$\|\mathbf{v}_b\|$ (kms^{-1})	l (degree)	b (degree)
Field		UNIFORM			WEIGHTED		
$R < 2000$ kms^{-1}	42	634 ±143	316 ±19	29 ±14	682 ±123	310 ±16	37 ±11
$R < 4000$ kms^{-1}	187	252 ±91	315 ±23	26 ±15	471 ±84	308 ±13	35 ±10
$R < 6000$ kms^{-1}	336	267 ±59	311 ±20	31 ±12	434 ±72	307 ±12	33 ±9
Groups/Clusters		UNIFORM			WEIGHTED		
$R < 2000$ kms^{-1}	44	230 ±130	284 ±29	24 ±13	128 ±85	277 ±25	37 ±11
$R < 4000$ kms^{-1}	166	0 ±88	275 ±21	-12 ±15	35 ±62	277 ±15	15 ±8
$R < 6000$ kms^{-1}	259	0 ±67	270 ±20	16 ±15	26 ±56	275 ±14	17 ±8