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ABSTRACT

We use Tully-Fisher distances for a sample of field late spiral galaxies to test the Lauer & Postman result suggestive of a bulk flow with respect to the cosmic microwave background reference frame, of amplitude of +689 km s^{-1} in the direction $l = 343°$, $b = +52°$. A total of 432 galaxies are used, subdivided between two cones, of 30° semiaperture each and pointed toward the apex and antapex of the LP motion, respectively. The peculiar velocities in the two data sets are inconsistent with a bulk flow of the amplitude claimed by Lauer & Postman. When combined in opposition, the peculiar velocity medians in shells of constant redshift width are never larger than half the amplitude of the Lauer & Postman bulk flow. Out to 5000 km s^{-1} the median bulk velocity in the Lauer & Postman apex-antapex cones is about 200 km s^{-1} or less, dropping to a value indistinguishable from zero beyond that distance. It can be excluded that field spiral galaxies within 8000 km s^{-1} partake of a bulk flow of the amplitude and direction reported by Lauer & Postman.

Subject headings: cosmology: cosmic microwave background — cosmology: large-scale structure of universe — cosmology: observations — galaxies: distances and redshifts — infrared: galaxies — radio lines: galaxies

1. INTRODUCTION

The dipole moment of the sky brightness distribution in the cosmic microwave background radiation (CMB) is thought to arise from the Doppler shift due to the deviation in the motion of the local group (LG) from smooth Hubble flow. That motion appears to be directed toward galactic coordinates (276°, +30°), with amplitude 627 ± 22 km s^{-1} (Kogut et al. 1993). Inhomogeneities in the mass distribution will produce deviations from smooth Hubble flow, also referred to as "peculiar velocities". Therefore, the CMB dipole raises the challenges of (a) identifying the sources of the LG motion, and (b) mapping the peculiar velocity field in the local universe, of which the LG motion is a single point sample. The coherence length scales and characteristic amplitudes of the peculiar velocity field are important cosmological parameters, which can, in principle, be obtained via the systematic determination of distances *and* redshifts of large samples of galaxies (which respond as point sources to the buffeting of the large-scale gravitational field). Alternatively, the moments of the light distribution of all-sky catalogs of extragalactic objects can be used. These techniques have been extensively applied, producing often conflicting results.

After the early measurements of Rubin et al. (1976) of the flux dipole of ScI galaxies, Aaronson et al. (1986, and references therein) made headway in the measurement of the infall of the Local Group toward the Virgo cluster. As Virgo was located nearly a radian off the CMB dipole apex, attention shifted toward the peculiar velocity field outside the local supercluster, with the expectation of finding a set of galaxies that would provide a reference frame with respect to which the amplitude and direction of the LG motion would match that revealed by the CMB dipole. Several authors pointed out the important role that might be played by the Hydra-Centaurus supercluster (Shaya 1984; Tammann & Sandage 1985; Lilje, Yahil, & Jones 1986), until the existence of a great attractor (GA), a mass concentration largely obscured by Milky Way dust, was invoked by the work of Lynden-Bell et al. (1988) and Dressler et al. (1987); the GA was placed at a redshift of 4300 km s^{-1}, about 10% farther than Hydra. More recent work, however, has raised the possibility that the local universe may instead be partaking in a flow of a larger scale, whereby the component of largest amplitude in the LG motion has a coherence length a few times larger than the distance to the GA. Scaramella et al. (1989) suggested that the Shapley Supercluster, at about 13,000 km s^{-1} and in the general direction of the GA, may constitute an important density inhomogeneity in determining our motion; Willick (1990) reported that the Perseus-Pisces Supercluster, located at a distance of about 5000 km s^{-1} and roughly antipodal to the GA, moves toward us—and thus toward the GA—at about 400 km s^{-1}. Courteau et al. (1993) reinforced that finding by reporting the measurement of a "bulk" flow—i.e., the global motion of all matter within a top hat average out to 6000 km s^{-1}—of 385 ± 38 km s^{-1} toward galactic coordinates (294°, 0°). The interested reader is addressed to the recent comprehensive review of Strauss & Willick (1995).

Mathewson, Ford, & Buchhorn (1992, hereafter MFB) carried out an extensive survey of galaxy distances in the Southern hemisphere and reported lack of backflow in the GA, corroborating the view that Perseus-Pisces, LG and GA share a bulk motion, may be produced by more distant gravitational sources; it was even suggested that the motion may have a nongravitational origin (Mathewson 1995). An important result was contributed by Lauer & Postman (1994, hereafter LP): they measured the dipole of the distribution of the brightest elliptical galaxies in 119 clusters, distributed over a volume of 15,000 km s^{-1} radius and with an effective depth of approximately 10,000 km s^{-1}. They found that *the reference frame defined by the group of clusters is in motion with respect to the CMB, at a velocity of* 689 ± 178 km s^{-1}, *and toward the direction of galactic coordinates* (343°, +52°) (±23°). A reanalysis of the LP data by Colless (1995) confirmed their result. Not only is this motion roughly orthogonal to the CMB apex and in large disagreement with that reported by other surveys, it also poses an embarassment to many models that attempt to reproduce the characteristics of large scale structure, as they encounter difficulties in accomodating bulk flows of large amplitude and scale (e.g., Dekel 1994; Strauss et al. 1995). The work of Riess et al. (1995), which uses a sample of 13 SN Ia (now extended to 20; R. Kirsher 1996, personal communication), disagrees with the LP bulk motion result, suggesting agreement with the CMB apex.

Here we report on a simple test of the LP result. We utilize a set of distances to field (SFI) and cluster (SCI) spiral galaxies, obtained using the Tully-Fisher (1977) technique in the I band. They are part of an all-sky sample of more than 2000 objects; while preliminary results of the survey have been reported by Giovanelli et al. (1994, 1995a), Freudling et al. (1995), and da Costa et al. (1996a), a more general and detailed analysis of these data will be presented elsewhere.

2. DATA SELECTION

We have obtained CCD I-band images and velocity widths for a sample of late spiral galaxies north of declination −40°, which we have combined with the southern data published by MFB to obtain an all-sky sample of spiral galaxy distances extending to about 8000 km s^{-1}. Sample selection criteria are described in Giovanelli et al. (1994). Detailed descriptions of data reduction and analysis are in preparation.

A test of the LP result using this data set is relatively straightforward, thanks to the high-galactic latitude of the LP apex. Since our sample of field galaxies ends in regions of high extinction and thus of low galactic latitude, the testing of bulk flows with apices close to the galactic plane, such as that reported by Courteau et al. (1993), requires a more careful reconstruction of the peculiar velocity field, which we will present elsewhere (da Costa et al. 1996a). Here we restrict ourselves to testing the LP result.

We select two subsets of the data, corresponding to cones each subtending an angle of 30° half-aperture, centered respectively on the apex [(l, b) = (343°, +52°)] and antapex directions of the LP bulk flow. The antapex cone includes 235 galaxies with measured distances, of which 84% are drawn from our observations and 16% from those of MFB; the apex cone includes 197 galaxies, 2/3 from our own and 1/3 from MFB observations. The optical rotation widths of MFB have been reanalyzed to obtain consistency with the techniques applied to our data. MFB contain a mixture of 21 cm radio widths and widths derived from optical rotation curves. An important concern has been that of removing the bias introduced by optical rotation curves that insufficiently sample the galactic disks and thus appear to be still rising at the last measured point; these objects, which tend to be more frequent in the GA region, sometimes yield severe underestimates of the velocity widths, and, as a consequence, systematically large positive peculiar velocities. Several objects have been rejected for this reason, while for others velocity widths at a radius encompassing 83% of the light ("optical radius") were estimated, using the folded versions of the rotation curves of MFB produced by Persic & Salucci (1995). In cases in which the MFB rotation curve did not reach as far out as the optical radius as defined above, an extrapolation was carried out using the Persic & Salucci (1991) "universal rotation curve" parametrization, which relates the shape of a rotation curve with the galaxy's luminosity. A total of 69 of the MFB galaxies used here have velocity widths derived from optical rotation curves; the derived widths at the optical radius appear to be reliable estimates. It should be pointed out that the remainder of the MFB widths, as well as all of our own, were obtained at 21 cm, and, therefore, are unaffected by recalibration. The recalibrated MFB data follow the same TF relation as those with 21 cm widths.

3. MOTIONS IN THE LAUER & POSTMAN APEX AND ANTAPEX CONES

Peculiar velocities are computed for each galaxy from the observed radial velocity measured in the CMB reference frame, $v_{\rm cmb}$, and the Hubble velocity obtained from the inverse TF relation, $v_{\rm tf}$, via $v_{\rm pec} = v_{\rm cmb} - v_{\rm tf}$. The inverse relation was used because, as shown by Freudling et al. (1995), the bias that affects the estimates of $v_{\rm pec}$ is significantly reduced when the inverse rather than the direct TF relation is adopted. Peculiar velocities are not corrected for the inhomogeneous bias; this correction is not necessary for our purposes, as we discuss when we present Figure 2 further below.

In Figure 1, we display the peculiar velocities of the galaxies in the LP apex and antapex cones, plotted versus the galaxy radial velocity and measured in the CMB reference frame. Rather than plotting error bars for each point, we inset dashed lines that reflect the mean error on the peculiar velocity, as derived from a mean scatter in the Tully-Fisher relation of 0.35 mag. The amplitude of the LP motion is also inset as a solid horizontal line at ±689 km s^{-1}. Filled symbols identify objects observed by us, while unfilled ones are from MFB. Note that the horizontal axis in Figure 1 is the galaxy redshift $v_{\rm cmb}$ rather than the Tully-Fisher velocity $v_{\rm tf}$, and, therefore, the reader is cautioned against directly reading of the horizontal axis as a distance parameter.

Galaxies of four cluster regions are part of the apex and antapex samples; in Figure 1, they are plotted at their own $v_{\rm cmb}$ rather than that of the cluster. Galaxies in the clusters ESO 508 and A3574 are in the apex region: ESO508 is near $V_{\rm cmb} = 3200$ km s^{-1} and A3574 is near $V_{\rm cmb} = 4800$ km s^{-1}. Galaxies in the cluster A400 and in the Eridanus group, near $V_{\rm cmb} = 7000$ km s^{-1} and near 1500 km s^{-1}, respectively, are in the antapex region. The systemic peculiar velocities of the four clusters are −128 ± 235 km s^{-1} for A400, −343 ± 70 km s^{-1}

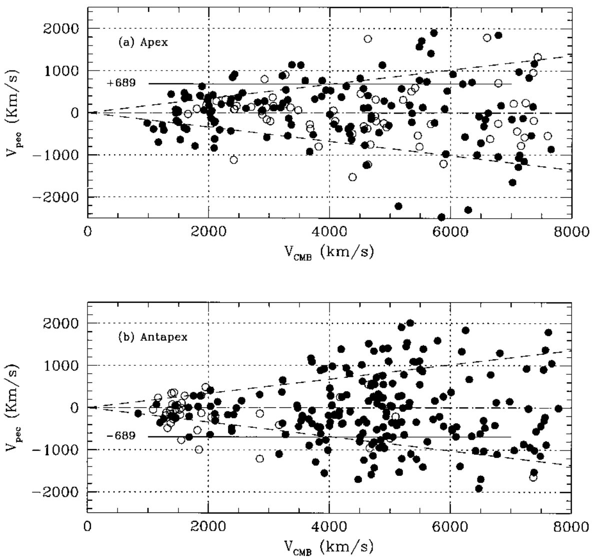

FIG. 1.—(*a*) Peculiar velocity of spiral galaxies in the LP apex cone; the abscissa is the radial velocity in the CMB reference frame. Dashed lines identify a mean scatter in the TF relation of 0.35 mag. The +689 km s^{-1} level corresponds to the amplitude of the LP bulk velocity, inset for comparison. Filled symbols refer to galaxies observed by us, while unfilled symbols correspond to data from MFB. (*b*) Analogous plot to that in panel (*a*), except that it refers to the LP antapex cone. A small number of objects lie outside the plot margins.

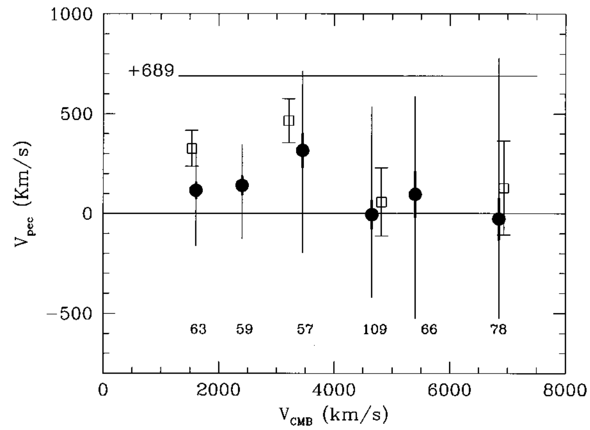

FIG. 2.—Median peculiar velocities, binned by shells of radial velocity 1000 km s^{-1} wide; values refer to the total bulk velocity of the apex and antapex regions in each shell, added in opposition so that the sign is that of the net velocity in the LP apex direction. Thin error bars refer to the range spanned by data within the two inner quartiles, and thick error bars identify our best guess of the accuracy of the median value determination, akin to a standard error on the mean. Numbers under each symbol identify the number of galaxies used in each bin. The LP bulk flow amplitude of 689 km s^{-1} is inset as a horizontal line for comparison. The peculiar velocities of the four clusters in the apex-antapex cone are plotted as unfilled symbols; they are, from low to high V_{CMB}, Eridanus, ESO508, A3574, and A400. The plotted velocity of A400 and Eridanus are the opposite of the measured velocities, as a positive bulk velocity is one directed in the apex direction.

for Eridanus, +465 ± 140 km s^{-1} for ESO508, and +44 ± 185 km s^{-1} for A3574 (also known as Klemola 27). The large amplitude in the peculiar velocity field in the antapex region between 4000 and 5500 km s^{-1} is associated with infall and backflow in the high-density regions of the Perseus-Pisces supercluster.

The 30° semiaperture of the apex and antapex cones implies that if all galaxies in the sample shared a bulk velocity directed along the LP dipole, the radial peculiar velocity component of any galaxy should be at least 87% the bulk velocity amplitude. The plain visual inspection of Figure 1 reveals that, over the redshift regime sampled by our data, the mean motion of the spiral galaxies falls well short of that required by the LP finding. However, the scatter in the data is large. It should also be pointed out that the LG motion of 630 km s^{-1} with respect to the CMB, if shared by galaxies in the sample, should project at roughly half that amplitude (about 300 km s^{-1}) in the direction of the LP apex and antapex.

An alternative representation of the comparison between our data and the LP bulk flow can be obtained by combining the apex and antapex regions, as done in Figure 2. We bin the data in redshift windows of 1000 km s^{-1} (except for the last window, which includes objects between 6000 and 8000 km s^{-1}), combining in opposition the apex and antapex data sets, and we obtain for each bin a median value of the distribution of peculiar velocities. The thin error bars about each point subtend the range within which the second and third quartile of the distribution of peculiar velocities are enclosed. Mean values and standard deviations are not used because the distributions depart substantially from a normal one, partly because of real motions and, in part, because of the presence of a few very high peculiar velocity points (which are unlikely to have a physical origin, and may reflect undetected inadequacies of the data for Tully-Fisher application). The number of galaxies contributing to each data point are given in the lower part of the graph. A rough estimate of the accuracy of the estimate of the median values is indicated by the thick portion of the error bars; this estimate is obtained by dividing half the peculiar velocity range, over which two thirds of the points are found, by the square root of the number of points in each bin, producing a number that for a normal distribution would be close to the standard error on the mean.

As we pointed out at the beginning of this section, the peculiar velocities are uncorrected for Malmquist bias. As shown by our Monte Carlo simulations (Freudling et al. 1995), if peculiar velocities are averaged in bins of redshift, rather than TF velocity, and if the inverse TF relation is used to estimate v_{pec}, then no significant Malmquist bias is present in the averages (see their Fig. 5*d*). Any small, residual Malmquist bias present would, at any rate, be cancelled out by the combination of peculiar velocities in the apex and antapex cones shown in Figure 2. These results are corroborated by the estimate of the bulk motion from the reconstruction of the three-dimensional velocity field within a 6000 km s^{-1} top hat, obtained by da Costa et al. (1996a).

Every median value in Figure 2 lies below the LP bulk velocity amplitude; in fact, most points do not exceed half that amount. The median value of the bulk velocity within a volume of 5000 km s^{-1} redshift radius is less than 200 km s^{-1}, while that in the volume between 4500 and 8000 km s^{-1} appears indistinguishable from zero. The component of the LG motion with respect to the CMB (as obtained from the CMB dipole), along the direction of the LP apex-antapex amounts to about 300 km s^{-1}. This compares reasonably well with the amplitude of the motions of the galaxies within 4000 km s^{-1}, and is consistent with the idea that those may be, in part, travelling companions of the LG with respect to the CMB. Beyond that distance, the amplitude of the motion appears reduced; a more detailed interpretation is hampered by the presence of large infall and backflow motions in the Perseus-Pisces supercluster at 5000 km s^{-1}, which are visible in the LP antapex cone. In Figure 2, we also plot as unfilled squares the peculiar velocities of the four clusters that lie within the apex-antapex cone, namely Eridanus, ESO508, A3574 and A400, as derived by Giovanelli et al. (1996); for A400 and Eridanus, which are in the antapex region, the plotted values are the opposites of the measured velocities, as a positive bulk velocity is one directed in the apex direction. The motions of the clusters agree, within the accuracy of the measurements, with the individual medians of the galaxies.

4. SUMMARY

We have analyzed the motion of spiral galaxies in two cones, each of 30° semiaperture, centered, respectively, about the apex and the antapex directions of the bulk flow reported by LP. The median amplitudes of the bulk velocities identifiable in our data, in any redshift shell within 8000 km s^{-1}, are generally less than half the LP result. The median peculiar velocity within a redshift of 5000 km s^{-1} hovers between 0 and 350 km s^{-1}, depending on the redshift bin in which it is measured, and the flow appears to subside at redshifts of about 4500 km s^{-1} and larger. An average bulk flow with respect to the CMB as large as 689 km s^{-1}, of galaxies within the volume subtended by these data, which extend out to 8000 km s^{-1}, can be excluded. This result is corroborated by the analysis presented by da Costa et al. (1996a). What cannot be excluded, of course, is the possibility that much of the LP flow signature arises in shells external to the maximum redshift sampled by the data: we would then be presented with the unusual geometry of an envelope in coherent, large bulk flow, about a core region that would not share in that coherence.

The results presented in this paper are based on observations carried out at the National Astronomy and Ionosphere Center (NAIC), the National Radio Astronomy Observatory (NRAO), the Kitt Peak National Observatory (KPNO), the Cerro Tololo Interamerican Observatory (CTIO), the Palomar Observatory (PO), the Observatory of Paris at Nançay, the Michigan-Dartmouth-MIT Observatory (MDM), and the European Southern Observatory (ESO). NAIC, NRAO, KPNO and CTIO are respectively operated by Cornell University, Associated Universities, inc., and Associated Universities for Research in Astronomy, all under cooperative agreements with the National Science Foundation. Access to the 5 m telescope at PO was guaranteed under an agreement between Cornell University and the California Institute of Technology. This research was supported by NSF grants AST94-20505 to R. G., AST90-14850 and AST90-23450 to M. H., and AST93-47714 to G. W.

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