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STREAMING MOTIONS IN THE LOCAL UNIVERSE: EVIDENCE FOR LARGE-SCALE, LOW-AMPLITUDE DENSITY FLUCTUATIONS

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ABSTRACT

Using a new set of Tully-Fisher distances for northern spirals, we show that the previously detected motion of the Perseus-Pisces region toward the Local Group is not solely produced by the Great Attractor. Rather, a significant fraction of its motion may arise from a large-scale, parallel streaming flow that includes all galaxies within a sphere out to at least 6000 km s^{-1} in radius around the Local Group. This finding is supported by a new bulk flow analysis that uses more than 3000 galaxies. The magnitude of this flow, 360 ± 40 km s^{-1}, is consistent with *COBE* $\Delta T/T$ fluctuations but inconsistent with present limits on $\Delta T/T$ at 1° scale and potentially conflicting with a recent measurement of bulk flow on much larger scales.

Subject headings: cosmic microwave background — galaxies: distances and redshifts — galaxies: photometry — large-scale structure of universe — surveys

1. INTRODUCTION

This *Letter* reports the major results from the first Tully-Fisher survey of galaxy peculiar motions covering the entire northern sky. Peculiar motion surveys are the preferred means to map the true distribution of matter in the universe (Bertschinger et al. 1990), but a deep, comprehensive survey of the northern hemisphere has so far been lacking. The only previous deep northern survey is the elliptical catalog of Lynden-Bell et al. (1988, hereafter LB88; Faber et al. 1989), but ellipticals provide only sparse coverage. The present survey, coupled with the new southern sky survey of Mathewson, Ford, & Buchhorn (1992b), yields a much improved map of galaxy streaming motions out to 6000 km s^{-1} in all directions.

The aim of this *Letter* is twofold: first, to describe the general character of motions visible over the northern sky and to compare with the detailed pictures of the Perseus-Pisces supercluster in the north by Willick (1991, hereafter W91) and others. Willick detected an inflowing motion of Perseus-Pisces (PP) of ~350 km s^{-1} toward the Local Group (in CMB coordinates), but the cause of that motion could not be ascertained, whether due to acceleration by the Great Attractor/Local Supercluster or part of a larger scale bulk flow. Since the present survey provides several lines of sight that are both transverse to the indicated bulk flow axis and also directed away from the Great Attractor, it is well suited to distinguish these two possibilities. A second goal is to combine the new survey with published data to create a homogeneous catalog of galaxy peculiar motions containing some 3171 objects. We have used the new catalog to calculate the bulk streaming of galaxies out to 6000 km s^{-1}, with much improved error bars. The second part of this *Letter* summarizes these new results and compares to predictions from *COBE* and recent measurements of peculiar motions.

2. OBSERVATIONS OF THE NORTHERN SAMPLE

2.1. *Sample Selection and Data Reduction*

We have identified all Sb-Sc galaxies from the Uppsala Catalog of Galaxies (Nilson 1973) meeting the following criteria: $m_B < 15.5$, blue major axis diameter $\leq 4'$, and inclination between 55° and 75°. The upper inclination limit is to prevent distortion by dust obscuration on the optically measured rotation curves (Courteau & Faber 1988). Galaxies with Galactic extinction $A_B > 0.5$ mag (Burstein & Heiles 1984) and all peculiar and interacting galaxies were also eliminated. No upper redshift limit was imposed. This basic sample numbered 381 objects, of which complete data on a random subset of 326 objects were obtained. To check our velocity widths and estimated distances, 50 extra cluster calibrators were added from the catalog of Bothun et al. (1985). These cluster galaxies were also studied by Willick for his derivation of a new r-band Tully-Fisher (TF) calibration (W91).

Photometric observations were carried out at Lick, Palomar, Kitt Peak, and Las Campanas; 335 galaxies were measured, 157 of them at least twice. Exposure times of ~900 s with a 40″ telescope enabled accurate surface photometry to 26.5 r-mag arcsec^{-2} in most cases. Comparison of 99 matching observations with W91 shows rms differences of $2\overset{\circ}{.}8$ in inclination, $0\overset{\mathrm{m}}{.}053$ in total extrapolated magnitude, and negligible systematic error. Total magnitudes were corrected for Galactic absorption, internal extinction, and K-correction as described by Courteau (1992).

Spectral observations were made at Lick and Las Campanas. Exposure times were 1500–1800 s, and rotation velocities were measured from the line width of Hα. The final collection includes 353 galaxies, with 76 galaxies observed more than once. Typically, the rotation curve ends at ~75% of the optical radius (25 r-mag arcsec^{-2}), far enough to sample

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the maximum rotational velocity. The optical ΔV measured from velocity histograms agree internally to ± 12 km s^{-1} and to ± 24 km s^{-1} with 21 cm ΔV from R. Giovanelli & M. P. Haynes (1990, private communication). The final line widths were corrected for inclination and redshift broadening. For further details see Courteau (1992).

2.2. *The Distance Indicator*

We have used a "forward" r-band TF calibration to infer galaxy distances, derived from a set of 10 northern clusters (Bothun et al. 1985) plus ~ 100 field spirals in a region of quiet Hubble flow (see below). Details will be presented elsewhere (Willick, Courteau, & Faber 1993). The calibration is

$$M_{\rm TF} = 15.064 - 7.258\eta ,$$

where $M_{\rm TF}$ is the predicted r-band magnitude at the distance of Coma and $\eta \equiv \log \Delta V - 2.5$. The scatter about the fit is 0.30 mag, or an error of 14% in distance. Galaxy distances derived from a forward TF calibration are subject to Malmquist-type biases (LF88, W91). As the galaxies in our northern sample are fairly uniformly distributed, we have assumed a homogeneous Malmquist correction, given by $\exp(0.74\Delta^2)$ where $\Delta = 0.30$ mag. This correction amounts to $\sim 7\%$ per galaxy. For a few galaxies in groups or clusters (of N objects), the median distance of the group is used, and Δ^2 is replaced by Δ^2/N. The peculiar velocity (PV) of a galaxy is the difference of its recessional velocity relative to the CMB frame, $v_{\rm CMB}$, minus its inferred distance (in velocity units), $v_{\rm TF}$.

3. RESULTS FROM THE NEW SAMPLE

Figure 1 shows the projected motions of the galaxies in the northern survey within 22°.5 of the supergalactic (SG) plane. Large peculiar motions are visible in the PP region (lower right), but the northern Galactic hemisphere ($Y > 0$) is rather quiescent. Galaxies with strongly negative PVs are either falling toward the Local Supercluster ($v_{\rm TF} \lesssim 3000$ km s^{-1}) or onto the backside of the PP region. Galaxies with statistically positive PVs are visible on the nearside of PP falling outwards, although with smaller velocities than galaxies falling in from behind. Some portion of the apparent infall pattern around PP is due to distance errors, but, using the above error estimate, at least half of the observed variance around PP is due to real motions (the scatter at the core of PP is 0.49 mag).

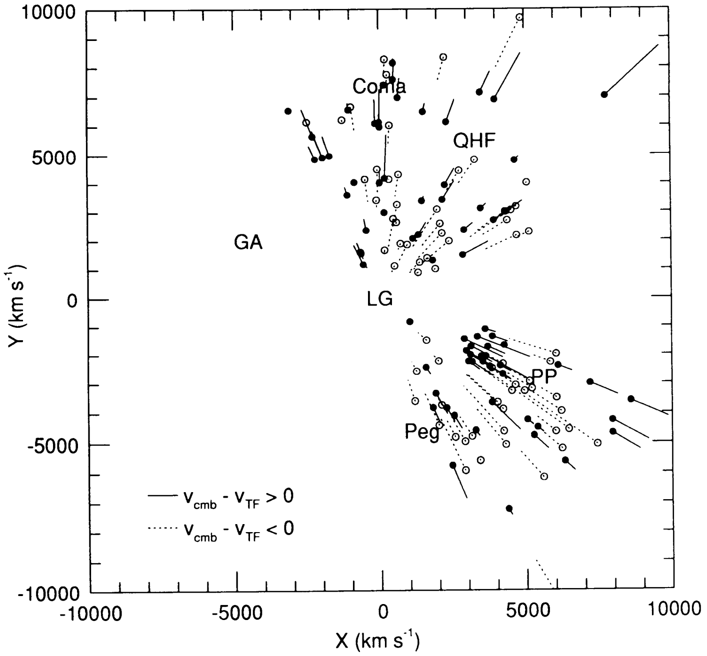

FIG. 1.—Map of measured peculiar velocities in the new northern sky survey within $\pm 22°.5$ of the supergalactic (SG) plane. Local infall to the Perseus-Pisces supercluster is visible at lower right; by the section with $Y > 0$, in the north Galactic hemisphere ($b > 0$), is a region with quiet Hubble flow (QHF). Galaxies are ungrouped in this figure.

No other feature comparable to PP, either in PVs or number density of galaxies, is visible in the northern Galactic hemisphere. The Great Wall is perpendicular to this slice and intersects it near Coma, but no large-scale pattern is visible there, nor is it in the larger compilation we present in § 4. Infall onto Coma has been detected by Bothun et al. (1992), but only on small scales very close to the cluster.

The existence of the northern region of quiet Hubble flow (QHF) provides an independent check on the TF scatter using field (as opposed to cluster) galaxies. For galaxies beyond 4000 km s^{-1} (where the LSC perturbation has clearly shut off), the rms scatter about the mean Hubble flow for $Y > 0$ is only $0^{\rm m}.34 \pm 0^{\rm m}.02$. This provides an upper limit to the real TF scatter and confirms that the motions in the QHF region are indeed small.

As Figure 1 makes clear, the geometry of the new survey allows us to test for the origin of the acceleration responsible for the inflow motion of PP toward the Local Group. If the Great Attractor alone were responsible, then a similar inflow would be visible looking outwards to comparable distances in the *north* Galactic hemisphere (assuming similar contributions from the distant matter distribution in both directions). Visual inspection indicates that no such inflow is present (beyond 4000 km s^{-1}). This impression can be quantified in the following way. In Figure 2*a* we compute the mean peculiar velocity of galaxies binned by $v_{\rm TF}$ for the entire QHF region. If the TF distances of these galaxies are properly corrected by homogeneous Malmquist bias and our TF relation is properly zero-pointed, this quantity should be a true measure of absolute galaxy motion. The result, for galaxies beyond 4000 km s^{-1}, is -55.1 ± 77.1 km s^{-1}, consistent with no significant net flow at distances comparable to PP.

Using the same technique for PP would be dangerous because PP is manifestly inhomogeneous, and the homogeneous Malmquist correction does not apply. Instead, we bin galaxies by $v_{\rm CMB}$ rather than by $v_{\rm TF}$. As emphasized by J. Roth (1991, private communication) and W91, galaxy peculiar motions binned this way are free of Malmquist bias but *are* subject to selection biases. The raw motions are therefore not meaningful, but we can exploit the fact that our galaxy sample is homogeneously selected over the whole northern sky. By subtracting QHF from PP, selection biases cancel out, and the *difference* is valid. The average difference (PP − QHF) is -383 ± 58 km s^{-1} (Fig. 2*b*). If the QHF region is taken to be at rest, this value then represents the motion of the PP supercluster toward the Local Group. (The net motion of PP using the homogeneous Malmquist $v_{\rm TF}$ method is -401 ± 96 km s^{-1}, in good agreement with this value, although less rigorously justified.) This streaming motion of PP toward the Local Group agrees well with the value of 350 ± 55 km s^{-1} measured by W91 and 420 ± 115 km s^{-1} measured by Han & Mould (1992) (see also Ichikawa & Fukugita 1992).

In light of these independent confirmations, a streaming

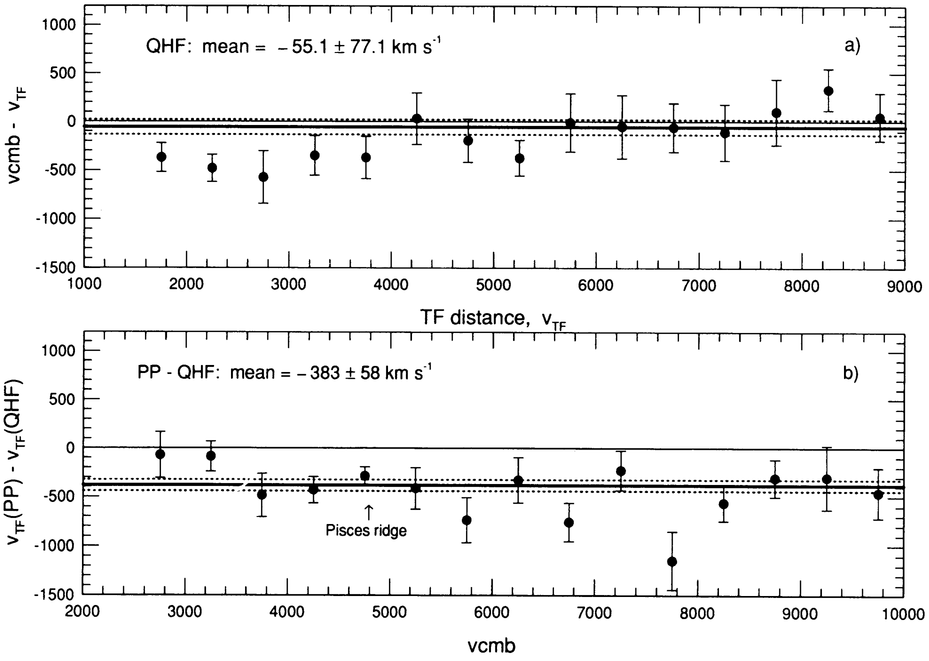

FIG. 2.—(*a*) Mean peculiar velocities of galaxies in the QHF region ($Y > 0$), binned by $v_{\rm TF}$. A homogeneous Malmquist correction to $v_{\rm TF}$ has been applied. The average value is consistent with no net radial flow. (*b*) Mean difference velocities (PP − QHF), binned by $v_{\rm CMB}$. Selection bias cancels in this difference, giving a true value of PP − QHF. PP seems to be moving toward the Local Group relative to QHF beyond 4000 km s^{-1}.

motion of ≈380 km s^{-1} at PP appears to be clearly established. We also showed above that a similar inflow does not extend to the northern Galactic hemisphere, arguing against the Great Attractor as the major source of PP's motion. Rather, it appears that the motion of PP toward the Local Group is an extension of the motion of the Local Group, the Local Supercluster, and even the Great Attractor region, such that there exists a bulk streaming motion directed along the PP-Great Attractor axis and involving a region out to several thousand km s^{-1} around us. A similar bulk motion was proposed by Dressler et al. (1987) as a possible explanation for the streaming of their all-sky sample of 385 ellipticals. More recently Mathewson, Ford, & Buchhorn (1992a), using their southern data and the data of W91, supported the claim of bulk flows generated on large scales while also questioning the existence of the Great Attractor. Investigating this bulk streaming quantitatively and providing a clearer overall picture of the velocity field is the aim of the following sections.

4. A NEW VELOCITY COMPILATION

To determine the local bulk streaming motion with high accuracy, we have combined existing surveys into a homogeneous catalog of galaxy distances. This catalog also yields an excellent map of the underlying total mass distribution, assuming the gravitational instability picture, and enables a derivation of Ω using nonlinear velocity effects in voids and high-density regions (Dekel et al. 1993). The new all-sky compilation includes 537 ellipticals (Lucey & Carter 1988; Faber et al. 1989; Dressler & Faber 1991) and 2584 spirals (Aaronson et al. 1982; Bothun et al. 1984; Dressler & Faber 1990; Mould et al. 1991; W91; Courteau 1992; Mathewson et al. 1992b; Han & Mould 1992; Mould et al. 1993). We have adopted the system of Han & Mould 1992 to reference all data sets to the same TF zero point. Details of this catalog will be given in Willick et al. (1993).

We model the local expansion field in a manner analogous to LB88. A simple bulk flow solution using a volume-weighting scheme to minimize the bias caused by sparse sampling (Dekel, Bertschinger, & Faber 1990) gives a bulk motion of 360 ± 40 km s^{-1} in the direction of $\ell = 294° \pm 5°$, $b = 0° \pm 4°$ with respect to the CMB over a top-hat sphere ∼6000 km s^{-1} in radius (see Table 1). The solution within 2000 km s^{-1} is close to the motion of the Sun relative to the CMB, but the component perpendicular to the supergalactic plane is reduced. On the largest scale, the direction of streaming is similar to the early report of bulk motion by Dressler et al. (1987), but the amplitude is smaller because the sample is much less dominated by rapidly moving galaxies near the Great Attractor, and because we further de-emphasized the Great Attractor by our volume-weighting scheme. We also obtain similar solutions using a different technique based on potential analysis (Dekel et al. 1993). The apparent disagreement with Mould et al. (1993) on the 6000 km s^{-1} scale is unexplained at present; this will be discussed further in Courteau et al. (1993).

TABLE 1

BULK FLOW VELOCITIES[a]

Reference	Volume	$V_{\rm bulk}$	-ℓ	b
This paper	0–2000	409 ± 66	295°	+35°
	0–4000	385 ± 38	279	+11
	0–6000	360 ± 40	294	0
	2000–4000	363 ± 48	273	0
	4000–6000	430 ± 41	305	−12
Rubin et al. 1976; ScI's as revised by Schechter 1977	3500–6000	730 ± 250	329	+33
Dressler et al. 1987: Egals	0–3200	599 ± 104	312	+6
Mould et al. 1993: 38 clusters	0–6000	559 ± 107	326	−9
Lauer & Postman 1993: BCGs	0–15000	730 ± 174	339	+50

[a] Velocities and volume limits are in km s^{-1}.

5. DISCUSSION

This bulk flow solution confirms our inference from Figures 1 and 2 that there exists a large-scale streaming motion of 300–400 km s^{-1} parallel to the PP-Great Attractor axis that extends out to $\sim$6000 km s^{-1} around the Local Group. Toward PP we look directly upstream and see the full magnitude of this flow. Downstream, we see the Great Attractor moving *as a whole* with comparable or perhaps slightly smaller velocity (see also Mathewson et al. 1992a). Toward the rest of the sky, including the northern QHF region, we look crosswise to the flow and see little motion.

The most likely explanation for the origin of this bulk motion is that of low-amplitude density fluctuations generated on very large scales, at least in an Einstein–de Sitter universe ($\Omega = 1$) (Clutton-Brock & Peebles 1981; see also Scaramella et al. 1992). Density fluctuations at the 10% level generate the overall large-scale streaming motions, while massive attractors like the Great Attractor, PP, or the Shapley Concentration (Scaramella et al. 1989) account for smaller scale motions which are superposed on the large-scale flow.

Our measurement of bulk motion is completely consistent with both the CMB temperature fluctuations of $\sim 10^{-5}$ on scales of a few degrees detected by *COBE* (see e.g., Dekel 1993) and predictions from cold + hot dark matter models (Klypin et al. 1993). We note, however, a discrepancy with the small-scale CMB $\Delta T/T$ limit of 1.4×10^{-5} on scales of 1° by Gaier et al. (1992). This upper limit is inconsistent with our measured bulk flow at about the factor of 2 level, as also noted by Górski (1992), and is therefore comparably inconsistent with *COBE*. However, this measurement is soon to be superseded by more sensitive measurements, which may yield larger values.

How large a volume must be probed for the peculiar velocity field to damp out is unclear. Lauer & Postman (1993) recently reported a very large scale bulk flow in a sphere of radius 15,000 km s^{-1} (see Table 1). This detection is very similar to the old Rubin-Ford effect (Rubin et al. 1976), but it probes a volume 15 times greater. The direction of motion is quite different from ours, and the amplitude is much larger. Even if one were allowed total freedom in choosing the true cosmic rest frame, it is still doubtful that any standard dark matter scenario (see Klypin et al. 1993) could reproduce the *difference* between these two values, which is completely independent of the adopted cosmic rest frame. Lauer & Postman's study seriously challenges models of large-scale structure formation, but awaits independent observational confirmation. Clearly, it is essential to continue to probe the Hubble flow on the largest possible scales.

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