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# PECULIAR VELOCITY DIPOLES OF FIELD GALAXIES

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## ABSTRACT

The Tully-Fisher (TF) relation is applied to obtain peculiar velocities of field spiral galaxies and to calculate dipoles of the peculiar velocity field to $cz \simeq 8000$ km s$^{-1}$. The field galaxy sample is spatially coextensive with and completely independent of a cluster sample, for which dipole characteristics are given in a separate paper. Dipoles of the peculiar velocity field are obtained separately by applying (1) an inverse version of the TF relation and selecting galaxies by redshift windowing and (2) a direct TF relation, with velocities corrected for the inhomogeneous Malmquist bias and windowing galaxies by TF distance. The two determinations agree, as they do with the cluster sample. When measured in a reference frame in which the Local Group is at rest, the dipole moment of field galaxies farther than ~4000 km s$^{-1}$ is in substantial agreement, both in amplitude and direction, with that exhibited by the cosmic microwave background radiation field.

*Subject headings:* cosmic microwave background — cosmology: observations — distance scale — galaxies: distances and redshifts

## 1. INTRODUCTION

It is generally assumed that the Doppler shift arising from the solar motion is responsible for the cosmic microwave background (CMB) radiation dipole moment. Allowing for solar motion with respect to the Local Group (LG) of galaxies, the CMB dipole (Lineweaver et al. 1996) translates into a velocity $\boldsymbol{V}_{\rm CMB}$ of the LG with respect to the comoving reference frame of amplitude $611 \pm 22$ km s$^{-1}$, directed toward $l = 273° \pm 3°$, $b = 27° \pm 3°$. Most of the uncertainty arises from that on the motion of the Sun with respect to the LG, which we assume to have an amplitude of 300 km s$^{-1}$ and directed toward $l = 90°$, $b = 0°$ (de Vaucouleurs, de Vaucouleurs, & Corwin 1976).

In linear theory, the peculiar velocity induced on the LG by the inhomogeneities present within a sphere of radius $R$ is

$$\boldsymbol{V}_{\rm pec,LG}(R) = \frac{H_0\Omega_0^{0.6}}{4\pi}\int \delta_{\rm mass}(\boldsymbol{r})\,\frac{\boldsymbol{r}}{r^3}\,W(r,R)d^3\boldsymbol{r}, \qquad (1)$$

where $W(r, R)$ is a window function of width $R$, $H_0\boldsymbol{r}$ is the distance in kilometers per second, $\delta_{\rm mass}$ is the mass overdensity at $\boldsymbol{r}$, and $\Omega_0$ is the cosmological density parameter. Assuming that the CMB dipole is the result of a Doppler shift, then there must be identity between $\boldsymbol{V}_{\rm CMB}$ and $\boldsymbol{V}_{\rm pec,LG}(R)$ as $R \to \infty$. As $R$ increases, $\boldsymbol{V}_{\rm pec,LG}(R)$ converges toward $\boldsymbol{V}_{\rm CMB}$ if the average value of $\delta_{\rm mass}$ within a shell of radius $R$ approaches zero. In a universe that on large scales is homogeneous, it is thus reasonable to expect that the *reflex* motion of the LG, with respect to the contents of a shell of large enough radius $R$, will exhibit a dipole that closely matches that of the CMB radiation field. How large should $R$ be for that convergence to be observed? The issue is widely debated, and positions can roughly be divided—with much grey area in between—between two main camps: one in which the vast majority of the local dynamics is determined by mass fluctuations within $cz \simeq 5000$–10,000 km s$^{-1}$ and one in which a very substantial fraction of that motion arises outside $cz \simeq 10{,}000$ km s$^{-1}$. The latter is substantiated by several studies, from the early suggestion of Scaramella et al. (1989) on the importance of the Shapley supercluster to the results of Lauer & Postman (1994), based on the reference frame defined by 119 Abell clusters within roughly $cz \sim 15{,}000$ km s$^{-1}$. Lauer & Postman found the reflex motion of the LG with respect to the cluster sample to be given by a vector $\boldsymbol{V}_{\rm LP}$ of amplitude $561 \pm 284$ km s$^{-1}$, directed toward $(l, b) = (220°, -28°) \pm 27°$. The lack of coincidence between $\boldsymbol{V}_{\rm LP}$ and $\boldsymbol{V}_{\rm CMB}$ implies an overall bulk flow of the Lauer & Postman cluster reference frame of $689 \pm 178$ km s$^{-1}$ toward $(l, b) = (343°, +53°)$. This result was confirmed by a reanalysis of the Lauer & Postman data by Colless (1995) but was found in conflict with the studies of Riess, Press, & Kirshner (1995) and Giovanelli et al. (1996).

Here we analyze the dipole signatures of the peculiar velocity field of the sample of field spiral galaxies (SFI). The characteristics of the sample are briefly described in § 2; for further details, see Giovanelli et al. (1994) and the data presentation in Haynes et al. (1998a, 1998b). In § 3 we present the results of the dipole fits and discuss their amplitudes and significance in connection with the issue of the convergence depth of the local universe.

## 2. SFI SAMPLES AND PECULIAR VELOCITY CALCULATIONS

The SFI sample was selected by adopting strict angular size limits for the target galaxies, which varied with redshift in order not to underpopulate more distant shells (see Giovanelli et al. 1994). Galaxies observed by our team north of $\sim -35°$ were combined with data obtained by Mathewson, Ford, & Buckhorn (1992); the combined sample was severely trimmed in order to obtain a homogeneous all-sky sample of 1289 *field* objects, extending to $cz \simeq 6500$ km s$^{-1}$. This sample is complemented by several hundred additional objects, which extend to higher

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TABLE 1

SFI DIPOLE SOLUTIONS

| Set<br>(1) | $N_c$<br>(2) | $V$<br>(km s$^{-1}$)<br>(3) | $(l, b)$<br>(deg)<br>(4) |
|---|---|---|---|
| Inverse Tully-Fisher | | | |
| 1a. 0–6500 | 1112 | 349 ± 52 | (258, +40) ± 11 |
| 1b. | 1112 | 433 ± 82 | (269, +24) ± 19 |
| 2a. 0–6500 + | 1631 | 391 ± 39 | (255, +30) ± 8 |
| 2b. | 1631 | 454 ± 91 | (259, +25) ± 17 |
| 3. 0–2000 | 163 | 215 ± 96 | (268, +64) ± 26 |
| 4. 0–2000 + | 275 | 270 ± 80 | (245, +49) ± 19 |
| 5. 1500–3500 | 379 | 370 ± 71 | (265, +23) ± 14 |
| 6. 1500–3500 + | 549 | 410 ± 69 | (255, +21) ± 12 |
| 7. 2500–4500 | 417 | 670 ± 72 | (256, +18) ± 12 |
| 8. 2500–4500 + | 580 | 620 ± 76 | (255, +15) ± 11 |
| 9. 3500–5500 | 499 | 603 ± 83 | (263, +24) ± 13 |
| 10. 3500–5500 + | 689 | 585 ± 92 | (265, +19) ± 13 |
| 11. 4500–6500 | 435 | 450 ± 99 | (269, +21) ± 16 |
| 12. 4500–6500 + | 635 | 544 ± 98 | (270, +16) ± 15 |
| 13b. 5500–9500 + | 506 | 620 ± 128 | (274, +21) ± 19 |
| Direct Tully-Fisher, IMB Corrected | | | |
| 14a. 0–6500 | 1139 | 430 ± 47 | (260, +38) ± 9 |
| 14b. | 1139 | 430 ± 79 | (262, +31) ± 14 |
| 15. 0–2000 | 113 | 258 ± 84 | (268, +57) ± 29 |
| 16. 1500–3500 | 336 | 422 ± 78 | (272, +25) ± 18 |
| 17. 2500–4500 | 398 | 483 ± 91 | (269, +20) ± 14 |
| 18. 3500–5500 | 525 | 597 ± 82 | (259, +28) ± 12 |
| 19. 4500–6500 | 552 | 609 ± 70 | (252, +28) ± 13 |

redshifts with lesser degrees of completeness. This extended sample, which has no significant sky coverage bias but rapidly decreasing completeness to $cz \sim 9500$ km s$^{-1}$, will be referred to as "SFI+." These two field samples are completely independent of the sample of cluster galaxies (SCI), presented in Giovanelli et al. (1997a, 1997b). A study of the SCI dipoles is presented in a complementary paper (Giovanelli et al. 1998).

The SFI and SFI+ samples are dense enough to allow estimates of dipoles for separate volume shells, centered on the LG. However, the windowing of such shells can introduce bias in the results. Such bias can be avoided if (1) the selection is done by observed redshift $cz$, when the *inverse* Tully-Fisher (TF) relation (Tully & Fisher 1977) is used to estimate peculiar velocities, or if (2) the selection is done by TF distance $cz_{\rm TF} = cz - V_{\rm pec}$, when the *direct* TF relation is used (for details see Freudling et al. 1995). In case 2, however, it is necessary to correct the derived peculiar velocities for the so-called "inhomogeneous Malmquist bias" (IMB). We have computed the IMB at the location of each sample galaxy by estimating locally the gradient of the density field, as obtained from a redshift catalog (see Freudling, da Costa, & Pellegrini 1994 for details). Such a catalog yields IMB corrections of quality that decreases rapidly with distance. For the SFI+ sample, which is deeper than the strict SFI, IMBs are not available and the dipole calculations are carried out only with peculiar velocities obtained using the inverse TF approach.

## 3. DIPOLE RESULTS

Since we are interested in the comparison with $\mathbf{V}_{\rm CMB}$, $\mathbf{V}_{\rm LP}$, and other dipole determinations, we shall estimate the dipole of the *reflex* motion of the LG with respect to our cluster set. If $-V_i$ is the peculiar velocity of the $i$th galaxy in the sample and $\epsilon_i$ is the uncertainty on that quantity, we solve for the vector $\mathbf{V}_d$ of the dipole moment by minimizing the merit function

$$\chi^2 = \sum_i w_i \left(\frac{V_i - \mathbf{V}_d \cdot \hat{\mathbf{r}}_i}{\epsilon_i}\right)^2, \qquad (2)$$

where $\hat{\mathbf{r}}_i$ is the unit vector in the direction of the $i$th galaxy and $w_i$ is a weight. $\epsilon_i$ is obtained from the TF scatter function that we have obtained for the well-determined TF template relation of cluster galaxies (Giovanelli et al. 1997b), which varies with velocity width $W$ as $-0.325(\log W - 2.5) + 0.32$ mag. Our adoption is justified because the $\epsilon_i$ obtained for cluster galaxies is not affected by the cluster motions, which had been corrected for before the TF scatter function was estimated. Such correction is much more difficult for field galaxies, since it would require precise knowledge, point by point, of the unsmoothed peculiar velocity field. As shown by Giovanelli et al. (1997b), there is no dependence of the scatter amplitude on the distance of the galaxy from cluster centers: we thus feel justified in adopting the cluster galaxy scatter function for the field galaxies.

The weights $w_i$ are intended to provide a correction that accounts for the fading selection function of the sample with increasing distance. For computations of dipoles of galaxies within shells, the application of a weight $w_i$ is of limited impact. However, in the calculation of the dipole and bulk flow of the field over volumes including a large range in distances, the application of weights is necessary in order to obtain an estimate that is independent of the particular selection function of the sample. The global motion of a volume bound by a top-hat window can be approximated by using weights that are proportional to $r_n^3$, where $r_n$ is the distance to the $n$th nearest neighbor to galaxy $i$ in the sample; $n$ is a number usually chosen between 3 and 9. We have computed such weights for $n = 4$, which matches the estimated accuracy of the approach with computational ease.

Table 1 lists the amplitude and apex galactic coordinates of SFI dipoles, computed for a variety of cases and subsamples. The calculations are carried out with $V_{\rm pec}$'s obtained using the inverse TF relation (solutions 1–13) and with IMB-corrected $V_{\rm pec}$'s obtained using the direct TF relation (solutions 14–19). The latter are only computed for the SFI sample for the reason given in § 2. The former are computed for both the SFI (odd-numbered solutions 1–11) and for the SFI+ samples (even-numbered solutions 2–12 and 13), as indicated in column (1). Uncertainties on the dipole parameters are not estimated from the formal errors of the fit but rather from a replacement bootstrap procedure, whereby 500 synthetic data sets are used, each with 63% of the objects randomly chosen among those in the original data set and the remaining 37% of the entries being duplicated ones. Dipole amplitudes are corrected by the "error bias" discussed by Lauer & Postman (1994), which in our case is of moderate or negligible importance on the results. Each line of Table 1 gives the dipole solution for a subset of the data, windowed in $cz$ (for the inverse TF) or in $cz_{\rm TF}$ (for the direct TF) as indicated. For the global solutions (1, 2, and 14), we give separately the dipole parameters estimated for $[w_i] \equiv 1$ (solutions labeled "a") and for equal-volume weights as described above (solutions labeled "b"); the other solutions are averages of the two cases, albeit the differences between the two averaged values are usually quite small and well within the uncertainties of each determination. The number of galaxies used in each solution (listed in col. [2]) differs between the direct and inverse solutions for a given shell, since the windowing is carried out for different variables ($cz_{\rm TF}$ and $cz$, respectively). A small fraction of objects with large (greater than 1.5 mag), possibly spurious magnitude offsets from the adopted TF relations were excluded in the calculations of dipole parameters.

The parameters of the dipole solutions 3–13 and 15–19, as listed in Table 1, are displayed in Figure 1. The amplitudes are shown in Figure 1*a*: inverse TF solutions are identified by circles (*open* and *filled* for the SFI and SFI+ samples, respectively), while direct TF solutions are displayed as starred symbols. The horizontal dashed line is the 611 km $s^{-1}$ amplitude of the CMB dipole. Figure 1*b* shows the apices of the dipole solutions, plotted in galactic coordinates. The large, crossed circle identifies the CMB dipole, and the large square is the apex of the LG motion with respect to the Abell cluster sample reported by Lauer & Postman (1994).

The reflex motion of the LG with respect to field galaxies within 2000 km $s^{-1}$ exhibits a relatively small amplitude and appears directed toward high galactic latitude. This is in agreement with the expectation that such motion is largely affected by the presence of the density enhancement represented by the Local Supercluster, centered on the Virgo cluster (M87 is at $l = 284°$, $b = +74°$). As the radius of the shell increases, however, the LG reflex motion asymptotically approaches $\boldsymbol{V}_{\rm CMB}$, both in amplitude and apex direction. Within the uncertainty of the measurement, the two quantities become indistinguishable at distances larger than ~4000 km $s^{-1}$. This result is consistent with the determination obtained with a completely independent cluster data set by Giovanelli et al. (1998) and excludes with a high degree of confidence (greater than 99.99%) the possibility that the LG may exhibit a dipole such as reported by Lauer & Postman (1994), with respect to the contents of any shell within a distance of 8000 km $s^{-1}$.

The dipoles of the global samples (1, 2, and 14) depart from the CMB dipole at a significant level. The equal-volume–weighted solutions (labeled "b") are noisier than those obtained with $[w_i] \equiv 1$, an expected result since the former give higher weight to more distant objects and errors in the peculiar velocity rise linearly with distance. The difference ($\boldsymbol{V}_{\rm CMB} - \boldsymbol{V}_d$) for any of the solutions in Table 1 yields the bulk flow motion of the corresponding sample with respect to the CMB. Because many of the dipole solutions match the CMB dipole so closely, resulting bulk flows are quite modest and their directions largely unconstrained. Bulk flows associated with solutions 1b, 2b, and 14b give an estimate of the motion, filtered by a top-hat function, of the local universe within 6500 km $s^{-1}$. The average of those three solutions is 200 ± 65 km $s^{-1}$ toward $(l, b) = (295°, +25°) \pm 20$. This is in general agreement with the direction of bulk flows reported in other studies (da Costa et al. 1996; Courteau et al. 1993; Dekel 1994), but it is smaller than other determinations, which range between 270 and 400 km $s^{-1}$. It agrees well in amplitude and direction with the bulk motion with respect to clusters of galaxies within 9000 km $s^{-1}$ and with measured TF distances (Giovanelli et al. 1998). It should be pointed out that the bulk flows associated with solutions 1a, 2a, and 14a are somewhat larger, approaching 300 km $s^{-1}$ amplitude in the case of solution 1a. These solutions do, however, weigh nearby galaxies heavily, and the bulk flow solutions are representative of a significantly smaller effective volume than those for cases 1b, 2b, and 14b.

In summary, we obtain that the reflex peculiar motion of the LG with respect to field spiral galaxies approaches convergence with the CMB dipole within 6500 km $s^{-1}$. The dipole moment of the LG motion with respect to the outer shells of that volume agrees with the CMB dipole within the uncertainties. The motion of the LG with respect to spiral galaxies within 2000 km $s^{-1}$ is consistent with its being influenced by the mass excess represented by the Local Supercluster. It can be excluded to a high degree of confidence that the LG motion may exhibit a dipole like that reported by Lauer & Postman (1994), with respect to the contents of any shell within a distance of 8000 km $s^{-1}$. Finally, the bulk flow with respect to the CMB reference frame of a sphere of 6500 km $s^{-1}$ radius, bound by a top-hat window, is 200 ± 65 km $s^{-1}$, directed toward $(l, b) = (295°, +25°) \pm 20$.

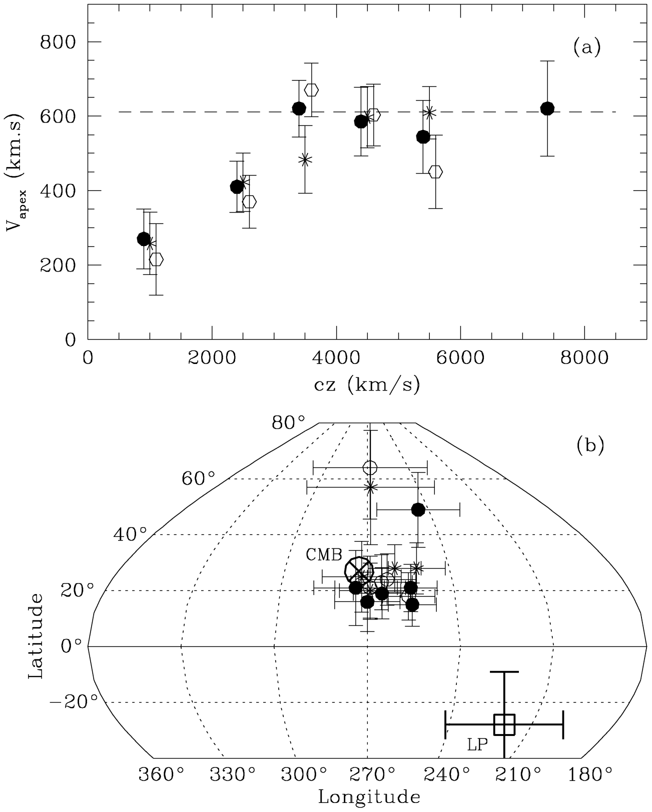

FIG. 1.—Dipole parameters of solutions 3, 5, 7, 9, and 11 are plotted as open circles, those of solutions 4, 6, 8, 10, 12, and 13b are plotted as filled circles, and those of solutions 15–19 are plotted as starred symbols. The dashed line in (*a*) corresponds to the amplitude of the CMB dipole, 611 km $s^{-1}$. The apices of the LG motion with respect to the CMB and the Lauer & Postman (1994) cluster sample are labeled as "CMB" and "LP" in (*b*).

The results presented in this Letter are based on observations carried out at the Arecibo Observatory, which is part of the National Astronomy and Ionosphere Center (NAIC), at Green Bank, which is part of the National Radio Astronomy Observatory (NRAO), and at the Kitt Peak National Observatory (KPNO), the Cerro Tololo Interamerican Observatory (CTIO), the Palomar Observatory (PO), the Observatory of Paris at Nançay, and the Michigan-Dartmouth-MIT Observatory (MDM). NAIC is operated by Cornell University, NRAO by Associated Universities, Inc., and KPNO and CTIO by Associated Universities for Research in Astronomy, all under cooperative agreements with the National Science Foundation. The MDM Observatory is jointly operated by the University of Michigan, Dartmouth College, and the Massachusetts Institute of Technology on Kitt Peak, Arizona. The Hale telescope at PO is operated by the California Institute of Technology under a cooperative agreement with Cornell University and the Jet Propulsion Laboratory. This research was supported by NSF grants AST94-20505 and AST96-17069 to R. G., AST95-28860 to M. H., and AST93-47714 to G. W.

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